MODULATED SOLAR SHIELDING OF BUILDINGS:

A study of a solar radiation control strategy for low energy buildings in hot dry and semi-arid climates

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To my parents who gave me a firm foundation;

To God who gave me, as everyone else, some talent to develop, and

To my wife for giving me the freedom to do so.

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Modulated Solar Shielding Of Buildings: A study of a solar radiation control strategy for low energy buildings in hot dry and semi-arid climates

(Gbadamosi Salami Yakubu)

SUMMARY

This study investigated the use of modulated solar shielding in the context of solar radiation control in hot-dry and semi-arid climates. Solar shielding refers to the solar protection of the entire or large parts of the building's external fabric and not just those elements which directly transmit solar radiation. The study was undertaken with particular reference to the hot semi-arid climate of northern Nigeria.

A conceptual and climatic analysis provided a contextual background for the work. A study of the use of shading devices indicated that their strength in some climates may be their weakness in others, especially the hot dry and semi arid climates. A multiplicity of inherent climatic and environmental elements were not fully addressed by formal shading techniques. The concept of solar shielding was conceived from the interplay of the climatic and environmental factors of hot dry and semi-arid lands.

Lack of measured solar radiation data in the reference climate necessitated the development of an interactive computer program to generate this and other relevant design data. A literature review provided a theoretical foundation underpining a series of full scale field measurements, scale model experimentation and thermal simulation studies.

Full scale measurements in a building were instructive on a possible impact of solar shielding on indoor thermal conditions. Model scale wind tunnel tests on the reference building and studies on full size louvres, using a pressurisation test facility, culminated in the development of airflow models through louvres. Finally, parametric thermal modelling studies enabled not only the optimisation of the technique but also a comparison with formal shading methods. Measured and simulated data portrayed not only a significant agreement but also indicated that solar shielding could have a higher solar protection efficiency than shading devices.

Contents

Chapter 1

Introduction

1.1 Preamble

This chapter presents the **introduction** to the study, the **definition** of the **problem** that is being addressed, the **scope** and **limitations** of the study, and the **research methodology** adopted for its execution. It also introduces the concept of modulated solar shielding as a solar radiation control strategy followed by a discussion of some of its implications for daylighting and outward view.

1.2 Climate, Culture and Building

Of all the factors and elements affecting the built environment in any part of the world, **climate** seems to be the most significant. Depending on the location, buildings either need to be heated or cooled to maintain comfortable indoor conditions. In the tropical zone, which is the hottest climatic belt in the world, the main problem is how to maintain comfortable indoor climate by cooling, either passively or mechanically. In the hot dry and semi arid climates the heat is even more intense and therefore there is an even greater need for evolving an architectural philosophy that can effectively cope with the stress of the climate.

Although the elements of climates are variable and difficult to determine they are relatively more constant over a period of time than those constraints imposed by man such as style, function and aesthetic taste. The data of climatic features over a very long period of say, 100 years, can be relied upon as the basis upon which design decisions can be made. This cannot be said for man's aesthetic taste and fashion. However, there are human constraints which have a similarity to the lasting nature of climatic features, namely the socio-cultural and traditional idiosyncrasies of a people. It may be observed, through careful scrutiny of cultural/traditional profiles of various parts of the world, that there is probably some salient relationship between climate and culture. But this is for the social scientist to establish. The crux of the matter within the scope of this study is that architecture must respond both to the climate and the tradition/culture of the user. It is debatable whether architecture and building form are mainly a response to the culture and way of life of the people as postulated by Rapoport, (1969) and Rudofsky, (1964, 1977) among others, or to the dictates of the climate as put forward by the exponents of bioclimatic design including Olgay and Olgay (1957), Olgay (1963), Koenigsberger *et al* (1973), Givoni (1976), Evans (1980) and so on. In any case, if a building is able to passively meet the demands of the climate, it will have gone a long way to satisfying the cultural needs since both are not mutually exclusive, but it is doubtful if the reverse is true.

Responsiveness to climate has almost become synonymous with responsiveness to the sun, which is quite understandable in some respects since the sun is the source of the prime energy that shapes the climatic belts and life therein. The sun is the ultimate source of energy on which the life force of the earth and it's inhabitants is dependent, and whose movement across the sky gives Man a perception of rhythm, having a strong bearing on time, climate and the seasons. As stated by Knowles, (1981),

> "The sun is fundamental to all life. It is the source of our vision, our warmth, our energy, and the rhythm of our lives. Its movements inform our perceptions of time and space and our scale in the universe".

Generally places on the earth surface closer to the sun have hot/warm climates because of the high intensity of solar radiation, while places relatively further away towards the poles receive less radiation and therefore have temperate/cold climates.

The power of the sun to sustain life on earth is so fundamental and dependable that man cannot conceive of life without energy from the sun (Cook, 1977). The benefit of this solar energy with respect to buildings is not only subjective but also a function of the location on the earth surface and consequently the climate. Solar radiation is "magnanimous" in cold/temperate climates where heat is not only needed for comfort but also vital for survival. In warm/hot climates solar radiation is a source of discomfort and every effort is made to cool the building to a comfortable level.

It is well documented that some of the earliest dwellings in Ancient Greece and some other different parts of the world were built with emphasis on access to the sun for heating in the winter season and/or ability to protect the habitable spaces against solar radiation in summer and therefore facilitate cooling. The famous words of Socrates in this regard as quoted by Xenophone in "memorabilia" epitomised the fundamentals of what is now called *passive solar* design techniques in high latitude climates and perspicuously indicate the root of the stereotyped form of contemporary passive solar houses in this climatic region.

There abound many examples in ancient and medieval buildings and settlements of the application of this *"solar architecture"* principle, including the Paleolithic camps in the south of modern France, Stonehenge in Salisbury Plains in the south of England, the palace of Knossos in Ancient Crete, (Tabb, 1984). Others include Abu Simbel in Ancient Egypt, the Teotihuacan in Central Mexico, the Pueblo and Anasazi dwellings of the American South West (Cook, 1977), the Ancient city of Olynthus and Priene and the Ancient Chinese city of Ch'angan (Butti and Perlin, 1980). More contemporary examples of forms responsive to climate include the windowless Eskimo igloo, The Malay house, the tropical African huts, the tropical steep-roof dwellings and the various vernacular forms in different climates [Oliver, (1971), Rapoport, (1969), Bourgeois and Pelos, (1983)].

The responsiveness of buildings to the stress of the climate is equally crucial in a hot dry/semi-arid climate which is so severe that life is hinged on the fringe of survival. Much of the discomfort is due to the heat from the scorching solar radiation. Daytime temperatures of 49^{o} C or more (far higher than skin temperature) have been recorded while on the other hand night time temperatures could be as low as 10^{o} C or less. The air is hot and dry with relative humidity as low as 10% or less (Golany, 1980). Sand storms and dust adversely affect breathing and keep the throat dry. Vegetation is sparse while rainfall is generally little. The sky is radiant clear most of the year and sky temperature is lower than the air temperature when the sky is clear. Ground *surface* temperature is usually higher than the air temperature (Holm, 1981). Also, flies and mosquitoes constitute a great nuisance as well as a health hazard.

1.3 The Problem and its Scale

Architectural response to climate can be found throughout the entire history of building in hot dry/semi climates. Many so-called "primitive" and "vernacular" inward-looking forms with massive walls and roofs of *adobe* were apparently fashioned with detailed knowledge of the climatic conditions and the use of suitable materials and techniques to achieve the desired climatic control objective. There are numerous literature in the field praise-singing the virtues of these ancient and medieval vernacular. Presently, however, everyone seems to want a complete break with these forms which are, *unfortunately*, fast becoming relics of the past. The great pace of urbanisation, increase in labour cost, changes in lifestyle and so on, may have virtually rendered these traditional buildings unsuitable. Although contemporary or "modern" architectural forms in hot climates, especially in hot dry and semi arid, were supposed to have developed as an improvement upon earlier forms, it is ironical that they have turned out to be remarkably unsuited to the climate. One would ponder upon the rationale behind the design and construction of a glass house in the name of "modernity" or "international style",in a climate as severe as that of Kano, Sokoto, Maiduguri (hot semi-arid) or Lagos, Port Harcourt and Enugu, (hot humid). Do our architects ***deliberately*** design ***ovens*** and put human beings in them to ***bake***? For example Fathy (1986) has stated that
"a 3m by 3m glass wall in a building exposed to solar radiation on a warm clear tropical day will let in approximately 2000 kilocaries (8.37 MJ) per hour. To maintain the microclimate of a building thus exposed within the human comfort zone, 2 tons of refrigeration capacity is required." And that is only a 3m by 3m glass wall. There are numerous example of an almost **complete glass facades** in **Lagos**. (See Figures 1.1 and 1.2).

Obviously, there are **a few people** who can afford to spend a fortune to cool down the ***ovens*** so created and live in them but there are **millions** who cannot and have to be condemned to live in misery. Anyone who has lived in or visited developing countries within the hot dry climatic belt will have experienced the horror of inappropriately designed contemporary buildings. There are many reasons for this sad state of affairs.

Paramount among these is that of the initial links with the outside word in the context of the profession and practice of architecture. Taking Nigeria for

Figure 1.1: A typical glass facade in a tropical climate
(Lagos, Nigeria.)

example, all the pioneering architects were trained abroad in those early days, far removed from the realities of their climates and where few schools had any programmes specifically designed to meet the demands of students from tropical countries. When these pioneers returned home they, naturally, *danced to the foreign tune*, either in practice or in teaching. With the *passion* for anything foreign, the work of these early architects were adopted as **models** both in theory and practice. The result of this, coupled with our ill-conceived city growth, has been an unmitigated urban disaster. It echoes the truism of the hypothesis that people have simply exported architectural solutions as if they were some standard consumer items. With the passion for, and total adoption of a misplaced ideological conception of what a good building should be, the schools of architecture in the country have, hitherto, not provided any respite from the *status quo.* When the student finally enters the profession, he carries with him all that he had learnt and of course, the vicious cycle continues. In any case being only a student's thesis, it is considered that this is not an appropriate medium to delve *too much* into so controversial an issue.

Furthermore, and as a result of the above, many designers in the country, and perhaps in most developing countries, are at best indifferent to the programme of bioclimatic design, for many reasons paramount among which is insufficient grounding on bioclimatic design principles (many schools do not satisfactorily execute the bioclimatic design requirements in their programmes, due to shortage of relevant equipments and personnel).

There is now a paramount preference for the so-called "modern" buildings by the public at large, especially the "nouveau riche" who build them for sheer pride and prestige and can afford their exorbitant cost of construction, maintenance and use, which rely heavily on mechanical air-conditioning. There is little consideration for the health hazards of excessive air conditioning use in spite of the growing concern in this regard in the developed countries.

In this light the continued 'praise singing' extolling the virtues of massive mud houses and expressing the need to continue with these *traditional* forms seems to be an exercise in futility since the tide of change that has taken place in favour of modern buildings is potentially irreversible. In spite of the virtues and climatic suitability of traditional buildings, the country, as with most parts of the developing "Third World" is experiencing a great change that is forcing an almost complete break with the past, to the extent that "every concept and every value has been reversed... in the name of progress and modernity" (Fathy,1986). It is very easy to lay blame on advancement in science and technology. But the fault lies not with technology but with designers who have failed to apply science and technology in harmony with man's physical, physiological and socio-cultural needs. To a great extent, technology has brought a new dimension to life on earth, and has made living on the planet increasingly easier, in many respects.

What seems paramount at this time is that architects and engineers in developing countries should use science and technology to design in harmony with nature and in resonance with the rhythm of the universe as well as within the context of the socio-cultural and economic development. The words of Hassan Fathy (Fathy, 1986) aptly emphasized this responsibility of modern architects in the developing world when he stated that we

> "must renew architecture from the moment when it was abandoned; and must try to bridge the existing gap in it's development by analysing the elements of change, applying modern techniques to modify the valid methods established by our ancestors, and then developing new solutions that satisfy modern needs."

1.4 The Search for Solutions

The search for such solutions is rife in the field of bioclimatic or the recently coined "passive solar" or "low energy" design. Although there has been serious and genuine concern by workers in the field for viable solutions to the passive cooling needs of hot dry and semi-arid climates, using modern techniques and materials as opposed to the traditional ones, the solutions proposed have so far fallen short of the paramount problem of solar radiation control in contemporary buildings.

1.4.1 Double Roof Shells and Cavity Walls

It is well documented that the major source of solar heat gain in the tropics, apart from the glazings, is the roof. In attempting to minimise the heat build-up through the roof the double roof shells concept has sometimes been adopted. This is exemplified by, among many others, Le Corbusier's Hall of Justice in Chandegarh, India, which was conceived as a huge concrete parasol roof supported by massive pillars. The main building was separated from the parasol roof by a space which permitted free air circulation. Whilst the use of concrete was more of a means of achieving a preconceived aesthetic rather than a thermal control objective, the concept of the double roof shell as a solar protection technique seems quite apparent. However lack of performance data made its assessment impossible.

The main weakness of such materials as concrete for the upper roof is the high thermal inertia apart from its considerable dead load. The high thermal mass curtails their efficiency of reducing the solar heat gain. The use of a light upper roof made of discontinuous membrane that facilitates air circulation and maximises cooling area has been advocated.

The use of cavity walls has also been shown to be a feasible approach to reducing solar heat gain. It entails the use of two solid walls which may or may not be the same material, with a small air gap in between them to facilitate convective circulation.

The main impediments to applying both the double roof shells and cavity walls is the extra cost of adding the outer secondary skin, lack of information on the cost effectiveness or energy savings of its use on cooling loads. Furthermore, the air gap between the roof shells are usually small and hardly well ventilated. These factors seriously hamper their passive cooling efficiency.

1.4.2 A *Normalised* Shading Philosophy?

As far as seeking solutions to the problem of solar radiation control in building is concerned, the basic approach has been the adoption of the concept of shading and/or sun control strategy which, in earnest, should mainly be used in higher latitude climates for which they were conceptually designed and for which they are suitable. This concept is based on the use of shading devices to protect glazed areas of the building fabric against direct solar rays.

One of the most prominent features of all shading devices is that they have been designed and optimised with a fundamental underlying consideration of having a capability to give maximum shading during the hot summer and conversely let in the maximum sunlight in winter. The Olgays were very emphatic about this

when they suggested (Olgay and Olgay, 1957) that
"...the effectiveness of a shading device depends on the proportionate success with which it covers a given surface during the overheated period without intercepting the sun's energy during the under-heated times".

In hot dry and semi arid climates however, there is a constant need to keep the sun out, throughout the year. Unfortunately, this shading philosophy is used for contemporary buildings in this climate, as in all tropical climates. Has the shading concept been **normalised** to make it applicable to all climates world-wide? In light of the fact that there is no universal architecture, form or typology that meets the needs of all climates it is suggested that a shading philosophy must be so evolved as to reflect regional climatic diversity. In whatever perspective the inclements of the climates are viewed, the case of hot-dry/semi-arid climates is especially precarious.

The experience of people living and working in this climate has shown that the problem far goes beyond that of the scorching heat from the sun which is paramount and so dominating that the other problems are overshadowed: The dust storms, the swarms of flies (especially in the rainy season), the sheer stress caused by the high diurnal temperature range and the dry air, the choking *harmattan* dryness that cracks almost anything including the skin and lips, and the contrast of a relatively humid but brief rainy season - all of these are equally severe problems.

Furthermore, the need for protection against glare and against the diffuse and multiple intereflected irradiances, especially from the ground, calls for an alternative solar protection philosophy for hot dry and semi-arid climates.

In addition there is the great thermal stress experienced as one moves from indoors to outdoors which is due to the sharp contrast between the excessively hot outdoor and the relatively milder indoor respective environments. An effective shading or solar protection methodology should be able to meet these additional needs.

The unglazed part of the fabric of contemporary buildings, constructed with modern materials such as concrete and concrete block do absorb relatively more heat than the *adobe* fabric of the traditional buildings. Thus there is need for some form of **thermal barrier** between the fabric and the harsh outdoors. Creating this thermal barrier would call for an alternative shading strategy that would not in application necessarily be on the immediate facade of the building structure, a principle upon which the use of shading devices is based. Quoting Marcel Breuer, Olgay and Olgay (1957) emphasised this, saying:

> "The sun control device has to be *on the outside* of the building, *an element of* the facade, an element of architecture..."

Harkness and Mehta (1978), and some relatively recent research on solar radiation control in buildings have demonstrated how shading devices on the fabric of the structure can be so designed as to be more effective as well as transform the fabric into an aesthetically and visually pleasing forms. Most contemporary research on shading deal with variations of the mode of use/design of different solar protecting devices based on this concept and the effects of these variations on parameters of indoor thermal comfort.

1.4.3 The concept of modulated solar shielding

Taking inspiration from some simple analytical reviews (e.g. Yakubu, 1987(a), 1987(b)), the contextual and theoretical reviews undertaken for this study, and the direct experience of living in a hot semi-arid climate, the theme of this research effort was conceived. It is based on the concept of **modulated solar shielding**. Solar shielding refers to the solar protection of the entire or large parts of the building's external fabric (and not just those elements which directly transmit solar radiation), by an impermeable or semi-permeable structural membrane located away from the building fabric by a *usable* space. The structural membrane is referred to as the shielding system, while the boundary space between the *shielding system* and the building fabric is called the *shielded space.*

Thus the concept is based on the *shielding* of the building fabric, (as opposed to mere shading of the glazed openings), by a controllable or adjustable system separated away from the parent structure by a usable space. This space thus becomes a semi outdoor space, creating a buffer zone between indoors and outdoors. The shielding structure itself becomes a semi-porous secondary shell acting either as a *selective filter* or an *excluder* depending on the weather condition and the time of day, (see Figures 1.3a and 1.3b). The object is to study the application of this concept as a passive solar radiation contol strategy for the hot dry/semi-arid climatic belt, especially with respect to the reduction of solar heat gain.

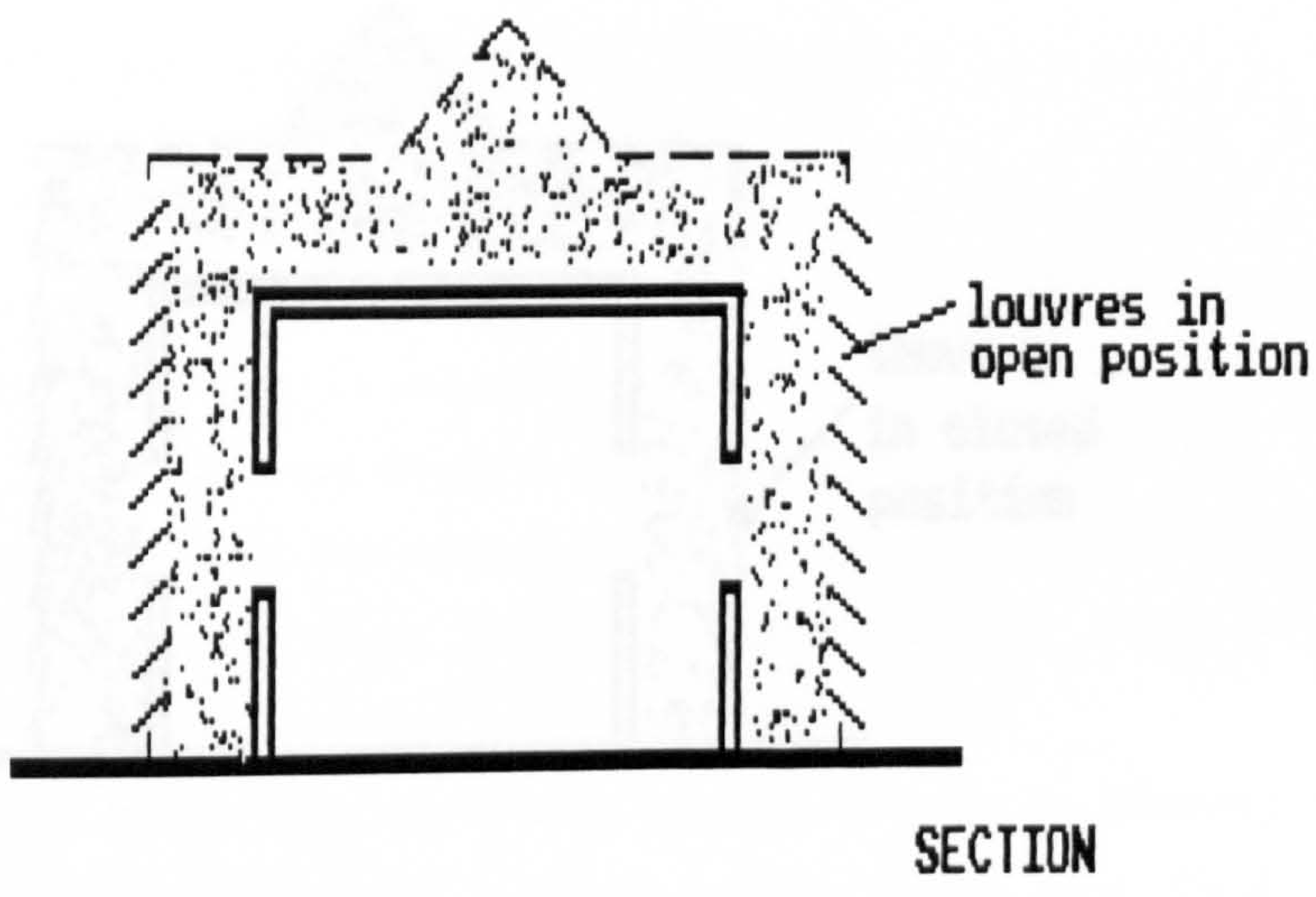
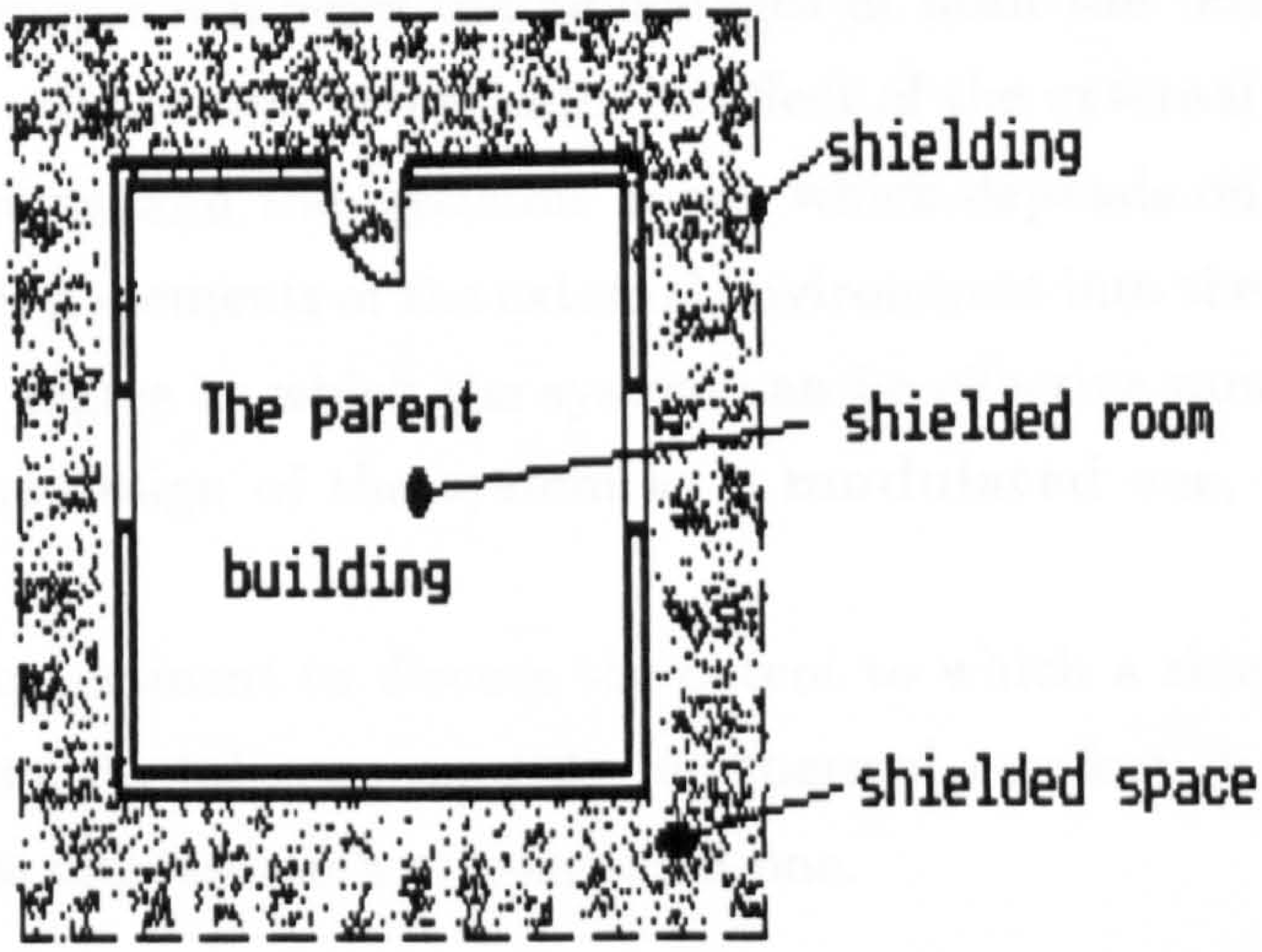


Figure 1.3a: The concept of solar shielding: A louvre shielding system in the open mode



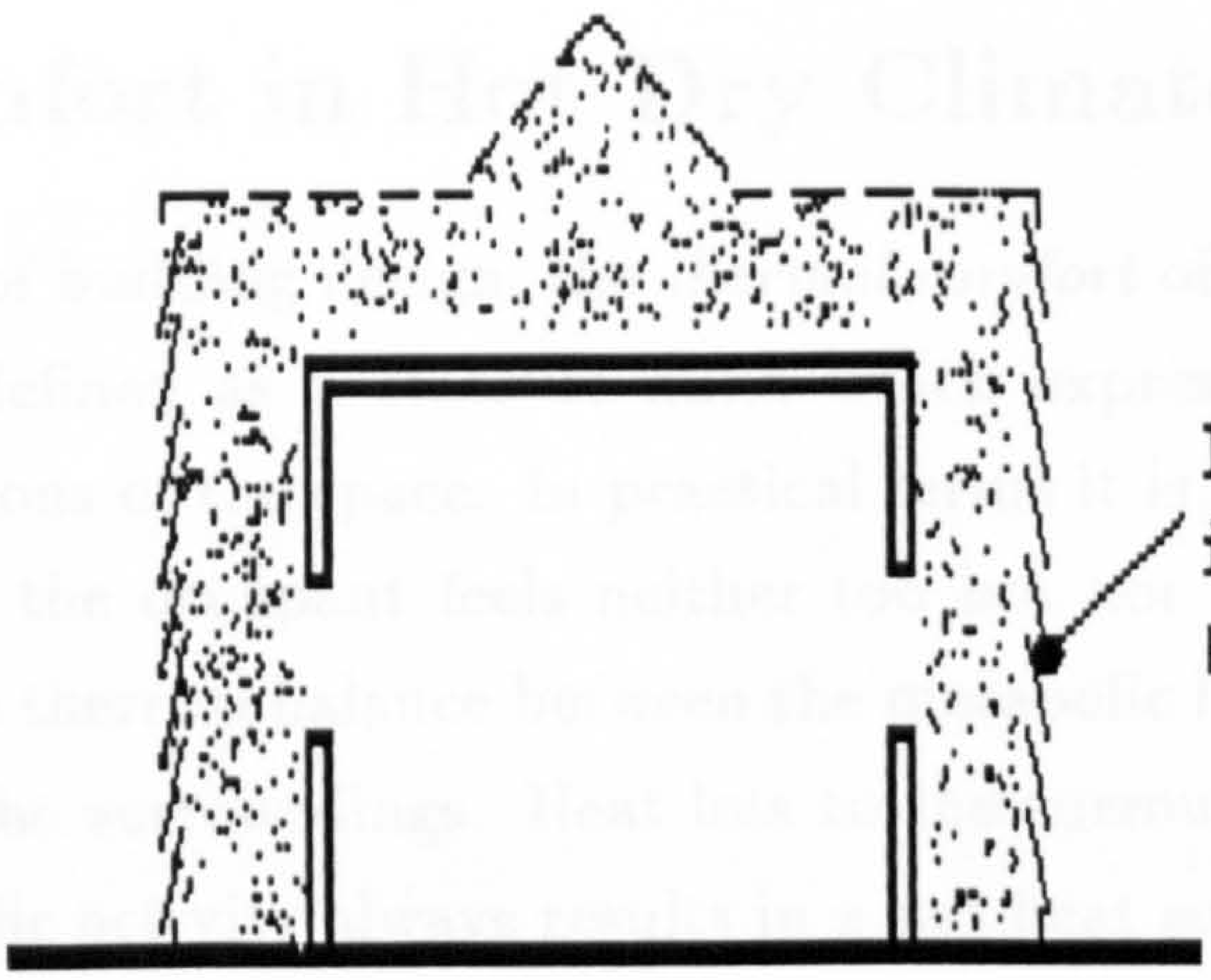


Figure 1.3b: The concept of solar shielding: The louvre shielding system almost completely closed

Thus the technique combines the advantages of both the '*exclusive*' mode in which the control system aims to exclude the effect of the external environment upon internal conditions, and the '*selective*' mode which depends on the selective admission of substantial elements of the external environment into the building (see Hawkes, 1982). The degree to which the system can be effective would depend to a large extent on the design of the system as a **modulated** one, with *suitable* materials.

It may also be pertinent to discuss the extent to which a shielded building may meet the environmental requirements for thermal comfort in hot dry and semi-arid climates, as opposed to a non-shielded one.

1.5 Environmental Requirements for Thermal Comfort in Hot Dry Climates

In the context of building design, the *thermal comfort* of an occupant in a defined space can be defined as a state of mind which expresses satisfaction with the thermal conditions of the space. In practical terms it is that condition within the space in which the occupant feels neither too hot nor too cold i.e. the state at which there is a thermal balance between the metabolic heat gain by the body and heat losses to the surroundings. Heat loss to the surrounding is a necessity since human metabolic activity always results in a net heat surplus.

The body's heat to the environment is governed by four processes namely radiation, convection evaporation, and to a less extent, conduction. Under a normal comfort situation, the relative magnitudes of these mechanisms of heat loss from the body have been suggested to be radiation (45%), convection (35%), evaporation (20%), and conduction (less than 1%) (Baker, 1987) The body also has self-regulatory physiological mechanisms which control the heat loss in order to balance the metabolic gains.

The three main mechanisms of body heat loss above (i.e. radiation, convection and evaporation) are controlled by four key environmental parameters, namely, mean radiant and air temperatures, relative humidity and air movement (air speed and direction). These may be considered as the key parameters which govern a person's sense of thermal comfort. The other important non-environmental factors are the clothing level and the level of body activity.

1.5.1 Mean Radiant Temperature - (Radiation)

The mean radiant temperature is the area weighted average temperature of all the surfaces of an enclosure. The radiation heat loss of the body to the surroundings is governed by the mean radiant temperature because the body's heat loss by radiation is dependent on the relative temperatures of all the surrounding surfaces such as floor, wall and ceiling surfaces. If the mean radiant temperature is greater than that of the body surface, then there will be heat gain by the body and vice versa.

1.5.2 Air Temperature and Air Movement (Convection)

Convective heat loss or gain by a body is *dependent upon* a function of the temperature difference between the surface and the air. The layer of air in contact with the body is heated up but because air is a poor conductor of heat, the loss relies on the removal of the warm air layer by air currents, which may be locally induced by buoyancy effect or externally induced by wind forces or by means of mechanical a fan.

1.5.3 Relative Humidity and Air Movement (Evaporation)

Evaporative heat loss relies on heat absorption from the surface of the skin (latent heat of vaporisation) in order to evaporate perspiration. The evaporation rate is influenced by both the relative humidity and air movement.

1.5.3.1 Comfort zones and Comfort Indices

Because thermal comfort may be attained by many different combinations of the mean radiant and air temperatures, relative humidity and air movement, attempts have been made to establish target boundaries within which a set of conditions is judged most comfortable by the largest number of people. Even within the "comfort zone" established by such a target set conditions, there is no single combination of values of the above variables that satisfies everybody. The concept of "bioclimatic design" was first introduced by Victor Olgay (Olgay, 1953) who defined the "comfort zone" on a "bioclimatic chart" (Figure 1.4a). Using the psychrometric chart, Givoni (1976), produced the *building bioclimatic chart*, defined the comfort zone and established the *probale limits* of ambient conditions under which certain passive thermal control techniques would give indoor thermal comfort. (Figure 1.4b)

Many tests have been carried out to establish the comfort zone. Researchers at Kansas State University (KSU) found that the most comfortable condition for subjects wearing light clothing (0.4 - 0.6 clo) corresponded 26.1 °C at 50% relative humidity, for air speed of less than 0.18m/s at an activity level of 1 Met.

One of the most common set of comfort conditions is that of the ASHRAE comfort standard 55-74, which is based on the responses of sedentary adults (activity level 1.0 - 1.2 Met) wearing light office clothing (0.5 - 0.7 clo). The comfort zone extends from 22.2°C to 25.5°C on the Effective Temperature (ET) scale, bounded by vapour pressures of 667 and 1187 *Pa*, with an assumption of air speeds of less than 0.23 m/s. It also represents the limits within which 80% of the subjects, tested at the J.B. Pierce Foundation at Yale University, expressed satisfaction with their thermal environment under carefully controlled conditions.

1.5.4 Corrected Effective Temperature

Various attempts have also been made to create a single comfort index which combine the effect of the four environmental parameters. One such index is the Corrected Effective Temperature (CET), which was experimentally obtained by varying comfort parameters in test rooms and determining the conditions judged comfortable by test subjects. Figure 1.5a shows the nomogram from which the CET may be estimated. This index is given units of "effective temperature" which could be defined as "*the temperature where the mean radiant air and wet bulb temperatures are all the same, and air movement is zero, which gives the same comfort sensation as the combined effect of the prevailing comfort parameters*" (Baker, 1987).

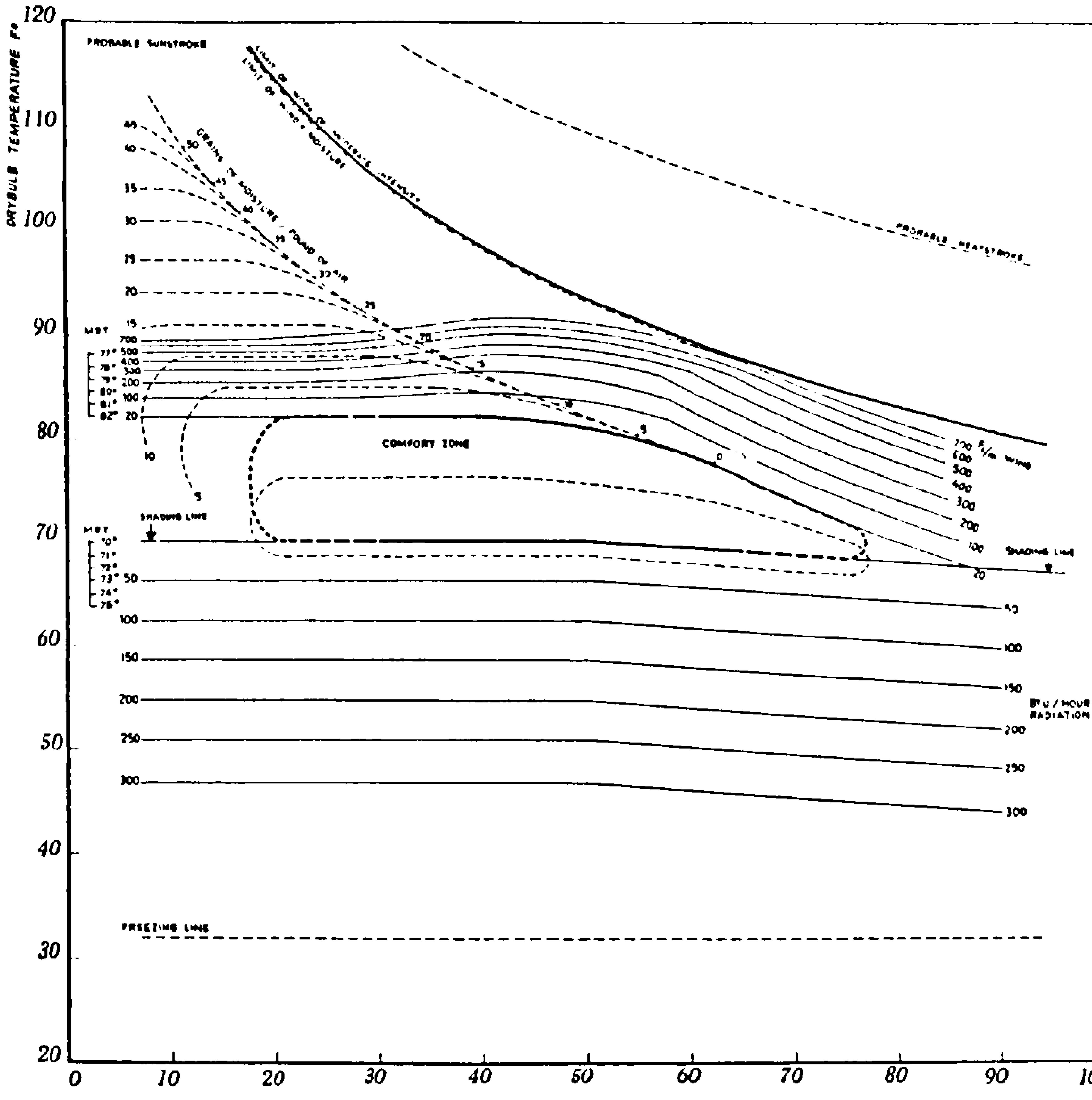


Figure 1.4a: The Bioclimatic Chart (after Olgay, 1953)

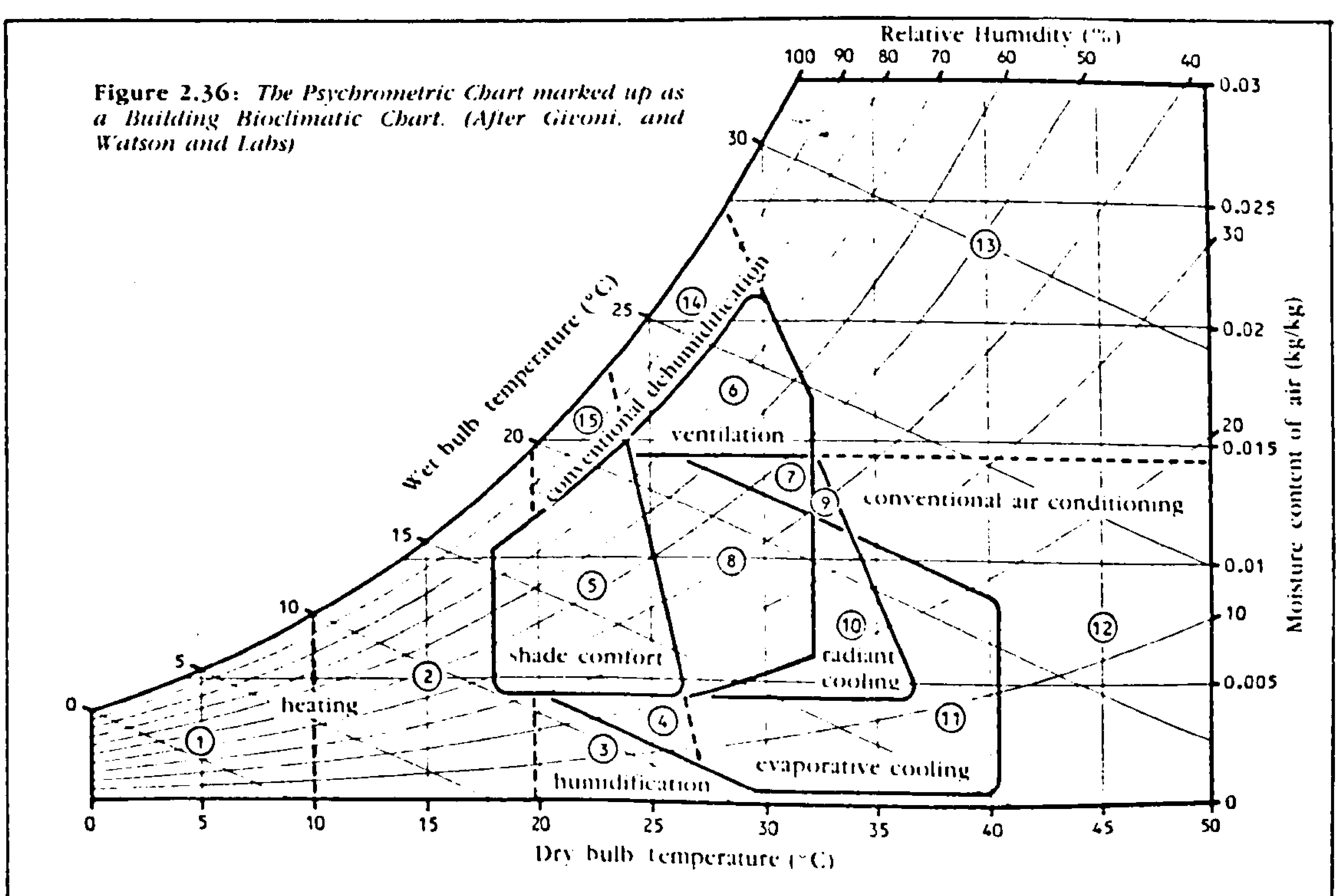


Figure 1.4b: The Bioclimatic Chart (after Givoni, (1969, 1976))

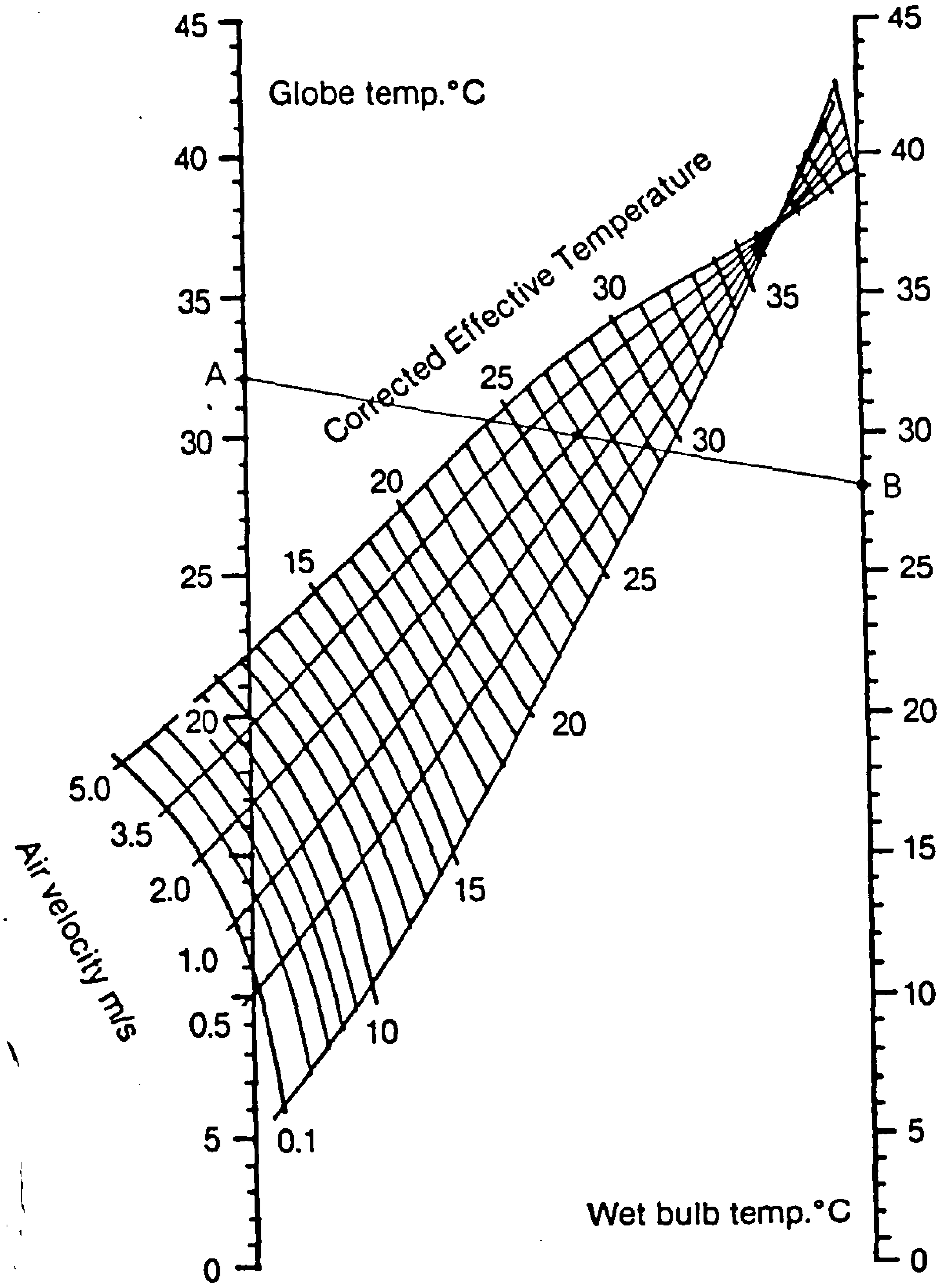


Figure 1.5a: The Corrected Effective Temperature Nomogram

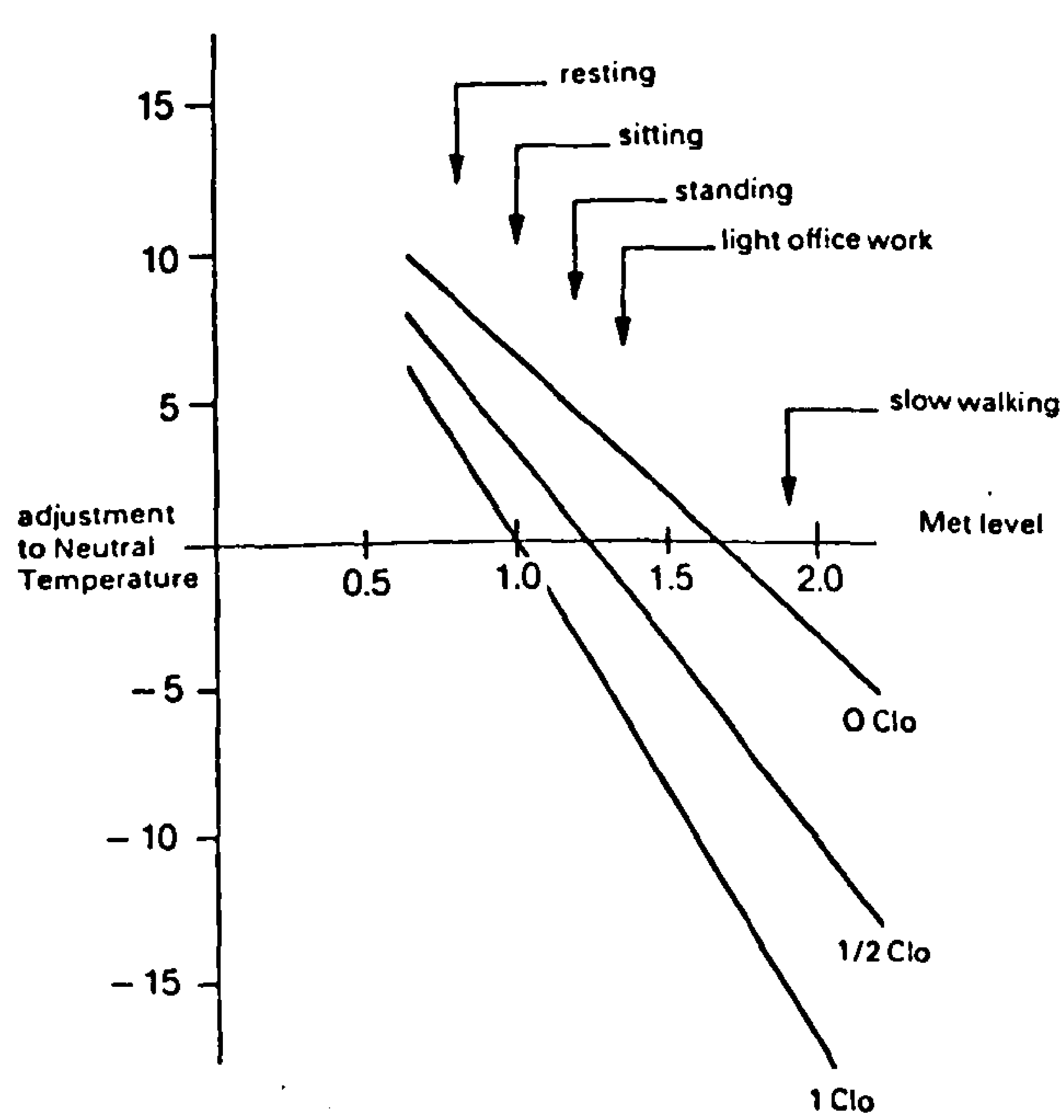


Figure 1.5b: Effect of activity and clothing levels on the neutral temperature

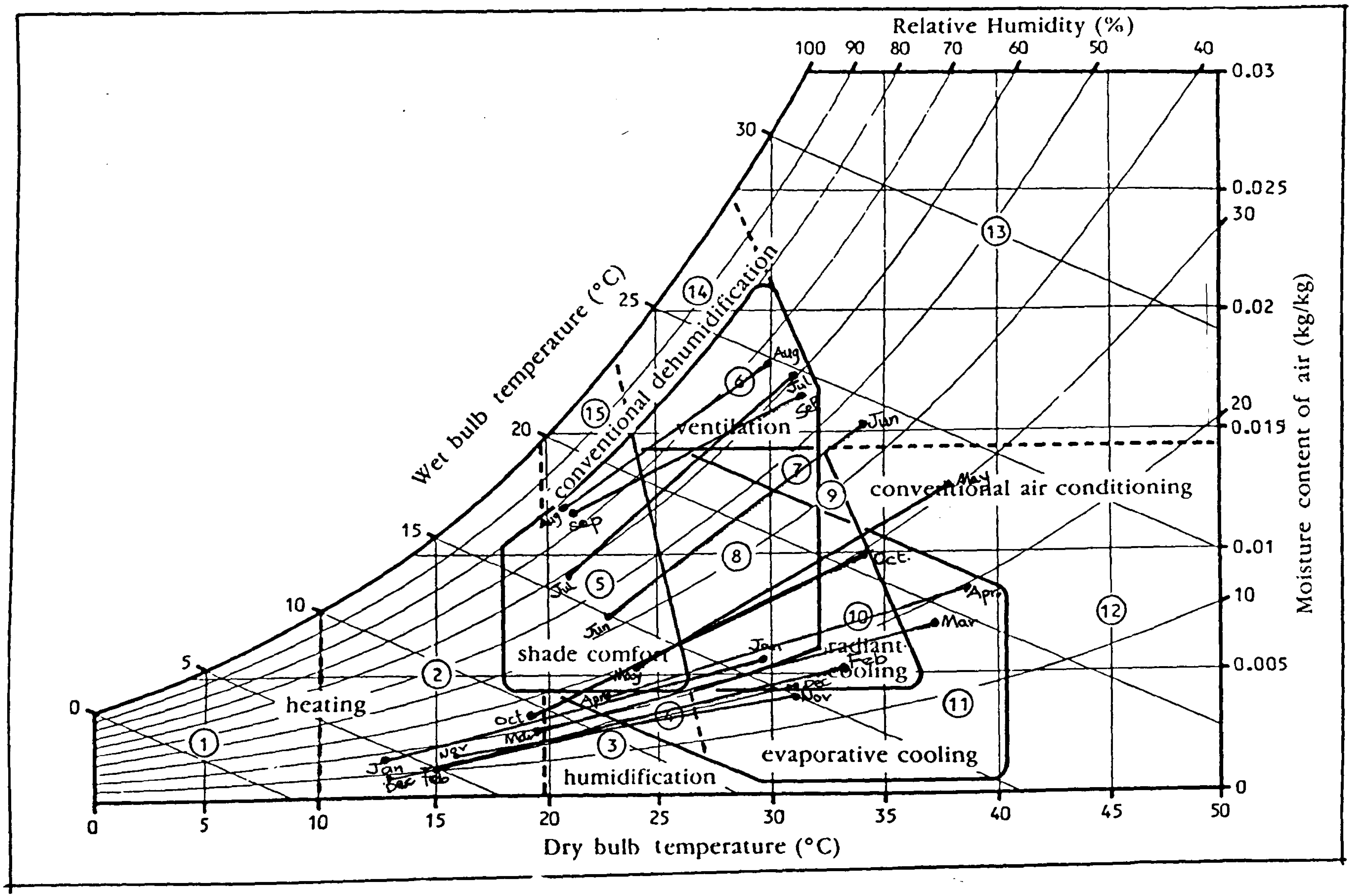


Figure 1.5c: Comfort analysis for Kano, northern Nigeria

1.5.5 Neutral Temperature

The concept of the Neutral Temperature has been deviced to establish target value of the CET. The neutral temperature may therefore be referred to as the temperature at which most people are comfortable. Among the many expressions for the neutral temperature is that due to Humphrey (1976), which expresses the neutral temperature as (see Baker, 1987)

$$T_n = 11.9 + 0.534 T_{amb} \pm 2.5^oC \tag{1.1}$$

where T_{amb} is the mean monthly outdoor temperature, the 2.5^oC band indicates the temperature zone over which 80% of the people judge to be between "comfortably cool" or "comfortably warm".

The standard neutral temperature is usually calculated for a person at rest and corrected for different clothing level and level of activity. Figure 1.5b shows the influence of both these factors on the neutral temperature.

1.5.6 Comfort Analysis

In order to establish the environmental requirements for thermal comfort in a hot-dry/semi-arid climate, the concept of the CET and the neutral temperature were used to carry out a climatic comfort analysis for Kano, Latitude 12° 03'N, Longitude 08° 30'E, a city located within the hot semi-arid climate of northern Nigeria.

The analysis of the annual cycle is plotted on the building bioclimatic chart (Figure 1.5c). The environmental requirements for thermal comfort for maximum temperature (maximum daytime discomfort) conditions are conventional (active) air conditioning (May and June), evaporative and radiant cooling (February, March, April and October), and ventilation (July, August, September), while January is almost within the comfort zone and a little air movement will suffice. Solar gain must be restricted for daytime thermal comfort throughout the year, by means of effective solar thermal control techniques.

For the minimum temperature (maximum night time discomfort) conditions, indirect passive heating measures are appropriate for January, February, October, November and December. Indirect heating by means of thermal mass would be very useful for these months. A combination of ventilative, evaporative and radiative cooling would be vital for March, April and May, while only radiative and ventilative cooling would be effective for the rest.

The above apply to the extreme conditions. For average conditions, the CET was used to analyse the climate using long term monthly averages of maximum daytime and night-time temperatures. For the night-time conditions, the 24-hour mean temperature and relative humidity were used. (Table 1.1). The neutral temperatures and the lower and upper limits of comfort throughout the year, for daytime and night-time conditions , are shown on Tables 1.2 and 1.3 respectively. The CETs were derived from the 24-hour mean values of temperature and relative humidities. The CET values enclosed in the box are those that are less than the neutral temperature, for $CET_{0.1}$, $CET_{0.5}$, CET_1 and CET_2, representing CETs at 0.1, 0.5, 1.0 and 2.0 m/s respectively.

The CET analysis shows that during the daytime, ***on the average***, 0.1m/s airspeed is enough to get within the $5°C$ band bordering the neutral temperature, for all the months of the year except the very humid months of June to September inclusive. This is unrealistic, especially for the hot season. The analysis also gives a rather erroneous impression that the climate may not be as severe as it really is. This may be due to the limitations inherent in the CET concept, namely (see Baker, 1987):

1. The use of mean values do not show the variations on either sides of these values;

2. The globe temperature is assumed to be the same as the air temperature when calculating the CET. This alludes to assuming that no solar or low temperature radiant sources are present;

3. The external conditions analysed are unmodified either by the local site conditions or the building itself.

1.5.7 Shielded and Non-Shielded Buildings

The extent to which a shielded and a non-shielded building can meet the above requirements for indoor thermal comfort would depend upon many factors. It will be borne in mind that *shielded* and *non-shielded* buildings in the context of this discussion refer to contemporary dwellings built with modern materials and

Table 1.1: Monthly average climatic data for Kano, Nigeria

	Aver. Temp			Max. temp		Min. temp	
Month	DBT	WBT	RH	DBT	WBT	DBT	WBT
Jan	21.0	11.9	30%	29.7	16.0	12.7	4.0
Feb	24.2	13.3	24%	33.0	16.5	15.1	5.0
Mar	28.3	15.9	23%	36.8	19.0	19.5	8.5
Apr	30.8	19.6	34%	38.4	21.0	23.3	11.0
May	30.3	22.1	50%	37.3	23.0	24.1	13.5
Jun	28.0	22.7	65%	34.3	24.0	22.8	15.0
Jul	25.7	22.5	77%	31.1	24.5	21.3	16.0
Aug	24.7	22.4	82%	29.8	24.5	20.9	17.5
Sep	75.7	22.6	78%	31.5	24.0	21.1	17.5
Oct	26.7	20.0	58%	33.9	21.0	19.7	9.5
Nov	24.3	15.0	36%	33.1	15.7	15.9	6.0
Dec	21.7	12.8	32%	30.6	15.4	13.3	4.0

Table 1.2: Climatic/Comfort Analysis (Daytime Conditions)

Month	Neutral	T_{lower}	T_{upper}	$CET_{0.1}$	$CET_{0.5}$	$CET_{1.0}$	$CET_{2.0}$
Jan	23.1	20.6	25.6	22.5	21.8	21.0	20.5
Feb	24.8	22.3	27.3	24.0	23.3	22.7	22.0
Mar	27.0	24.5	29.5	26.0	25.6	25.2	24.8
Apr	28.3	25.8	30.8	27.3	27.0	26.3	26.0
May	28.1	25.6	30.6	28.0	27.5	27.0	26.5
Jun	26.9	24.4	29.4	27.8	27.0	26.4	25.6
Jul	25.6	23.1	28.1	27.0	26.0	25.0	24.2
Aug	25.1	22.6	27.6	26.5	25.5	24.5	23.5
Sep	25.6	23.1	28.1	26.6	25.8	25.0	24.0
Oct	26.2	23.7	28.7	26.0	25.5	25.0	24.2
Nov	24.9	22.4	27.4	23.5	23.0	22.5	22.0
Dec	23.5	21.0	26.0	22.3	21.5	21.0	20.3

Table 1.3: Climatic/Comfort Analysis (Night Conditions)

Month	Neutral	$CET_{0.1}$	$CET_{0.5}$	$CET_{1.0}$	$CET_{2.0}$
Jan	22.1	17.2	16.0	14.0	12.7
Feb	23.8	19.0	18.0	16.8	15.2
Mar	26.0	22.0	21.0	20.4	19.4
Apr	27.3	24.5	23.9	23.0	22.2
May	27.1	25.2	24.5	23.5	22.5
Jun	25.9	24.5	23.5	22.4	21.4
Jul	24.6	23.8	22.5	21.4	20.0
Aug	24.1	23.2	22.0	20.8	19.0
Sep	24.6	23.8	22.5	21.4	20.0
Oct	25.2	23.2	22.0	21.0	20.0
Nov	23.9	20.0	18.5	17.2	16.0
Dec	22.5	17.8	16.2	14.5	13.0

techniques and not the compact - plan, traditional courtyard dwellings. It will also be remembered that in the context of this thesis, we are dealing with passive low-rise *domestic* buildings.

1.5.7.1 Solar Radiation Control

In the reference climates, the most crucial requirement, virtually all-year round, is solar radiation control and minimisation of solar thermal gain through the building envelope, so as to minimise or prevent building overheating. A solar shielded building has excellent opportunities to effect this control and minimise or prevent overheating because modulated solar shielding would no only completely prevent the direct component of solar radiation from reaching the fabric of the building but would also minimise the ingress of sky diffuse and inter-reflected radiation (see also Chapter 9).

A non-shielded building on the other hand is not so efficient in meeting the above requirement. The shading of the transparent parts of the fabric with conventional shading devices reduce solar thermal gain a little by either fully or partially preventing the direct component of solar radiation from penetrating through the transparent parts of the fabric. The experience of people living and working in a climate as severe as the reference climate has shown that this mode of solar protection has not been found to be effective (Etzion, 1990) due largely to the fact that they do not address the problem of diffuse sky and intereflected radiation and the fact that the entire building fabric is exposed to the intense global and reflected shortwave radiation during the day.

1.5.7.2 Radiative Heat Loss to the Radiant Sky

The extent to which a shielded building can meet this requirement would highly be dependent upon the extent to which the shield is conceived and designed as a *modulated* one. In any case, the rate of radiative heat loss of a shielded building, even if the shield can be modulated and opened up at night, would be invariably lower than that of a non-shielded one because the effective area of the parent walls and roof that "sees" the sky would still be less than the non-shielded one. However the modulation strategy can be so conceived as to reduce the impairment of radiative cooling to the minimum possible.

Therefore a non-shielded building would have a higher capacity for radiative cooling since, barring any obstructions, its entire fabric would be exposed to the cold radiant night sky. During the cold season, heat loss to the night sky is a serious disadvantage and should be minimised. A shielded building is better placed to effect this control.

1.5.7.3 Passive Ventilation Cooling

Passive ventilation would be useful at night during the hot season, and the mild-season, and useful both daytime and night time during the humid rainy season, but should be discouraged during the cold harmattan season, especially at night.

A shielded building can control airflow to match the external climatic conditions, building use, and the seasons. Passive ventilation cooling may be hampered by the shielding system depending on how it is designed and used. Again, the modulation of the shielding system is a crucial factor. It seems obvious that airflow through a shielded building even when the shielding system is in the open mode, would be less than that of a non-shielded building, but is doubtful if this reduction in airflow would constitute a very critical factor even during the relatively more humid rainy season.

A non shielded building would therefore promote passive ventilation more since it does not have anything beyond its facade that would impede airflow. However its efficiency in meeting this requirement would also depend on how far the building is designed to take optimum advantage of the prevailing airflow and direction, mode of use, and so on.

1.5.7.4 Evaporative Cooling

This is not only very useful during the hot and mild seasons but also in the dry harmattan season for a different reason - the humidification of the air through evaporation provides a relief. During the humid rainy season, evaporative cooling is not effective.

A shielded building can incorporate evaporative/convective cooling measures effectively within the buffer spaces on the sides and even on the roof. This would not only minimise the heat transfer from the shielding elements inwards but would also humidify the air within the buffer space, and thereby enclosing the entire building by a *well-tempered* microclimate, much less harsher than the external climate it would have had to cope with.

Non-shielded contemporary buildings on the other hand hardly incorporate this requirement as an integral part of the building but merely as ad-hoc measures. A non-shielded contemporary building has to have an open-pond roof system to take full advantage of evaporative cooling, but this has not been found to be very practical for many reasons - scarcity of water in the hot arid zone, roof leakage etc. A shaded roof pond (as may be found in a solar shielded building incorporating this measure) has been found to be more efficient in one of the series of studies by Baruch Givoni (see Givoni, 1983).

All in all, whilst a solar shielded building may be efficient in the control of solar radiation and prevention of building overheating, it may not, depending on its design and use, be so efficient in passively letting the heat out. This significant factor must be borne in mind in the design and operation of the shielding system, and ensuring that whilst it should *exclude* the external thermal environment and minimise its influence upon the indoor thermal conditions during certain seasons and times of the day, it could also enable the coupling of the building to some ambient heat sinks, at other appropriate times/seasons.

Furthermore, and in relation to the above, the casual heat gains, especially from cooking must be kept to a minimum. For example the kitchen should either be separated from the rest of the building by specially designed thermal boundaries, to prevent heat conduction to the living spaces, or should be a totally separate adjoining structure to the main building, and in both cases, well coupled to the ambient with efficient chimneys, so designed as to let out as much heat as possible during and after cooking rather than conduct it into the living spaces.

A complete overview will not have been given without considering other side effects of modulated solar shielding, which are presented in the subsequent section. In this context, in order to remain within the scope of this work, no comprehensive study of the different fields of research was intended and only a brief discussion of some relevant studies are presented

1.6 Side Effects of Solar Shielding

Whilst modulated solar shielding may be a potentially effective solar radiation control technique, it is subject to some major constraints such as
(a)The need for admitting controlled levels of diffuse daylight.
(b)The requirements for views out of the building.
(c)The maintenance of an effective airflow and direction.

1.6.1 Solar Shielding and Daylighting

Solar shielding aims to optimise the reduction of building overheating by effectively controlling or possibly excluding both direct and diffuse components of solar radiation. Whilst the direct component can be effectively excluded, the diffuse cannot, and should not, be totally excluded due to conflicts with the need for a degree of daylighting of interior spaces. But since light is a part of the radiant energy spectrum, it's ingress and absorption by any of the building surfaces, including shading devices, constitutes a heat input. This is as true for direct sunlight as for diffuse daylight. Hence the need for selective admission of daylight must also be taken into consideration in evaluating the efficiency of the shielding system.

Due consideration must be given to daylighting for the reasons that apart from the fact that it is free, and would therefore reduce the overall energy bill of the building, its "luminous efficacy" (i.e. the useful visible light in relation to the total energy of the radiation) is quite high. Hence it is better than any form of artificial light and causes less heating effect. Hence there is little to be gained by completely cutting off natural light by the shielding system only to substantially depend on artificial lighting during the day time. Thermal consideration apart, a building without the touch of natural light is devoid of the spirit of life and, in a sense, inhabitable. Louis Kahn has said that *"No space, architecturally, is a space unless it has natural light"*, while Le Corbsuier has described architecture as *"the conscious, correct and magnificent interplay of volumes in light"*.

1.6.2 Influence of the Shielding System and other Shading Devices on Daylighting

The light entering a room consists of 3 components, namely (a) the direct sunlight, (b) Diffuse sky light, and (c) Diffusely reflected light from the ground and off the surfaces of other buildings. In the tropics, the first one should be almost always excluded, while the others are selectively admitted to a varying degree.

The quality of indoor daylighting is quantitatively expressed by the Daylight Factor (DF), which is defined as the ratio of the daylight illuminance in the space to the simultaneous illuminance outdoors, expressed as a percentage. (Koenigsberger *et al*, (1973), Baker, (1987))

$$DF = 100\frac{E_i}{E_o} \tag{1.2}$$

where DF is the Daylight Factor (%), E_i is the illumination at the given point indoors (lx) and E_o is the illumination outdoors from an unobstructed sky hemisphere (lx). Whilst the DF is constant for the geometry of the building, it is variable for a building which uses adjustable or modulated shading devices which can vary the Daylight Factor in response to the varying sky illuminance.

The light falling onto a point within the building, which is expressed in terms of the daylight factor, may be split into three components; namely

(a) The sky component (SC)

(b) Externally reflected component (ERC), and

(c) Internally reflected components (IRC).

The magnitude of the sky component depends on the area of the sky considered from the point and its average altitude angle and therefore on the size and relative position of the openings, thickness of opening frame members, type of glazing and its cleanliness and external obstructions. The externally reflected component depends on the area and reflectances of the external surfaces visible from the point, while the internally reflected component depends on the size of the room, ratios of wall, ceiling and floor surfaces in relation to window area and the reflectance of these surfaces.

Daylighting design of indoor spaces would vary from one climate to another in accordance with the variation of the corresponding sky conditions. In the temperate zones which have predominantly cloudy skies, daylighting design is based upon this assumed condition, and because there is rarely natural conditions of

heat stress for occupants in this climatic zone, the over-provision of daylight is not considered a disadvantage. In the tropics where the sky brightness is very high, the result of over illumination can be detrimental for indoor thermal conditions, and the daylight factors tend to be lower. Moreover there is in this climatic region a somewhat psychological association between glare and thermal discomfort. The importance of glare control cannot therefore be over-stressed. Koenigsberger *et al*, (1973) has suggested three basic guide-lines for glare control in tropical climates.
(a) Permit view of sky and ground near to horizon only - within 15^o above and below horizon;
(b) Exclude view of bright ground and sunlit blade or louvre surfaces;
(c) Daylight should be reflected from the ground and louvre surfaces onto the ceiling surfaces which should be of light colour.

Figure 1.6 shows a typical illustration of the above requirements which also ensures adequate ventilation.

1.6.3 Influence of Shading Devices

Any shading device placed over or above an opening reduces the sky component from any reference point in the room. In the case of modulated louvres and sun screens the sky diffuse and diffuse reflected light are reduced as well by adjusting the louvres and screens to suit varying sky conditions. In the case of the louvres system concept of the Diffuse Transmission Factor (DTF) has been introduced (Baker, 1987). This is the ratio of the diffuse light passing through an opening with louvres shading to that of the same opening unshaded. This factor is applied to the Daylight Factor of the unshaded opening. Tables 1.4 and 1.5 show the Diffuse Transmission Factors for dark horizontal and vertical louvres for various ground reflectances, louvre angles and depth to spacing ratios of the louvres (Figure 1.7) The efficiency with which the louvre system eliminates direct sunlight and control diffuse daylight is high when the depth to spacing ratio is greater than unity.

Different configurations of louvre systems may provide the same shading mask, but in varying the parameters of the slats, the solar protection efficiency of the system is not only altered but also greatly influences the interior illuminance. In dealing with the implications of modulated solar shielding for daylighting, it would be instructive to rely on research findings in the field which deal with the effect of

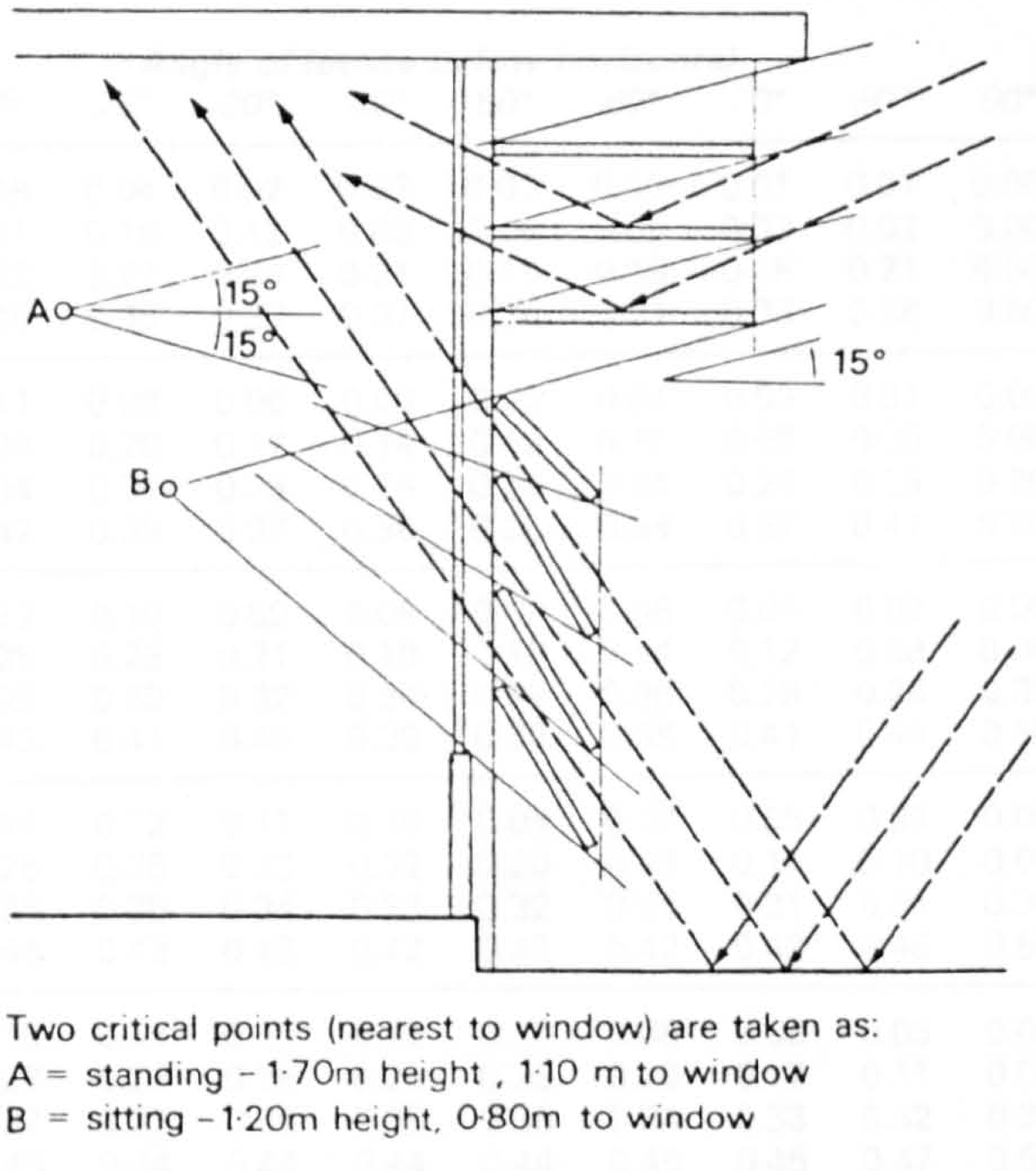


Figure 1.6: A special louvre system (After Koenigsberger *et al*, 1973)

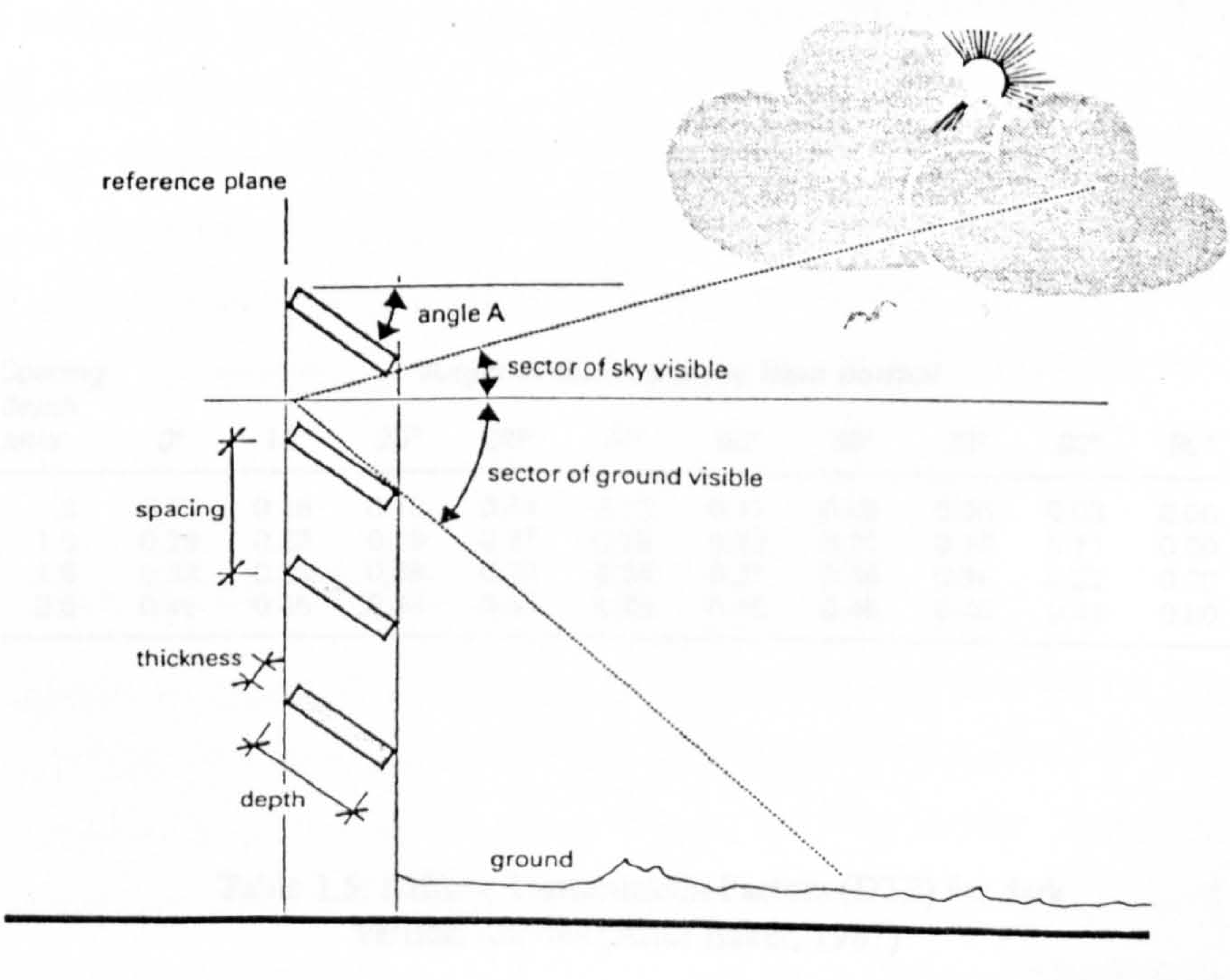


Figure 1.7: Reduction of diffuse light transmission by louvres (After Baker, 1987)

ground reflec.	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	spacing/ depth ratio
.1	0.15	0.08	0.04	0.02	0.02	0.02	0.02	0.01	0.01	0.00	.5
	0.28	0.21	0.16	0.12	0.09	0.06	0.05	0.03	0.02	0.00	1.0
	0.38	0.32	0.27	0.24	0.21	0.19	0.18	0.18	0.21	0.30	1.5
	0.45	0.40	0.36	0.33	0.31	0.30	0.31	0.33	0.38	0.50	2.0
.3	0.15	0.11	0.08	0.06	0.06	0.05	0.04	0.03	0.01	0.00	.5
	0.28	0.24	0.20	0.17	0.14	0.12	0.10	0.08	0.06	0.00	1.0
	0.38	0.34	0.31	0.28	0.26	0.25	0.24	0.24	0.25	0.30	1.5
	0.45	0.42	0.39	0.37	0.36	0.35	0.36	0.37	0.41	0.50	2.0
.5	0.15	0.12	0.10	0.09	0.08	0.07	0.06	0.04	0.02	0.00	.5
	0.28	0.25	0.23	0.21	0.19	0.17	0.14	0.12	0.08	0.00	1.0
	0.38	0.35	0.33	0.32	0.30	0.29	0.28	0.28	0.28	0.30	1.5
	0.45	0.43	0.41	0.40	0.39	0.39	0.39	0.41	0.44	0.50	2.0
.7	0.15	0.14	0.12	0.11	0.10	0.09	0.07	0.05	0.03	0.00	.5
	0.28	0.26	0.25	0.23	0.22	0.20	0.18	0.14	0.10	0.00	1.0
	0.38	0.36	0.35	0.34	0.33	0.32	0.31	0.31	0.31	0.30	1.5
	0.45	0.44	0.43	0.42	0.42	0.42	0.42	0.43	0.46	0.50	2.0
.9	0.15	0.15	0.14	0.13	0.12	0.10	0.08	0.06	0.03	0.00	.5
	0.28	0.27	0.27	0.26	0.24	0.22	0.20	0.17	0.11	0.00	1.0
	0.38	0.37	0.37	0.36	0.35	0.35	0.34	0.33	0.32	0.30	1.5
	0.45	0.45	0.44	0.44	0.44	0.44	0.45	0.45	0.47	0.50	2.0

Angle of louvre below horizontal

ground reflectance
spacing/depth ratio

Table 1.4: Diffuse Transmission Factors (DTF) for dark horizontal louvres (After Baker, 1987)

Spacing depth ratio	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
.5	0.15	0.16	0.15	0.14	0.13	0.11	0.09	0.06	0.03	0.00
1.0	0.28	0.28	0.28	0.27	0.25	0.23	0.21	0.18	0.11	0.00
1.5	0.38	0.38	0.38	0.37	0.36	0.37	0.36	0.34	0.32	0.30
2.0	0.45	0.46	0.44	0.45	0.45	0.45	0.46	0.46	0.47	0.50

Angle of louvres away from normal

Table 1.5: Diffuse Transmission Factors (DTF) for dark vertical louvres (After Baker, 1987)

external louvre systems on internal illuminance distribution. These findings may throw some light on the combinations of the shielding systems slat parameters that would optimise solar shielding performance as well as let in adequate diffuse light. One of the results of Gusev, (1965) was that horizontal control devices having a high number of slats gave the lowest illuminance inside the room.

Some of the significant research work on daylight design with louvres was that of Plant, (1965, 1967), and Givoni *et al* (1968). Plant's work established not only that reflected sunlight off a louvre system contributed to internal illuminance but also that an increase in the window area increased interior illuminance. Plant also found that

(a) The effect of external opposing facades upon interior illuminance is very little unless the surfaces are highly specular.

(b) The difference between the sun and skylight contribution to illuminance is very large. The direct contribution of skylight is very small.

(c) Givoni *et al* (1968) established that the effect of internal wall reflectance on interior illuminance is very little near the window but uniformly large at the rear areas of the room. The effect of louvre reflectance is uniformly high throughout the room but much greater within the window vicinity.

(d) When louvre slats are used, the greatest proportion of natural illuminance into the rooms comes not from the sky but from sunlight reflected from the ground and the shading device itself.

The significance of the sunlight reflection from the surfaces of louvre slats upon indoor illuminance has also been established by Narasimhan and Kumar (1973), as pointed out by Fikry (1981). They also showed that horizontal louvres provide maximum internal illuminance, followed by vertical and eggcrate louvres respectively.

1.6.4 The work of Fikry

Another significant study of the impact of external louvre system on internal illuminance was that of Fikry, (1981). Fikry investigated the effect of varying some physical parameters of the louvre slats (Figure 1.8) on indoor illuminance levels. The parameters investigated include the number of slats, the thickness of the slats, the inclination of the slats, from horizontal, the slats surface reflectance, the solar

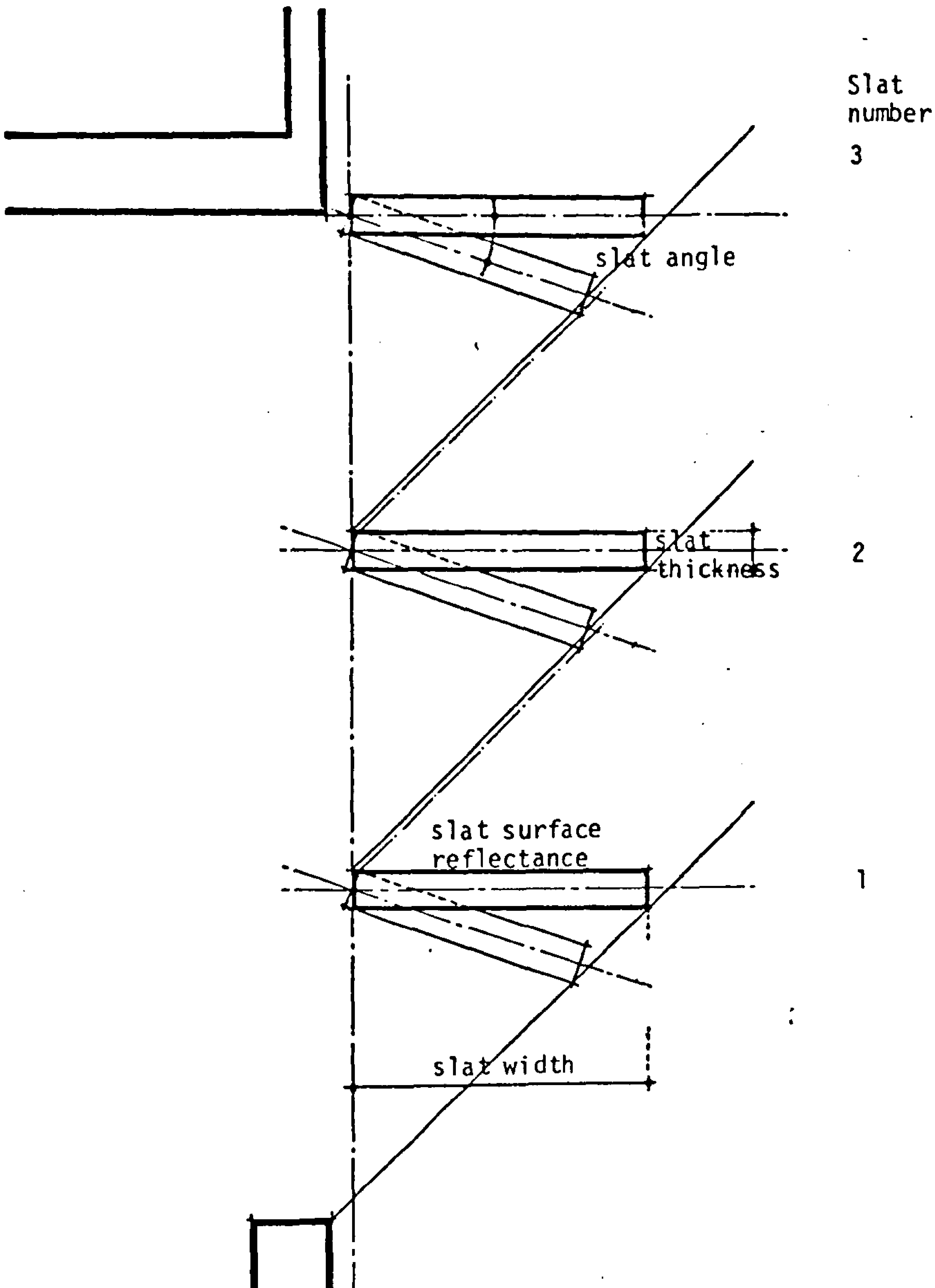


Fig. 2.3.4

Section through a window anerture emphasising the different slat parameters

Figure 1.8: Some important physical parameters of a louvre system (After Fikry, 1981)

altitude and the window aperture area.

Fikry carried out model-based measurements underpined by a theoretical study of the variation of the above parameters on interior levels of illuminance. In the study an experimental model of a standard room of 4.0m square and 3.0m height with a window of 4.0m by 2.0m and sill height of 0.9m was constructed to one-tenth scale. The sun was simulated with a 650 Watt lamp and since no internal reflections were to be considered, all the internal walls were painted black. Measurements of reflected sunlight from the louvres were made along the centre line of the room perpendicular to the window at both the ceiling and the sill levels. The experimental approach was verified against that of Plant, 1965. The model window was simulated with 2, 4, 8 and 16 horizontal louvres of 3 mm slat thickness, each giving the same amount of shade on the model window, and painted white to give a 90% reflectance factor.

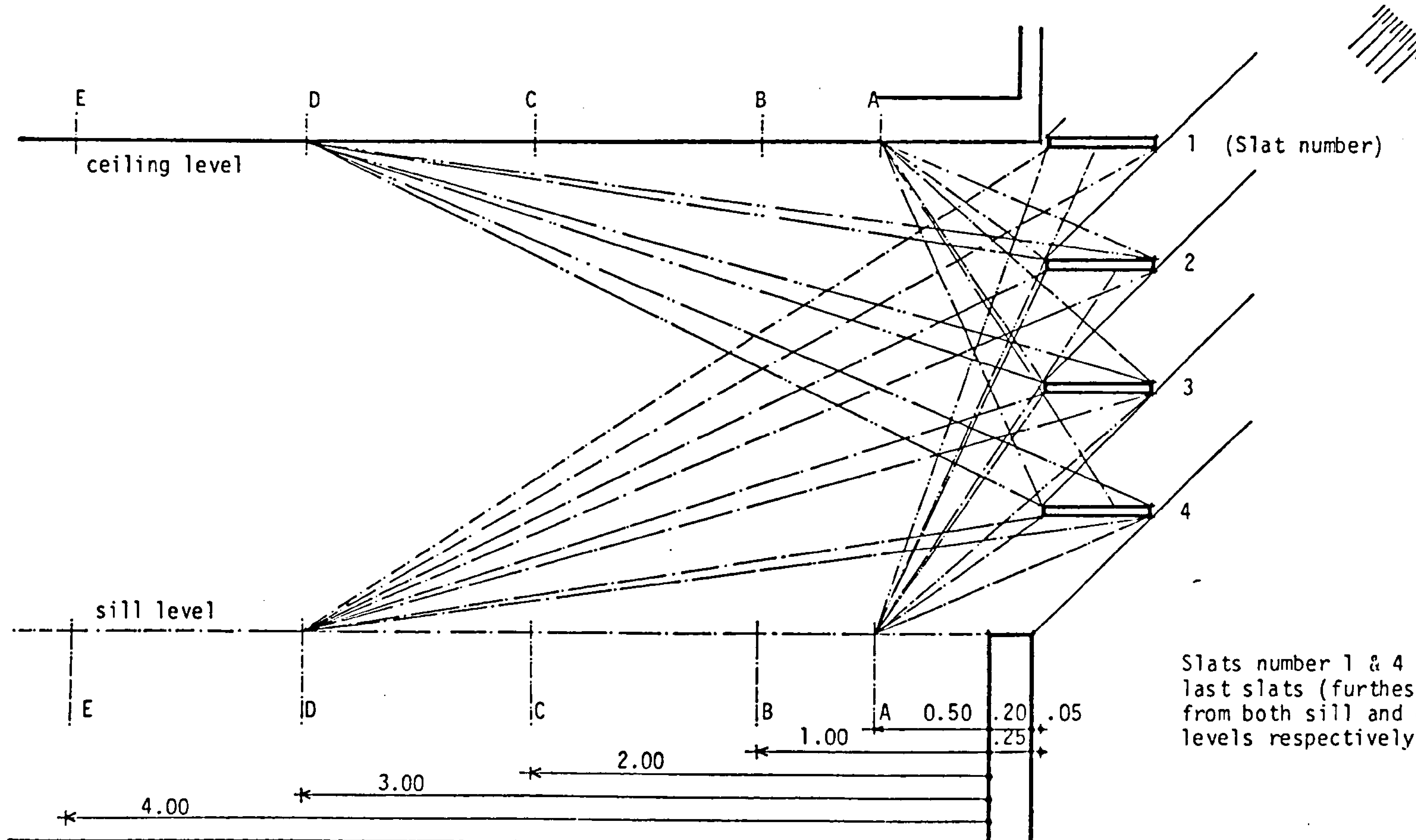
1.6.4.1 Parametric Study

A mathematical model, which was verified with the experimental study, was used in a computer program to carry out a parametric study in which the slat parameters and later, the window area and the solar altitude, were varied. In all the tests, whilst the sun was completely excluded from the room, it was ensured that each louvre was in sunlight.

1.6.4.2 Results

The results showed that each louvre slat configuration gave a different illuminance level throughout the room at both the sill and ceiling. It was found that:

1. The **number of slats** that gives the maximum internal illuminance varied according to the position of the reference point in the room. For the reference position (A) nearest to the window (Figure 1.9), the optimum number of slats for maximum illuminance at the ceiling level was six, seven for position B, and eight for positions C, D and E which were furthest from the window. At the sill level the same pattern of results were obtained up to the second reference point after which the opposite effect occurred. The optimum number for reference points A and B were six and seven respectively while reference positions C, D and E which were furthest from the window were six, five and



Slats number 1 & 4 are the last slats (furthest away) from both sill and ceiling levels respectively.

Section through the room and window aperture, emphasising that the reference positions at ceiling level are not affected directly by slat number (1) while the reference positions at sill level are.

Figure 1.9: The reference positions from the window at both the ceiling and sill level (After Fikry, 1981)

four respectively (Figure 1.10).

2. Increasing the **slat thickness** decreased the internal illuminance at both the sill and ceiling levels. This is due to the fact that increasing the slat thickness decreases the reflecting surface area of the slat seen by a reference point in the room. This decreased surface area is due principally to the reduction of the *effective width* of the slat as its thickness is increased.

3. Generally increasing the angle of the slat resulted in a decrease in the amount of reflected sunlight at the ceiling level, at both positions A and C. This was due to the decrease in the view factor, as the slat angle increases from horizontal. However at the sill level, the situation is more varied, as the number of slats also played a significant role (see Figure 1.11). For position A, the configurations with the higher number of slats reflected greater amount of sunlight into the room at 15^o (than at 0^o) although the reflection declined thereafter as the slat angle decreased. The effect of the variation of slat angle is not significant at points furthest from the window (position C).

4. An increase in the **solar altitude**, while keeping the slats completely sunlit, resulted in an increase in the amount of reflected sunlight, at both the ceiling and ceiling and sill levels throughout the room. This is due mainly to the resultant decrease in the *effective width* of the slats. Again, it depends on the number of slats.

5. The increase in the **window area** (keeping the height constant) resulted in increased internal illuminance intensity at both ceiling and sill levels.

1.6.5 Thermal and Airflow Considerations

In terms of thermal and airflow considerations, Fikry, (1981) also established, for louvre surface reflectance factor of 80%, and solar altitude of 45^o and zero azimuth that:

1. The increase in the number of louvre slats resulted in a net increase in the quantity of reflected shortwave radiation reaching the room surfaces, up to a turning point at about 6 slats (for the walls, and 5 slats for the ceiling) after which there is a gradual decrease in the quantity of reflected radiation

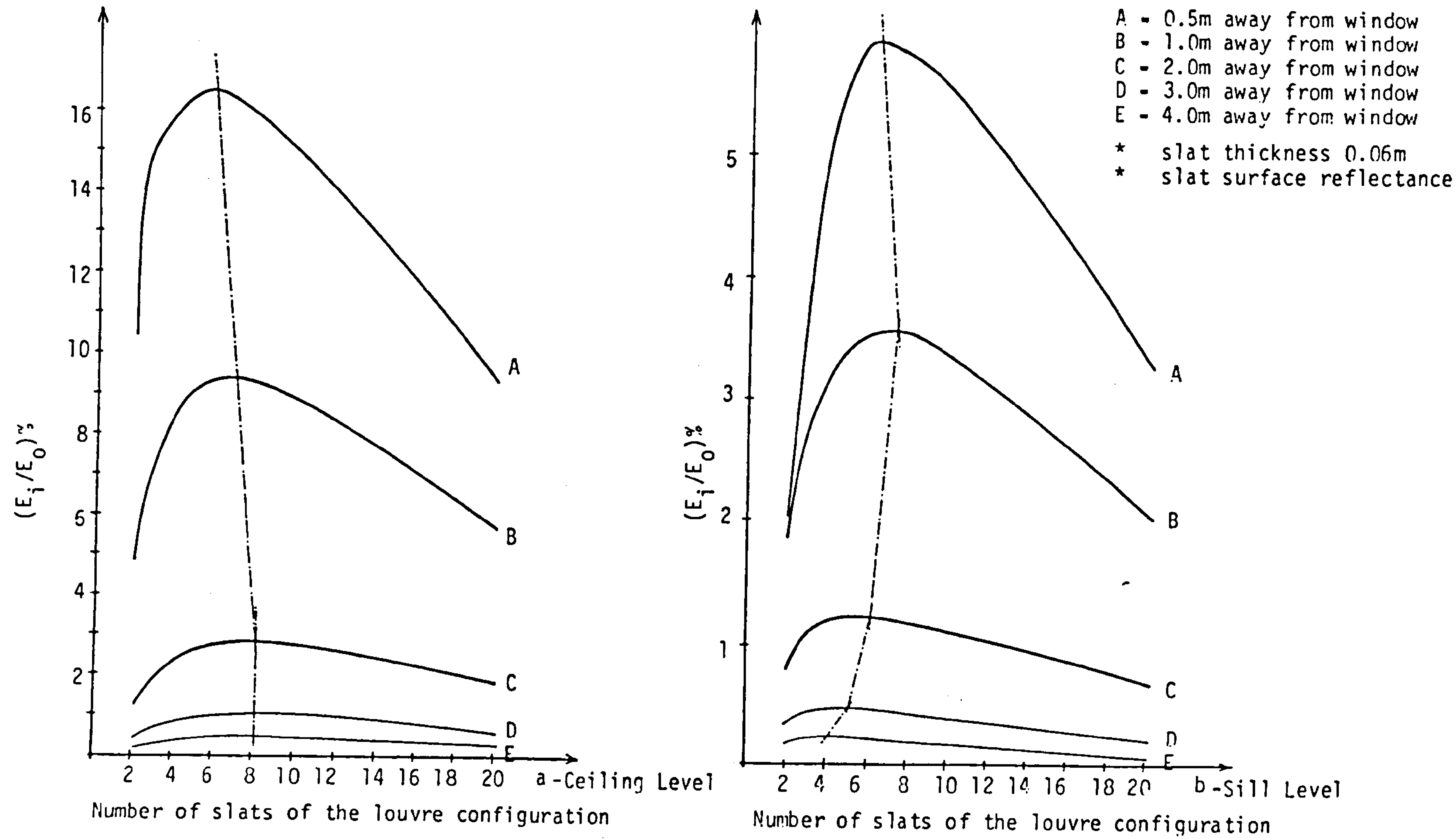


Figure 1.10: The effect of varying the number of slats on the interior illuminance (After Fikry, 1981)

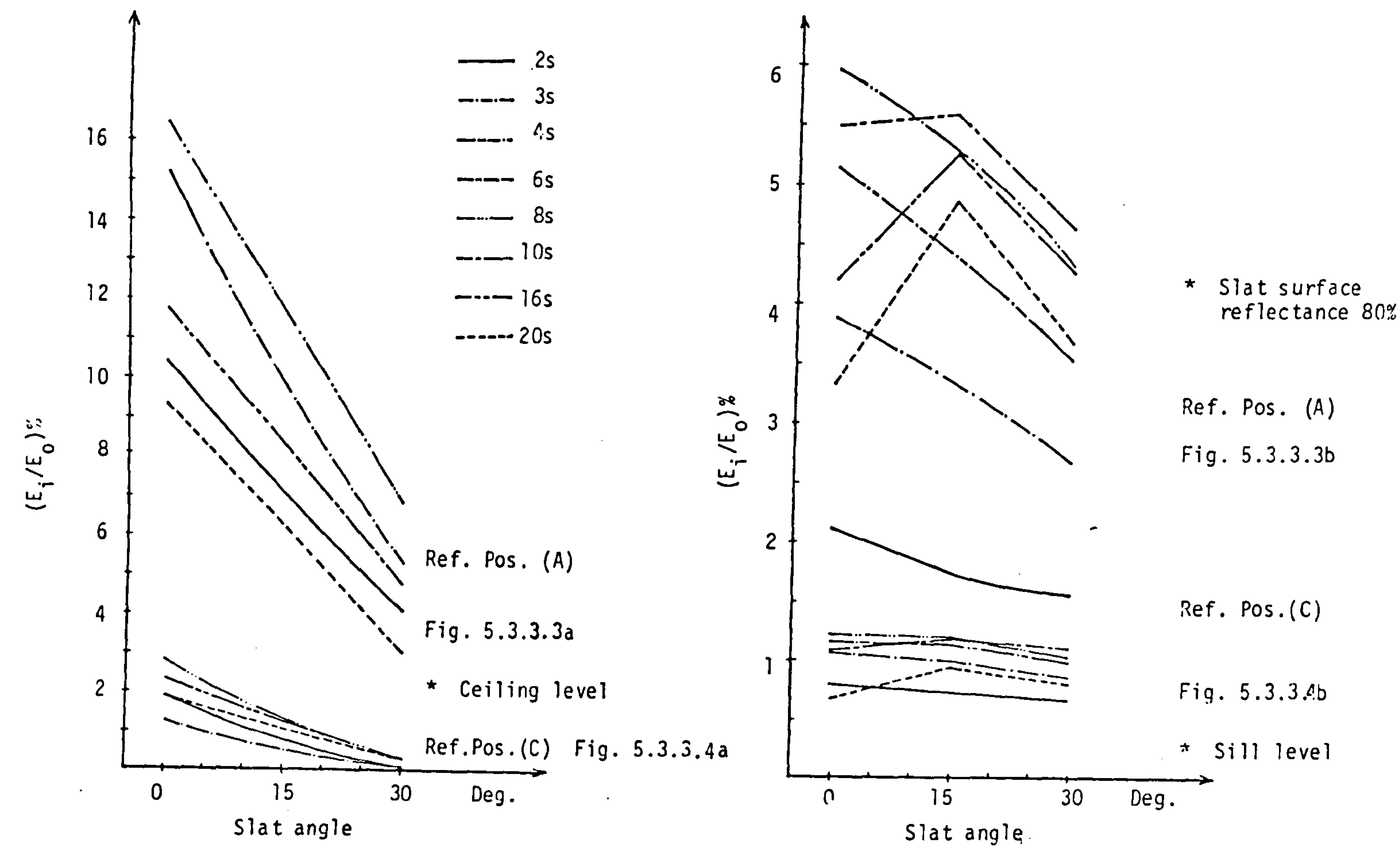


Figure 1.11: The effect of varying the slat angle on the interior illuminance (After Fikry, 1981)

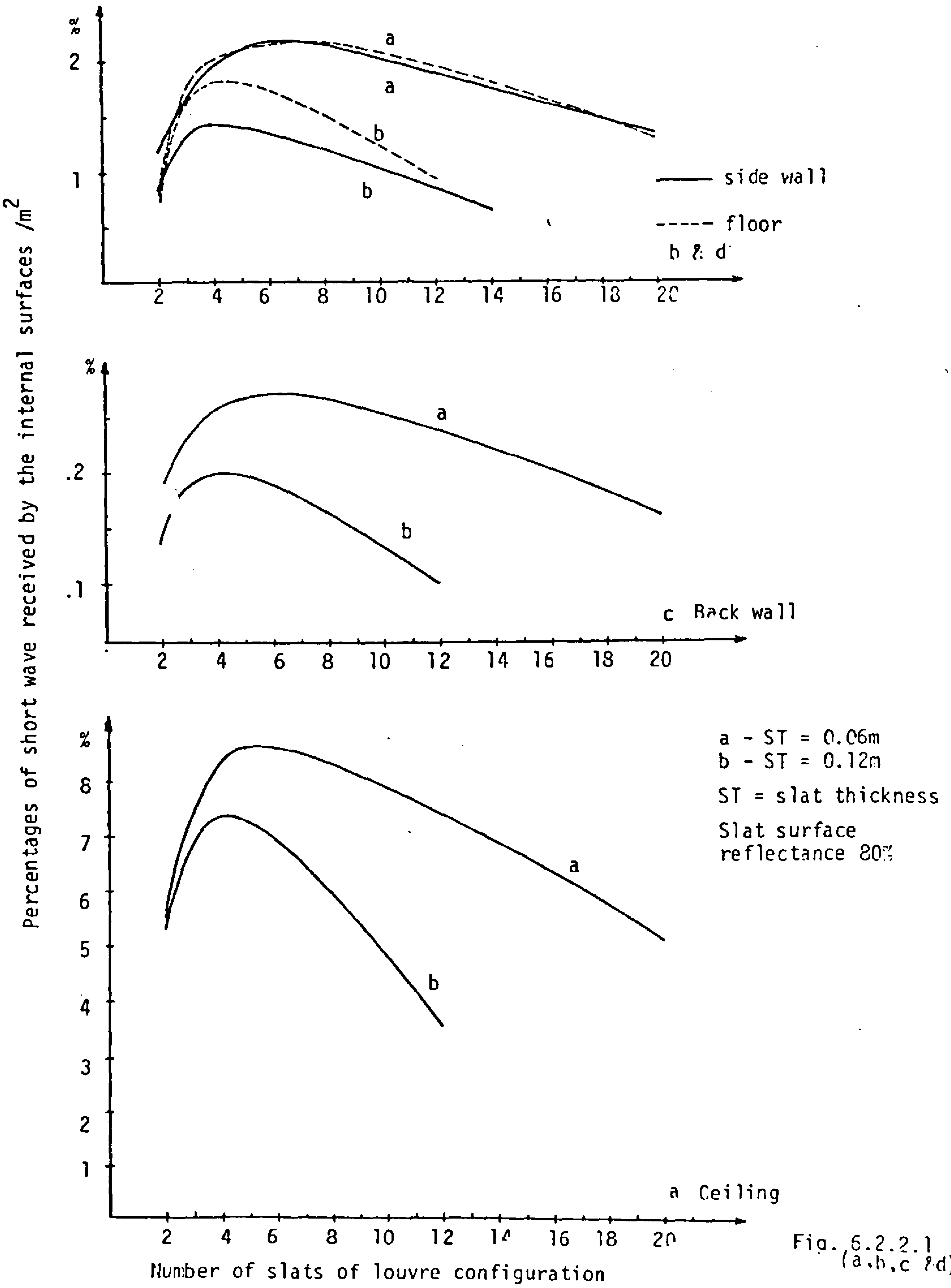


Figure 1.12: The effect of varying the number of slats on the internally transmitted solar radiation (After Fikry, 1981)

as the number of slats is further increased (Figure 1.12). This is due mainly to the resultant increase in the view factor. Expectedly, the ceiling receives the highest quantity of reflected shortwave radiation.

2. Increasing the slat thickness decreased the quantity of reflected shortwave radiation for all the internal surfaces.

3. It was also observed that increase in the slat angle resulted in the airflow being more directed towards the ceiling while the increase in the number of slats made the airflow more widely distributed through the window aperture to the room.

The similarity in the results for internal illuminance and the quantity of reflected solar radiation received by the internal surfaces of the room connotes the truism that the increased level of reflected sunlight is accompanied by a corresponding increase in the quantity of reflected shortwave radiation. Somewhere along the line, a compromise has to be reached between conflicts of maximising indoor illuminance and minimising the ingress of reflected shortwave radiation.

Also the louvre system can be used to hinder or facilitate airflow, and to channel its direction – either up to the ceiling or down to the floor, as desired (see also Evans, (1980) and Konya, (1980)).

One of the weaknesses in the present methods of determining the indoor illuminance is that they are often solely based on the day light factor which does not consider the effect of the direct sunlight incident upon the surface. It has been established (Shukuya and Kimura, 1983), that the total internal work plane illuminance for the case of windows with horizontal and vertical louvres, is approximately twice as large as that obtained by conventional daylight factor method, when the direct sunlight-, the sky light- and the reflected daylight- factors are all taken into consideration. This development is very significant for tropical architecture, for which these 3 factors must be borne in mind when evaluating indoor illuminance for cases involving horizontal and vertical louvres.

Shukuya and Kimura, (1983, 1986) advocated the use of these combined factors. In tropical buildings that are shaded completely from direct sunlight, the appropriate factors that must at least be considered are both the skylight and reflected daylight from the ground and opposing facades.

The significance of solar-optical properties of complex multi-layer fenestration systems (such as those incorporating venetian blinds, horizontal/vertical louvres, solar screens) for the determination of the indoor illuminance has been expressed by Papamichael and Winkelmann (1986). For the complete description of the radiant behaviour of such complex fenestration, and the accurate determination of their luminous and thermal performance, the solar optical properties should be expressed as functions of both the incoming and outgoing directions of the radiant flux instead of simply as a function of the incident angle of the incoming radiation only. A mathematical model, based on a matrix representation of the bidirectional properties of fenestration layers and system was proposed to determine the overall hourly, seasonal or annual luminous and thermal performance of fenestration systems of arbitrary complexity under varying environmental conditions.

However, one of the most crucial issues that has not been fully addressed is the fact that whilst operable shading devices are more flexible with respect to controlling daylight admission, view, glare and thermal requirements, they are also much more complex than fixed shading systems since every adjustment made results in an optically and thermally different system. Operable shading systems such as that of louvres may be operated under many different control strategies, each strategy having different effects on view potential and on the luminous and thermal environments. The tradeoffs of the various possible control strategies are not yet well understood (Papamichael *et al*, (1986), Kim *et al* (1986), Littlefair, (1984)).

There has also been a significant body of research on the luminous efficacy of daylight which enables the direct and diffuse illuminances to be calculated from available solar radiation data (see Navvab, *et al*, 1986, Littlefair, 1985, 1986). The spectral luminous efficacy of a radiant flux at a given wavelength is defined as the quotient of the luminous flux at the wavelength derived by the radiant flux at the same wavelength, (expressed in lumens per watt). By integration over the whole spectrum, the luminous efficacy of a light source is equal to the ratio of the total luminous flux emitted, and the total radiant flux. Since the spectral composition of sunlight reaching the earth surface is affected by the atmosphere, its luminous efficacy is also variable, and is dependent on gas composition, water droplets, dust and other particles suspended in the atmosphere.

With the growing interest in daylighting as a passive and low energy design option, there has emerged attempts at integrating not only the energy implications of solar thermal gain with the value of dayligting, but also integrating the conflicting need to *minimise* solar gain with operable shading devices and *maximise* outward view while letting in enough daylight to offset the need for artificial lighting during the day time.

An example of the first form of integration is that of Baker (1989), who attempts to integrate the *benefits* of solar gain (in non-tropical climates) with the value of daylighting and the need to minimise cooling energy. The work presented a design tool which integrates the light and thermal energy of glazing, incorporating a model which predicts annual primary energy consumption as a function of the local climatic conditions, orientation of the facades, the fraction of the glazing area in the facade, and the type of glazing. An example of the second form of integration is discussed in the subsequent section.

1.6.6 Solar shielding and outward view

Whilst the significance of the impairment effect of a louvre shielding system, or indeed most shading devices, on outward view from the building cannot be over-stressed, very little detailed investigations have been carried out to evaluate the effect. This is perhaps due to the fact that outward view from the building is not as critical a parameter as that of daylighting or solar thermal control. Nevertheless good views help to enhance the sense of well being of the occupant, creates a link between indoors and the external environment and minimise claustrophobia and a feeling of isolation, or being *cooped up*, and depression and tension (Ludlow (1976), Ruys (1970), Roessler (1980)). According to Terman (1986), the body's natural physiological and rhythmic functions may be jeopardised by daylight deprivation since the human physiology has evolved to synchronise with the external solar cycle. It has been argued that as a result of the human species' long evolutionary history of living in a *natural* as opposed to a *built* environment, our perceptosensory systems are predisposed to respond *positively* to nature, and to features of the environment that may have had a bearing on early survival and well-being (Heerwagen, 1986).

Therefore, whilst impairing outward view to some extent may be tolerated, total exclusion of view all of the time would not make for a meaningful architecture, especially for the *human specy.* It will be borne in mind that people respond to the built and natural environments in fundamentally different ways (see Kaplan, (1978), Orians, (1980), Ulrich, (1983)). However, it has been found (Collins, (1975)), that generally, human attitudes towards windowless spaces are somewhat unfavourable, especially in small, restricted and static environments such as hospital wards and small offices. Kaplan, (1983), found that the opportunity to view trees and woods through the windows had a significant positive effect people's respond to their social and physical environments. Human appreciation of outward view may be dependent upon the building use, the building size, the scenery, or view content and the window size and shape and, of course, personal preference. All in all, little evaluation of human response to the tree-less, dusty, hot and often hostile external environments of hot arid lands have yet been done, but it would be surprising if similar results suggesting emotional, intrinsic and intuitive attachment to the dust and sand dunes, by the dwellers, do not emerge.

Another reason why there is relatively little research with regard to view is the fact that outward view, being a psychological parameter, is difficult to evaluate, albeit, quantify. However, interest in evaluating this parameter has increased in recent times. Some recent studies include the investigation of the visual interference of different types of shading devices on the outward view and its influence on window size and shape. This study is being carried out at the University of Sheffield and has been partly reported (Tabet and Sharples (1989) (1990)). Some of the emerging results include the fact that whilst shading devices are a positive sun-control feature, their main disadvantage is their impairment of the outward view. The results also indicate that not only does the view content have a determinant effect on the window size and shape but also that visual requirements were best met by windows of a horizontal shape with distant views requiring wider apertures. The height of the skyline was also found to influence the settings of the window height and sill.

The opportunity to modulate a shielding system should meet the requirement for outward view reasonably well in a climate as severe as the one under study. It could also enable the control of this parameter in line with prevailing climatic conditions. This would be dependent on the pattern of building use.

1.7 The conflict in-between

The conflict between the needs to *minimise* solar thermal gain by means of operable shading devices, and *maximise* outward view, and acceptable level of daylighting, is even more significant for solar shielded buildings than non-shielded ones. In the context of this study, this conflict revolves round the interaction of the issues dealing with not only thermal comfort but the over-all well-being of an occupant of a building in the reference climates. The over-all well-being of an occupant depends on a combination of what may be called physical, percepto-psychological and psyco-social factors.

The physical factors include the thermal, lighting, and acoustical conditions, and the air quality. The percepto-psychological factors include the perception of space, with its dimensions, proportions, colours, outward views, the quality of the view content, and so on. The psyco-social factors which influence the overall evaluation of well-being include intrinsic value of privacy, sense of security, religious beliefs, etc.

All the above factors must be satisfied by any good design, at least to a varying extent. As a result of the conflict and contradiction between design features which attempt to meet different requirements for the overall well-being of the occupant, a good design usually craves for balance and rational compromises. In assessing a solar shielding design option therefore, attempts must be made to strike this balance. It would be necessary to establish the lower limit at which daylight would be intolerably impaired (for the required tasks) and the upper limit at which any further ingress of daylight would produce glare. The shielding performance should be evaluated within the above limits, with a view to integrating and rationalising the physical, percepto-psychological and psyco-social factors as mentioned above. Compromises would have to be made.

As a result of the thermal severity of the climate, the lower limit should be the dominant design factor as the acceptable minimum of light is desirable. The bottom line should be to maximise the shielding system's efficiency to prevent building overheating arising from the ingress of solar and ambient energies, and to limit the impairment of the building's longwave heat loss by the shield. Eventually, the overall performance of the shield would be a function of the design and material specification of the shield, its modulation in response to the variation of the ambient conditions, occupancy schedules, personal preference, and so on.

An occupant with an open-door, live-with-nature lifestyle may hate to be cooped up behind closed doors and windows of a traditional house in the hot arid regions, but may find greater flexibility in a solar shielded house. Moreover, he can bring in natural elements into the peripheral buffer zones. That flexibility gives him opportunities to choose, and the final choice is always his. But it is the designer's responsibility to present him with the likely consequences of those choices.

As for outward view, it may be mentioned that people in the hot arid climates are usually quite prepared to *tolerate* the impairment of the view and even a relatively unsatisfactory levels of daylighting (Evans, 1990). In Israel, it is against Building Regulations to design windows without shutters in the hot dry areas (Shaviv, 1990). The traditional buildings of the hot arid zones are noted for their small windows, (both in number and in size), which are usually located above the eye level to minimise the ingress of reflected radiation from the ground. Moreover, the Islamic tenet which extols the virtues of strict privacy for women is another important factor.

All the above considerations will therefore influence the *design* and *mode of use* of the shielding system. For a louvre shielding system for example, they will influence the number, width, thickness, surface reflectance, colour and even the location of the louvre slats.

1.8 The Objective and Significance of this Study

The main objective of this research study was to investigate the potential advantages by showing the quantitative reduction, if any, of the solar heat load, by the use of the modulated solar shielding concept in a hot/semi-arid climate. It was also necessary to investigate the potential reduction to airflow by the use of an external shielding system such as a modulated wooden louvre system. The potential problems associated with the use of the concept, especially with respect to its possible impairment of daylighting, outward view and longwave heat loss are also discussed in line with developments in the field, although no detailed investigations of these aspects were carried out.

Presently there is a serious need to not only obtain relevant design data but also to acquire the increasingly vital analytical and design skills for modern low-energy building design in the tropics in general and in the hot dry/semi-arid climates in particular. The overall intent of the study therefore was to provide data and some understanding of the use of this concept as there is total lack of information in this regard, unlike the case of the use of shading devices on glazed openings which has been studied extensively. This is due to the fact that, whilst the need for a better understanding of *passive solar* or *bioclimatic* design has long been established, very little research has been aimed at assessing the effect of alternative solar radiation control strategies beyond parametric studies with shading devices. It is envisaged that the results from the study would contribute to the body of research efforts aimed at the development of design concepts and the accumulation of new data, to enable optimisation of design alternatives, upon which a more realistic architecture for this climate depends.

1.9 Scope of the Study

The study is limited mainly to the investigation of the reduction of the building solar heat load by the use of the modulated solar shielding concept, in order words, it's thermal implications. The study of it's implication for other environmental parameters such as ventilation and daylighting do not fall within the scope of the study.

1.10 Establishing a Framework for the Study

The research involved studies embracing parameters at both the environmental climatic level and the level of the building itself. Most research efforts in the field deal with one or more design constraints such as structure and/or material, climatic and/or environmental, socio-economic and political, etc. This study was concerned mainly with the climatic/environmental constraint. The specific climate in question and it's climatic features were established and analysed. The analysis of the climatic features were done at both micro and macro climatic levels.

In the analysis, particular attention was paid mainly to the overheated periods because it is believed that if the building can keep out enough heat at this period then it will have gone a long way to maintaining a desirable indoor environment for all other periods.

There was neither the intention to deal comprehensively with thermal comfort analysis as this has been dealt with extensively in the field, nor to dabble into the so-called *comfort period*. It was considered unrealistic to apply thermal comfort indices established on the basis of climatic analysis in higher latitudes which have a very different climate as the one in question. The purpose of an index of thermal comfort is to estimate the influence of environmental factors either on the thermal sensation of people at rest (or engaged in light activities) or on their physiological responses, such as skin temperature, rectal temperature, pulse rate and sweat rate. The main interest of the building designer however should be to evaluate the relative warmth or coolness of an indoor environment of a building, to determine whether the conditions are below, within or above the **comfort conditions**, based on the analysis of the **actual climate** in which the building is built. Such comfort conditions have really not been established for most hot climates including the one under study, although a *general* index of thermal comfort for tropical conditions have recently been suggested by Sharma and Ali, (1986). The authors developed series of equations expressing thermal sensation in terms of environmental variables.

In real terms the definition of what is considered comfortable varies not only according to the climate and the features of acclimatization of the people but also from one individual to another. The main object of this study was the minimisation of solar heat gain, *especially* at the overheated period and/or season.

At the building level attention was paid during the analysis, to the building structure and its immediate periphery. Passive cooling strategies were examined. These embraced such techniques as evaporative, convective, and radiative cooling, the use of roof-pond systems underground structures, landscaping, daylighting and shading of glazing. However, means of minimising and/or reducing solar heat gain, by use of shading devices were treated in more detail.

Solar thermal control is presently being done:

(1) at the surface of the building fabric (by shading the glazed areas)

(2) at the interior living spaces (e.g. by natural ventilation, natural evaporative and convective cooling etc),
(3) within the structure (e.g. with thermal mass, thermal insulation, movable insulation, etc),or
on the roof-top (e.g. roofponds and skytherm systems). Whilst all these were duly examined, an investigation was made of the rejection of solar heat gain by means of a system which protects the entire fabric of the building, both the opaque and the glazed parts. The major aim was to let in enough breeze some of the time and to keep out the sun at all times taking cognisance of current building practice and use of materials.

1.11 Research Methodology

An attempt was made from the inception of the research to carry out a study that embodied a balanced analytical and empirical investigations, including computer simulations. The whole study consisted of 3 main stages.

1.11.1 Stage 1: Contextual and Theoretical Background

This stage consisted of establishing the **problem definition**, carrying out **contextual** and **climatic** analysis as well as the **review of literature** of related research. Firstly the *macro and micro* climatic characteristics of the area of study was made. This was followed by specific analysis of the microclimate with collected and collated data, and where relevant data were unavailable, they were generated using validated empirical correlation models. These measured and generated data were to later serve as inputs for computer simulation stages. The climatic analysis enabled the problem definition and this in conjunction with the literature review enabled the conceptualization's of a hypothetical theme for the research study. The hypothesis was that the use of modulated solar shielding was a viable and potentially effective solar radiation and environmental control strategy for a hot semi-arid climate. This hypothesis was tested, in later stages of the study against measured data obtained from a full scale fieldwork and simulated data obtained from using an existing thermal model (SERI-RES).

This stage therefore did not only establish a background to the study and the *modus operandi* of its execution but also provided a general overview as well as the necessary theoretical and empirical framework for the study. It also provided a *contextual* underpining for bioclimatic design criteria in a *developing* tropical country. This part of the study forms the first part of the thesis consisting of Chapters 1, 2 and 3.

1.11.2 Stage 2: Measurements, Modelling and Simulation

This stage consisted mainly of experimental and modelling studies. Full-scale field work of temperature and solar radiation measurements were made on a contemporary building in Kano, northern Nigeria, (latitude 12° 03'N and longitude 08° 32'E) which is located within the hot semi-arid climatic belt. This building was one constructed with modern techniques and materials in which some degree of solar shielding was used. The measurements were made on hourly basis for a 60-day period and other climatic and/or meteorological data for the same period were collected from the local meteorological station and from Bayero University, Kano.

Later with a detailed scale model of the same building, a boundary layer wind tunnel investigation was carried out in the Sheffield University Boundary Layer Wind Tunnel Laboratory. The external wind pressure distribution on the surface of the building were measured with a view to establishing the airflow pattern around the building according to seasonal variation of wind direction throughout the year. The experiment was not only instructive in itself but also provided relevant data of estimated airflow rates for the building for the thermal simulation with SERI-RES.

Furthermore, in order to provide some understanding of the airflow characteristics across a typical shielding system, pressurisation techniques were used to establish relationships between the airflow rate and the pressure drop across a modulated wooden louvre system at full-scale dimensions.

Finally, a series of computer thermal simulations were carried out on the same building using SERI-RES, a multizone building thermal simulation model (version 1.2) to investigate the reduction in solar heat load by the use of the modulated solar shielding technique. Details of all experimental measurements, modelling and simulations form the middle part of the thesis and are presented in Chapters 4 to 7 inclusive.

1.11.3 Stage 3: Synthesis and Conclusion

This stage synthesized the results of the study and drew conclusions (or made generalisations). Finally these conclusions were considered in conjunction with other design parameters to establish recommendations or guidelines for the application of the concept for low energy building design for hot, semi-arid climates, and made suggestions for areas of further research. These provided the necessary *feedback linkage* to the broad theoretical background at the beginning of the study, to complete the **cyclic** planning process.

1.12 Conclusion

This chapter presented an introduction to the study, its scope and objectives, and the research methodology. It also briefly discussed the problems inherent in creating an effective climate-responsive architectural solutions to ameliorate the hazards of hot dry and semi-arid climates, and the dangers posed by the so-called *international* style. Furthermore it introduced the concept of modulated solar shielding in the context of solar radiation control for low energy buildings in hot dry and semi-arid climates and discussed some of its side-effects. The next chapter presents the contextual and climatic backgrounds to the study.

Chapter 2

Contextual and Climatic Background

2.1 Introduction

This chapter presents the climatic and geographical characteristics of Nigeria, with particular reference to the hot semi-arid climatic region of northern Nigeria which constitutes the *area of study* for this work. This was meant to provide the necessary background to the study. Details of the study of suitable correlation models for the estimation of solar radiation data from meteorological parameters are also presented. Having established a suitable model that could effectively simulate the peculiar characteristics of the hot semi-arid climate, the development of an interactive computer program that generates solar radiation and other bioclimatic design data was undertaken. Results from the program and other parameters relevant to its development are also included.

2.2 A Contextual Framework

The Federal Republic of Nigeria, a developing country located in West Africa, occupies a large area of about 923,769 square kilometres and with a population of about 100 million people. It is the most populous country in Africa which has a total population of just over 500 million. (Table 2.1 gives some key facts and figures of the country). Attention would promptly be directed at the issues that concern this part of the study namely (1) the climate of the country and how it has shaped the typologies of buildings in different parts of the country with emphasis

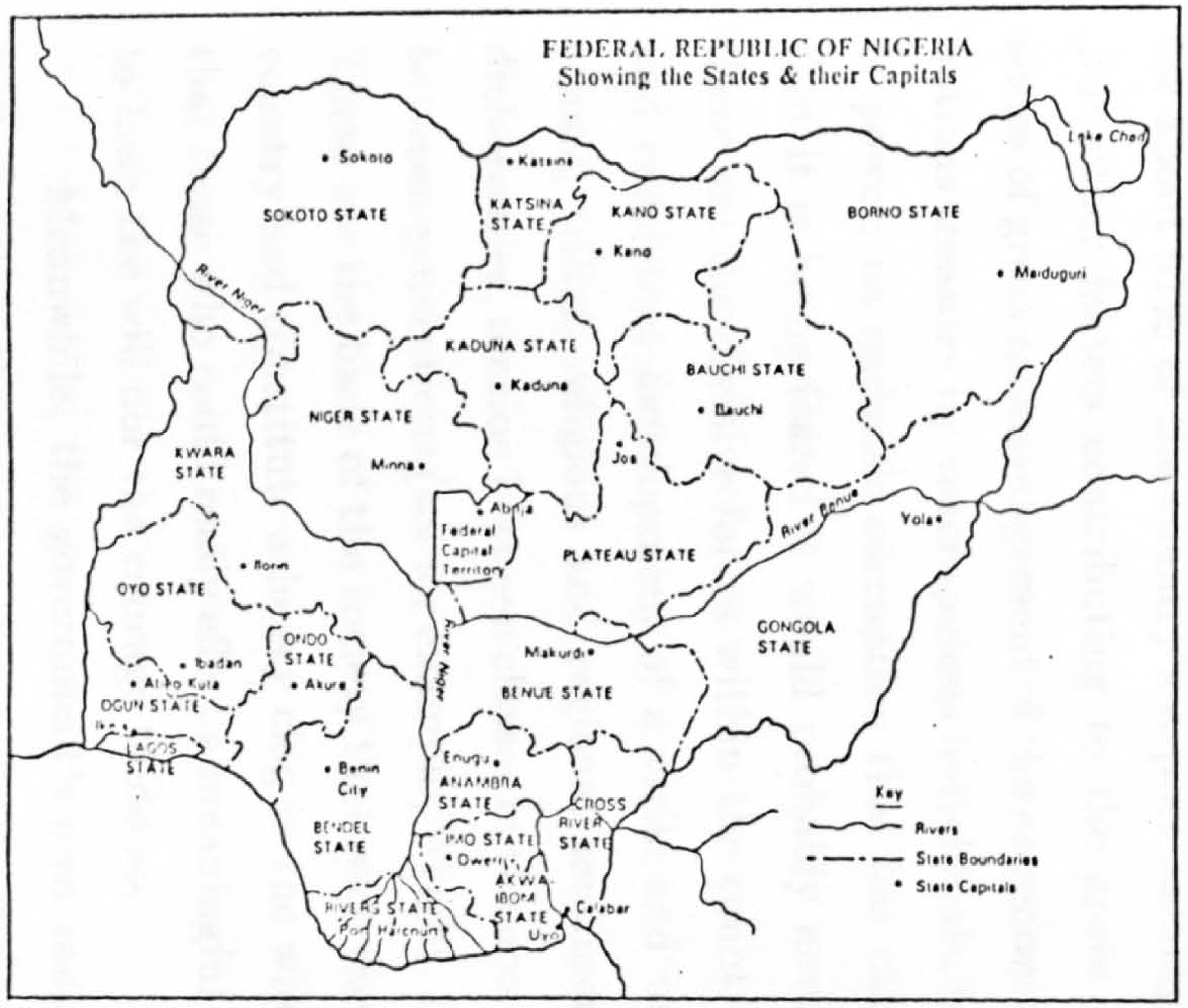
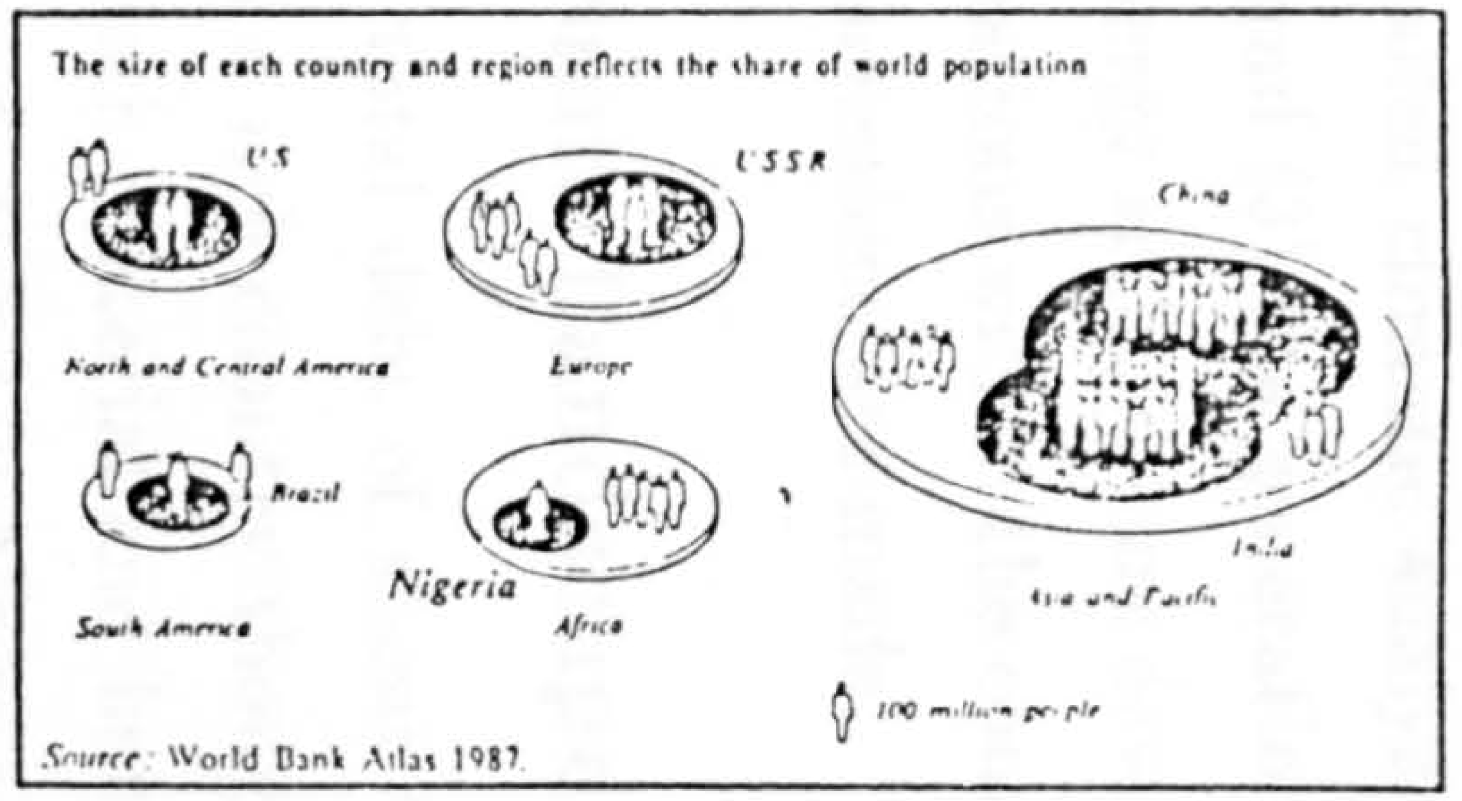


Table 2.1 Some key facts and figures on Nigeria (Source: *The Courier*, **106**, December 1987)

Official title: Federal Republic of Nigeria
Head of State: Major-General Ibrahim Babangida
Constitution: a federal republic, comprising a Federal Capital Territory and 21 states, each with a State Governor
Capital: Lagos (new Federal Capital: Abuja)
Independence: 1 October 1960
Official language: English (Hausa, Yoruba and Ibo widely spoken. Many other local languages)
Surface area: 923 769 km²
Population: 99.7 million
of which: 30% urban
49% of working age
growth rate: 3.1% p.a.
per doctor: 9591
per hospital bed: 1251
Life expectancy: 50
Infant mortality: 110/1000
Average no. of children: 6.9
School enrolment: 59%

Currency: Naira
1 Naira = ECU .21 / US$ .24 } (Aug. 87)
GNP: $ 75 940 million
Real growth rate: (1973-85) 0.3%
GNP/capita: $ 760
GDP growth rate: −6.3% (1986)
Inflation: +14% (1986); +20% (1987 estimate)
Investment: (average 1980-85) − 18%
Imports: $ 5 800 million
Exports: $ 6 800 million
Trade balance: $ 1 000 million
Total ODA: $ 32 million per annum
Total debt: $ 22.7 billion
Ratio of debt / GDP: 11% (1980); 29% (1985)
Ratio of debt servicing / export revenues: 4.8% (1980); 36.4% (1985)
Principal exports: petroleum (97%) (28% of GDP), cocoa, gas



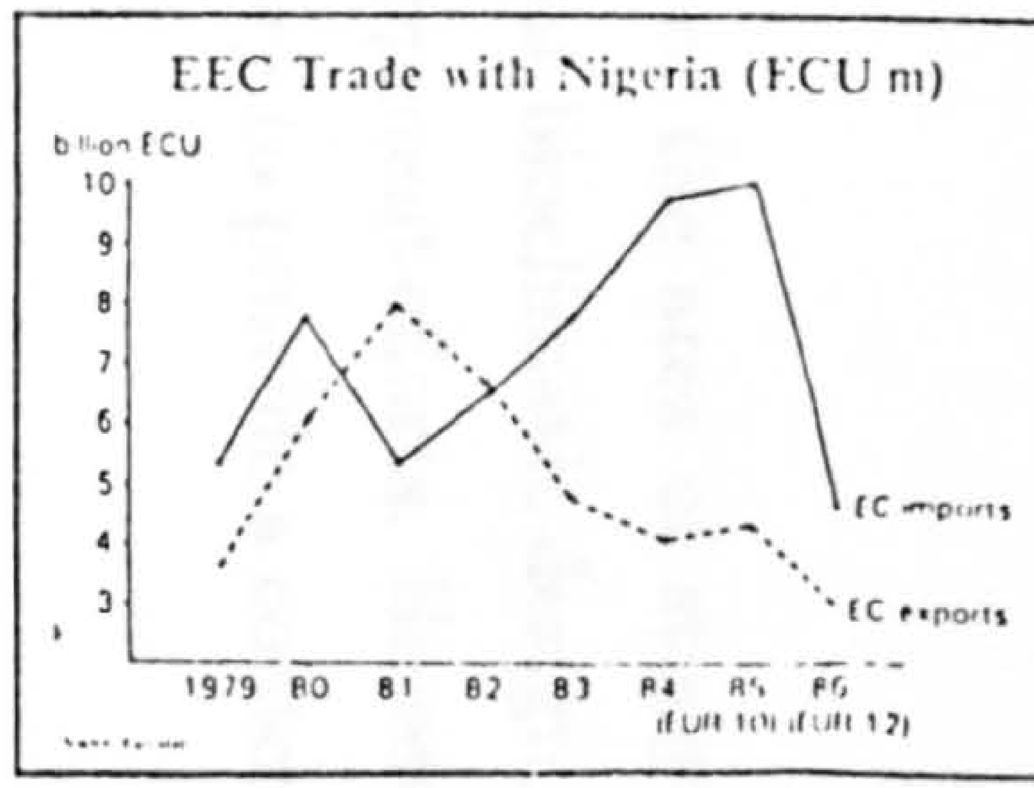
Source: World Bank Atlas 1987.

Economic sectors: % of GDP and of population active in sector

	Agriculture		Industry and Mines		Services	
	% GDP	AP*	% GDP	% AP	% GDP	% AP
1965	53	72	19	10	29	18
1980-84	27	68	30	12	43	20

* Active population.

Sources: IMF, IBRD, OECD, World Bank Atlas, Central Bank of Nigeria.



on the area of study; (2) A detailed climatic analysis of the area of study and some other parts of the country and (3) the generation of bioclimatic design data relevant to the passive and low energy architecture development efforts. However it is pertinent to appreciate the situations within the country to provide a contextual background against which the discussions are made.

2.2.1 The Socio-Economic Landscape

As a developing country with a total debt of about $22.7 billion hanging down her neck, Nigeria is by no means a rich country though it is potentially so, being blessed with a lot of resources, both material and human (the country is the 6th largest oil producer in the world and second in Africa after Libya, and she has such mineral resources, as limestone, tin, columbite, coal, iron ore, lead, zinc, gold, etc).

The present gloomy economic situation is readily attributable to the decline in oil prices and hence the country's export earnings since petroleum now accounts for about 97% of the country's export earnings and 66% of government earnings. But other factors contributing to the grave situation are all too well-known – series of gross mismanagement of the economy coupled with constant looting of the nations treasury by unscrupulous individuals, both within and outside the corridors of power; an endemic corruption that has eaten so deep into the nation's fabric that it is being feared it would probably never completely disappear. Of course there are the divisive forces within the country that do not make for meaningful and consistent development of a virile and united nation. These forces include ethnic, tribal, religious and regional sentiments, the north-south and east-west dichotomies, tension between classes in the economic and social strata and divisions between generations (see for example, Wright, 1986 on Nigeria as a divided society). These are the bane of the society that rock the very foundation of the unity of the country and constitute a heavy clog in the wheel of progress. It is rather pathetic that those who could really effect a meaningful change for the country seem neither to have the will nor the courage to do so.

Meanwhile, the government's own *indices* of "industrial growth" seem to indicate that the country has a *fairly steady economic growth* in terms of the number of industrial plants and factories, though it is arguable if this is indicative of the *actual* industrialisation of a country which should be

> *"the process of developing the capacity of the country to master and locate within its borders, the whole industrialisation process: production of raw materials; production of intermediate products for other industries; fabrication of the machines and tools required for the manufacture of the desired products and of other machines; skills to operate, maintain and reconstruct the machines and tools; skills to manage the factories and to organise the production process"*
> (Abba *et al*, 1985).

The above discussions are meant only to give a realistic picture of the economic situation but this shouldn't be misconstrued as inferring that these problems are insurmountable. This is by no means so. Nigeria is only a *poor* rich country, a *sleeping* giant in Africa with a great potential. The country can still be transformed into an economic power in spite of the present predicaments.

Another consideration is the situation of the *construction industry* in the country which would undoubtedly have significant implications on any meaningful passive solar program. The construction industry embraces both the building construction and civil engineering works and both are served by industries manufacturing cement, metal rods, bars and sheets. Against a backdrop of hyper-inflation it has been extremely difficult for the industry to meet the soaring demand for construction equipments and tools (see Wahab, 1986). Moreover, it is, and has always been dominated by the formal sector, which consists of a few construction firms with foreign connections and which are virtually monopolists. These firms have the prerequisite skills and expertise which are lacking in the informal sector. Their main clients are the public establishments and governments, private and public firms and some rich individuals. They handle the major construction contracts in the country and are engaged in building expensive "modern" structures.

The informal indigenous sector on the other hand contents itself with the relatively cheap vernacular and quasi-"modern" buildings which constitute over 80% of the built environment in the urban centres. Unless the indigenous sector avails itself of skilled manpower through training, and local technology is developed to meet construction needs, the above situation would persist for a long time. This implies that the building of passive or low-energy homes with modern construction materials and techniques would depend mainly on importation of both materials and skills, nurtured by monopolist firms and would therefore be so expensive that only the rich can afford them. Furthermore it would be very difficult if not impossible to sustain any passive solar or low energy programme within the country under such circumstances.

Also it cannot be over-stressed that a special emphasis be placed on the production of local building materials in the country. Making building materials available locally does not end with erecting a few cement factories. It should be accompanied by the development and expansion of the basic machine-tool factories and the iron and steel industry should be expanded to cater for the construction and other industries while striving towards meeting the requirements for producing machine parts and machine tools. Small scale local industries should be encouraged and given a measure of protection against foreign competition, and research into the use of local materials must be stepped up.

Also the construction industry and its distribution systems are plagued by many parasitical middlemen and touts, with little skill, capital or ability - beyond contacts - who call themselves *contractors*. They create artificial scarcity in the distribution system and often exorbitantly increase the price of building materials. The results are numerous unfinished projects and very high cost of construction. A mechanism must be devised to rid the industry of these idle workers.

Our main concern as designers within the above scenario is to seek means of reducing the plight of the people, both rich and poor but especially the latter, of the huge expense they incur just to make their homes a ***habitable*** place via mechanical air conditioning. This can mainly be done by adopting a genuine bioclimatic or passive design approach that is not only functional but would also offer more respite from the inclements of the climate. This would also alleviate the pain and suffering of those who cannot afford the "luxury" of mechanical air-conditioning and have to brave the discomfort of their poorly designed homes. The government also stands to gain from the huge energy and financial savings that can be made. The ever-increasing energy demand in the country so outstrips the supply that there is always a continual power failure. Anyone who has lived in or visited Nigeria will have experienced the frustrating "on-off" power supply that has become a way of life. With a cut-back on the huge power consumption in the domestic sector, the country would have more power to go round, and possibly eliminate the need for imported portable generators. This would translate into huge savings and make more funds available for productive investment.

2.2.2 Climatic Features

Although there is probably an infinite variety of climates over the earth with every place being slightly different in some aspects from all others, some form of climatic classifications have been developed to enable the identification of some major or significant differences in climates. This classification has produced series of "climate types" mapped out into climatic regions, with succinct descriptions of likely climatic conditions together with an explanation of their causes and indications of their variability or stability with time. One of the most well-known climatic classifications is the *Koopen* classification which may be found detailed in many texts, including Henderson-Sellers and Robinson, (1986). The most often-used parameters for climatic classification are temperature, water content in the atmosphere and precipitation.

The data of the chosen parameters over a long period for the whole area is thoroughly examined and cartographic techniques are used to produce "mapped out" climatic regions. However some of the inherent problems with such mapping include the fact that climate is a spatially continuous variable while the observations are made for discreet points. Hence regional boundaries must be established by interpolation, the accuracy of which depends greatly on the network of observation stations (see Henderson-Sellers and Robinson, (1986).

The variability of climates has often been alluded to the effects of different atmospheric phenomena. A detailed description of some of the various atmospheric phenomena which attempt to demystify the complexity of climates has been given by Oke, (1978).

The climate of Nigeria is as complex and varied as the country is large, as exemplified by the diverse and contrasting environmental conditions within the country. The country straddles several distinct natural regions and falls within the *tropical* climatic belt which is basically *located between the tropics of Cancer and Capricorn the parallels at 23.45° North and South of the Equator respectively* (Nieuwolt, 1978). Nigeria is located approximately between latitudes 4°N and 14°N and longitudes 3°E and 15°E. The longest east-west distance is over 1120 km while that of north-south is over 1040 km. The natural climatic belts straddled by this vast expanse of land consist of the southern forest zone (consisting of mangrove and freshwater swamp forests) which occupies approximately one-third of the country and the series of savannah grasslands (consisting of guinea, sudan and sahel savannahs) which occupy the rest (Mabogunje, 1968). The only major variation in the north is the Jos and Mambilla plateaux. The middle belt is characterised with the grassy savannah alternating with tree-covered parklands.

The climatic belts and vegetations are mainly dictated by the level of rainfall, the prevailing winds and proximity to the sea in the southern border and to the hot-dry land mass of the Sahara desert which separates the West African coastal countries from North Africa. With plenty of rain, it is relatively warm and humid in the south and gets hotter and drier progressively northwards, up to and including the hot semi-arid sahelian zone in the extreme north which is the hottest and driest single climatic belt in the country. The mean monthly average daily maximum temperature in the southern forest zone is about 30°C compared to the value of 36°C in the sahelian belt of the extreme north. This is as a result of the heavy cloud in the south which shields off much of the direct radiation from reaching the ground whereas the sahelian belt with its clear blue skies most of the time, receives relatively more direct radiation during the day. However the Jos plateaux with summits of over 1500 metres above sea level is a conspicuous exception. Its mean temperatures are about 5°C lower than that of the surrounding plains and has a pleasantly cool climate (e.g. Jos, 1285m, 21.8°C average temperature). Figure 2.1 shows features of regional variations in climate.

These climatic variations have also had a bearing on architectural typologies in different parts of the country. The south is characterised by buildings with large window and wide eaves with high pitched roofs of asbestos, aluminium, or corrugated iron sheets (or even thatch in the villages). The walls are either sandcrete or concrete blocks or even of adobe depending on whether they are indigenous or contemporary (the so-called "modern") buildings. The aggregation of buildings is relatively sparse with wide set backs between houses accentuated by wide streets.

In the extreme north however the indigenous buildings are made of thick walls and roofs of mud or *adobe* and characterised by small window both in number and in size and flat roofs with little or no eaves. Building aggregation is very compact, with narrow, winding streets and other features characteristic of hot dry lands. Examples of these are the famous mud walls of Kano city, Zaria, Sokoto, Maiduguri and Daura. In some other areas, the 'temporary' structures of the nomadic Fulanis, made of reeds straw and thatch, can be found dotting the sparsely

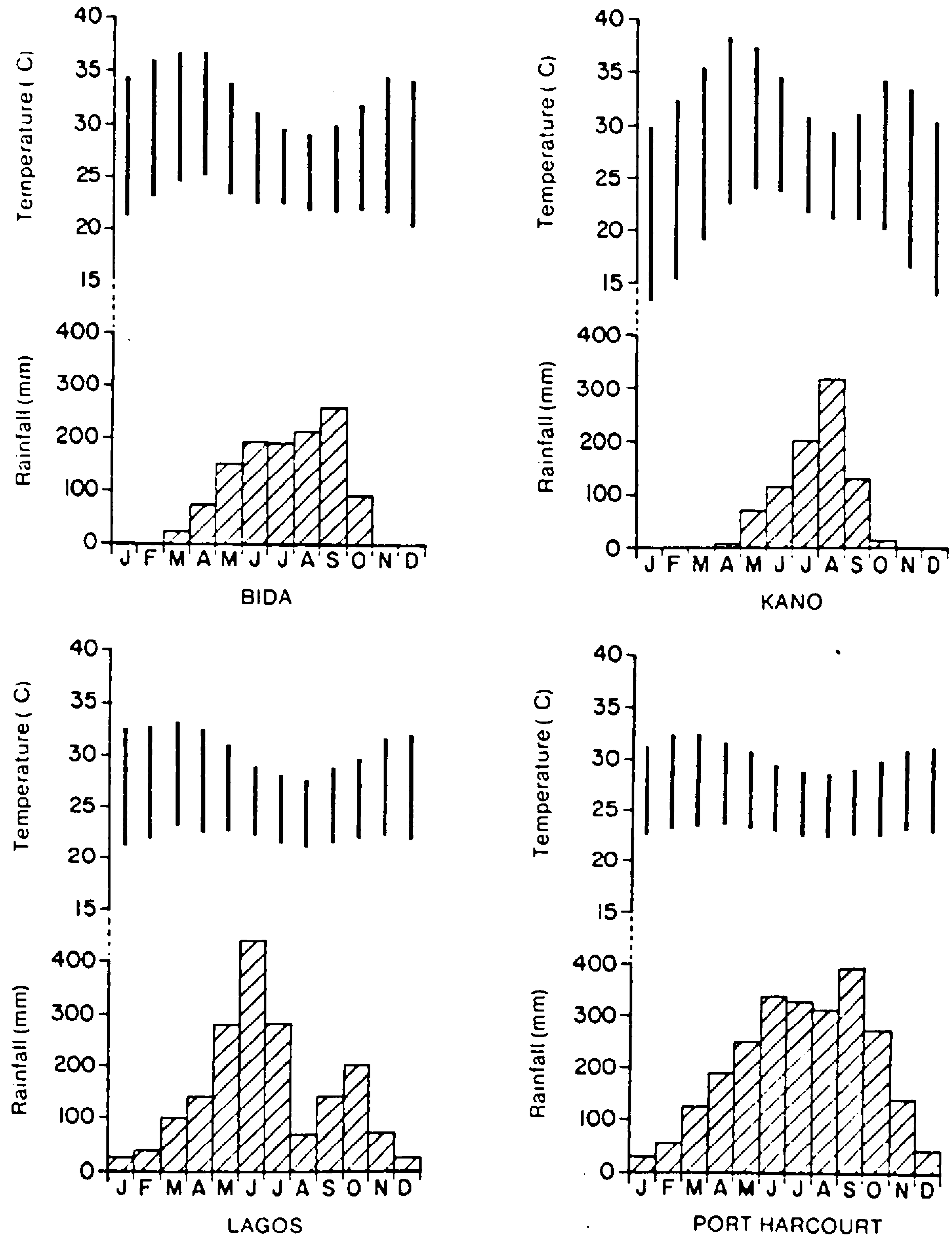


Figure 2.1 Regional variations in the climate of Nigeria. (Source: Morgan, 1983)

vegetated plains.

Between these two extremes is the middle belt where the building typologies are more or less similar to those in the forest zone with varying adaptation to the climate, with a gradual shift towards the dry climate architecture as one moves towards the north.

2.2.3 The Sahelian Semi-arid Climatic Belt

The actual climatic zone which constitutes the area of study for this thesis is the northern fringe of the country, consisting of sahelian semi-arid climate. It is enclosed between the line which extends from the north-western border approximately through Birni Kudu, Funtua, Potiskum and Maiduguri to the northern border with Niger Republic. Some other important locations within this belt include Potiskum, Nguru, Hadejia, Kano, Daura, Katsina, Wurno and Sokoto (See Figure 2.2). Figures 2.3 to 2.7 show the variations of temperature profiles within the area of study.

2.2.3.1 Climatic Analysis

Rarely do climatic elements have the same characteristics or effects in different locations, no matter the apparent similarity of their climate. Whilst there are minor variations from one location to another within this climatic belt, it is *generally* characterised by a dominant period of dry season which is about 8-9 months, and a very brief period of rainy season of about 3 months. It has a dry atmosphere, with low relative humidity except during the short period of rainy season (between end of June and early September). There is generally high maximum and low minimum temperatures, giving rise to relatively high temperature range except in the relatively more humid rainy season.

2.2.3.2 Seasons

In Kano for example, there are four main seasons namely (a) hot season (early March to middle of June); (b) rainy season (middle of June to early September); (c) mild season (middle of September to end of November) and (d) Harmattan season (December to early March).

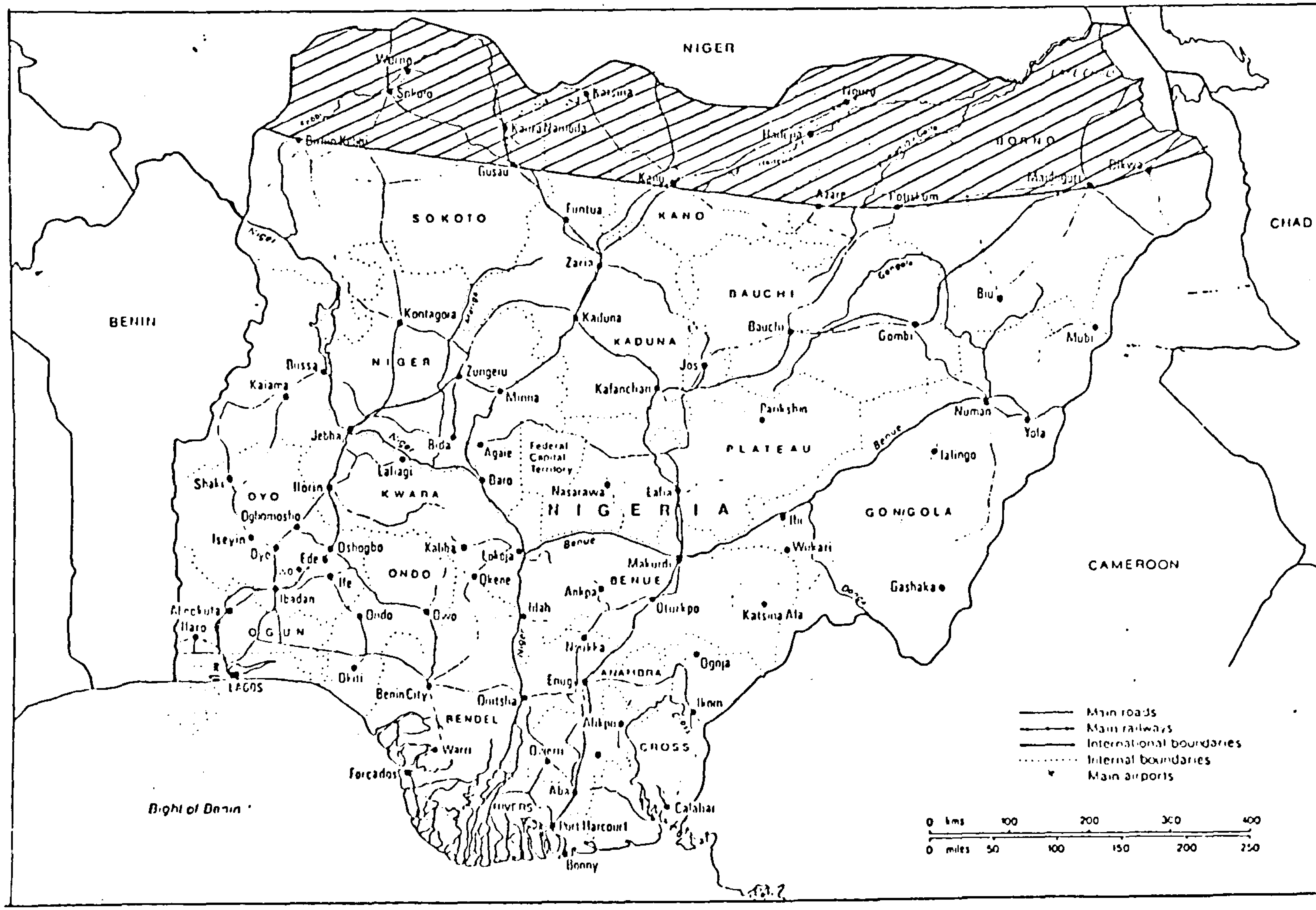
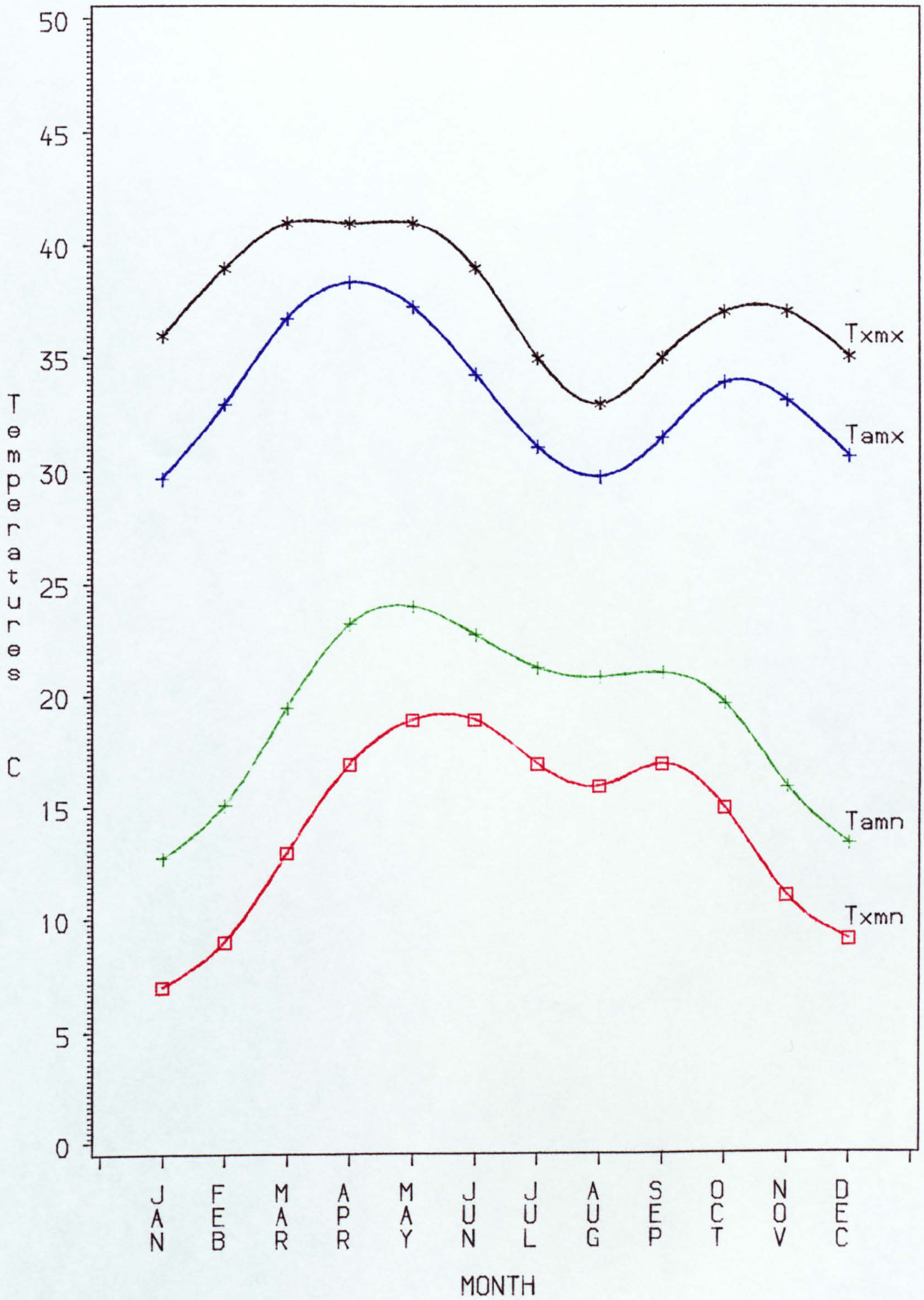
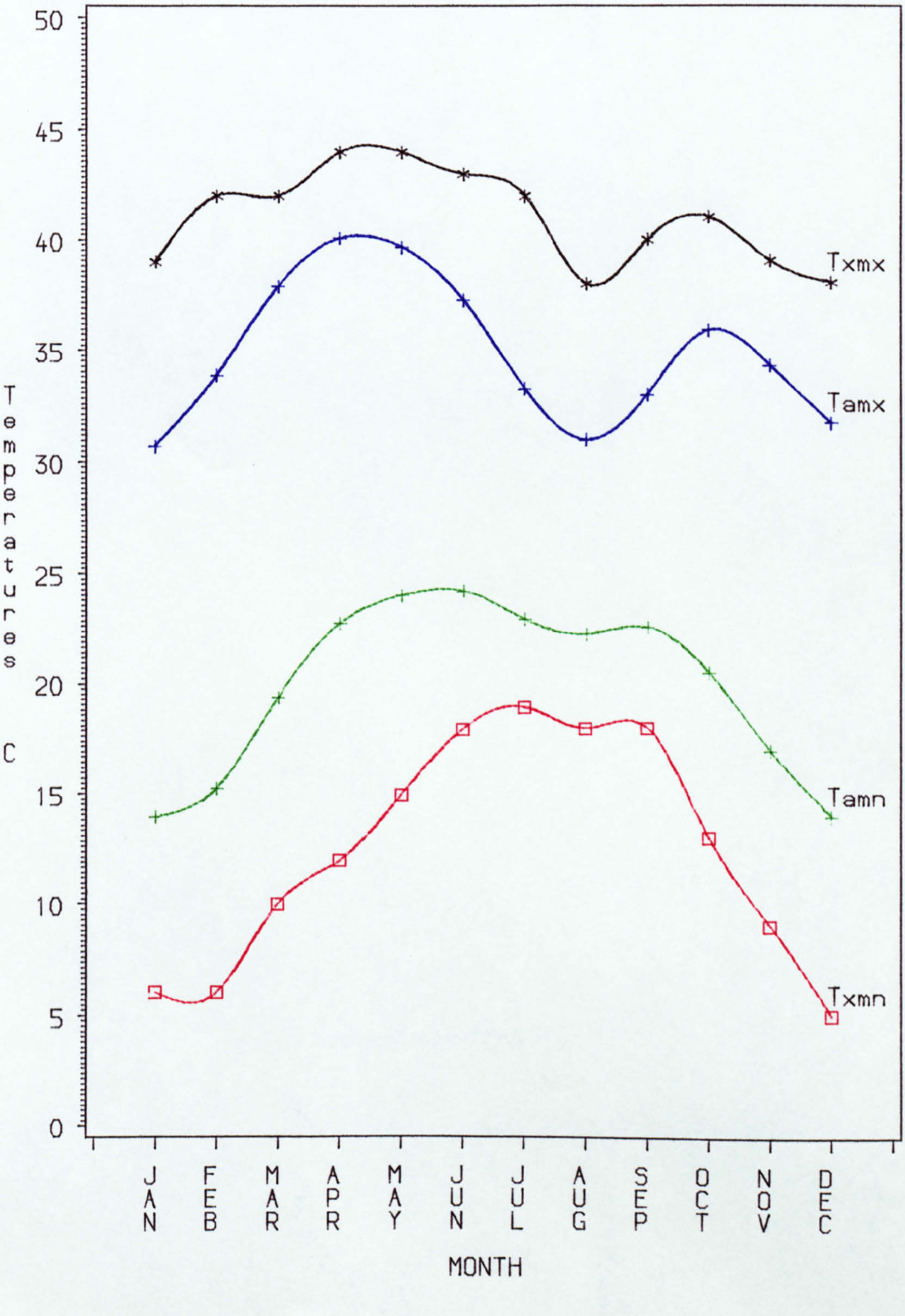


Figure 2.2 The area of study: The hot semi-arid climatic belt of northern Nigeria.



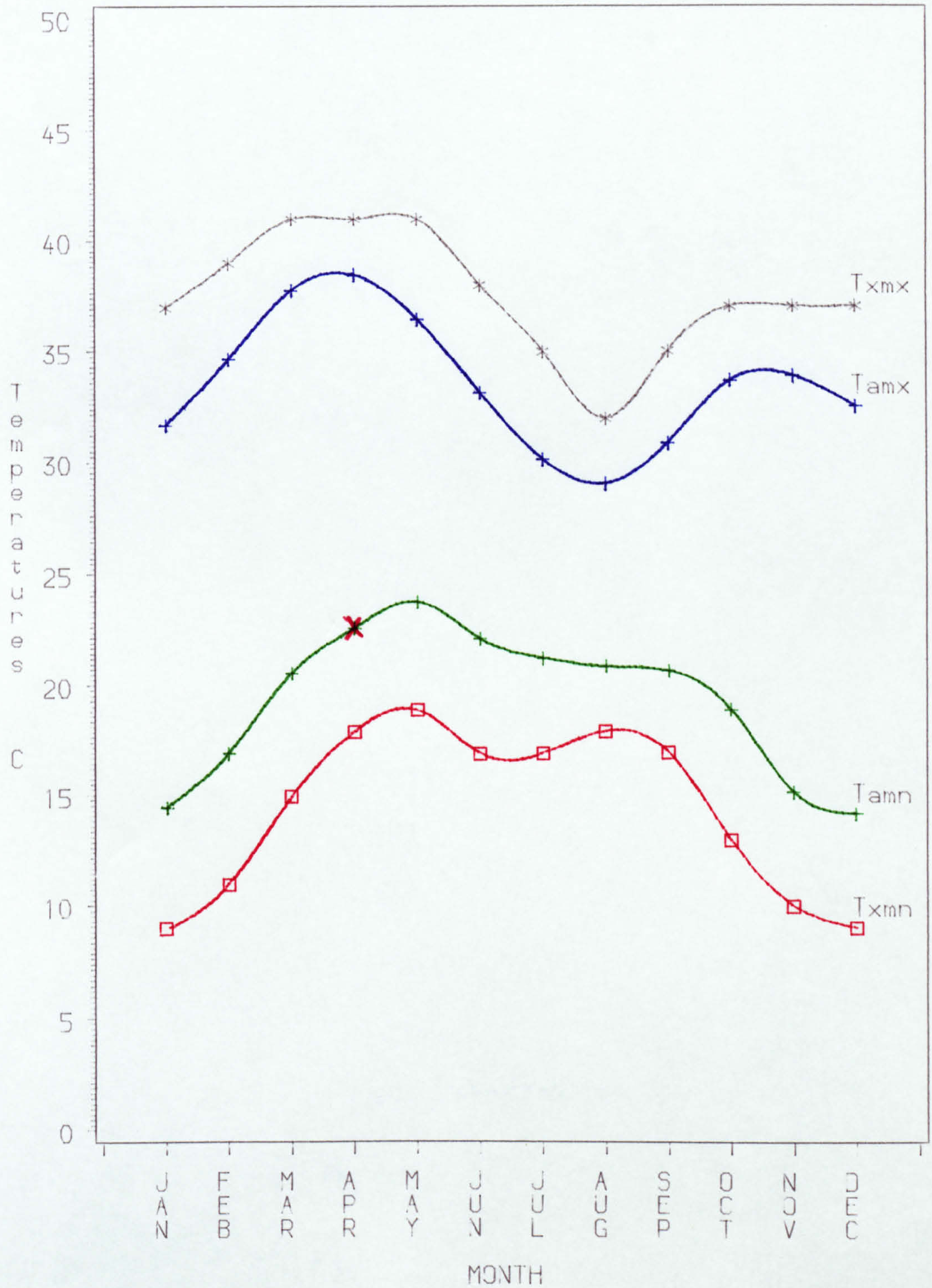
Txmx = Extreme daily maximum
Txmn = Extreme daily minimum
Tamx = Average daily maximum
Tamn = Average daily minimum

FIGURE 2.3 KANO: TEMPERATURE PROFILES



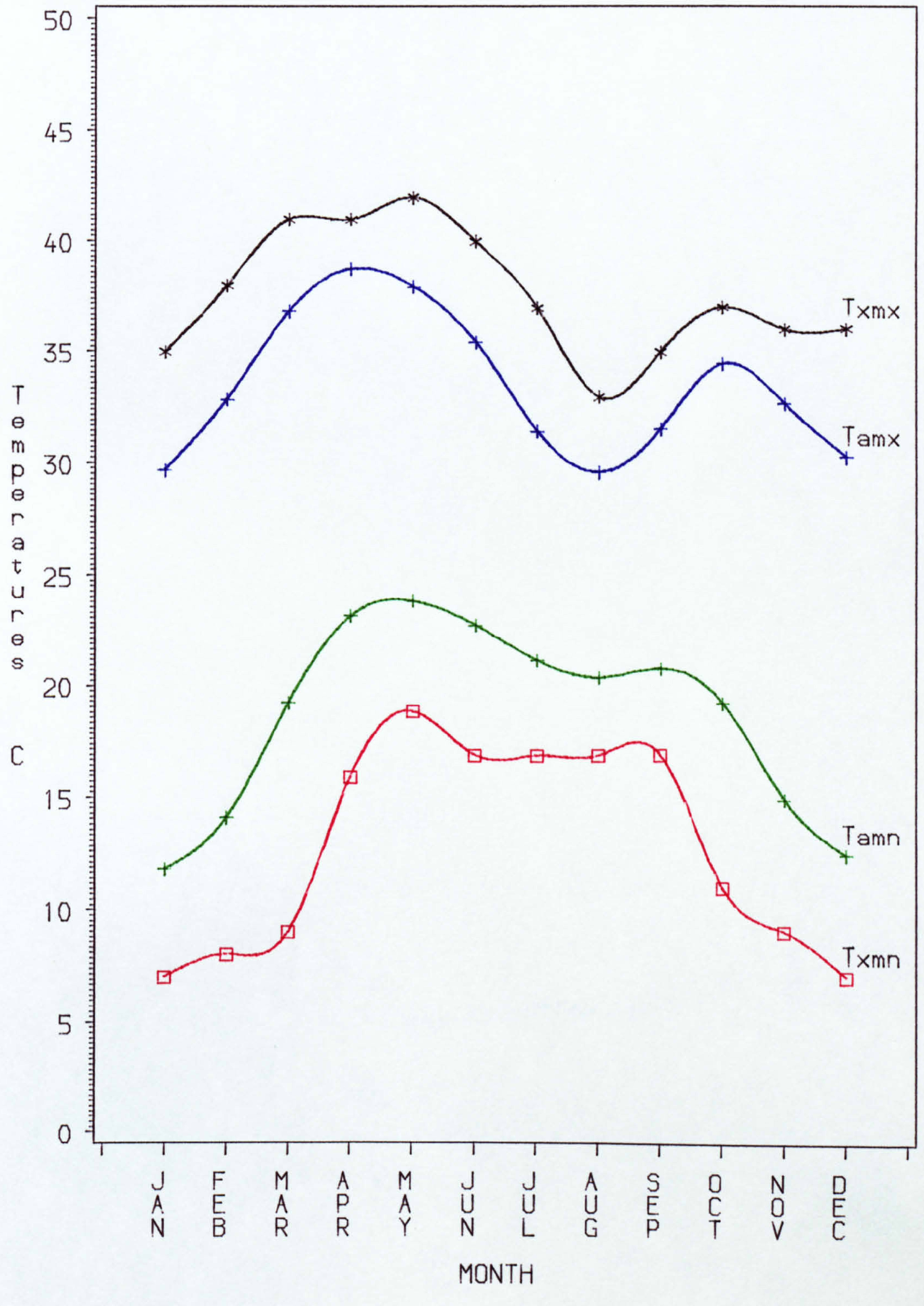
Txmx = Extreme daily maximum
Txmn = Extreme daily minimum
Tamx = Average daily maximum
Tamn = Average daily minimum

FIGURE 2.4 NGURU: TEMPERATURE PROFILES



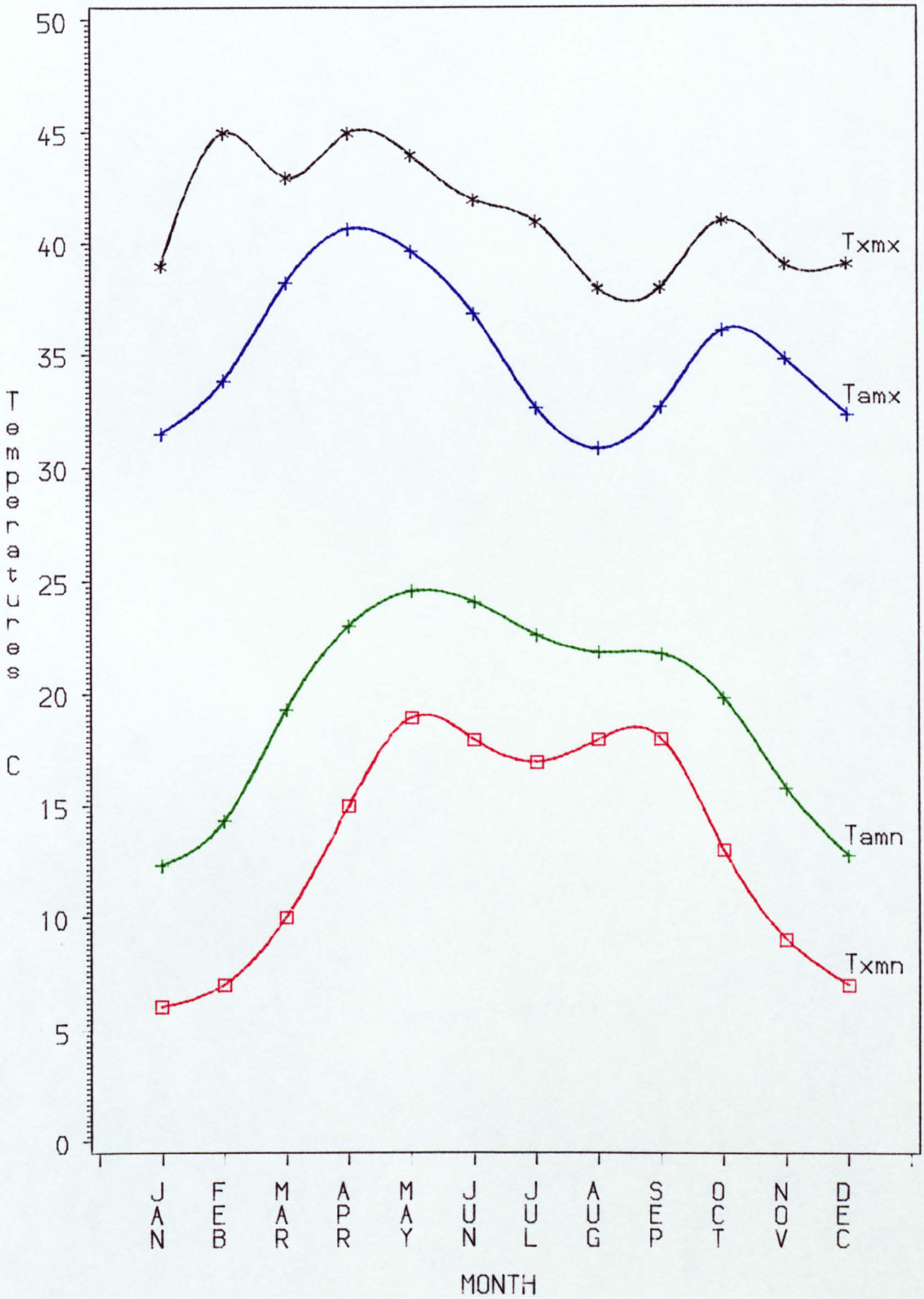
Txmx = Extreme daily maximum
Txmn = Extreme daily minimum
Tamx = Average daily maximum
Tamn = Average daily minimum
✕ = Corrected Data Value

FIGURE 2.5 GUSAU: TEMPERATURE PROFILES



Txmx = Extreme daily maximum
Txmn = Extreme daily minimum
Tamx = Average daily maximum
Tamn = Average daily minimum

FIGURE 2.6 KATSINA: TEMPERATURE PROFILES



Txmx = Extreme daily maximum
Txmn = Extreme daily minimum
Tamx = Average daily maximum
Tamn = Average daily minimum

FIGURE 2.7 MAIDUGURI: TEMPERATURE PROFILES

2.2.3.3 Building Types

In this climatic belt, the traditional buildings are mainly courtyard compounds with thick walls and roofs of reinforced adobe. The thick roofs are flat and can also be used for outdoor sleeping. Detailed description of these traditional buildings can be found in such works as Denyer, (1978) and Saad, (1981). In the brief description below, which may constitute a typical *design brief* to an architect for a traditional compound in this climatic belt, the underlined words are the actual names in the local *Hausa* language, the most widely spoken language in Nigeria:
The typical compound is compact in plan with rooms (daki) facing inwards into the courtyard. A large compound may have multiple courtyards dividing the compound into sections (sashe) which are partitioned off by walls (danga) or matting (zana). Depending on whether the location is rural or urban, the courtyards may have pens for animals such as fowl pens (akurki) or granary (rumbu). The entrance (kofar) of a typical household leads into the (zaure) or reception space. Most compounds have an open space, (farfajiya) in front of the zaure for ceremonies such as child naming, marriage or funeral. The zaure is a very important space as it is where the family head, (maigida) receives his guests and/or transacts business and it is a point of transition between the outside world, (waje) and the inner section of the house inhabited by women folk who should not be seen by the males (except their husbands) due to the strict practice of purdah (kulle), which is an Islamic institution. However some side entrance (barauniyar kofa) may be provided to enable women and children to pass in and out of the compound without disturbing the guests at the zaure.

The semi-private section of the compound (sachen kofar gida) is occupied by the adult and adolescent males who are yet to be married. When married, they either move into the (cikin gida) with their wives or move out to establish a new household. The section for the head of the household (sachen maigida), is usually so located as to give the maigida a visual command of the movement between the inner private cikin gida of his wives and the semi-private sachen kofar gida.

These buildings are responsive both to the climate and the traditional socio-religious indiosyncracies of the people.

2.2.3.4 Contemporary Buildings

The contemporary vernacular and "modern" buildings are virtually not different from the contemporary buildings in the rest of the country, either in form or in the use of materials. The only minor differences is that the windows and eaves are relatively smaller. Whilst the traditional courtyard planning is not adhered to, attempts are made in most cases, to give women their much needed privacy in accordance with islamic tenets. However the buildings, as I have pointed out earlier, are not well adapted to the climate.

Within this climatic belt, as in other parts of the country, there are some meteorological stations from which local climatic data could be obtained. However, due to stringent difficulties, non of the stations actually takes solar radiation measurements.

2.3 Generation of Solar Radiation and other Design Data

2.3.1 Introduction

Apart from the fact that the thermal simulation aspect of this study requires solar radiation data, the knowledge of the amount of global, direct and diffuse irradiation at a place is necessary for most building thermal analysis and many solar energy applications. However the necessary equipments for their measurements are often unavailable especially in developing countries. It is hardly surprising therefore that in Nigeria the measurement of radiation data is at the moment only being carried out in a few cities. A few research stations record the daily global radiation for some cities such as Ibadan, Nsukka and very recently, Onne (near Port Harcourt) which have daily global radiation recorded by the International Institute for Tropical Agriculture (IITA), Ibadan. In fact Ibadan is likely to be the only Nigerian city where the daily global radiation has been continuously recorded as far back as 1972. It has therefore been necessary to estimate the global direct and diffuse radiation values for this climate from meteorological data by means of correlation models.

2.3.2 Analytical and Empirical Models

A number of approaches have been used for the estimation of solar radiation data in different parts of the world for a long time. Such approaches include the use of measurable atmospheric parameters such as turbidity, surface reflectivity and quantity of precipitable water (e.g. King and Bukius, 1979; Barbaro *et al*, 1979; Ideriah, 1981), cloud layer (e.g. Davies and McKay, 1982), total cloud amount (e.g. Monteith, 1962; Kasten, 1983) and the use of empirical relationships between global radiation and such meteorological parameters as sunshine duration (Angstrom, 1924; Prescot, 1940; Page, 1961,1976) sunshine duration plus relative humidity (e.g. Swartman and Ogunlade, 1967) and a combination of sunshine duration, relative humidity and temperature (e.g. Sambo, 1986) and so on. Many examples exist in which these parameters have been used severally or jointly for the estimation of global radiation.

The correlation between global irradiation and bright sunshine hours by Angstrom (Angstrom, 1924) and later modified and used at different times by Prescot (Prescot, 1940) and Page (Page, 1961) has perhaps been the most widely used in different parts of the world including such locations as Yemen Arab Republic (Khogali, 1983) Sudan (Khogali, 1983(b)), Greece (Flocas, 1980), Austria (Neuwirth, 1980), Hong Kong (Leung, 1980) and Lesotho (Gopinathan, 1988).

For the estimation of diffuse radiation, the empirical correlation by Liu and Jordan, 1960 and Page, 1976 seem to be the most widely used. But many new empirical relationships have been developed and applied to various locations (e.g. Lewis, 1983; and Iqbal, 1979).

Of all the meteorological parameters used for estimation, **sunshine duration** appears to be the strongest determinant for the quantitative value of global radiation and its component parts. The governing relationship which is originally due to Angstrom and later modified by Prescot and Page, is given by

$$\frac{H}{H_o} = a + b\left(\frac{n}{N}\right) \tag{2.1}$$

where H is the monthly mean daily global radiation incident on a horizontal surface, ($MJm^{-2}day^{-1}$); H_o is the monthly mean extra-terrestrial daily global radiation incident on the same horizontal surface ($MJm^{-2}day^{-1}$); n is the monthly mean daily average bright sunshine hours (h); N is the monthly mean maximum possible daylength *(h)*; while a and b are regression coefficients (the ratio $\left(\frac{n}{N}\right)$ is often referred to as percentage possible sunshine). The wide spatial variation of the values of coefficients a b for different locations around the world (Table 2.2) indicates their dependence on the location and its characteristics (see Lewis, 1989). This has contributed to the proliferation of correlation models even up till the present times (Sahsamanoglou and Bloutsos, 1989; Kierkus and Colborne, 1989; Newland, 1989; Suehrcke and McCommick, 1989; Copolino, 1989; Fenillard *et al*, 1989; Raja and Twidell, 1989) and is likely to continue into the future.

Another reason attributable to the proliferation of models is the empirical nature of the equations developed which are without any cohesive structure or even a firm theoretical basis and thus often stand isolated from one another. In this light, models developed can only but be suitable solely for the locations for which they were developed, unless a theoretical basis is developed to lay a foundation for the understanding of the various constants in the empirical models and the relationships between them. One of the first efforts in this regard is that of the models recently developed by Castro-Dietz *et al*, 1989.

In another development, Gopinathan, 1988, has proposed an analytical relationship between the coefficients a and b in the Angstrom-type equation and the latitude, altitude and the percentage possible sunshine duration, for different locations around the world. This was to enable non empirical but analytical determination of a and b. This analytical correlation was expressed in the form

$$a = A_o + A_1 \cos\theta + A_2 h + A_3 \left(\frac{n}{N}\right) \tag{2.2}$$

$$b = B_o + B_1 \cos\theta + B_2 h + B_3 \left(\frac{n}{N}\right) \tag{2.3}$$

where θ is the latitude of the location (degrees), h is the elevation of the location above sea level (km) and A_o, A_1, A_2, A_3, B_o, B_1, B_2 and B_3 are all constants.

Available data on a, b, θ, h, and $\left(\frac{n}{N}\right)$ for 40 locations around the world were used in a multiple linear regression analysis to obtain constants in equations (2.2) and (2.3). In conclusion, correlations of the form

$$a = -0.309 + 0.539 \cos\theta - 0.0693h + 0.290 \left(\frac{n}{N}\right) \tag{2.4}$$

$$b = 1.527 - 1.027 \cos\theta + 0.0926h - 0.359 \left(\frac{n}{N}\right) \tag{2.5}$$

were recommended for calculating the coefficients a and b for any location on the earth surface.

Table 2.2: The values of regression coefficients in the Angstrom-type equation, obtained at selected locations.

Location	a	b
Abu Dhabi	0.307	0.312
Athens, Greece	0.230	0.460
Cairo, Egypt	0.140	0.610
New Delhi, India	0.341	0.446
2 Locations in Alabama, U.S.A.	0.210	0.500
30 locations in Italy	0.177	0.692
Dhahran, Saudi Arabia	0.175	0.552
8 locations in Zambia	0.240	0.513
4 locations in Nigeria	0.245	0.486
25 locations in the 22^0N to 20^0S tropical belt	0.300	0.400

Source: Lewis, (1989)

Gopinathan's approach was based on earlier developments by Rietveld (1978) who observed that coefficient a is related linearly and b hyperbolically to the mean values of percentage possible sunshine, and Glover and McCulloch (1958) who expressed them in terms of the latitude of the location and its percentage possible sunshine.

Rietveld (1978) expressed a and b as

$$a = 0.10 + 0.24\left(\frac{n}{N}\right) \tag{2.6}$$

$$b = 0.38 + 0.08\left(\frac{n}{N}\right) \tag{2.7}$$

giving

$$\frac{H}{H_o} = 0.18 + 0.62\left(\frac{n}{N}\right) \tag{2.8}$$

while Glover and McCulloch (1958) expressed $\left(\frac{H}{H_o}\right)$ for any location as

$$\frac{H}{H_o} = 0.29\cos\theta + 0.52\left(\frac{n}{N}\right) \tag{2.9}$$

(for $\theta \leq 60°$)

In a recent development, Davies and McKay (Davies and McKay, 1989) made a comparative evaluation of some twelve selected models which simulate solar irradiance on horizontal surfaces with data from seven countries. These included models which use such atmospheric parameters as cloud layer amount (Davies and McKay, 1982; Josephson, 1985), total cloud amount (Kasten, 1983; Monteith, 1962), and *sunshine-based* models (Barbaro *et al*, 1979; Page, 1961; Rietveld, 1978). The others were models which represent the Liu and Jordan radiation-partitioning techniques, (Collares-Pereira and Rabl, 1979; plus Erbs *et al*, 1982) which estimate daily irradiation values and (Orgill and Holland, plus Erbs *et al*, 1982) for estimating hourly values.

Their results suggested that the cloud layer models provided the best estimates and can be successfully used in most parts of the world, even with incomplete cloud layer information. It was also found that Rietvelds' procedure for estimating constants a and b in the Angstrom equation did not improve upon irradiation estimates from the Page, 1961 model which uses fixed parameter values. The use of sunshine based models were not recommended for world-wide use but were considered suitable for their particular climates for which they were empirically formulated. It was acknowledged that the performance of models based on surface meteorological measurements and observations is probably limited more by the inadequacy of the surface measurements than by modifiable defects in the models themselves. Another weakness of sunshine-based models is that even though the Angstrom equation can be tuned easily to the climatic conditions of any place, by simple regression analysis, it nevertheless requires irradiation measurements in the first instance, without which the prediction equation cannot be derived. Furthermore with the temporal as well as spatial scatter in the values of the regression constants even for nearby and climatologically similar locations there is always difficulties in assigning the values a and b to locations without measured data. In addition, a and b may also be dependent on the sunshine recording instrument; different sunshine recording equipments may produce different values of a and b for the same location (Page, 1976).

In view of all of the above, it was necessary for the purpose of accuracy, to use correlation coefficients empirically derived in the area of study. Fortunately, in Nigeria, a few research workers have been actively engaged in the field of the derivation of solar radiation data from atmospheric and meteorological parameters.

2.3.3 Models for Estimation of Solar Radiation Data in Nigeria

Some theoretical models for predicting or calculating the direct (beam) and diffuse components of the global insolation on a horizontal surface have been put forward by several authors in Nigeria. Among the several models that now exist is that of Ideriah, 1981 which is an extension of the work of King and Buckins, 1979, for the calculation of both direct and diffuse radiation under cloudy sky conditions. The model computed the daily insolation for Ibadan for the year 1977 and compared them with experimental data.

The main components considered by the model are (a) Scattering transmittance (b) Absorption transmittance (c) Water vapours (d) Sunshine hours (e) The zenith and/or the hour angle. The model suggests that the daily direct radiation under clear sky conditions I_c is given by

$$I_c = \int_{t1}^{t2} I \cos \theta dt \qquad (2.10)$$

where I is the direct solar radiation on a horizontal surface, W/m^2, θ is the zenith angle, and t_1 and t_2 are the times of sunrise and sunset respectively. This value decreases with the presence of clouds in the sky, by some factor which depends on the sky cloudiness. This factor is taken to be related to the relative sunshine n/N. Thus it expresses the daily direct radiation for a cloudy sky I_d as

$$I_d = K\frac{n}{N}I_c \tag{2.11}$$

K being a constant. Similarly, the model expressed the daily diffuse radiation for a clear sky as

$$J_c = \int_{t1}^{t2} J\cos\theta dt \tag{2.12}$$

(J being the diffuse solar radiation on a horiz. surf.), and finally suggested that the daily diffuse radiation for a cloudy sky J_d may be expressed as

$$J_d = \left(\frac{n}{N}\right)J_c + f\left(1-\frac{n}{N}\right)(I_c + J_c) \tag{2.13}$$

where f is an empirical transmission coefficient whose values vary for different latitudes.

Secondly there is the Bamiro, 1983 model which gives empirical relationships for the calculation of solar radiation from measured temperature, relative humidity and sunshine hours for Ibadan. In a very exhaustive empirical analysis, the model eventually suggested that the daily total radiation H is given by

$$\frac{H}{K} = C_o + C_1(TD) + C_2R^{1/2} + C_3\left(\frac{RT^{1/2}}{K}\right) + C_4\left(\frac{RD}{K}\right) \tag{2.14}$$

where K is a constant related to the latitude of the place, C_o, C_1, C_2, C_3 and C_4 are regression parameters, R is the relative humidity, T is the dry bulb temperature ($°C$) and D is the sunshine ratio $\left(=\frac{n}{N}\right)$.

The estimated diffuse component of total radiation, s H_D was obtained by setting D=0 in the above equation, giving

$$\frac{H_D}{K} = C_o + C_2R^{1/2} + C_4\left(\frac{RT^{1/2}}{K}\right). \tag{2.15}$$

The model also suggests an expression relating the diffuse ratio K_D and the clearness index K_T (i.e. H/H$_o$) as

$$K_D = 1.28 - 1.12K_T \tag{2.16}$$

($0.4 \leq K_T \leq 0.6$) Eventually, an empirical relation of the form

$$\frac{H}{K} = C_o + C_1(TD) + C_2R^{1/2} + C_3\left(\frac{RT^{1/2}}{K}\right) + C_4\frac{(RD)}{K} \tag{2.17}$$

was established by the model. The above expression is said to predict a linear relationship between the daily diffuse radiation and the daily total radiation in line with previous linear model by Liu and Jordan, 1960 but with different coefficients such that the diffuse component is higher.

Ideriah, (Ideriah, 1983) has also developed an extended work on his previous model (Ideriah, 1981) to establish correlations for the diffuse insolation for the city of Ibadan on a daily, weekly and monthly average basis. The correlations include both calculated and experimental values of the daily global insolation for the city.

Ezekwe and Ezeilo (Ezekwe and Ezeilo, 1981) had earlier carried out a comparison between measured diurnal global irradiation at Nsukka with values calculated from five different empirical models. Climatic data such as sunshine hours, relative humidity, Maximum air temperature as well as declination angle, latitude and altitude, were used as inputs for the models. The comparisons show that the modified formula of Swartman and Ogunlade, 1967 gave the best agreement with the measured data. The results of the investigation also highlights the variance of daily irradiance with seasons, especially during the dry season with its dusty 'harmattan haze', though this is more significant in the northern part of the country.

Also a correlation model by both Ideriah and Bamiro has been developed (Ideriah and Bamiro, 1982) which is based on comparison and analysis of the previous theoretical model of Ideriah, 1981 and the empirical model of Bamiro, 1983. Correlation equations were given, and the daily diffuse ratio K_d was presented in relation to the clearness index. Equation of correlation is given as

$$K_d = 1.89 - 1.67K_T - 11.4K_T^2 + 28.1K_T^3 - 18.4K_T^4 \tag{2.18}$$

(for $0.28 \leq K_T \leq 0.75$)

Sambo, 1985 has also suggested a correlation model for the global solar irradiation in Kano with: percentage possible sunshine, temperature and relative humidity as parameters.

A relationship between the global irradiation and the percentage possible sunshine was established with the usual Angstrom-type regression equation (Equation 2.1) and constants a and b were determined for a 60-month period to be 0.403

and 0.241 respectively, though the constants were also found for the different seasons. Thus

$$\frac{H}{H_o} = 0.403 + 0.241\left(\frac{n}{N}\right) \tag{2.19}$$

Similarly, the global irradiation was correlated with the sunshine hours, minimum and maximum temperature and relative humidity in the form

$$K_T = C_o + C1\left(\frac{n}{N}\right)^{C_2} + C_3(\theta)^{C_4} + C_5(\phi)^{C_6} \tag{2.20}$$

where θ is the monthly mean daily ratio of the minimum to maximum temperature, ϕ is the monthly mean daily relative humidity, and constants $C_o - C_6$ are obtained by multiple regression analysis. These coefficients were also determined for the different seasons in Kano. A correlation between the diffuse ratio K_d and the clearness index K_T was expressed as

$$K_d = -4.157 + 32.486K_T - 64.867K_T^2 + 39.501K_T^3 \tag{2.21}$$

(for $0.4 \leq K_T \leq 0.7$)

Sambo has further developed an improved correlation model (Sambo, 1986) which was based on the multiple variable approach of the previous (Sambo, 1985) model. The model developed one-variable correlation (sunshine duration), two-variable correlations (sunshine duration plus temperature ratio, relative humidity, air temperature or water vapour content) and three-variable correlations (sunshine duration plus any other two of all the above variables), and compared their predictions with measured global irradiance values. There were sixteen equations in all. It was suggested that one of the three-variable correlations produced the best fit to the data measured in Kano between 1980-1984 and gave the least root mean square error (RMSE). This correlation is of the form

$$\frac{H}{H_o} = a_o + a_1\left(\frac{n}{N}\right) + a_2\left(\frac{n}{N} - R - \theta\right) + a_3\left(\frac{n}{N}.\theta\right) \tag{2.22}$$

where R is the mean monthly daily relative humidity; θ is the ratio of the minimum to maximum mean monthly daily temperatures; a_o, a_1, a_2, a_3 are regression constants, which for the most suitable equation were 0.621, -0.294, 0.178 and 0.491 respectively with RMSE of -0.45.

The root mean square error RMSE is given by

$$RMSE = \left[\frac{\sum\left(\frac{H}{H_{ox,est}} - \frac{H}{H_{ox,ms}}\right)^2}{Y}\right]^{1/2} \tag{2.23}$$

where $\frac{H}{H_{ox,est}}$ and $\frac{H}{H_{ox,ms}}$ are respectively the xth estimated values of $\frac{H}{H_o}$, and Y is the total number of observations.

Doyle has also suggested a model (Doyle, 1982) for the estimation of the mean optical thickness and the air mass, and established a relationship between them and the solar irradiance. He also proposed a model for estimating the hourly diffuse irradiance from known values of total global irradiance predicted by the mean-optical thickness approach. However these two pieces of work were not in resonance with the available meteorological data in the area of study and were therefore not of immediate interest to the study. Same applies to the correlation proposed by Doyle and Sambo (Doyle and Sambo, 1988) which predicts diffuse radiation in terms of the air mass.

The Sambo, 1986-model was considered most suitable for the prediction of solar radiation data for this study and was used in the iterative computer program that was developed to generate these data and other relevant building design data for the area of study. The main reasons for the preference of the Sambo, 1986-model include the fact that (1) It was empirically developed for the area of study. (2) It gave a very good fit to the measured data and the least RMSE. (3) It is a multi-variable model rather than just a single variable model based solely on percentage possible sunshine ($\frac{n}{N}$) which has not been found to effectively simulate the peculiar characteristics of the climate.

2.4 The Computer Program for the Generation of Design Data

An interactive computer program, SURFRAD, (for surface radiation) was developed in *FORTRAN 77* to generate solar radiation and other relevant climatic design data. This entailed (1) Generating daily totals of global radiation for the hot semi-arid climate of Northern Nigeria from measured meteorological parameters; (2) Dispersing the generated totals into hourly values; (3) Splitting the hourly global radiation values into diffuse and direct (beam) radiation components; (4) Generating solar radiation data for vertical surfaces (or surface of any orientation and inclination).

2.4.1 Development Methodology

The method adopted to meet the above requirements was to use different suitable and *compatible* models to develop each stage of the work. First, the Sambo, 1986-model was used to generate daily values of global (direct + diffuse) radiation in the first instance. Then the hourly irradiance values were calculated according to Collares-Pereira and Rabl, 1979. These values were then split into their direct and diffuse components according to Orgill and Holland, 1977 technique as modified by Spencer, 1982. For the radiation data on inclined surfaces the Klucher, 1979 model was used to estimate the sky diffuse irradiance on surfaces of any orientation and inclination while the Temps and Coulson, 1977-model was used to estimate the ground reflected irradiance on inclined surfaces.

2.4.2 Some Important Parameters for Solar Radiation Calculations

2.4.2.1 Solar Declination (δ)

The solar declination is the angle between the earth's equatorial plane and the line joining the earth and sun centres. It varies between -23.45° on 21st December (winter solstice) and +23.45° on June 21st (summer solstice), i.e. ($-23.45 \leq \delta \leq 23.45^o$).

The solar declination can be obtained from the equation of Cooper, (1969) as adapted and used by Collares Pereira and Rabl (1979):

$$\begin{aligned} \delta &= \sin^{-1} 23.45 \sin\gamma \\ &= 0.3979 \sin\gamma \end{aligned} \tag{2.24}$$

where γ is the circular orbit of the earth, approximation (in radians) for which is

$$\gamma \approx \gamma_o = 2\pi \left(\frac{J + 284}{365.24}\right) \tag{2.25}$$

where J is the day number in the annual cycle. For greater accuracy the following expression is used

$$\gamma = \gamma_o + 0.007133 \sin\gamma_o + 0.032680 \cos\gamma_o - 0.000318 \sin 2\gamma_o + 0.000145 \cos 2\gamma_o \tag{2.26}$$

The solar declination δ can also be calculated according to Dogniaux (1973) using the expression

$$\begin{aligned}\delta &= 0.33281 - 22.984\cos(kJ) + 3.7872\sin(kJ) - 0.3499\cos(2kJ) \\ &+ 0.03205\sin(2kJ) - 0.1398\cos(3kJ) + 0.07187\sin(3kJ) \qquad (2.27)\end{aligned}$$

where $k = \left(\frac{2\pi}{366}\right)$.

2.4.2.2 Solar Altitude and Azimuth

Some relevant aspects of solar geometry are illustrated in Figures 2.8 to 2.10 inclusive. The solar altitude and solar azimuth are the two angular co-ordinates which describes the position of the sun in the sky (Figure 2.8). The solar altitude h is the angle between a direct solar ray and the plane tangent to the earth surface at the site. The solar azimuth is the angle measured *clockwise* between the true north and the projection of the solar ray on the aforementioned plane. The solar altitude is given by the expression (Rogers, Souster and Page, (1981), Sattler,(1986))

$$h = \sin^{-1}(\sin\phi\sin\delta + \cos\delta\cos 15t) \qquad (2.28)$$

where h is the solar altitude (degrees), ϕ is the latitude of the site; δ is the solar declination and t is the number of hours from solar noon, (p.m. being negative). The angle $15t$ is the hour angle (ω) i.e

$$\omega = 15t \qquad (2.29)$$

t is given by the expression

$$t = 12 - LAT \qquad (2.30)$$

where LAT is the Local Apparent Time or true solar time (TST) which is related to the Local Mean Time (LMT), (i.e. the clock time at a particular place) by the expression

$$LAT = LMT + ET \pm (L_s - L_r)/15 \qquad (2.31)$$

where L_s is the longitude of site under consideration, L_r is the reference longitude of the time zone, and ET is the equation of time which is further explained below. The times of sunrise and sunset (t_s) is given by

$$t_s = \frac{1}{15}\cos^{-1}\left(\frac{\sin(-50') - \sin\phi\sin\delta}{\cos\phi\cos\delta}\right) \qquad (2.32)$$

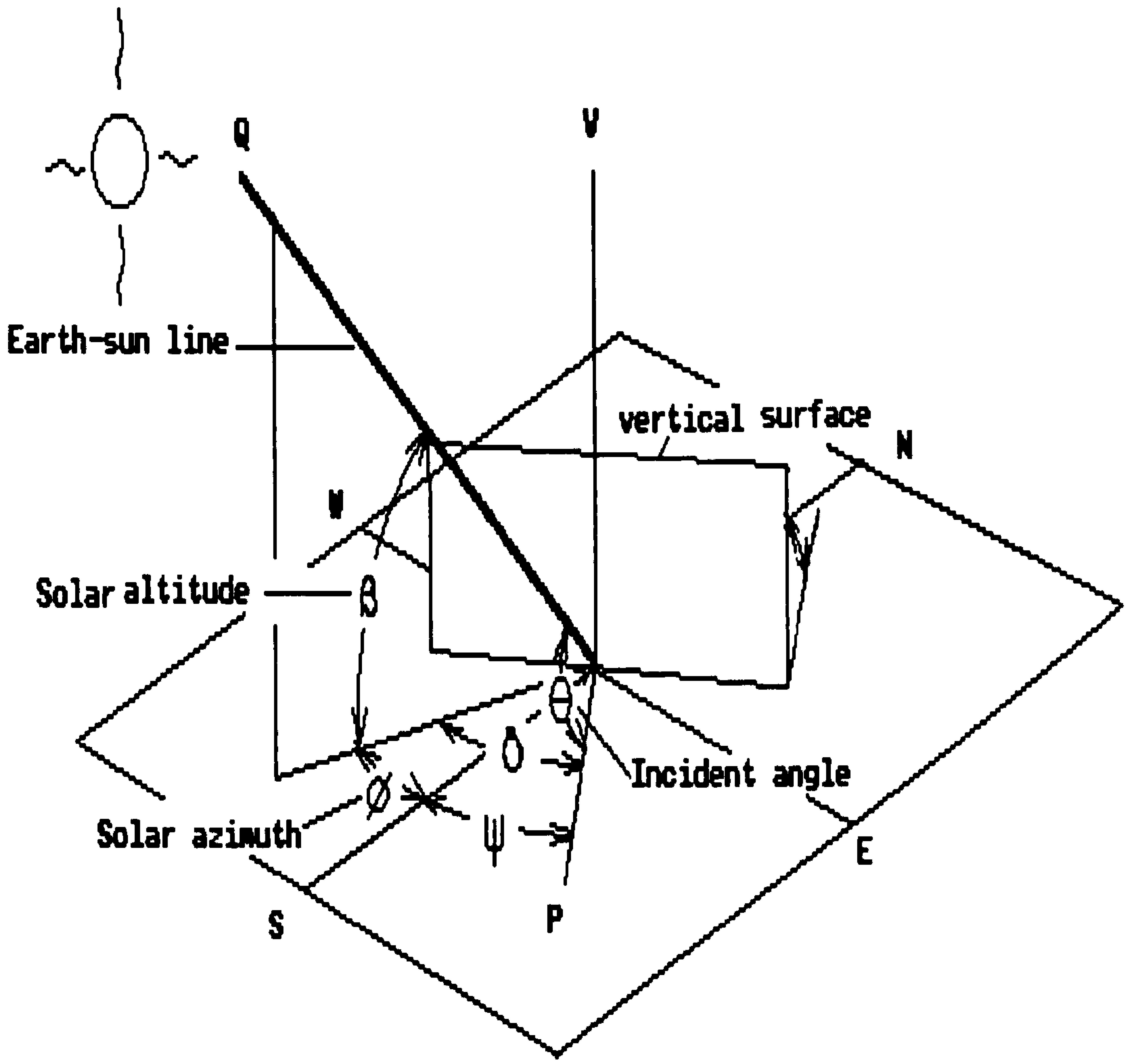


Figure 2.8

The solar angles of a surface.

which is usually approximated to

$$t_s = \frac{1}{15}\cos^{-1}\left(\frac{-\sin\phi\sin\delta}{\cos\phi\cos\delta}\right) = -\tan\phi\tan\delta \tag{2.33}$$

where ϕ and δ are the latitude and solar declination respectively. From the above, the maximum possible daylight hours N (or daylength as it is often called) is given by

$$N = 2t_s = \frac{2}{15}\cos^{-1}\left(\frac{\sin(-50') - \sin\phi\sin\delta}{\cos\phi\cos\delta}\right) \tag{2.34}$$

Similarly the sunset hour angle (ω_s) (which equals $(2\pi t_s/24)$ or $(15t_s)$), is given by

$$\omega_s = \cos^{-1}\left(\frac{\sin(-50^1) - \sin\phi\sin\delta}{\cos\phi\cos\delta}\right) \tag{2.35}$$

or approximated simply to

$$\omega_s = -\tan\phi\tan\delta \tag{2.36}$$

2.4.2.3 The Equation of Time (ET)

The concept of the equation of time has been deviced to make corrections for the deviation between the theoretical day length which is based on exactly 24 hour period and the solar day which is variable in length as a result of the slight variation in the velocity of the earth in its orbital movement around the sun. It is given by this expression as used by Dogniaux, (1973)

$$ET = \frac{1}{60}\left[0.00037 + \sum_{i=1}^{3}(a_i\cos(ikJ) + b_i\sin(ikJ))\right] \tag{2.37}$$

where ET is the Equation of Time, $k = \frac{2\pi}{366}$; and J is the day number in the annual cycle, and the constants a_i and b_i are as shown in the table below

i	a_i	b_i
1	0.43177	-7.3764
2	-3.1650	-9.3893
3	0.07272	-0.24498

2.4.2.4 Correction for Sun-Earth distance

Due to the elliptical shape of the earth's orbit round the sun, there is a variation in the value of the solar constant Gsc, which is the direct solar irradiance measured normal to the solar beam outside the earth's atmosphere at mean sun-earth distance. Dogniaux, 1973 proposed the adoption of a correction factor to account for this variation in the sun-earth distance. The correction factor is applied to the calculation of the solar constant and is given by the expression

$$CF = 1 + 0.033 \cos\left(\frac{360J}{365}\right) \tag{2.38}$$

where *CF* is the correction factor and J is the day number in the annual cycle.

2.4.2.5 Angle of Incidence

The angle of incidence is the angle of the direct (beam) radiation on a surface and the normal to the surface. It can be obtained from the following expression for surfaces of any inclination and orientation:

$$i = \cos^{-1}(\sin\alpha \cos h \cos\gamma_s + \cos\alpha \sin h) \tag{2.39}$$

where α is the angle of inclination of the surface, h is the solar altitude and γ_s is the horizontal shadow angle.

2.4.2.6 Horizontal and Vertical Shadow Angles

The horizontal and vertical shadow angles are the angles of the sun's position as measured from a normal to a wall in the horizontal and vertical planes. These angles may best be illustrated as shown in Figure 2.9(a,b) (Harkness and Mehta, 1978). If we consider a pin OP fixed at a normal to the vertical wall and whose shadow is OA, Figure 2.9(a) and if we consider the relationship in plan between the wall azimuth (A_w) and solar Azimuth (A_z) as in Figure 2.9(b), it can be seen that the horizontal shadow angle γ_s (angle BCA) is the difference between the solar azimuth A_z and the wall azimuth A_w. Thus

$$\gamma_s = \cos^{-1}(\cos(A_w - A_z)) \tag{2.40}$$

The vertical shadow angle β_s (angle OPB) is the angle between the pin OP and the projection BP of its shadow in the vertical plane of the wall. From the trigono-

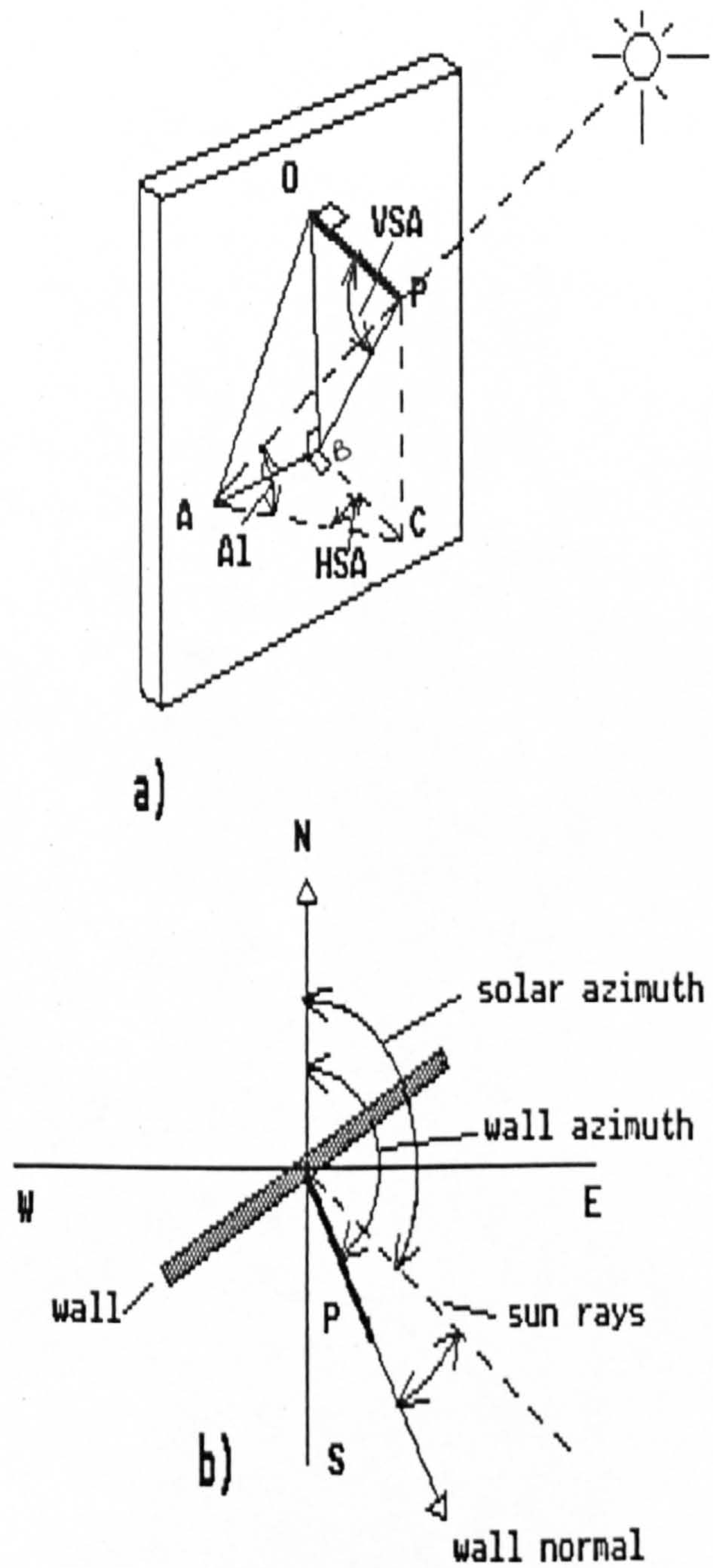


Figure 2.9 :

Solar azimuth and wall azimuth

(After Harkness
and Mehta, 1978)

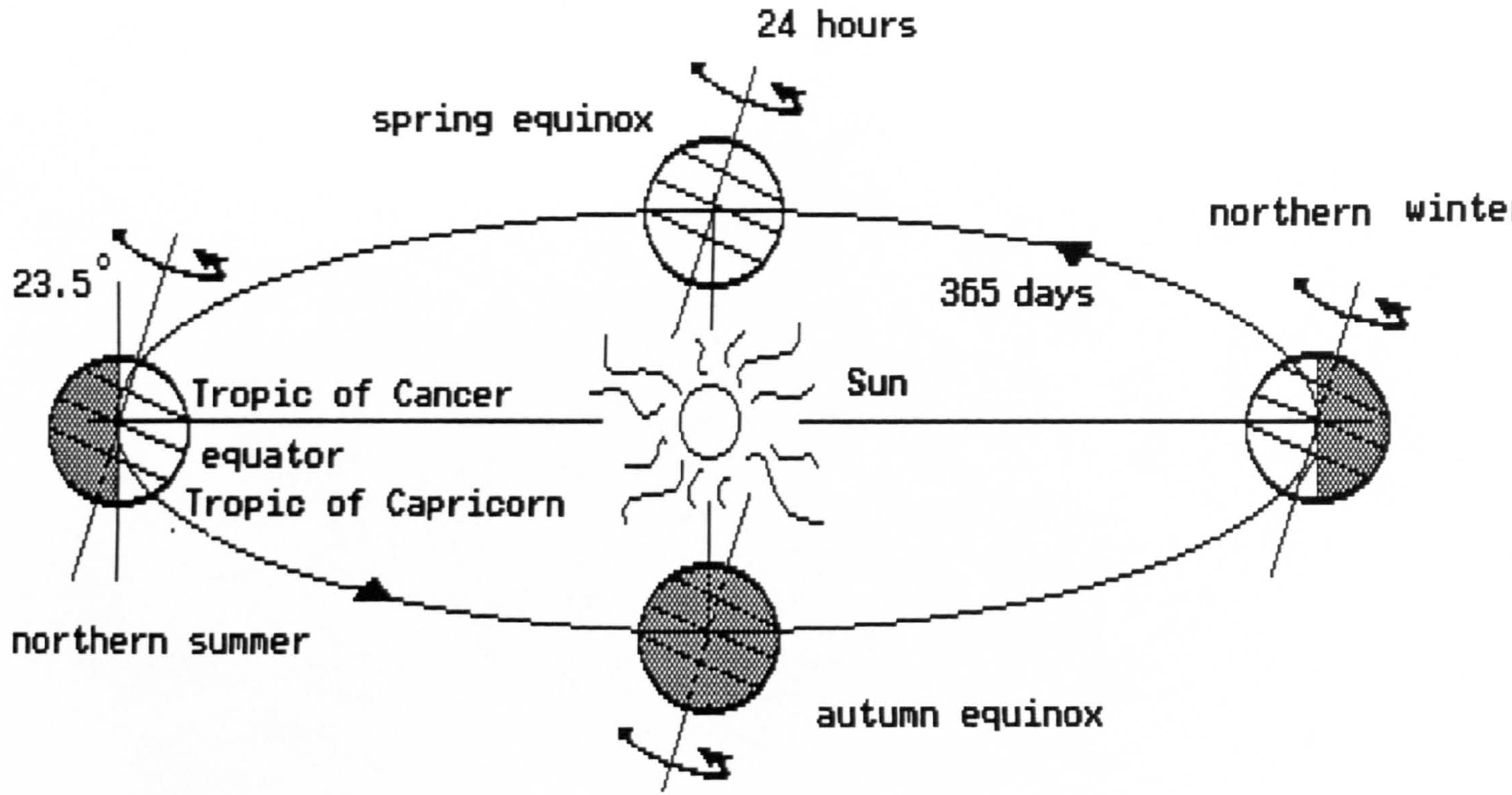


Figure 2.10: Solar geometry of the seasons and the Tropics
(After Baker, 1987)

metric relationship,

$$\tan\beta_s = \frac{OB}{OP} = \frac{PC}{BC} = \frac{PC}{AC}\cdot\frac{AC}{BC} = \tan h \sec\gamma_s \tag{2.41}$$

Hence

$$\beta_s = \tan^{-1}\left(\frac{\tan h}{\cos\gamma_s}\right) \tag{2.42}$$

2.4.3 Calculation of the daily totals of global radiation on horizontal surfaces

Sambo (1986) had suggested that the most suitable equation for the calculation of the daily totals of global radiation on a horizontal surface for the hot semi-arid climate of Northern Nigeria is given by the expression

$$\frac{H}{H_o} = 0.621 - 0.294\left(\frac{n}{N}\right) + 0.178\left(\frac{n}{N} - R - \theta\right) + 0.491\left(\frac{n}{N}.\theta\right) \tag{2.43}$$

where H, H_o, n, N, R and θ are as previously explained. This expression was thus used in the program. The ratio $\frac{H}{H_o}$ is often referred to as the clearness index K_T, in which case

$$H = K_T H_o \tag{2.44}$$

The extra terrestrial radiation H_o was calculated from the expression (Duffie and Beckman, 1980)

$$H_o = \frac{24}{\pi}G_{sc}\left(1 + 0.033\cos\frac{2\pi J}{365.24}\right)(\cos\phi\cos\delta\sin\omega_s + \omega_s\sin\phi\sin\delta) \tag{2.45}$$

where J is the day number in the annual cycle, beginning from 1st January, $(1 \leq J \leq 365)$; G_{sc} is the solar constant, with the new value of 1367Wm^{-2} which has been adopted as an international standard by the World Meteorological Organisation (WMO).

The solar declination (δ) was calculated according to Dogniaux (1973) (equation 2.27) for consistency.

2.4.3.1 Hourly Values of Global Irradiance on Horizontal Surface

The daily global irradiance values were dispersed into hourly values according to Collares-Pereira and Rabl (1979): The hourly global irradiance on a horizontal surface is expressed

$$H_{hr} = C_{fc}H \tag{2.46}$$

C_{fc} being given by

$$C_{fc} = \frac{\pi}{T}(c + d\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s} \tag{2.47}$$

c and d being respectively given by

$$c = 0.409 + 0.5016\sin(\omega_s - 1.047) \tag{2.48}$$

and

$$d = 0.0609 - 0.4767\sin(\omega_s - 1.047) \tag{2.49}$$

where H_{hr} = hourly global irradiance on a horizontal surface (Wm^{-2}), H = daily total of global radiation (Wm^{-2}), C_{fc} = conversion factor from daily total to hourly global irradiance, T = length of day (24 hours) (h), ω = hour angle (radians), and ω_s = sunset hour angle (radians).

2.4.3.2 Diffuse and Direct Hourly Irradiance on a Horizontal Surface

The hourly global irradiance values were split into their direct (beam) and diffuse components according to Orgill and Holland (1977) as modified by Spencer (1982) which used the concept of *hourly clearness index* (K_{hr}) (i.e. the ratio of the hourly irradiance on a horizontal surface (H_{hr}) to the *hourly* extra-terrestrial irradiance, $H_{o,hr}$) to estimate the fraction of the hourly irradiance that is diffuse. In this case it is necessary to calculate both H_{hr} and $H_{o,hr}$ in terms of the solar altitude. However, a minor alteration was made in this case by substituting the already generated hourly values for H_{hr} and calculating only $H_{o,hr}$ in terms of the solar altitude. In this case $H_{o,hr}$ is given by

$$H_{o,hr} = G_{sc}CF\sin h \tag{2.50}$$

where h is the solar altitude and CF is the Correction Factor for the sun-earth distance according to Dogniaux (1973) (equation (2.38)).

Therefore the hourly clearness index is given by

$$K_{hr} = \frac{H_{hr}}{H_{o,hr}} \tag{2.51}$$

The fraction of the hourly irradiance that is diffuse is estimated from the expression

$$\begin{aligned} \frac{H_{d,hr}}{H_{hr}} &= e(for K_{hr} < 0.35) \\ &= f - gK_{hr}(for 0.35 \leq K_{hr} \leq 0.75) \\ &= K(for K_{hr} > 0.75) \end{aligned} \tag{2.52}$$

where e, f, g and K are constants given by

$$f = 0.940 + 0.0118\phi \tag{2.53}$$

$$g = 1.185 + 0.0135\phi \tag{2.54}$$

$$e = f - 0.3g \tag{2.55}$$

$$K = f - 0.7g \tag{2.56}$$

The difference between the global and diffuse irradiances gives the direct irradiance component for the horizontal surface i.e.

$$H_{b,hr} = H_{hr} - H_{d,hr} \tag{2.57}$$

2.4.3.3 Solar Radiation Data on Inclined Surfaces

For an inclined surface, the total global irradiance on the surface is given by the expression

$$H_\alpha = H_{b\alpha} + H_{d\alpha} + H_{r\alpha} \tag{2.58}$$

where α = angle of inclination of surface from horizontal,
H_α = global irradiance on the surface,
$H_{b\alpha}$ = direct solar irradiance on the surface,
$H_{d\alpha}$ = diffuse irradiance from the sky on the surface, and
$H_{r\alpha}$ = diffuse irradiance from the ground.

To obtain the direct (beam) irradiance on an inclined surface, the relationship between this value and the direct irradiance on the horizontal surface can be used. This is given by the expression

$$H_{b\alpha} = \frac{H_{bh} \cos i}{\sin h} \tag{2.59}$$

($\cos(i)$ being ≥ 0)

where i is the angle of incidence of the solar rays onto the surface and
h is the solar altitude.

2.4.3.4 The Sky Diffuse Irradiance on a Tilted Surface

The sky diffuse irradiance was calculated according to the anisotropic sky light distribution model suggested by Klucher (1979) which predicts sky diffuse irrandiances on surfaces of any inclination in accordance with variable sky conditions.

It is given by the expression

$$H_{d\alpha} = 0.5G_{dh}(1 + \cos\alpha)(1 + F\sin^3(\frac{\alpha}{2}))$$
$$(1 + F\cos^2 i \sin^3\theta_z) \tag{2.60}$$

where α is the angle of inclination of surface from horizontal; i is the angle of incidence between the outward facing normal of the surface and the solar rays; θ_z is the zenith angle (i.e. $90^o - h$) and F is the modulating function that varies with the clearness index of the sky and is given by the expression

$$F = 1 - \left(\frac{H_{d,hr}}{H_{o,hr}}\right)^2 \tag{2.61}$$

where $H_{d,hr}$ and $H_{o,hr}$ are as already defined.

2.4.3.5 The Ground Reflected Diffuse Irradiance on a Tilted Surface

The ground reflected diffuse irradiance on a tilted surface was calculated according to the anisotropic model for ground irrandiance suggested by Temps and Coulson (1977) which is given by the expression

$$H_{r\alpha} = AH(1 - \cos^2(\frac{\alpha}{2})(1 + \sin^2(\frac{\theta_z}{2}))(\cos\gamma_s) \tag{2.62}$$

where A is the albedo of the ground, H is the global irradiance on horizontal surface; α is the angle of inclination of the surface in question; and γ_s is the horizontal shadow angle.

The flow chart of the interactive computer program *SURFRAD* which was developed for the study is shown in Figure 2.11. The program is running on the *Apollo Workstation* in the Gable CAD Research Laboratory. Figure 2.12 illustrates the measured and computed values of *clearness index* (which is the ratio of the *global* to the *extraterrestrial* radiation) for Kano, while some of the results from the program are illustrated graphically on Figures 2.13 and 2.14.

2.5 Conclusion

The contextual and climatic characteristics of the area of study has been presented. The climatic studies brought to light among other things, the lack of measured solar radiation data in the hot semi-arid climate of northern Nigeria as in most parts of the country. This culminated in the development of an interactive computer program, based on validated correlation models, to generate solar radiation and other building design data from meteorological data. However this contextual background is only a prelude to the theoretical background to the study which is presented in the next chapter.

Figure 2.11: The structure of the computer program *SURFRAD*.

→ **START**

Select Input Option

If file option Does *RAD.DAT* file exist? NO → STOP

YES

Data Entry + Evaluation

Select data option, THEN

If meteorological data, input regression constants a,b,c,d, plus values of sunshine duration, rel. humidity, min. and max temperatures.

ELSE input measured values of global radiation.

Input Date and Site Data and Solar geometry of the surface and the ground albedo

Evaluate:
Solar declination, day number, time of day, and hour number beginning from the first hour on January 1

Global and Extraterrestrial Radiation on a horizontal surface and the daily clearness index.

Split the daily global radiation into hourly values

Geometric characteristics and shadow angles

Split the global radiation into direct and diffuse irradiances

The ground reflected components of the diffuse irradiance for different sky condtions and surface orientation/inclination.

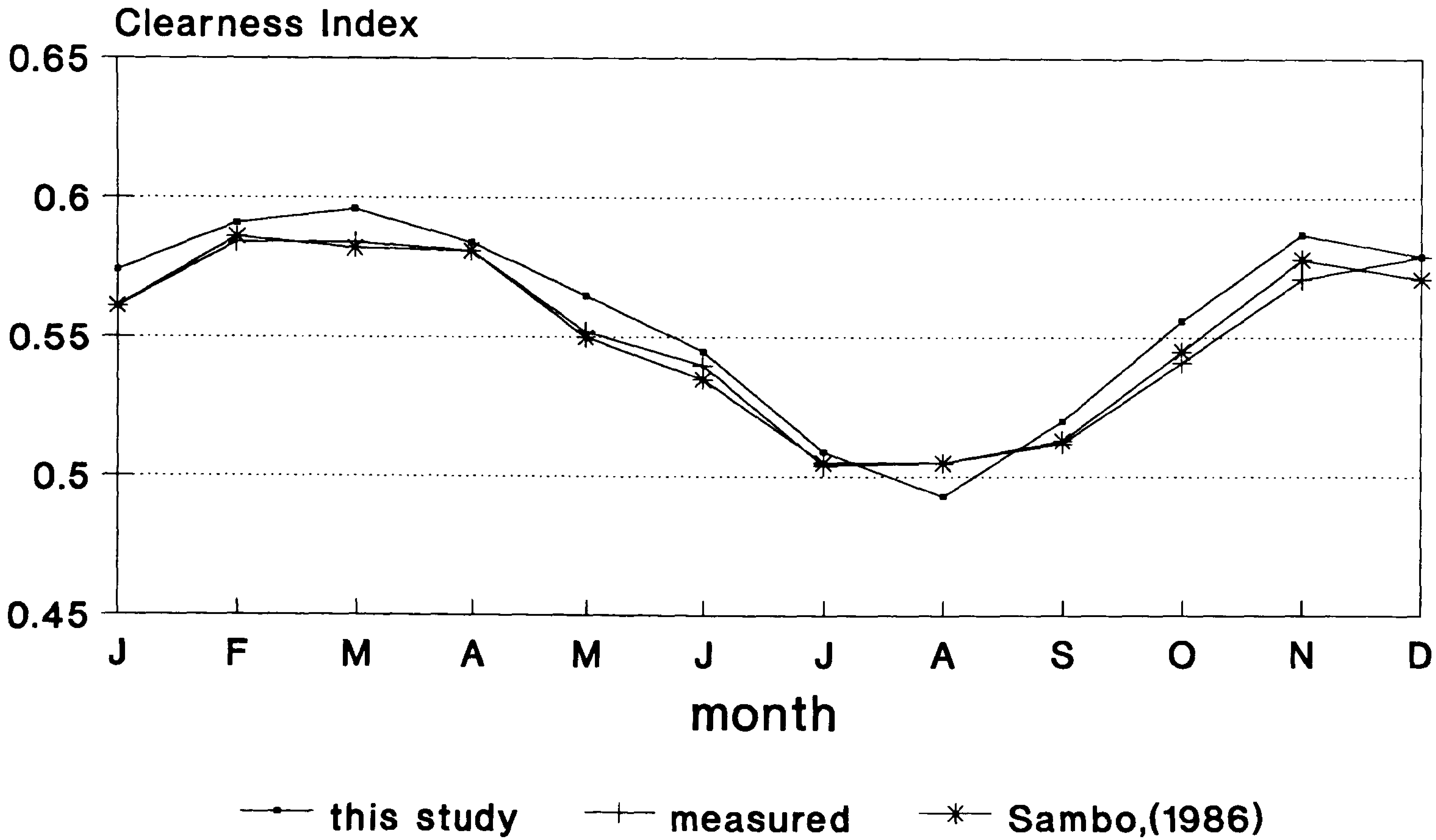
The Total Irradiance on the surface.

Output
Write results to *RAD.RES* file

and optionally into *SERI-RES* Weather file

← YES —— Another Run? —— NO → STOP

Fig 2.12 Clearness Index (Kano)
Measured and computed values



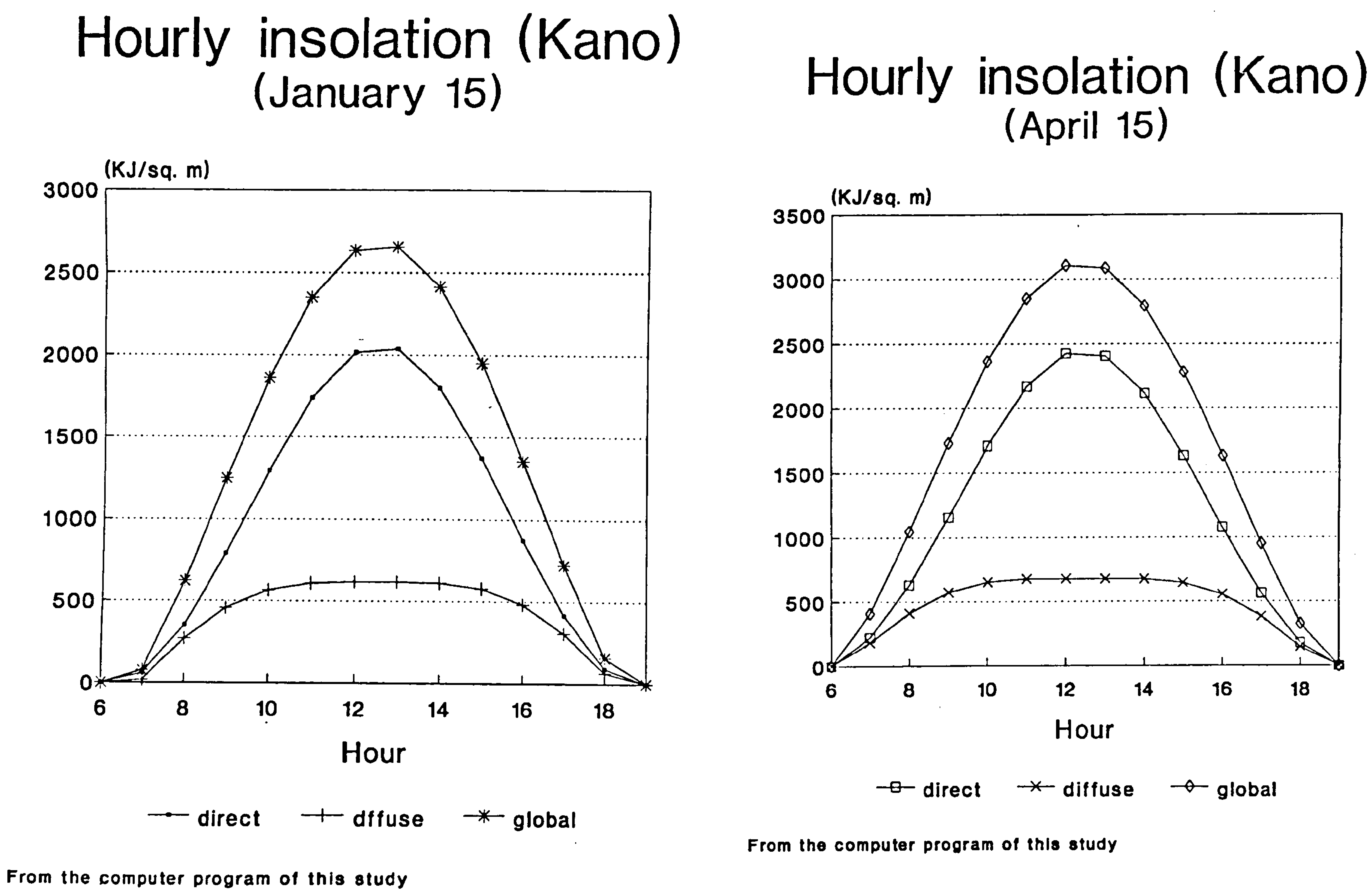
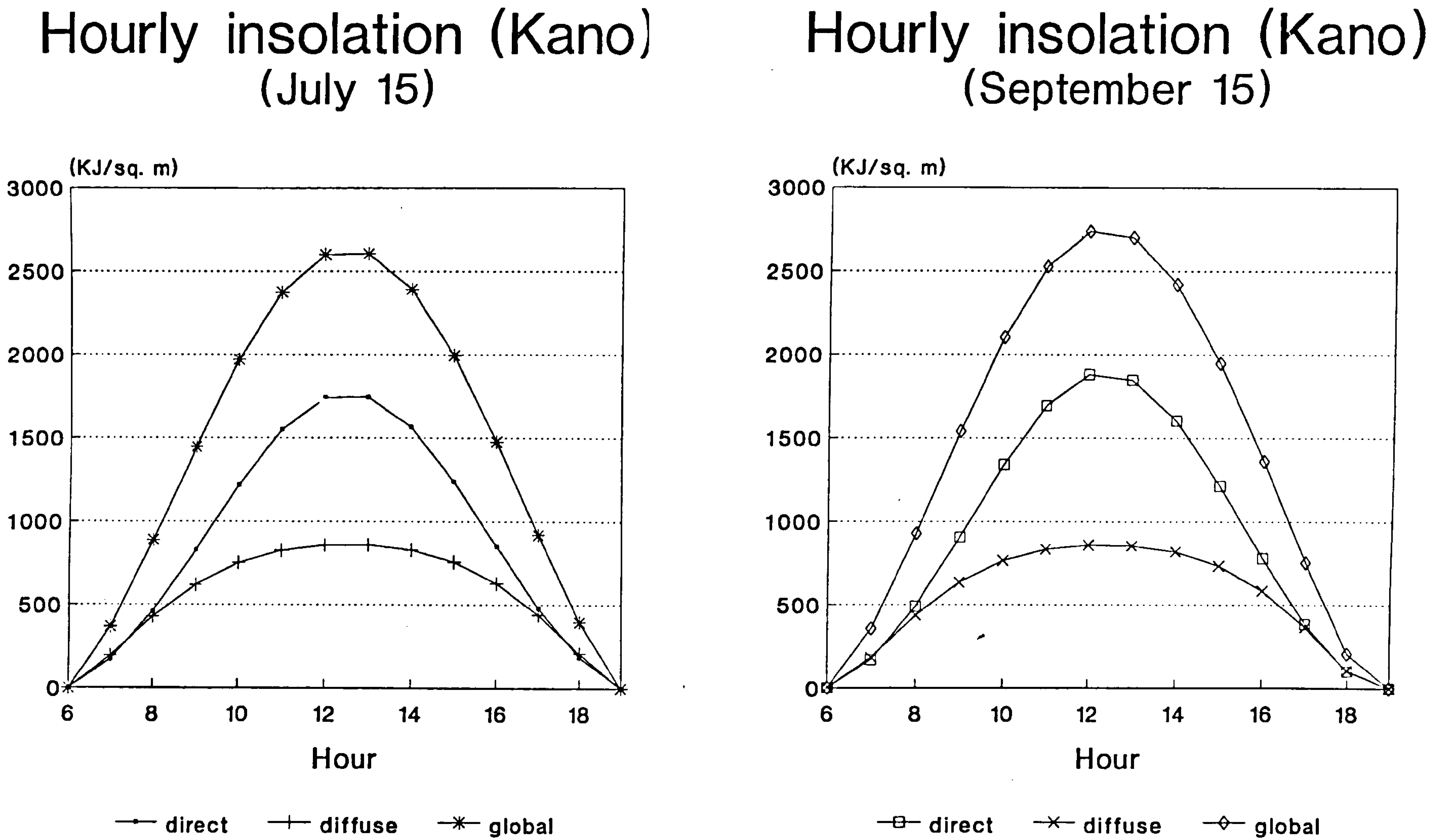


Figure 2.13: Hourly Insolation in Kano, Nigeria



From the computer program of this study.

From the computer program of this study.

Figure 2.14: Hourly Insolation in Kano, Nigeria

Chapter 3

Related Background Studies

3.1 Introduction

This chapter presents the review of related background research in the field, such as passive thermal control strategies in hot dry and semi arid climates, solar radiation control methodology in buildings and a review of the development of wind tunnel experimentation and pressurisation techniques in the studies of air movement in and around buildings. The review was done with a view to touching each of these sections as related with and applicable to the object of study rather than as a conglomeration of facts and details in text-book fashion.

In reviewing passive control strategies in hot dry and semi arid climates it was considered that a balance should be struck between the 'timeless' or 'ageless' strategies that had been passed on by tradition and by the wealth of experience of living, adapting and building in the hot dry climate, and the contemporary strategies based mainly on applied research. An attempt was made to highlight the main outcome of both traditional and contemporary approaches to passive thermal control in these climates.

The solar radiation control review was done with respect to the conceptual framework or methodology of the approaches rather than as techniques *per se*. Several conceptual methodologies were noted (e.g. solar protection of glazed areas by use of shading devices, protection by plants and/or vegetation.) the respective technique inherent in these methodologies are discussed.

The section dealing with prediction techniques for air movement in buildings deals mainly with wind tunnel tests and pressurisation techniques. It was considered that a complete review of predictions techniques for air movement in and around buildings, though acknowledged, would be beyond the scope of this thesis, especially where such techniques bear no relevance to the present work.

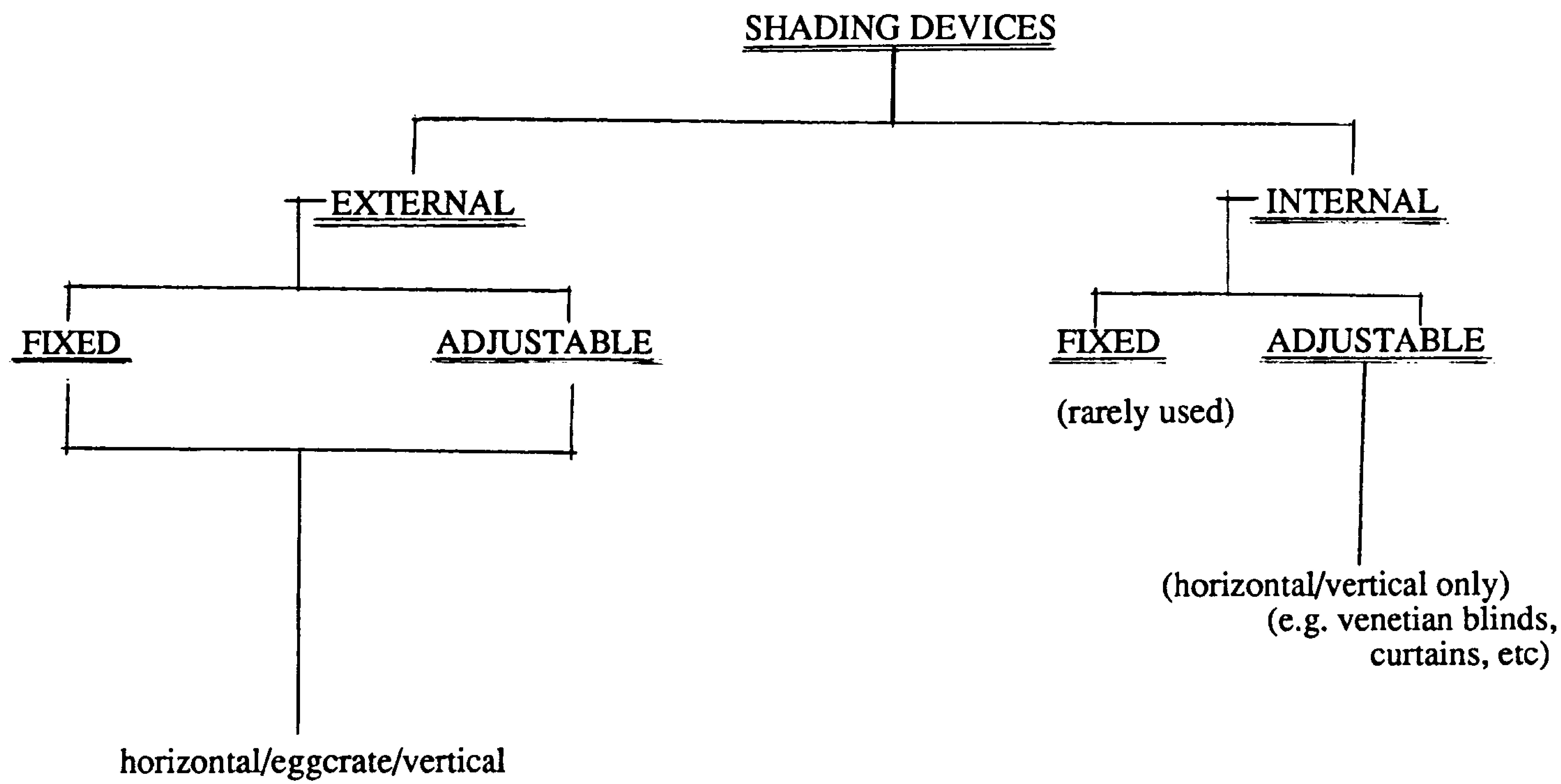
3.2 Development and Use of Shading Devices

3.2.1 Introduction

As a result of the profound effect of glazed openings on the indoor thermal conditions in terms of the 'green house' effect (Van Straaten, 1967), (Givoni, 1976,(a)) and the resultant elevation of indoor temperatures, it has become normal practice to use shading devices to protect the glazed area against direct radiation and thereby minimise solar heat gain. Ernst Danz, had suggested (Danz, 1967) that the use of shading devices on the **external** building surface has been done via a number of routes including the use of floor and roof projections, the use of balconies and logias, the use of thin structural shades (louvres, screens and blinds or a combination of these) and the use of window shutters and jalousies. There is also **internal** sun protection by use of vertical and/or horizontal blinds, venetian blinds, curtains and screens). In between the external and internal sun protection methods is the use of the so-called *"sun protection glass"* such as translucent or tinted glass, for glazing. It must be borne in mind however that there is no such thing as *"sun-protecting"* glass. There are only some glass that transmit less solar radiation than others.

Thus shading devices are either used externally, internally or between multiple glazing and are either fixed, modulated (i.e. adjustable or controllable) or retractable and they come in different shapes and sizes. They not only minimise or exclude solar radiation but also reduce glare, give protection from rain and, to a lesser extent, dust, control air movement patterns within the indoor space and enhance privacy. Table 3.1 shows an arbitrary classification of shading devices in common use from which it can be observed that while external shading devices may be fixed or adjustable, internal ones are usually of the retractable types (i.e. can be lifted, rolled or drawn back) but some are only adjustable in their angle. Shading devices used between multiple glazing (which are included among the internal types) may be venetian blinds, pleated papers and roller shades and are usually adjustable or retractable as most internal types.

Table 3.1: A simple classification of shading devices in common use



The advantages of adjustable or retractable devices over fixed ones is the ease with which they can be adapted to fulfil the varying requirements of shading at will while the fixed ones are rigid, very exerting and sometimes dominate the facade. The choice between the two types depends on the interplay of geometrical configuration, solar movement patterns, orientation, design objective and so on. What is certain is that shading devices have become a prominent feature of the architecture of hot climates resulting in cycles of renewed interest on studies of their design and evaluation.

Approaches to the design, evaluation and use of shading devices has been the subject of investigations in the field of climatic design for at least the past forty years. In the early stages, the main objective was to evolve a methodology of estimating shading performance of different shading devices as used in the glazed areas of the building fabric. This was basically done with the aid of sunpath diagrams and shading masks. Later the effectiveness of shading devices in terms of the quantitative reduction of solar heat gain and the subsequent beneficial effect on the indoor environment, came into focus. Furthermore because shading of the fabric openings has significant implications for ventilation and daylighting, the effect of some basic shapes of shading devices on air movement as well as it's effect upon the qualitative and quantitative daylight illumination of the interiors, under different sky conditions, became included in the themes of investigations. The little but significant body of research which looked into the impact of different types of shading devices on *thermal control* provides a useful background literature for the present research effort.

3.2.2 Development of Simple Design and Evaluation Methods

Whilst there has been a widespread use of shading devices on fenestration for quite a long time, based mainly on evolved experience, the first *recorded* formal research effort in the development of simple methodology for the design and use of shading devices for solar protection is the pioneering work by Aladar and Victor Olgay (Olgay and Olgay, 1957) at the Princeton University Architectural Research Laboratory. The Olgays did not only give to the field the unique term "bioclimatic design" (Watson and Labs, 1983, Olgay, 1963), but also laid down a theoretical as well as a technical framework which has formed the basis of a simple methodology for the design of shading devices. With the aid of sunpath diagrams, shading masks, architectural illustrations, and theory underpining their work Olgay and Olgay laid a solid foundation upon which most, if not all, other works thereafter have been based.

Their methodology basically involves *interpolating* overheated periods when shading is required with the sun's position in the sky over this period which would, in turn, help to determine the size and position of the shading device. The technique may be said to involve two major steps:
(a) Determining the *period* of shading need (based on 21 °C as the lower limit for overheating), and the sun's position in the sky during this period by use of sunpath diagram which shows the sky-vault projected onto the horizon plane. The sun's position is plotted over the overheated period.
(b) Determining the type (whether horizontal, vertical or eggcrate) and the position of a shading device that would provide the best solution (for 50% and 100% shading) and sizing it with the aid of the relevant "shading mask". The shading device is then designed by interpolating the overheated period with the sunpath diagram, enabling the determination of the relevant shading mask which itself defines the size and angle of the shading device. This angle defines the ratio of the depth of the shading device to the dimension of the opening. In other words, it is simply the angle between the reference point on the centre of the opening, and the edge of the fin or overhang. Many possible solutions can be found for the same opening because many devices, different in shape and appearance, may have the same shading mask and hence the same shading characteristics.

An important feature of the method is that the performance of both horizontal (overhang) and vertical (fins) shading devices can be specified completely in terms of horizontal and/or vertical angles from the reference point, implying that the shading mask is independent of the orientation of the opening or it's latitude. This enables the use of the shading mask protractor as an overlay on the sun chart for any latitude or window orientation.

Most research efforts in the post - Olgay era have invariably followed a similar approach namely analysing the climatic data, determining the overheated periods which is overlaid onto sunpath diagram and deriving a shading mask which is used to define the shading device. The only difference is that of variations in their suggestion on the scope of it's application and the different meanings ascribed to shading devices *effectiveness* and sometimes some extension of the scope to include other factors apart from temperature. Among many such derived methods include that suggested by Givoni (1976) and Evans (1980)

Bruce Novell (Novell, 1981) also developed a derived approach at the Alabama Solar Energy Centre (USA). His methodology describes shading needs, assesses the effectiveness of various options of shading devices, and suggested a method to develop shading devices and other passive cooling strategies based on weather data (mainly the monthly maximum and minimum temperatures and the temperature range). His method is structured into a fourteen step-by-step procedure which starts with monthly maximum and minimum temperature and mean coincident wet bulb data and produces "a timetable of climatic needs, an overlay of overheated periods on a sunpath diagram, and a plot of climatic conditions and passive/hybrid processes on a psychometric chart". It is obviously an attempted compilation of many of the previous methods into a simple, "easy-to-use" and flexible structure. However it is this attempt to combine so many previous methods into one procedure that may be it's main shortcoming since many designers may find the application of a 14-step procedure cumbersome. Moreover the accuracy of final results at the end of the long procedure which mainly entails series of graphical interpolations may be questionable.

3.2.3 Numerical Computation Approach

The numerical computation methodology involves the development of mathematical shadow equations as the basis for the derivation of the appropriate shading devices for different sizes of openings (windows). This latter approach was a follow-up to the interpolation approach. For example it was not until 1967, ten years after the pioneering work of the Olgay brothers that Tseng-Yao Sun (Sun, 1967) progressed by developing shadow area equations for windows with finite external shading devices (overhangs and side fins) which he used to develop a computer program to facilitate their application to the design of shading devices. He provided a detailed methodology that can easily and accurately calculate shadow areas on vertical windows by a computer. However the methodology did not address the cases of horizontal or tilted shading systems or the issues of shadows between overhangs, vertical projections as well as side fin shadow.

In 1975 a procedure for the design of external sunshades for windows of any orientation and at any place in the world was suggested by Edna Shaviv (Shaviv, 1975). Developed mainly from research carried out at the Israel Institute of Technology, the procedure essentially involves the determination of the necessary depth of the sunshade for full shading and then applying a developed computer program for calculations and graphical presentation of the results. There are three main steps involved:

(i) The first step is the determination of the period of shading need (hours, days and months).

(ii) The second step encompasses dividing the window or opening into a fine mesh and imagining a pole of length l say, perpendicular to the wall at each mesh point, l being so calculated as to give a shadow long enough to reach the window frame. The calculation is carried out for the 21st of every month of the period for which shading is needed, and it is the distribution of l in the field of the window that provide the required information for the design of the shading device.

(iii) In the third step, the maximum l for every month, $lmax$ (day), at each mesh point, and $lmax$ (month), the maximum of all $lmax$ (day) over all the months of shading need, are determined and the numerical results are graphically presented by means of computer-plotted axonometric projections.

The method shows how the numerical results and graphical output enables the considerations of all possible solutions to a shading problem at once. It seems a straight forward and easy method to use *provided* one has access to the program and a computer to run it. The input into the program consists of the geographical location, the window shape (rectangular, circular, triangular and so on), the orientation of the building and the period and hours of shading need. The output is $lmax$ (month) for every point in the window which is graphically presented in an axonometric projection.

The main shortcoming of this method is that it is computer based and one can only use it efficiently if one has access to a computer with which to run it, for although the steps involved can be worked out manually, it is rather laborious and tedious.

A graphical method for sizing the horizontal and vertical projection to shade a window of a given size was presented by Muniz, 1982. The method determines how much shade (horizontally and vertically) an existing or proposed shading device will provide. It is aided by a computer program which is aptly called the "shading device calculator". The results are presented in tables which can be easily interpreted and the program, on the whole, is quoted to be easy to use, simple and flexible since it can be used for any latitude and location. However as with most computer programs, the calculations procedures and/or algorithms are not presented and since no comparison with any previous method was presented, it is difficult to assess its accuracy and reliability.

Following the precedent set by Sun (1968) and utilising some of the principles suggested by the Task Group on energy requirements for Heating and Cooling (ASHRAE, 1975). Rodger Bekooy (1983) developed a computer program for shadow analysis for tilted windows and skylights shaded by overhangs, vertical projections and side fins, a technique which allows the designer the freedom to tilt the glazing system (windows) to any angle (through horizontal to vertical). It also addresses the issue of shadows being cast 'upwards' or 'downwards' by a tilted glazing system, depending on light source. The program is fast to use because it requires minimum input data and does not rely upon interactive analytic techniques. However the use of the methodology is limited only to rectangular windows that are shaded by rectangular shapes perpendicular to the plane of the window. It could also find application in the analysis of passive solar heating and cooling of buildings and the analysis of daylighting.

3.2.4 Evaluation of Performance of Shading Devices

Research dealing with the use, rather than design methodology, of shading devices has also been vigorously pursued in the field. There have been studies dealing with evaluation of the efficiency of adjustable shading devices, fixed shading devices or both.

A comprehensive study on the shading of sunlit glass was carried out by Pamelee and Aubele for the American Society of Heating and Ventilating Engineers (ASHVE) (now American Society of Heating, Refrigerating and Air-conditioning Engineers, ASHRAE) in 1952. The aim was firstly, to determine the absorbing, reflecting and transmitting characteristics of slat-type sunshades for solar radiation and secondly the influence of the shades on room heat gain by convection and re-radiation from sunlit glass. The tertiary aim of the study was to determine shading factors to apply to published design data for unshaded glass. Results from the study were presented in a series of papers by the authors at various general meetings of ASHVE.

In the first publication (Parmelee and Aubele, 1952) in which the authors presented the mathematical analysis of the first objective, a detailed analysis of the geometry of the slats assemblage, the definitions of angles and the calculated values of absorptance, reflectance and transmittance were given in tables and curves. The study of the curves enabled some general conclusions to be made regarding the effects of the several variables on the performance of a slat-type sunshade used at different angles of inclination. However the results had not been experimentally validated, nor was there any suggestion of the optimum angle of glass that gave both adequate daylighting and minimum heat gain simultaneously. Even though the results held great promise for immediate practical utility, there were inherent limitations upon the applicability of the results in the form in which they had been presented at that time, a fact which was acknowledged by the authors.

The second paper (Parmelee *et al*, (1953)), which presented a comparison between the experimental and computed data, suggested that the direct solar radiation transmitted by a slat-type sunshade can be broken down into two components, namely the *straight-through* component and the *reflected-through* component. The mathematical analysis showed that the first component is a simple trigonometric function of the slat geometry and profile angle while the second is dependent not only upon these two factors but also upon the reflectance or absorptance of the slat surface. The results also indicated that the theoretical treatment of slat-type sunshades seems to be validated by experimental results as a practical tool in the design data for shades. However the effects of polarisation and change of absorptance with variation of incident angle were not treated. Also disregarded was the issue of the reflected solar radiation from a horizontal surface such as a flat solid surface like verandah or balconies or the ground. These surfaces reflect much solar radiation upwards for which the slat-type sunshades have a high transmittance.

The third in the series of publications (Parmelee and Vild, 1953) presented not only a description of the characteristics of slat-type sunshades but also series of tables of design data which would enable the estimation of the instantaneous rate of heat gain for windows shaded with slat-type sunshades to be made.

3.2.4.1 Adjustable or Modulated Devices

While the configuration of adjustable devices does not affect their shading efficiency, since they can be controlled to cut off the solar rays, other factors are found to affect it. These factors include the position of the shading device with respect to the glass, their colour, the conditions of ventilation and airflow characteristics. Two main approaches have been used in the studies on the efficiency of modulated louvre systems:

(a) The calculation and/or measurement of the so-called '*shading factor*' which is the ratio of the heat that enters the window when shaded to that which enters when unshaded; An example of this is shown in Table 3.2 which is the result of heat gain calculation for a South-West facing window on 21st July at 2.00 pm in Israel with varying slat reflectivity and slat angle. The solar heat gain through the window when shaded was divided into three components (Givoni, 1976(b)).

(i) The component transmitted through the window when shaded after reflection between slats (q_{tsg}).

(ii) The component absorbed in the window glass (q_{ag}), of which about 1/3 is assumed to be transmitted indoors.

(iii) The component absorbed in the shading device which is assumed to be fully dissipated to the outdoor in the case of external shading devices and indoors, in the case of internal shading devices.

When the shading device does not intercept all solar rays, then a fourth component, namely the part entering between the slats of the shading device is then included in the computations. This usually lowers the efficiency of the shading device.

Table 3.3 illustrates the relative impact of varying the colour (expressed in terms of reflectivity) of horizontal internal and external shading slats all inclined at 45^o, on the total solar gain from which the great disadvantage of using dark colours for shading devices whether for internal or external shading can be deduced. It can also be observed that external devices are more efficient than internal ones. The difference in efficiency between external and internal devices increases with darker colour shade. While efficiency increases with darker colour for external shading devices, it increases for internal devices for lighter colour. External shutters seem very efficient, and with them it is possible to reduce solar radiation heat gain

Partitional heat gain (kcal/h m²) through different types of shading and the corresponding shade factors (%)

	a		q_{tsg}	$\frac{1}{3}q_{ag}$	q_{ag}	q_{in}	q_{in} (%)	q_{in} (%) experi-mental
Internal	30°	0·2	63·78	23·64	81·90	169·32	42·8%	—
		0·4	50·16	21·90	151·86	223·92	56·6%	54%
		0·6	21·12	19·62	218·94	259·23	65·6%	—
	45°	0·2	44·76	23·64	88·92	157·32	39·3%	40%
		0·4	30·90	22·20	150·18	203·28	51·4%	51%
		0·6	9·92	20·24	214·92	245·08	62·0%	61%
External	30°	0·2	63·78	1·38	5·04	70·20	17·8%	—
		0·4	49·92	9·06	0·96	59·94	15·2%	—
		0·6	21·12	0·36	13·38	34·86	8·9%	—
	45°	0·2	44·76	5·16	0·84	50·76	12·9%	—
		0·4	30·90	0·59	9·01	40·50	10·2%	11%
		0·6	9·924	0·038	21·59	31·89	8·1%	—

Impinging radiation = 395 kcal/h m²
q_{in} = total solar heat gain.

Table 3.2. Patitional heat gain (Kcal/hm^2) through different types of shading and the corresponding shade factors (%), (After Givoni, (1976))

Shading factors of various glass-shading combinations (percent of heat gain through unshaded ordinary glass)

	Data						
	Computed (*)	Measured (**)	Measured (**)	Computed (*)	Measured (**)	Measured (**)	Measured (**)
	Combination of glass and						
Shading absorptivity	Internal shading slats at 45°	Internal shading slats at 45°	Internal shading slats at 45°	External shading slats at 45°	External shading slats at 45°	Roller shade	Cloth curtain
0·2	40·3	40	—	12·8	—	—	White 38·2
0·4	51	51·0	White cream 56	10·2	10	White cream 41·0	—
0·6	62·0	61	Average colour 65	8·05	—	Average colour 62·0	—
0·8	—	71	Dark colour 75	—	—	Dark colour 81·0	Dark colour 64·0
1·0	83	Black 80	—	5·0	—	—	—

(*) = Computations based on conditions in Israel, on July 21st at 2 p.m.
(**) = Measured at the ASHRAE Research Laboratory, Cleveland, U.S.A.

Table 3.3. Shading factors of various glass-shading combinations (percent of heat gain through unshaded ordinary glass), (after Givoni, (1976))

through a window by over 90%. Dark coloured internal shading are inefficient and with them about 75-80% of the incident radiation on the window is transmitted indoors.

However, increased efficiency of external shading with darker colours is only possible with closed windows. With open windows, it depends on the orientation of the window with respect to the wind direction. In most cases dark coloured external devices in windward East or West orientation would heat the air flow across them into the building and the indoor thermal load would be increased collectively. With large shading devices such as concrete sunbreakers their heating effect may continue long after sunset. Conversely, on the leeward side of the building, this convective heating effect is minimal.

The results presented by Treado et al (1984) for the National Bureau of Standards in the U.S. for a study on the shading performance of louvres and screens showed that "shading saves more energy in all-year cooled buildings than in summer-cooled buildings" but that "shading of summer-cooled buildings reduces over-heating due to solar gains in perimeter office areas". The economic analysis indicated that solar shading can be cost-effective, dependent upon the energy performance, initial cost and the expected life-span of the shading system and that the most effective shading strategy varies from one climatic location to another. In all cases, solar shading increased heating energy consumption and decreased cooling energy consumption and a net saving occurred when the cooling energy decrease exceeded the heating energy increase.

3.2.4.2 Fixed Shading Devices

The earliest recorded comprehensive study that analysed various types of shading devices in different orientations seems to be that presented by Givoni and Hoffman (1964) in which they computed three variables (the pattern of the intensity of solar radiation incident on the *unshaded window*, the percentage of the shaded areas as a function of the projection depth of the shading device and the intensity of solar radiation on the *unshaded portion* of the window) with which daily curves of the intensities of direct radiation impinging on windows with various types of fixed devices, for different months and orientations, were made.

Their results indicated that for East and West orientations egg-crate devices provide the best shading especially if the vertical members are oblique at 45° to the South and that not only are horizontal devices more effective than vertical ones, the latter also gives very poor performance in summer while cutting off almost all radiation in winter. The study also showed that horizontal windows are more suitable for East and West orientation than vertical ones. For South, South-East and South-West orientations, horizontal devices were also found to be more effective while the frame shape was the most effective.

In an earlier study in the semi-arid Negev region of Israel in 1961 by Givoni, in which temperature values were measured in full-scale residential buildings, in which windows were either closed and shaded, open and shaded or open without shading, it was found that temperatures were higher by about 1.5°C in the unshaded case, even with the small windows and the cross ventilation.

Two other studies were further reported by Givoni (Givoni, 1976(c)) in which indoor temperatures were also measured under different shading conditions. In the first one which was a full scale study, it was found that with windows and the external shutters closed, the indoor air temperature range was about 2°C below the outdoor maximum. When the windows are open and shutters partially closed, indoor temperature range was from 2 to 1 °C below the outdoor maximum while open windows *and* shutters gave an indoor temperature range of 4 °C. Finally, with closed windows and open shutters, indoor temperatures were again stabilized at about 1 °C below outdoor maximum. This shows that unshaded windows, even of very small size elevated indoor temperatures by about 1 °C.

In the second study which was a model-based investigation, indoor air temperatures of models with relatively large window-to-floor area ratio were measured under different shading conditions and compared with indoor air temperatures of a model with complete protection from radiation by an insulated panel fixed about 10cm in front of the window. The result showed that with internal shading, the elevations of the indoor maxima above the outdoor were 5.5 and 4.5 °C respectively for green and white venetian blinds (internal shading) while with external shading, the respective indoor temperature elevations were only 1.8 and 1.2 °C. The indoor maximum in the model with complete window shading was found to be about the same as outdoors.

However, all the above results were mainly for the study locations in Israel and no information was provided on what the performance would be for some other climatic locations.

Several other studies on the performance of shading devices have reported similar results as have been outlined so far (Phillips, 1965), (Stephenson and Mitalas, 1965), (Petherbridge, 1965) and (Loudon and Petherbridge, 1966 which presented a generalised discussion for both internal and external shading devices mainly with emphasis on high latitudes).

Yellot and Ewing (1976) investigated the opposing effects of the solar altitude and air mass on the quantitative value of direct irradiation on vertical windows. It is a truism that the most intense solar irradiation received at the Earth's surface is when the sun is directly overhead. The sun never reaches this position at any latitude except at the tropics, especially on the equator (latitude 0°). As the sun leaves the zenith its rays are incident on a vertical surface at angles decreasing from 90 deg and the intensity of the direct irradiation is found to be proportional to the sine of the angle of departure from the zenith. If this was the only factor involved, the maximum intensity of direct insolation would be at the zero incidence angle attained when the sun is at the horizon. But as the sun leaves the zenith, it's rays have to penetrate an increasing mass of the earth's atmosphere and the air mass traversed increases approximately as the cosecant of the sun's altitude, with the result that the lower the sun in the sky, the lower the intensity of the rays.

The results of this opposing effects at different solar altitudes for vertical windows facing the sun such that the window - solar azimuth $\gamma = 0^o$ is shown on Figure 3.1 in which it can be observed that the maximum intensity, including diffuse sky radiation occurs at a solar altitude of about 30^o for both winter and summer. Figure 3.2 shows similar data for winter, for which the indoor - solar azimuth angle is the independent variable. The declining insolation values as the solar altitude drops below 30 deg can be clearly observed.

This natural "shading performance" of the atmosphere makes it possible for external shading devices to receive relatively cool daylight reflected from the lower parts of the sky and from the ground while they still intercept the intense direct solar radiation at higher solar angles. Thus they have the advantage of selectively transmitting the invisible radiation and daylight received from various parts of the sky.

The study also discussed the variations of the overhang shading concept and concluded, that the most effective way to reduce the solar heat transmission

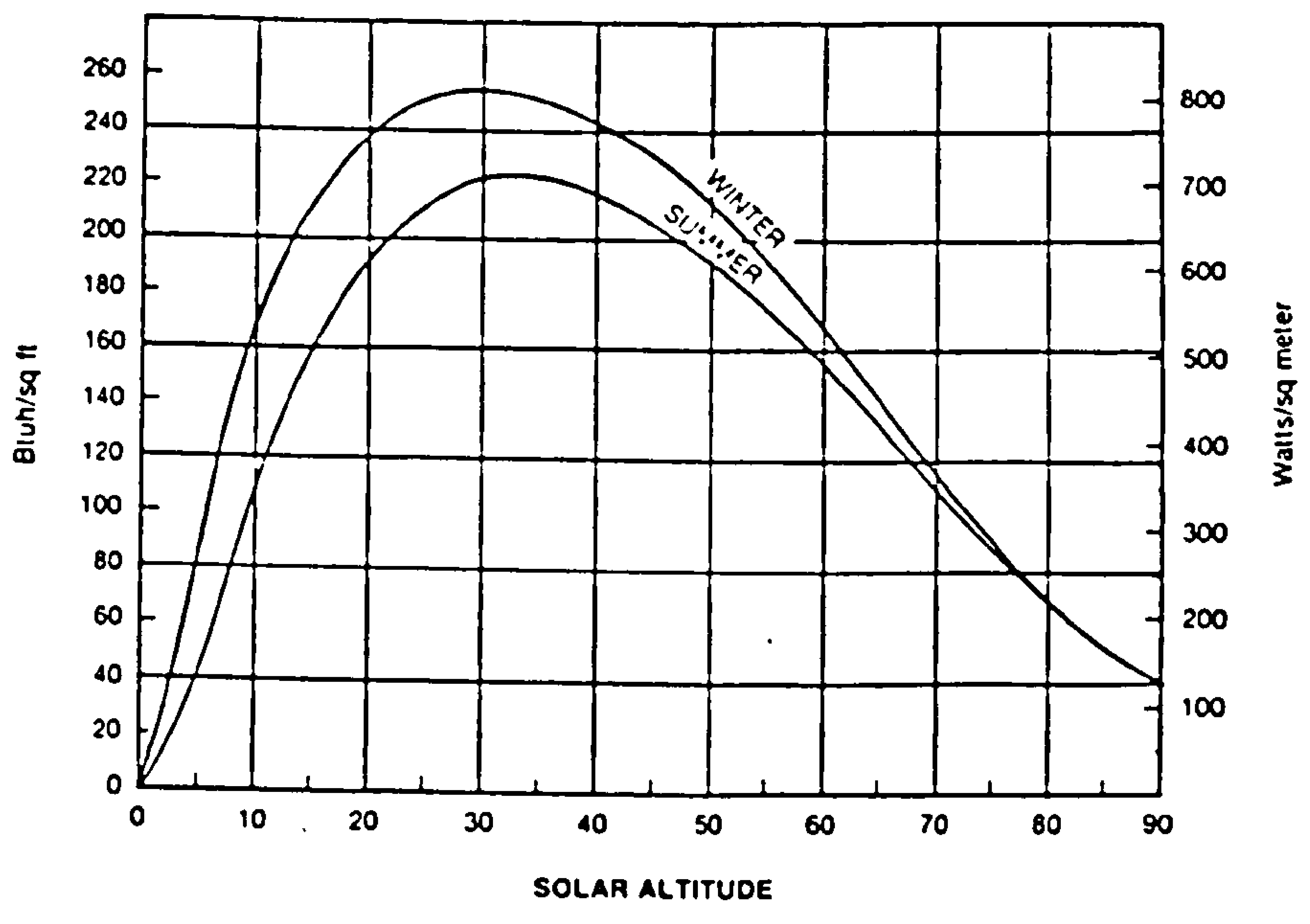


Figure 3.1: Variation of solar heat gain factor with solar altitude, winter and summer, for sun-facing windows (After Yellot and Ewing, (1976))

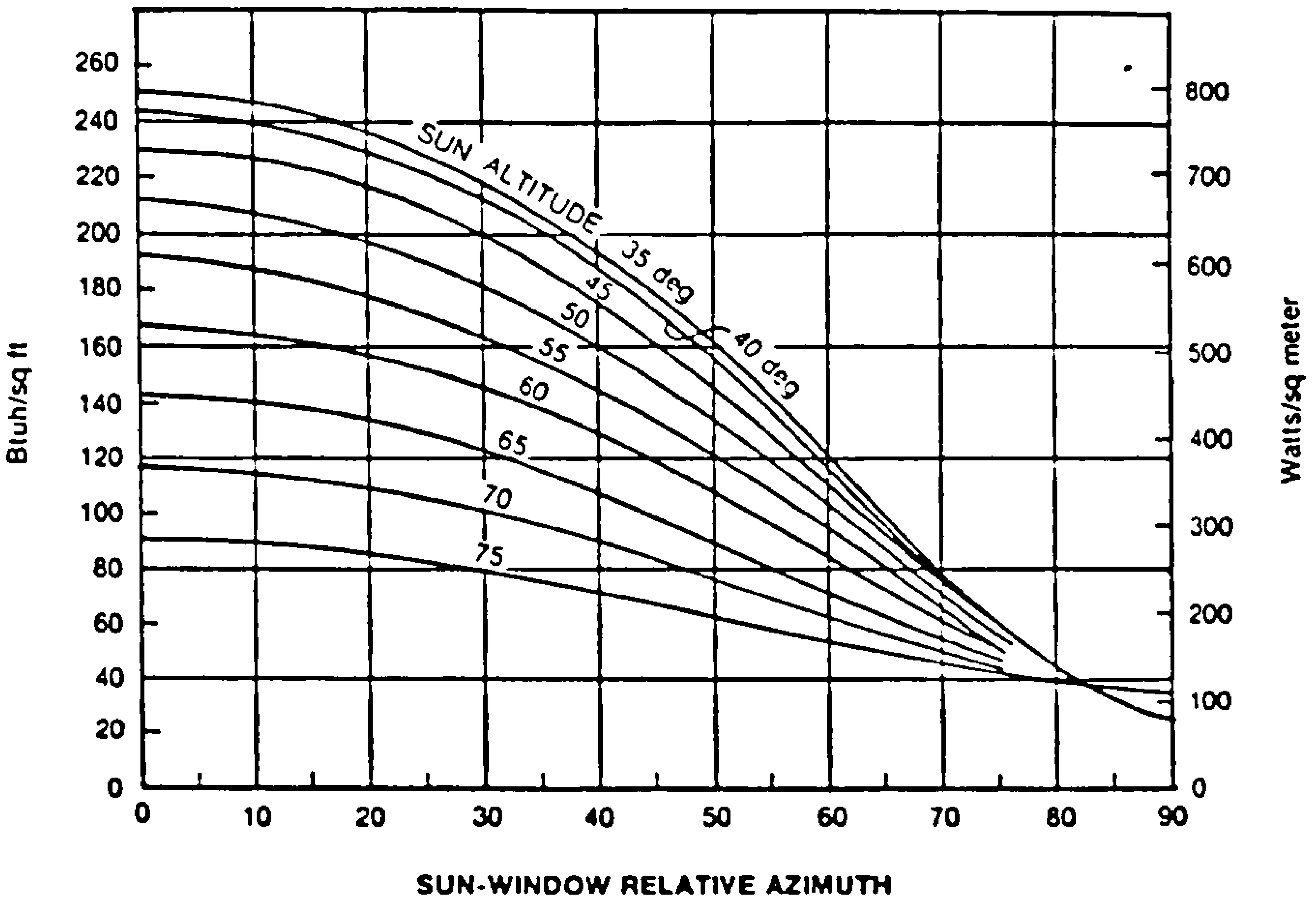


Figure 3.2a: Variation of solar heat gain factor with sun-window relative azimuth, solar altitudes from 35 to 75 deg (After Yellot and Ewing, (1976))

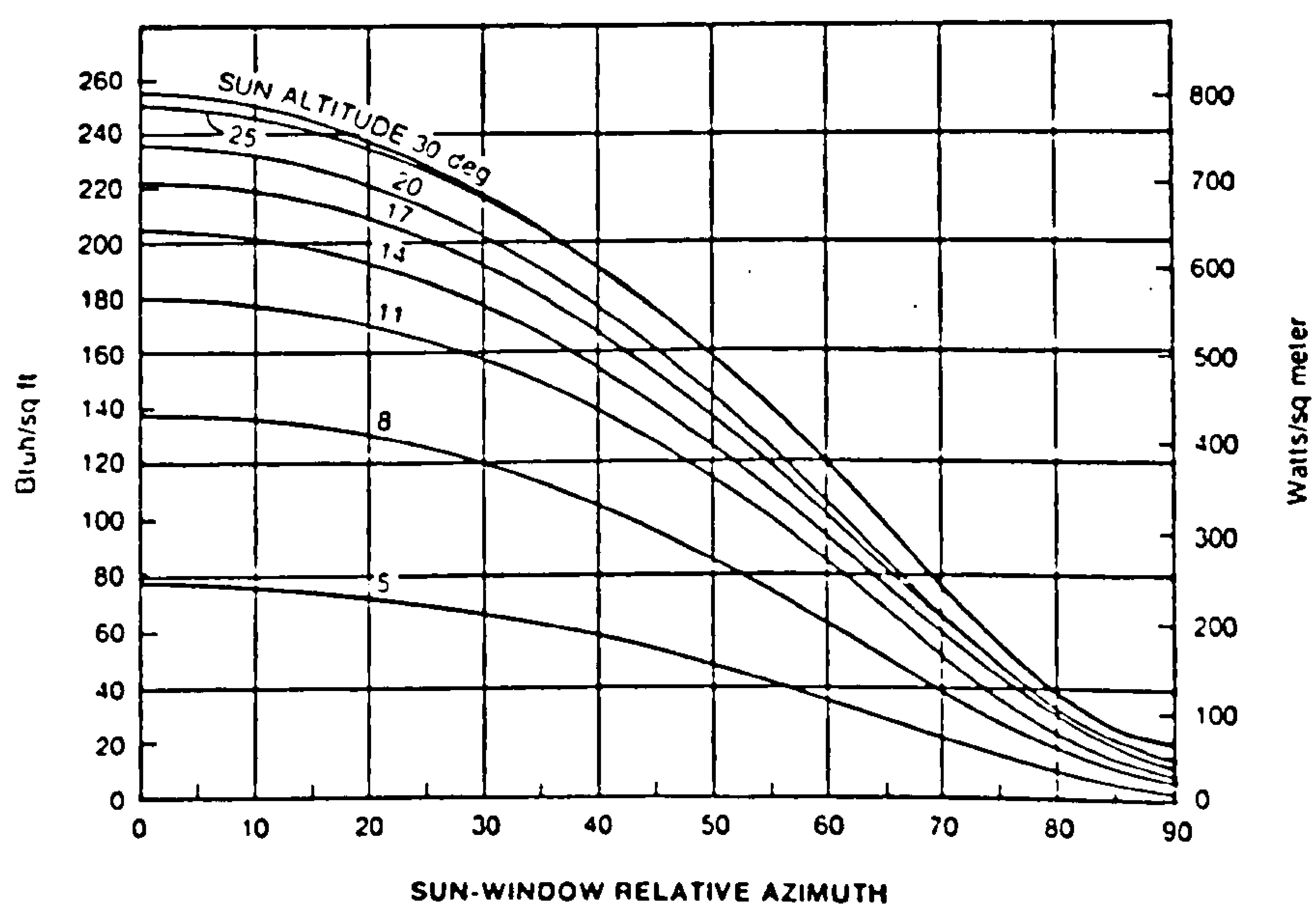


Figure 3.2b: Variation of solar heat gain factor with sun-window relative azimuth, solar altitudes from 5 to 30 deg (After Yellot and Ewing, (1976))

through windows is to intercept the rays before they reach the window glass - in other words by almost any form of exterior shading.

In 1980, Edna Shaviv (Shaviv, 1980) presented a computer simulation model which calculates and presents results of thermal performance of a building with and without sun shades, based on the total energy consumption for cooling, heating and lighting. The program is said to integrate the analysis of natural and artificial illumination, combine it with the required level of illumination and add the total to the building energy consumption. Shaviv presented several studies involving the use of this program and the one mentioned earlier (Shaviv, 1975) and arrived at a conclusion which concurred with the series of results by Givoni that among other things, external devices provide the best shading for windows.

Robert Jones (Jones, 1981) examined the reduction of summer heat gain by fixed horizontal overhangs in passive solar heated buildings. He found that the overhang performance in the various cases depended not only on the latitude but also, the location, the building load collector ratio *lcr* (i.e the ratio of the building load coefficient to the total collector area) and the coefficient of performance of the cooling system relative to the auxiliary heating system. He also found that there is no strict optimum overhang configuration but that the energy savings continue to increase as the overhangs and separation ratios increase along the line of their local optima, within the limits of practical overhang sizes (the overhang ratio is the ratio of the overhang projection to the height of the window while the separation ratio is ratio of the distance between the top of the window and the bottom of the overhang to the window height). The majority of the benefit were reached by overhang ratios of 0.3 or 0.4 and little additional energy savings were available beyond that.

Most other studies dealing with the cost benefit analysis of using various types of shading devices particularly associated with passive heating have reported more or less the same pattern of results. The feature common to all of them is that they consider only a summer of constant shading period and of optimisation done with regard to seasonal changes especially with regard to letting the maximum solar energy through the window in winter and keeping the maximum out in summer.

3.3 Discussion

One of the most prominent feature of all shading devices is that they all have been designed and optimised with a fundamental underlying consideration of having a capability to give maximum shading during the hot summer and conversely let in the maximum sunlight during the winter. The Olgay brothers were very emphatic about this when they suggested (Olgay and Olgay, 1957(b)) that
"...the effectiveness of a shading device depends on the proportionate success with which it covers a given surface during the overheated period without intercepting the sun's energy during the under-heated times".

Shading devices fashioned with such design philosophy have been used with *careless abandon* in hot dry climates which have a constantly severe weather all through the year (as we have seen in chapter 2) and it is unsurprising that they have not been found to be very effective in these regions. Hot dry climates need to evolve solar protection techniques completely unique to its peculiar climatic needs, especially with respect to the severity of the intense insolation during most parts of the year and the fact that there is hardly need for passive solar heating. The only times when the outdoor temperatures are 'low' (average 15^o C - 18^o C) is during the night, long after the sun has stopped shining. Therefore the need to let in the sun *at any time* does not arise. There is need for constant shading all through the year, and as aptly put by (Holshansen, 1967) solar protection is always required in the tropics "no matter what time of the year it may be".

The effectiveness of shading devices designed by application of these methodologies are dependent on the accuracy with which the overheated period is determined and this in itself is dependent upon average temperature values which may not be readily available and may have to be estimated, e.g. by using nomograms (Evans, 1980(b)). It is therefore very difficult to ascertain a realistic lower limit for the overheated period.

Furthermore each 'new' derived methodology for the design of shading devices tends to be a combination of most, if not all, previous methods before it (except in computer models) thereby increasing its complexity and the chronology of numbered "procedural sequences" by which the new approach could be applied. For example the Olgay brothers (1957) method had only 4 steps of implementation whereas the Novell (1981) method, which had several other derived methods before it, had the whole of 14 steps of implementation. Yet each new method is often quoted or implied to be *simpler, more convenient*, or sometimes even more accurate than previous ones. This issue of increasing complexity may be a dissuading factor in their use by designers, especially in developing countries, where there is a consequent tendency to use the most basic of the rules of thumb and/or copy some oft-repeated shading configuration.

The effectiveness of the use of heat-absorbing glass in a climate as thermally severe as this as suggested by various workers in the field is questionable. This is because even for some of the best heat absorbing glass a substantial amount of solar radiation is transmitted indoors for example, for 0.25 inch-thick "solex" glazing up to 70% of the incident solar radiation still penetrates indoors, (45% transmitted, 25% re-radiated) (Olgay and Olgay, 1957).

Also the issue of the protection of the interior spaces against the effect of diffuse and multiple interreflected radiation is not presently being addressed by contemporary solar control philosophy. This is quite understandable in the sense that direct solar radiation is very dominant with respect to penetration through glazing. However in severe climates the diffuse and interreflected components can be quite substantial and contribute greatly to raising outdoor air temperature as well as heat up the building fabric.

In addition the present solar control design methodologies, (apart from being complex, not easily usable and are often based on estimated variables) are not inherent in the design process. It is not yet something the architect is 'naturally' aware of in the process of fashioning the building form but something that tends to come into consideration afterwards. This is especially so in developing countries most of which are located in the hot climatic regions of the world. In these countries particularly, and for further development in the field of bioclimatic design generally, there is need for the development of a methodology that is inherent in the design process, a methodology that is not only a part of the synthesis of form, but also an important form determinant.

Apart from solar radiation control methods there are other passive thermal control strategies that have been used in attempts to make buildings responsive to the climates of hot dry and semi-arid regions. These strategies are reviewed in the following section.

3.4 Passive Thermal Control Strategies In Hot Dry and Semi-arid Climates

3.4.1 Introduction

Most contemporary research on the application of passive design techniques in hot climates are concerned predictably, with cooling since this is the greatest challenge for building designers in these climatic regions. Space cooling is most vital in the hot dry climates with their characteristic high temperatures which are sometimes as high as 46 °C or more. Moreover the air is very dry with it's very low relative humidity which is sometimes only 10%. There is also a high degree of solar radiation and very little rainfall and a high diurnal temperature range because nocturnal temperature can be as low as 7 deg C or less. Coupled with this is sparse or no vegetation and the frequent dust storms in some locations. In fact it is a region where, according to Golany (1982), the life of the flora and fauna is balanced on the threshold of survival because of the stressful condition of the climate.

In an earlier report, (Yakubu, 1987(a)), it was stressed that

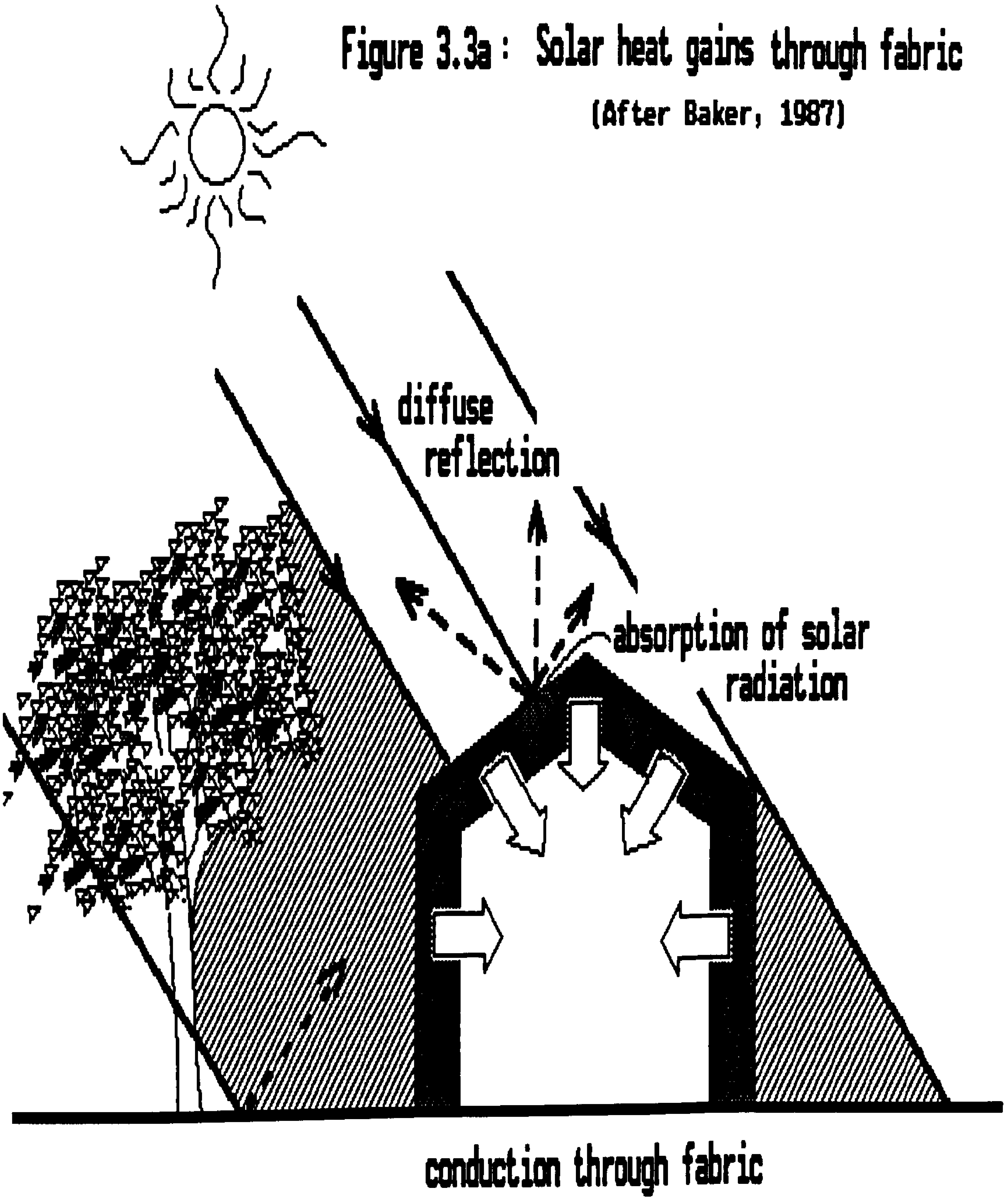
> "the application of passive design techniques for space cooling entails the ingenious use of a rational design philosophy, a harmonious synthesis of site factors, orientation and climatic conditions with systematic construction techniques, use of materials and a good understanding of the principle of building aerodynamics. The particular technique or combination of techniques applied in passive cooling design will depend on a number of factors among which are the characteristics of the micro climate within the hot dry zone, socio-cultural heritage, site conditions and the skills and materials locally available".

In a general perspective however, most passive cooling techniques in the hot dry climates are seen to be embodied in the traditional/vernacular architecture within the region, a reflection of the strong relationship between the ecological equilibrium and the quality of life in these climates (Bahadori, 1978), (Kesler and Peck, 1981), (Baroum, 1983).

Contemporary research has highlighted the application of basic scientific principles to get the best out of the climatic situation, for example the use of water in the form of fountains, sprays and pools for evaporative cooling, the roof pond

Figure 3.3a : Solar heat gains through fabric

(After Baker, 1987)



technique which was invented and patented as skytherm by Harold Hay in 1967, and which combine the principles of conductive, convective and radiative cooling. Many other sources referenced seem to have a degree of unanimity in highlighting the use of appropriate materials and colour, compact plans and reduced surface exposure, and other bioclimatic design principles relevant to hot dry climates. The use of aerated roof with a solar chimney is portrayed to be effective for natural cooling by Campo et al (1981) while a novel use of the principle of convective cooling has been suggested by Givoni (1983) whereby the coolness or "coolth" of the night is stored in a structural mass and is then used to cool the building the next day provided the building is well insulated and closed during the daytime.

Whatever technique is used the main aim has always been to create comfortable indoor conditions at a minimum cost. All passive cooling techniques are underpinned by some basic underlying principles.

3.4.2 The basic principles of passive cooling

Passive thermal control strategies are based on two groups of techniques as suggested by Baker (1987): *viz-a-viz*;
(1) Those techniques which are concerned with minimising the heat gain by the building i.e. *prevention of overheating*, and
(2) those that are concerned with getting rid of the heat within the building by passive means i.e. *passive cooling*.
The techniques that are concerned with prevention of overheating include
(a) The reduction of solar gains through the building fabric by means of any form of shading, the use of highly reflective finishes to reduce solar absorption, by roof and wall insulation, and by systematic design of roofs and walls.
(b) Reduction of solar gain through openings by use of shading devices or by natural shading of openings by vegetation and so on. The shading of openings in the fabric is either to eliminate or at least minimise the solar radiation effects:
(i) The increase in air temperature and mean radiant temperature due to absorption of solar radiation on to room surfaces.

(ii) Increase in the mean radiant temperature experienced by an occupant due to the direct impingement of solar radiation on to the occupant.

(iii) The discomfort glare and disability glare due to high intensities of

radiation from direct sun or diffuse sky.
(c) Reduction of lighting gains.
(d) Reduction of casual gains:- from people, equipments, etc.
(e) Reduction of ventilation heat gain.

The techniques which are essentially aimed at removing heat from the building structure using the principle of conductive, radiative, evaporative and convective cooling, are referred to as *passive cooling* techniques. The fundamental principle is to couple the building with ambient heat sinks, such as the radiant sky, the earth, and the ambient air, which, *of necessity*, have to be at a lower temperature than the building. These techniques include:
(1) Radiant/convective cooling of skytherm systems.
(2) Evaporative cooling - sprays, ponds, etc.
(3) Earth-couple/underground buildings - direct conduction, or by use of air pipes.
(4) Passive ventilation cooling at night.
(5) The use of the "trickle roof" - (radiative and evaporative cooling).
(6) The use of dehumidifying devices - not for hot arid regions.
(7) The use of solar chimneys.
(8) The use of air to air heat exchanger for coolth recovery.

The next section will examine both the traditional and contemporary passive thermal control techniques in the reference climates.

3.4.3 Traditional Techniques

Generally traditional architecture of the hot dry climates offer passive cooling that seem to be harmonious with the given environmental conditions because they evolved from a long period of direct experience with the climatic, environmental and other factors which has enabled the people not only to establish certain traditional building patterns but also to set certain standards and norms as design criteria. The passive cooling techniques often seen as being inherent in the vernacular architecture of this climate are as follows.

3.4.3.1 Natural shielding by plants and vegetation

The most significant of the traditional techniques is solar protection by plants and vegetation. This is because the conception of modulated solar shielding of buildings took inspiration from the amelioration of the microclimates around and within buildings due to the natural shading of building facades by plants and vegetation. Planting around buildings not only has psychological effects but also improves the microclimate around the buildings (Robinette, 1972).

Landscaping, in the form of trees, shrubs, flowers, grass and climbing vines of a pergola or an overhanging trellis, can provide shade and reduce glare in the courtyards and streets. It can also absorb dust and break wind storms. It also has a direct effect on temperature and humidity (Rizvi and Talib, 1981). Specifically, Parker (1981) experimentally investigated the effect of shading on wall temperature. He found that tree shading directly reduces wall temperature gained from solar radiation. Structural orientation is important for tree shading to give optimum advantage as a passive cooling device (Macpherson, 1981). Evergreen trees seem to be the best in this climate but for places within the climatic zone with a winter period, deciduous trees which have seasonal shading, are recommended.

Furthermore, the amelioration of the urban climate by trees and green spaces enhances the beauty and quality of city life by significantly improving the artificial climate. There abound many documentations of the importance of plants and vegetation as a modifier of meso- and microclimates. For example, a small green area in Frankfurt lowered the temperature by 3 - 3.5 °C, increased the relative humidity by 5 - 10% and provided fresh air for the overheated, dirty and polluted town centre (Bernatzky, 1982). The air temperatures in the Golden Gate Park in San Francisco averaged 8 *°C* less than the less vegetated neighbourhoods adjacent to the park (Duckworth and Sandberg, 1954). Plants' modification of air temperature, solar heat gain, longwave heat gain and heat loss by convection has been reported by Hutchison, *et al*, (1982), and Akbari, *et al*, (1987). Computer model results by Huang, *et al*,(1987) showed that an additional 25% increase in the urban tree cover saved 40% and 25% of the annual cooling energy of the average Sacramento and Phoenix homes respectively.

The impact of plant's shading on the microclimate of a building have recently been studied by McPherson, *et al*, (1988, 1989), Hoyano, (1988), and Thayer and Maeda, (1985). The computer simulations of irradiance reduction for residences in Tucson and Miami by McPherson, *et al*, (1988) showed that dense plant shading on all surfaces reduced annual cooling costs by 53% and 54% respectively.

A series of detailed studies by Hoyano, (1988) on the climatological uses of plants for solar control suggested that the use of planting in form of a pergola composed of a horizontal wisteria sunscreen, a vine sunscreen, an ivy sunscreen, or a row of evergreens, and rooftop turf planted on layers of loam and perlite, produced a significant attenuation of the solar heat gain and greatly lowered the indoor temperature profiles.

Furthermore, McPherson, *et al*, (1989) also carried out a detailed study, in which three similar 0.25-scale model buildings surrounded with different landscape types: **(a)** turf, **(b)** rock mulch with a foundation planting of shrubs, and **(c)** rock mulch with no plants. Irrigation and water use and the electricity needed to power the three room-size air-conditioners, the interior lights were measured for two weeks. It was found that the electrical energy consumed by the rock model was 20 - 30% more than for the turf and shade models. This was said to be due mainly to the dense shade that substantially reduced solar heat gain for the shaded model, a 16% difference in longwave radiation flux between the rock and turf treatments, and a maximum dry bulb temperature depression of 4 °C over the turf compared with the rock.

The cooling effects of shielding of surfaces by plants is due to a combination of changes of in the energy transfer process which have a direct bearing on the building energy performance (McPherson, *et al*, (1989)). These changes include:

1. changes in the solar heat gain: The benefit of shading is significant in hot arid climates mainly because solar radiation is the major source of heat gain by the building. Planting shades the building by the active heat-absorbing surfaces of leaves, which stores relatively little heat. Solar energy is converted to sinsible heat that is transfered quickly into the surrounding air, or to latent heat that is released during transpiration. Many field measurements (including McGinn, (1983) and Parker, (1983) and computer simulations (including Akbari, *et al*, (1987), and Thayer, *et al*, (1983)) have shown that heat flow into a building and air-conditioning costs may be reduced by 30 - 50% by plant shading.

2. changes in the longwave heat balance due to different ground, building, and vegetation surface temperatures and emissivities, as well as the view factor geometries. Outgoing longwave radiation from a driveway has once been found to be 26% more than from a lawn in Weslaco, Texas (Nixon, *et al*,

1980).

3. changes in the dry bulb temperature and conductive/convective heat gain due to evapotranspiration by vegetation.

4. changes in the airflow and therefore the convective heat balance of the building due to the shielding effect of the plants and vegetation.

3.4.3.2 The drawbacks of plant shading

There are two main drawbacks of shading by plants for climatic control in hot dry and semi arid climates. Firstly, planting and overhanging trees will also impair longwave heat loss by obscuring the cool, radiant night sky. However some evidence suggests that reduced solar heat gain from the shade outweighs the effects of reduced heat loss (McPherson, (1981). This drawback accentuates the significance of *modulated solar shielding* which, like the plants, can *"protect"* the building against solar radiation and other ambient heat sources during the daytime and, unlike the plants, can be modulated or controlled to minimise its effect of impeding heat loss at night.

Secondly, the scarcity of plants and vegetation in hot arid climates is all too well known. In such a water-scarce climatic belt which support little plant growth, the energy savings from reduced cooling loads by plant shielding may be offset by increased irrigation water costs. For example, landscape irrigation was said to account for 30 - 50% of the total annual residential water consumption in Southern Arizona. Mature trees are said to require over 325 litres per day to freely transpire in hot weather. This is one of the most significant reasons why natural shielding by plants is not resorted to for climatic control in the reference climates. Modulated solar shielding would not necessarily rely on plants but on suitable lightweight, low-conductivity, and non-heat-storing membranes. The shielding of the building surface against solar and other ambient heat sources can also be provided by a purpose-made lightweight structure of suitable materials, designed as an integral part of the building.

Other significant traditional passive thermal control techniques in hot dry and semi-arid climates but which have a less direct relationship to the *main* topic of this study are discused briefly as follows.

3.4.3.3 Compact planning

Both the dwellings and their layout on site are made compact so as to reduce the surface area exposed to solar radiation and to provide a cool area within the building (Baroum, 1983). Compactness implies shared or common walls and therefore makes the rooms easier to cool (Talib, 1983) as they adjoin one another and minimise volume and hence the cooling load. Compactness in site planning coupled with the high walls implies shading for the narrow streets thereby reducing glare and intensity of direct radiation. This reduces direct solar gain especially during the hot season (Elyas, 1983), (Mufti and Balto, 1983). In a dense settlement so created optimum orientation of streets in accordance with wind direction is essential for effective ventilation.

3.4.3.4 Massive wall and roof construction

As a result of the very high intensity of solar radiation and the great heat build-up during the day, coupled with the cold at night, massive walls have a high heat absorption/retention capacity, absorb heat during the day without immediately transmitting it to the interior spaces (*time-lag* factor) which therefore remain relatively cool, and then re-radiate the heat gradually during the cold night, warming the interior spaces and the cool night air (Karaman and Egli, 1981). Where the hot dry climate also has a cold winter the thick walls and roofs are advantageous as a passive heating medium (Turan et al, 1981). The capacitance of the walls, which are often made of adobe or sometimes, stone, is a prime factor in the delay and attenuation of the heat load (Faris, 1981). The walls are often very high, providing not only privacy and security but also shading for the walkways and courtyards. The roofs are flat, thick and also made of adobe; they do not only attenuate daytime heat, and warm the interior space at night but can also fulfil the additional function of being a sleeping place at night (Faris, 1981), or as in rural dwellings in the hot dry areas of northern Nigeria, a space for drying crops as well.

3.4.3.5 The courtyards

The courtyard is seen as a micro climatic initiator in vernacular houses which enhances ventilation, natural cooling, daylighting and view. They enable the houses to be inward-looking and give opportunities for openings into the dwellings since the thick walls facing the heat have to be with little or no fenestration (Sayigh, 1981). The courtyard is likened to a "paradise" giving comfort and privacy in the desert compounds (Bahadori, 1978); and Stead (1980) suggests that the cooling effect of courtyards is highly improved when they are deep, in which case the height of the adjoining walls are considerably greater than their width The courtyard is not only an integral part of the house but also the main living space where for greater part of the year "the family members sleep work, pray, wash and hang clothes, entertain guests, dry fruits and vegetables, and children play" (Imamoglu, 1980). The courtyard therefore not only initiates passive cooling but also carries out diverse functions that increase the sense of comfort to the dwellers in hot arid zones. It also stimulates the cultural trait of community living and enhancing the sense of belonging of the family unit.

3.4.3.6 Use of water as coolant

Evaporative cooling technique in the form of water fountains, pools and ponds in the courtyards is used to enhance passive cooling (Al-Mutawa, 1981). As the water evaporates, the required energy *latent heat of vaporisation* is obtained from the surrounding air, thereby cooling the air, increasing its moisture content and providing comfort. There is also what is regarded as "desert coolers" whereby dampened reeds are placed across window openings. As the water evaporates it cools the air that flows across it before it gets in contact with the occupants (Faris, 1981). This practice not only provides air control and cooling but also humidifies the air indoors, while the airflow itself increases the rate of evaporation.

3.4.3.7 Minimal openings

The use of small openings, both in number and in size, reduces the flow of hot air from outdoors to indoors and the effect of both direct and diffuse components of solar radiation and, as the windows are located high up the wall, the reflected component as well. Though there are openings in other directions, most of them are located towards the courtyards which are cooler (Sayigh, 1981).

3.4.3.8 Wind towers/wind catchers

The use of these devices is specifically developed by some dwellers of this climate to enhance passive cooling. The wind tower or wind catcher works like a chimney, with one end at the bottom of the building and running through to the top above the roof where it is shaped according to whether the wind is mono or multi directional. The tower functions by changing the temperature and hence the density of the air inside it thus creating a difference in pressure. This difference creates a draft pulling air up down the tower (Karaman and Egli, 1981). Its function also depends on time of day and the presence or absence of wind (Bahadori, 1978). Effective as they may be as passive cooling devices, they also let in insects, dust, sand and other particles into the dwellings while on the other hand, their initial and maintenance costs may be relatively substantial.

3.4.3.9 Building and use of materials

The use of domes and vaults is effective as a cooling measure (Bahadori, 1978) as they minimise heat transfer because of their greater volume/surface area ratio compared to that of flat roofs. The form of the building should be compact and rectangular with a shape ratio of about 1:1.3 which Olgay (1963), considers ideal though this ratio may vary according to location and other factors. For example, a recent survey (Turan et al, 1981) shows an average ratio of 1:2 in Mardin, a town in the hot arid region of Turkey.

The use of light harmonious colours and the creation of climate-responsive building texture are imperative. Light colours would reflect a higher percentage of solar radiation and in many cases, the brown colour is seen to be both responsive to this demand and harmonious with the colour of the environment and that of dust which is very common in hot dry lands (Al Mutawa, 1981). Good orientation, preferably along the east-west axis is considered ideal (Evans, 1980; Olgay, 1963) because in this position they not only minimise direct gain on the walls but also take maximum advantage of the winds. Where there is a winter period, except within the equatorial zone, rooms that are used mostly in the summer have northern orientation so that they are permanently shaded while the winter rooms have southern exposure.

The issue of *form* as a passive cooling tool is a pointer to the fact that natural cooling of a building can be enhanced by optimising *shape* and *proportion* at the early design stage.

3.4.3.10 The use of cave dwellings

Cave dwellings are also common as vernacular shelter in hot dry lands because the mass of the earth or stone around the cave is always a constant heat sink and, being underground, the building is always shaded, minimising heat gain from direct and diffuse solar radiation. Examples abound in many places such as Matmata in Southern Tunisia: Tripolitania in Libya; Aputia in Italy; Andalucia in Spain and Cappadocia in Turkey (Golany, 1980). Some ten million people or more are said to live and work in caves in Honan, Shensi and Shansi in the Loess belt of China where the climate is arid but cold (Stead, 1980).

There are two main types of cave dwellings: those with rooms along a cliff face with each room having its own window or door opening to the exterior, and those that open into a dug out pit which is like a courtyard.

3.4.4 Contemporary techniques

Contemporary techniques of passive cooling in hot dry climates involve the application of scientific principles ranging from those dealing with heat exchange (conduction, convection, evaporation and radiation) to daylighting, underground or earth cooling, and landscaping.

Passive cooling concepts in building design have been described by various authors in recent times (Bowen *et al* (1981), Sodha *et al* (1986)) and comparative studies of a selected number of concepts have been done for the purpose of optimisation (Verma *et al* (1986) Nayak *et al* (1982)). Different but sometimes conflicting *optimised* concepts have been suggested, but these to a large extent are dependent on the number and combination of concepts evaluated and upon the context in which the evaluation was made. For example Verma *et al* recommended evaporative cooling out of a menu of other options of wall insulation, cavity wall construction, white washed wall and the use of brick wall. The authors also noted that insulating a brick wall of normal size on its outer surface brings little relief. However Nayak *et al* (1986) who studied different approaches to the passive cooling of roofs recommended the use of a shaded roof (by means of a vegetable pergola) with a water film as the optimum choice.

Sometimes a combination of some of these techniques are applied to a particular situation and the choice would depend on climate, site characteristics, socio-economic factors and the design objectives.

3.4.4.1 Roof evaporative cooling

The cooling effect of water due to evaporation as described earlier found other practical applications in roof ponds and/or roof sprays which have been used in hot arid climates such as in Arizona. A roof pond is a layer of water on the roof commonly about 1 - 6 inches (25.4-152.4 mm) deep. A roof spray applies water to roof through a network of nozzles or pipes. The pond may or may not be designed so that the water evaporates completely in which case the roof is only kept damp but without standing puddles (Reaves, 1981). Other variations may occur in which case there may be various degrees of insulation for the roof and various levels of shading and ventilation for the pond (Givoni, 1981). The principle that has the major effect in a combination like this, (i.e. whether conduction, convection, evaporation or radiation) is a function of climate, time of day, weather conditions and the purpose for which the design is made.

The objective of the simple standing water pond is rejection of some of the incident solar radiation (as much of the heat is reflected from the water surface) and to cool the building through evaporative process during the day and radiative process at night. A variation of the simple roof pond was invented and patented as Skytherm by Harold Hay in 1967.

It basically involves placing water in plastic bags laid on metal roof and covered with movable insulation, to either heat or cool the building. During the summer, the insulating panels cover the water during the day and are drawn back at night to expose the pond to the night sky (the procedure is reversed in winter) and the heat stored would be released through nocturnal radiation. Heat rejection in the daytime is by both radiation and conduction because the thermoponds are covered by insulating panels. When the nocturnal dew point temperature is high, the ponds cool the building by evaporative process. Unlike the simple roof pond of open water, the objective of the skytherm system is not primarily rejection of incident radiation heat load but rejection of internal heat by conduction through the metal ceiling/roof (Reaves, 1981). Combination of roof pond and roof spray can be used in the same project; and detailed experiments by Givoni (1981), show the performance of the roof pond concept with various levels of insulation and shading. The results indicate that an exposed water pond does not provide satisfactory indoor condition in hot dry climates; a shaded water pond is only satisfactory in hot dry lands with warm winters, while the water pond with operable insulation, exposed at night and insulated during the daytime, (similar to skytherm) was the most suitable though it is also the most expensive option.

The roof pond concept appears to be one of the best passive cooling techniques recommendable for hot dry climates. In Atascadero, California, a test on a full scale house demonstrated that, with automation, thermoponds with movable insulation have the capacity to reduce indoor thermal discomfort than gas heating and electrical air conditioning. In Phoenix, Arizona, a prototype test room with transparent thermoponds and movable insulation room had temperatures maintained within the human comfort level though the ambient temperatures were up to 46 °C during the daytime or fell to the freezing point at night.

However, one factor that may mitigate against its large scale use in hot dry climates is the scarcity of water, especially in developing countries within the climatic zone, where irrigation is very expensive. Also the automation involved in the skytherm technique implies the use of auxiliary driving force (e.g. electric motor) which not only makes the system semi-passive (or hybrid) but also expensive. Moreover there is the problem of materials supply since these would have to be imported to make the steel roof decks, plastic liners, plastic bags and urethane or styrofoam panels with their aluminium cladding, though domestic production of these items could be easy for countries with oil and/or natural gas resources. The thermoponds may also need to be modified to meet local conditions and to meet the sensitivity to local and national skills, priorities, economic wherewithal and socio cultural aspirations. The implications of such a design change culminating from such modification must also be assessed.

The use of the so-called "**vary-therm wall**" for both passive heating and cooling in a composite climate has recently been suggested by Sharma *et al* (1989). The vary-therm wall is simply a modified form of Trombe Wall in which the glazing is replaced by some weather-resistant light material such as asbestos or wood sheets. It consists of an extra 2 vents at the bottom and at the top in addition to the normal 2 vents of a Trombe wall. It's use for both heating and cooling is similar in concept to that of the Skytherm (Hay and Yellot, 1969) and the roof radiation trap (Givoni, 1976(d)).

Different approaches to the reduction of heat gain through flat roofs, which have also been studied by Nayak *et al*, 1982 include roof shading by plants, use of removable canvas, evaporative cooling, a roof garden, and the placing of earthen pots over the roof. Of all these methods, the use of a shaded roof by pergola was found to give the optimum thermal levelling and least average heat flux into the room through the roof.

3.4.4.2 Convective cooling

A convective cooling system is one in which air is the major source of coolness and convection is the major mode of heat transfer. The driving force for the air is created when there is pressure difference between two layers of air as a result of difference in temperature, because the air column with the higher temperature rises and expands creating a difference in pressure. Increasing either the temperature difference between the two air columns or the height of the column (or both), or reducing the frictional losses in the flow passage, will result in increased rate of air flow.

Also the wind is a source of induced ventilation the driving force of which is created by the difference in pressure of the wind at the building openings. The higher the wind velocity and the lower the frictional losses the higher the ventilation rate. Since the night time temperature is always low, much of the ambient air should be circulated through the building fabric - walls, floors and ceilings - to remove the heat transferred to the building during the day. Natural circulation of air through the building openings such as windows and doors and the use of stack-effect ventilation is imperative.

Recent research works suggest that the night coolness or "coolth" can be stored either in a structural mass of the building and/or in a specialised thermal store as a rockbed; (Givoni, 1981, 1983; Bahadori, 1981). Givoni's experiment indicates that simple nocturnal ventilation does not provide effective structural storage and that special means have to be applied to improve the storage, such as:
(a) Increasing the surface area of the mass at the interface with the indoor space.
(b) Increasing the heat transfer rate (surface coefficient) by a higher air speed next to the surface of the structural mass.

(c) Increasing the thermal conductivity and heat capacity of the materials of the structural mass.

Effective cooling is usually achieved by a combination of several cooling sources such as night air coolness, evaporative cooling process and thermal radiation loss to the night sky.

3.4.4.3 Radiative heat loss

It is believed that any building element which "sees" the cold sky emits energy in the form of longwave radiation. As the roof is the most exposed element to the sky it is also the most effective longwave radiator. Most radiative cooling techniques are connected with the roof such as the different types of roof ponds and skytherm which also involve radiative cooling as afore-mentioned. Recent experiments (Conrad et al, 1981) on the assessment of nocturnal radiators indicate that metal roof surfaces are better radiators than plywood-based asphaltic surfaces, while studies on radiant floor cooling (Jachau, 1981) suggest that uncarpeted slab-on-grade floors offer substantial cooling and that night ventilation reduced cooling load dramatically.

Though the sky is cool even during a hot day radiative cooling is most effective at night because in the daytime the net radiant balance often results in heat gain since the body is exposed to solar radiation. The horizontal surface is the most effective radiant cooling surface and the amount of radiation varies in different parts of the sky, from 100% possible directly overhead at the zenith to 0 at the horizon (Elias, 1985).

Atmospheric particles such as water vapour, carbon dioxide and dust absorb and emit long wave radiation. Therefore there is always a balance between the radiation emitted by the roof towards the sky and the downward radiation from atmosphere. Thus the net radiant heat loss is effective for cooling the building, though any radiating surface also exchanges heat with the ambient air by convection. Radiative cooling is thus very effective in hot dry climates with their cold cloudless night skies though occasional dust cover and clouds could dramatically impair it's efficiency.

3.4.4.4 Underground or earth cooling

The suitability of cave dwellings in hot dry climates has led to the advocation for subterranean and underground settlements for the climatic region. The technique lies mainly in the recognition of earth or soil as either a great heat sink or a good cooling resource. According to Hancock's(1971) description of the micro climate of a kangaroo burrow in Arizona soil, while the external ground surface temperature was 71 °C the temperature at the end of the burrow just 0.5m beneath the earth surface was 27 °C, with an increase in relative humidity of three or four times that of the outside air.

However many factors mitigate against its large scale adoption, among which are the rigourous studies on sites such as its physical and chemical characteristics, the dynamics of temperature control at different depths, the terrain, orientation and elevation, before actual construction can take place. Other factors include problems of erosion and dust storms and other micro climatic features.

When well sited and built, subterranean and underground settlements offer effective means of combating the harsh climate of hot arid lands and the following factors will enhance their cooling potential:

(1) Effective ventilation which, apart from its cooling effect, is needed for health reasons and to enhance elimination of dampness.

(2) Evaporative cooling such as water fountains or pools in the courtyards.

(3) Effective landscaping of the courtyards.

3.4.5 Discussion

There are probably as many passive cooling techniques for hot dry climates as there are factors to be considered in parallel to their use, in order to achieve a balanced overall design objective. A subtle suggestion has recently been made that existing techniques fall into two categories: - those that are used for the prevention of overheating (i.e. minimising the heat gain) and those that are for passive cooling (i.e. getting the indoor thermal energy out, (Baker, 1987). In the field however, all the techniques are still being grouped under the umbrella of *passive cooling*. In whatever perspective the issue is viewed, the fact remains that there is no single technique that can, on its own, satisfy the passive cooling or the prevention of overheating requirements of a building in this climate. A combination of different techniques is therefore imperative. What has not been fully explored is the right proportions to which these combinations can be made (i.e. the right dosage from the menu of techniques to the appropriate size/use of building) to achieve the desired results.

Having examined the solar radiation control methodologies in buildings and the passive thermal control strategies in hot dry and semi-arid climates, the rest of this chapter reviews wind tunnel and pressurisation techniques for investigating air movement in and around buildings.

3.5 Wind Tunnel and Pressurisation Techniques for Investigating Air Movement in Buildings

3.5.1 Introduction

The investigation of air movement in and around buildings have been done via a number of routes. Firstly there is the use of **physical models** in wind tunnels. In this case models of a whole building or sections of it are made to a smaller scale and tested in a wind tunnel with a view to achieving some particular modelling objectives. Secondly **analogue methods** may be used which may include the use of digital computer or electrical and hydraulic simulations, all of which entail the use of mathematical models. Thirdly the use of **full-scale measurements** on real structures, though less common because of inherent problems in the method, is another approach. This method entails the use of pressurisation tests and tracer gas measurements of air infiltration rates. The main set-backs with full scale measurements is that they are affected by the variability of the weather. They are very expensive and often time-consuming.

In order to remain within the scope of this study, attention is being paid mainly to physical wind tunnel modelling and models of air infiltration study including pressurisation techniques. Details of water analogue methods can be found in many studies including (Kurek, 1965), (Malinowski, 1971) and (Bilsborrow, 1972), and so on.

3.5.2 Wind Tunnel Modelling

The similarity between wind flow over the earth's surface and the turbulent boundary layer flow over rough surfaces has been established by various researchers in the field (Morris, 1955) (Jensen and Frank, 1965), (Good and Jourbet, 1968), (Jourbet, Perry and Stevens, 1971) among others. Therefore buildings on the surface of the earth are considered as objects on a rough surface over which a turbulent boundary layer flows. Hence it has become quite acceptable in the field of the studies of air movement to make physical models of buildings and test them in boundary layer wind tunnels to predict airflow patterns or determine the relationship between wind speed and the relative magnitude and distribution of wind pressures over the building surfaces and so on. This approach, which has come to be known as physical modelling, has invariably become one of the most popular approaches to investigations of air movement and how it affects structures and the environment. The popularity is as a result of the advantages inherent in the method.

Physical modelling in wind tunnels alleviates the problems encountered in full scale measurements in existing buildings which are susceptible to the vagaries of different elements that embody what is commonly called "weather conditions". These variables and processes are themselves difficult to control and/or measure principally as a result of the complex interactions and interrelationships between them, all of which man is at best, yet to fully understand. In addition to this, the fixity of the orientation, location, height and surrounding characteristics of an existing building is a disadvantage for any meaningful parametric study since the above factors cannot be altered for the requirements are also relatively very expensive and time consuming. Scale models on the other hand can be moved around easily and can be used repeatedly and/or consistently in a boundary layer wind tunnel with simulations of various environmental conditions with a fairly high degree of accuracy. This perhaps explains why investigations in the field are highly dependent on scale model experiments as the main source of information.

This is not to say that physical modelling in wind tunnels does not have its drawbacks. It's main limitations are that, firstly, they are susceptible to scale effects. Wannenburg and Van Straaten (1957), pointed out that

> a model may be said to be subject to scale effect if a change in the Reynolds Number results in a change in the various non-dimensional

> flow parameters. For example, if pressure, measured at a point on the model, expressed non-dimensionally in terms of wind velocity head, is found to be constant over a range of varying Reynolds Number, then the model may be considered free from scale effects over the given range of Reynolds Number

as quoted in (Pitts and Ward, 1983). Ideally therefore the Reynolds Number in model tests should be equal to that at full size in order to ameliorate this limitation, a condition which has been found to be impractical as we would see later.

Secondly the simulation of the natural velocity profile in a boundary layer wind tunnel is only, at best, relatively accurate and never exactly equal to real life situations. Furthermore certain significant air movements such as the Ekman Spiral (caused by Coriolis effects) which are mostly prevalent at heights of 100m in the atmosphere, cannot be simulated in a wind tunnel.

3.5.3 Development of the Wind Tunnel

A wind tunnel has been described as a device for producing a moving airstream for experimental purposes (Pankurst and Holder, 1952(a)). For many years wind tunnels have been used to investigate the characteristic effects of the wind on structures, including buildings. The practice of using wind tunnel for the above purpose is referred to as wind tunnel modelling, the development of which began about eight decades ago. As mentioned earlier, the need for physical scale modelling necessitated the construction and use of wind tunnels. Scale models of actual structures are built and used in the wind tunnel with the aim, in most cases, either to determine the relationship between the wind speed and the magnitude and distribution of wind pressures over the surface of the building or the magnitude of airflow through the internal openings of the building, or both.

Conventionally wind tunnels are divided into two classes, namely *Low-speed* and *High-speed* tunnels. In the former, the predominant factors are inertia and viscosity and the influence of compressibility is negligible. The latter types are intended for the investigation of flows in which the forces due to inertia and compressibility (rather than viscosity) are of major importance.

The earliest wind tunnels were simple in design, and had models suspended in the middle of the working section. Contemporary tunnels now have a fairly uniform standard design configurations, with the model placed on the floor of the working section and in most cases it is possible to carry out a fairly accurate modelling of the natural airflow as close as possible to real life situation. Further details of wind tunnel design and construction may be found in Relf and Erving, (1923), Lavender, (1923), and Pankhurst and Holder, (1952).

The most influential example upon which most modern wind tunnel designs are based is the closed-circuit open-jet tunnel developed at Gottingen in West Germany (Relf, 1931), the main difference being that modern tunnels have closed-throat working sections (i.e. bounded by rigid walls). Examples of current wind tunnels suitable for the simulation of the atmospheric boundary layer has been described by many research workers in the field. Typical among these is Sheffield University Boundary Layer Wind Tunnel which was first described in detail by Lee (1977) and is presented in detail in Chapter 5. Others include the Monash University and the University of Sydney Wind Tunnel Laboratories (Aynsley and Vickery, 1977) and the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario, and many others in institutions and research establishments mainly in Europe, North America, Canada, Japan and China. Variations exist in current wind tunnel constructions and the process of creating a good simulation is said to be invariably dependent on intuition, and trial and error (Cook, 1978(a)). These variations also imply variations in the capabilities of different wind tunnel facilities and associated equipment around the world today, a factor which tended to create minor difference in the techniques used and assumptions made to achieve modelling objectives or requirements.

3.5.4 The Principle of Wind Tunnel Testing

Having established that the very basis of wind tunnel modelling is the similarity between wind flow over the earth's surface and the turbulent boundary layer flow over rough surfaces, it is imperative that for meaningful and useful results and for reasonably accurate prediction of full scale response of the building, the wind tunnel tests "should be carried out under precisely scaled conditions" (Fricke, 1973). This implies that theoretically, both the Reynolds Number of the flow and the velocity gradient in the boundary layer should be the same as at the full scale. While the full-scale velocity gradient can be modelled with a reasonable degree of accuracy in a boundary layer wind tunnel, it has often been found impractical to maintain the same Reynolds Number in both cases due to scaling problems and the huge expense it would involve unless other important parameters are altered. However it has been found that for structures which have well defined flow separation positions (i.e. with sharp-cornered edges), under turbulent flow, then the Reynolds number difference between the model and at full scale is minimal over a wide range of air speeds and can be ignored.

So far various attempts to simulate the velocity profile has produced only fairly accurate results though there is evidence that results are continuously improving. Even for a neutrally stable, atmospheric boundary layer, exact simulation is impracticable due mainly to the fact that "the differential equations which describe the flow in the atmosphere and in the wind tunnels are governed by different initial and boundary conditions" (Pitts and Ward, 1983). However there seem to be a consensus in the field that accurate results can be obtained, provided the model is sharp-edged, with plane faces, that the flow is sufficiently turbulent as to enable the Reynolds Number to exceed a certain "critical value" (Smith, 1951) and that it is the external pressures on the model surface that are being measured (measurements of internal ventilation rates in models does not seem, as yet, to be soundly established).

3.5.4.1 Pressure Coefficients

Results of wind tunnel tests are often expressed as a set of pressure coefficients (C_p) which expresses the ratio of the pressures measured at the model surface to the free stream (dynamic) pressure in the wind tunnel. Because C_p is non-dimensional, it enables results from model tests to be used in full-scale predictions. As a result of their large scale use, pressure coefficients are obtained in three ways namely
(1) by direct full scale field measurements,
(2) by scale model experiments in boundary-layer wind tunnels and
(3) by comparison with standard wind tunnel data.

3.5.5 Emerging Trends in Wind Tunnel Modelling

The quest to meet the needs of energy conservation which has gathered an increased momentum since the energy crisis in the early Seventies, has intensified interest on studies of wind effects on buildings, energy interchange between buildings and the atmosphere or between different zones of the same building. Many studies have dealt with prediction of air movement through building elements or building types with a view to assessing and possibly minimising ventilation and infiltration heat losses. In hot climates, the object has been with a view to optimising passive ventilation cooling. Also there have been investigations of the mean and fluctuating wind loads on isolated and grouped building forms and the combined effects of wind and rain. Studies on tall structures have also been undertaken to asses safety limits so that buildings are able to withstand great stresses imposed by wind forces.

In order to form a broad outlook for wind tunnel modelling research, it may be pertinent to split the published works in the field into 3 main groups.

(1) Studies dealing with the use and testing of different techniques to simulate the atmospheric boundary layer and the implications of changing some parameters and/or variables within some particular techniques. For example (Cook, 1978) presented a review of the performance of roughness, barrier and mixing device techniques of wind tunnel testing, and (Cook, 1982) presented details of the *practicalities* of the use of roughness, barrier and mixing-device methods ***in short*** *test-section wind tunnels*. Also in this category are studies of the effects of turbulence intensity and shear stress, profiles through the boundary layer including such studies as (Hunt, 1981), (Surry, 1982) among others.

(2) Investigations of qualitative and quantitative airflow in grouped building arrays and the urban environment. This is exemplified by such studies as Lee et al (1979), Hussain (1979) and Bauman *et al*,(1988).

(3) Investigations dealing with the prediction of infiltration and natural ventilation buildings.

The scope of this thesis makes it logical that this part of the study confines its attention to the third group namely, wind tunnel studies dealing with measurement and/or prediction of infiltration and natural ventilation with particular reference to low rise residential buildings, referring to the review of published papers for the necessary details.

3.5.6 Measurement and Prediction of Infiltration and Natural Ventilation

3.5.6.1 Introduction

Ventilation may be defined simply as the flow of air through a building via purpose-defined openings. Such openings consist of operable windows, doors, monitor openings, skylights, roof ventilator openings, stacks or vertical flues, and special-designed inlet or outlet openings. Ventilation is either ***natural*** or ***passive*** (in which case it is driven by wind pressure and thermal buoyancy including stack effect caused by temperature difference between the indoor and the outdoor air), or *forced*, (in which case it is mechanically driven by special systems including the use of air-air heat exchanger in cold climates to provide adequate positive ventilation with heat recovery, and of air-conditioning systems in hot climates to provide ventilation and indoor air cooling). While the former (natural or passive ventilation) is an important means of ventilation of small-sized buildings many of which are residential, and is relied upon by people in the low-income strata of both developed and developing countries as the primary source of ventilation the latter (forced ventilation) is invariably mandatory for large buildings or envelope-dominated structures to meet, at least, the minimum ventilation standards for the occupants. Such ventilation standards can be found in (ASHRAE, 1977), (ASHRAE, 1980), (ASHRAE, 1981) and (ASHRAE, 1985) as arrived at through a consensus of experts working in the field.

Different rationales have been developed in different parts of the world which have resulted in different ventilation standards (Klaus et al, 1970). Generally the main criteria used to measure ventilation standards at different times in the past have been such considerations as the amount of air required to expel exhaled air, moisture removal from indoor air, and the control of carbon dioxide (CO_2). Current ventilation rates are based largely on many research projects, especially that of Yaglou and Witheridge (1937) and Yaglou et al (1936). In spite of the variations of ventilation standards in different parts of the world, the ASHRAE standards seems to be internationally adopted.

Natural or passive ventilation in turn may be classified as either ***infiltration*** (and exfiltration) or *controlled natural ventilation*. Infiltration is the random, uncontrolled flow of air through unintentional openings (such as cracks, interstices etc.) in the building envelope driven by pressure differences across the shell. Infiltration is theoretically balanced by an equal amount of exfiltration since, except for transient conditions, there should be no net air storage in a building (law of conservation of energy). The term *air leakage* which is often regarded as synonymous with infiltration is slightly different in meaning in the sense that it is the sum of all parallel air flows through unintentional openings into or out of a building without regard to flow direction.

The *functions* of any form of ventilation, whether natural or forced, include firstly the supply of fresh air to meet at least the minimum standard and in the process dilute the indoor air with the outdoor air as a means of controlling (removing) indoor air contaminants including carbon dioxide (CO_2) and thereby improve indoor air quality. Secondly, ventilation air movement can provide a measure of evaporative and convective cooling of the indoor environment in hot climates. Conversely when outdoor air temperature is appreciably higher than the indoor air temperature, dilution of the latter with the former through ventilation can increase indoor temperature levels above the bearable limits. The reverse is also true for cold climates in which the lowering of indoor air temperatures is the result. Thus the energy required to cool (or heat) this outdoor air can be quite significant. Therefore lowering the magnitude of the airflow (and other thermal parameters) is important to enable the sizing of cooling (or heating) equipments, to estimate seasonal energy consumption and to ensure proper control of indoor contaminants and maintain a good level of indoor air quality.

3.5.7 Emerging Trends in Ventilation Measurement and Prediction

As a result of the above important functions of ventilation and the importance of the knowledge of airflow in and around buildings, ventilation and infiltration prediction through wind tunnel modelling has generated a great interest in recent times. Many studies including that of the effectiveness of ventilating residential buildings with unconditioned outdoor air as an adjunct to, or replacement for, conventional vapour-compression air conditioning as studied by Kammerud et al (1984), has indicated that ventilation has a great potential to substantially reduce cooling energy in the residential sector. Perusing through the literature has shown two main approaches to estimating natural ventilation namely (1) the traditional approach and (2) wind tunnel modelling. They both rely on some form of mathematical modelling though only the latter is backed up by initial experimental investigations. The traditional approach as may be found in many sources including (IHVE, 1972), (ASHRAE, 1981) entails the use of simple equations of the form

$$Q = E.A.V \tag{3.1}$$

where

Q is the airflow through the opening (m^3/s)

E is the efficiency of the opening, (usually between 0.25 and 0.60)

A is the *free* area of the opening (m^2) and

V is the mean external wind speed (m/s).

Other formulae include wind pressure differences across openings together with discharge coefficients.

While this approach is simple and easy to use it is usually accompanied by a range of correction factors for conditions which are known to affect the estimates. Furthermore, according to Aynsley (1982) and Aynsley (1985(a)) this approach cannot accurately account for

(1) Physical properties of the wind at a particular site in terms of mean wind speed profile or turbulence characteristics or the probability data on local mean hourly windspeed and direction relative to long term wind data from meteorological station. Boundary layer wind tunnel modelling can account for these factors (Aynsley et al, 1977)

(2) The effect of nearby obstructions, topographic features or vegetation, grouped form or building arrays etc. , on local wind speed. These can be dealt with by wind tunnel modelling (Holmes et al, 1979; Hussain, 1979; Soliman, 1976; Soliman and Lee, 1974; and White, 1954)

(3) The influence of architectural features such as extended roof eaves, sun-screen devices, or wall projections on surface pressure distribution around a building. This can be handled by wind tunnel as exemplified by Aynsley (1977).

(4) Influence of size, proportion and location of openings in a building on airflow pattern and pressure distribution. This can also be handled by wind tunnel modelling (Aynsley, 1979).

For obvious reasons therefore, attention would be paid in this part of the work mainly to the latter method. Exploring the emerging trends in wind tunnel modelling of ventilation and airflow around building immediately shows how development in the field has greatly advanced from the rudimentary Vitruvian days of antiquity (see Vitruvius, 1960) through advancement in fluid mechanics and aerodynamics to the present era of *advanced* techniques for qualitative and quantitative studies and prediction of ventilation and airflow in and around buildings. Although Shaw (1907) presented some laws of ventilation as early as 1907 at Cambridge, and Dick (1950) had used wind pressure distributions from wind tunnel studies with discharge coefficients to estimate natural ventilation through small vents and cracks around doors and windows, Smith (1951) was arguably the first study of airflow through purpose-defined openings modelled in a wind-tunnel. Working at the Texas Engineering Experiment Station, Smith studied airflow through window openings of a school classroom in a simple wind tunnel and advocated the use of wind speed coefficients referenced to external wind speed for ventilation prediction. This was closely followed by similar studies in Australia (Weston, 1954; Weston, 1956) and South Africa (Wannenburg and Van Straaten, 1957). In spite of the fact that these early studies were done in uniform flow conditions with no attempt made to simulate the natural boundary layer flow or control blockage effects they nevertheless provided the data upon which some formulated guide-lines for naturally ventilated buildings were based.

The advent of the *boundary layer* wind tunnel modelling brought to light the limitations of these early studies and the data therefrom. Results from these later studies were found to compare more favourably with full-scale measurements mainly because it is possible to simulate the natural boundary layer and other parameters fairly accurately in a wind tunnel. Through rapid development, it became possible about twenty years after Smith, for researches to start making parametric studies of airflow in boundary layer wind tunnels. For example at an International Conference in Tokyo in 1971, presentations were made for studies of the effect of high tunnel blockage (e.g. Mckeon and Melbourne, 1971), and so on.

Parametric studies of a similar nature dominated the field throughout the seventies and are still being done to continuously improve and refine wind tunnel modelling in order to produce accurate and reliable data. But attention was also being increasingly paid to improving the functional role of natural ventilation for comfort cooling in hot climates as exemplified by some notable research works including Aynsley's doctoral dissertation (Aynsley, 1977).

By the early eighties wind tunnel techniques were considered as being sufficiently accurate for reliable ventilation measurements/prediction purposes (Vickery, 1981) and a broad consensus had been established in the field on the wind tunnel modelling parameters that need consideration in order to obtain reliable results (Reinhold, 1982)

A comparison between wind tunnel data and full-scale field measurements for natural ventilation has also been done by Ashley and Sherman (1985). The study entailed the use of field measurements, computer simulation and wind tunnel modelling. Measurements of temperature, humidity, wind velocity and surface pressure and after carrying out a simulation of the natural atmospheric boundary layer in a suitable wind tunnel and carrying out the wind tunnel test on the building models, the results were compared with the actual experimental data from field tests by Akins, (1979), and also compared the latter with results of computer simulations using the NCEL computer program. Results from the study not only demonstrated that "wind tunnel data can be substituted for full scale data on pressure coefficients" but also that wind tunnel data can be used to develop a computer program as a design tool for the prediction of the effects of natural ventilation.

However the authors made an assumption which may have influenced the results. In order to offset the effect of shielding from trees, buildings and so on, they initialised the leeward pressure coefficients to zero and set the windward pressure coefficients to represent the pressure difference coefficients. The effect of this was up to the extent of even underestimating the pressure difference coefficients whereas many existing wind tunnel data do overestimate these coefficients (e.g. Chien et al, 1951; Jensen and Franck, 1963) a fact which was acknowledged earlier by one of the authors (Ashley, 1983).

Also it would have been very informative if a mention was made as to what degree of accuracy wind tunnel data "can be substituted for" actual full-scale data of pressure coefficients. This level of detail is understandably lacking in most literature. However, Aynsley (1985), has stated data derived from wind tunnel studies can be expected to be within 10% of actual values provided the criteria for some modelling parameters are met. These parameters include (1) wind tunnel blockage, (2) length scale, (3) ability to reproduce small architectural details, (4) modelling the surrounding environment, (5) Reynolds Number influences and (6) time scaling for measurements. He also recommended due consideration for some key parameters that influence the simulation of the boundary layer namely (a) the vertical profile of the mean longitudinal velocity, (b) the vertical profile of the turbulence intensity and (c) the power spectral density of the airflow. All these must be accurately modelled. Also, the fluctuating indoor components of pressure and velocity can be modelled in boundary layer wind tunnels to within 10% of actual values (Aynsley, 1980).

With this background more intensive ventilation airflow studies are presently being embarked upon with a view to evaluating natural ventilation through large openings as a cooling resort for thermal comfort in hot climates (Aynsley, 1982); (Aynsley, 1985); (Arens et al, 1984); (Vickery and Karakatsanis, 1987); (Aynsley, 1988). With these studies several approaches to the estimation or prediction of natural ventilation airflow have emerged.

(1) The *first* approach is the use of either pressure coefficients in conjunction with discharge coefficient data, thermal comfort criteria and climatic and wind speed data; or the use of wind speed coefficients in conjunction with thermal comfort criteria and wind frequency data.

3.5.7.1 (a) The Discharge Coefficient Option

This offers an improvement over the traditional method in situations where a particular building does not warrant the expense of a special wind tunnel study but it is not regarded as being as accurate as the wind speed coefficient option (Aynsley et al, 1977, Aynsley, 1982). This option uses equation of the form

$$V_o = C_d[(C_{p1} - C_{p2})V_z^2]^{1/2} \tag{3.2}$$

for the mean wind speed V_o(m/s) through an opening of appropriate discharge coefficients, C_d, and pressure coefficients for total windward pressure C_{p1} and leeward static pressure C_{p2}, referenced to the dynamic pressure of the mean windspeed V_z (m/s), z being the height (m) (usually 10m) above the ground for which long term windspeed data is available.

In terms of volumetric flow rate Q (m^3/s) the discharge coefficient option uses the equation of the form

$$Q = C_d.A[(C_{p1} - C_{p2})V_z^2]^{1/2} \tag{3.3}$$

where A is the free area of the opening.

This equation for airflow through a single opening is adapted for several openings in series [where internal airflow follows a single path through a building without branching, a feature of most buildings designed to encourage natural airflow (Figure 3.4)] in the form

$$Q = \left[\frac{(C_{p1} - C_{p(n+1)})V_z^2}{\frac{1}{C_{d1}^2.A_1^2} + \frac{1}{C_{d2}^2.A_2^2} + \frac{1}{C_{d3}^2.A_3^2} + \cdots \frac{1}{C_{dn}^2.A_n^2}}\right]^{1/2} \tag{3.4}$$

where n is the number of openings. Under more complex flow conditions involving internal branching of the flow, the solution is much more complex, and involves the iterative solution of simultaneous equations with numerous coefficients (see for example, Vickery, 1981).

In using this approach for estimating indoor thermal comfort the volumetric discharge necessary for comfort through each opening is calculated for each wind direction and then substituted into the discharge equation to determine the corresponding wind speed necessary for comfort. The frequency of occurrence (in percentages) for each wind speed interval exceeding that necessary for comfort for a particular wind direction is summed. This is done for all wind directions and the total of all percentages of occurrence indicates the total percentage of time for which thermal comfort is likely to be achieved near the openings by natural ventilation.

Whilst there is a measure of attraction for using this approach largely as a result of the pressure distribution data available from boundary layer wind tunnel studies, its accuracy is highly dependent on the choice of appropriate discharge coefficients as well as very accurate wind speed data presented in usable format. The discharge coefficients of openings themselves are approximated, and their use is only valued when they are used with their associated pressure difference.

3.5.7.2 (b) The Wind Speed Coefficient Option

This option is used where it is possible to accurately model internal spaces and building openings in a boundary layer wind tunnel enabling internal flows to be

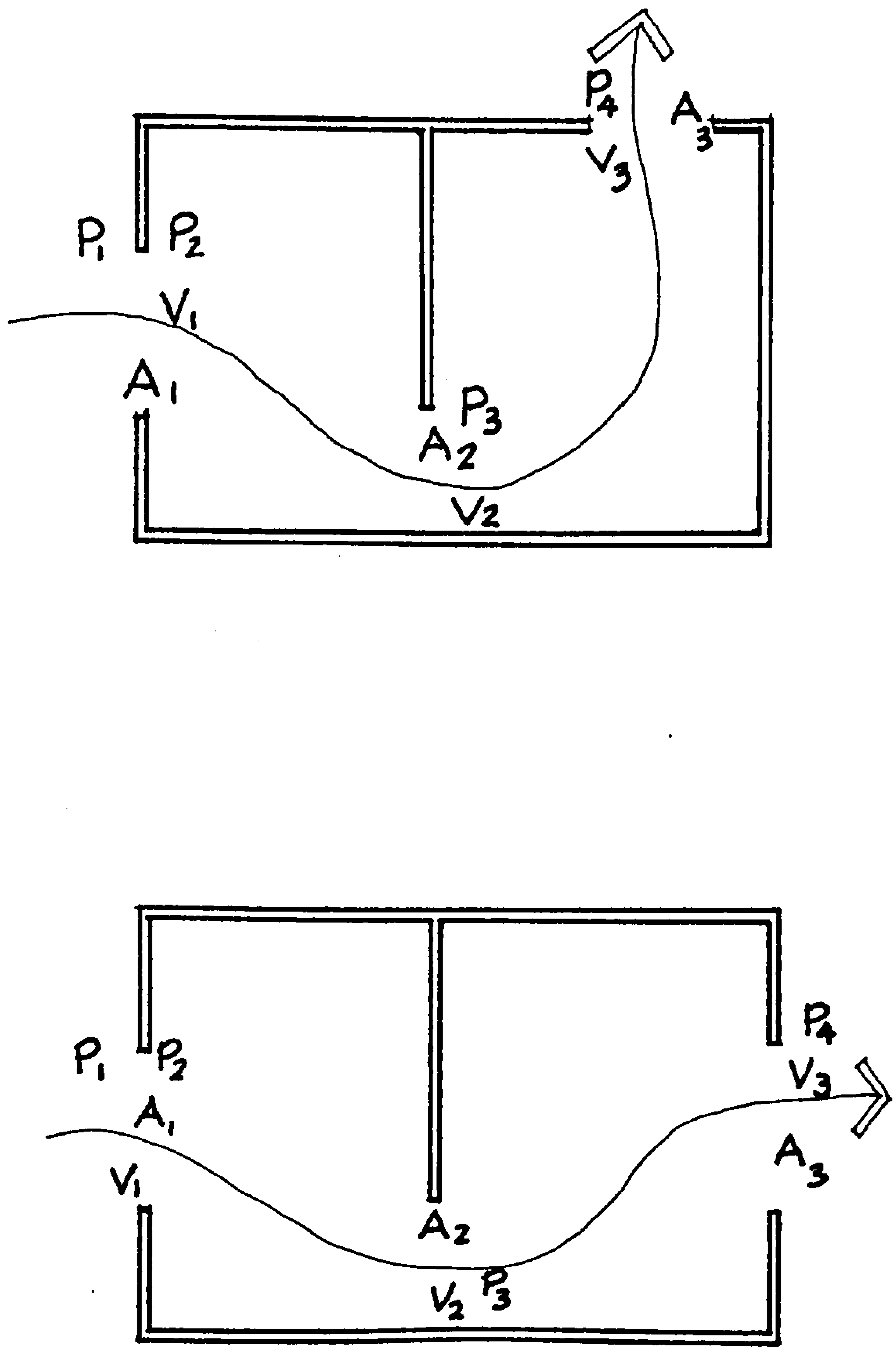


Figure 3.4: Designing to encourage natural airflow: window openings in series. (After Aynsley *et al*, 1977)

measured and compared with external wind data and consequently deriving the wind speed coefficients. The mean wind speed coefficient C_{v1} is therefore the ratio of the mean wind speed V at a point indoors (usually 1m above the floor) to the mean hourly wind speed V_z at a specified reference height, z (usually 10m above the ground) upstream from the building in the undisturbed flow. Thus

$$C_{v1} = \frac{V_1}{V_z} \tag{3.5}$$

Therefore, with appropriate C_v, from wind tunnel study, with the model at the appropriate wind direction, V_1 can be estimated, such that V_1 (full scale) = $C_{v1}.V_3$ (full scale).

The main advantage of this approach is its simplicity and the fact that it is suitable for buildings of complex and unusual shapes. Moreover mean wind speed estimates can be made at any desired position. However the expense and time involved restricts the use of this method to low budget projects. Also it requires larger and more detailed models than for pressure coefficient distribution studies. Moreover full scale effects of screens and louvres and wall components with curved sections cannot, presently, be used in wind tunnel models due mainly to differences in Reynolds Numbers of the flow at model and full scale.

Studies involving the use of this approach include Weston (1954) (industrial buildings); Givoni (1962) (housing); Van Straaten (1967) (school classroom); Chand (1972) (housing); Vickery and Apperley (1973) (housing) and the series of housing studies by Aynsley (Aynsley, 1980, Aynsley, 1982, and Aynsley, 1985).

Most of the early wind speed coefficients were based on low level external wind speed and on tests that were carried out in uniform airstreams; both factors do not enable a realistic estimate of actual velocities from meteorological wind data to be made. Taking cognisance of the effect of the natural velocity profile on wind pressure on low buildings (Hamilton, 1962) Aynsley has stressed the need for the reference wind speed to be measured in an appropriate wind speed profile *and* at a height for which adequate *long term* wind data is available. With careful modelling an *accuracy level* of the order of 10% of actual full-scale values is said to be achievable with the wind speed coefficient method.

(2) The *second* approach for the calculation of natural ventilation airflow is the use of some recently developed procedures or algorithms. These algorithms are based on correlation of some selected pressure coefficient data developed from wind

tunnel studies world-wide, and includes various correction factors for different parameters such as angle of wind incidence, building geometry, shielding effects etc. , all of which influence the value of pressure coefficient (C_p). This approach has been suggested by researchers in the field including Swami and Chandra, (1987, 1988) who presented a structured procedure for the calculation of wind-driven ventilation airflow rates which is an enhanced version of the Vickery (1983) algorithm for calculating airflow through buildings. An example of its application is also presented together with details of the correlation and synthesis of C_p data from a wide range of building shapes.

While this approach provides an alternative method for formal wind tunnel experimentation to generate pressure coefficients and an apparently sound procedure for ventilation flow calculations, it is to a large extent yet to be tested in the field although the authors suggested that the procedure is quite accurate after comparing measured and its predicted ventilation rates. Furthermore the procedure apparently embodies many generalisations and assumptions in attempting to use C_p data from a variety of sources, different building shapes etc.

It may be said by way of concluding this section that the calculation of ventilation airflows through a building is quite difficult and can hardly be done with precision by any particular method or procedure.

3.5.8 Pressurisation Techniques

3.5.8.1 Introduction

In order to avoid problems associated with scale effects it is usually necessary to model infiltration through critical openings (such as cracks, interstices, etc.) or airflow through some particular building elements such as louvres and screens, at full scale. Also, full-scale studies of one or more sections of a building or whole buildings are usually made, where feasible, to measure infiltration (and exfiltration) rates and test building air tightness. Two methods, in broad terms, are used for such studies namely (1) Pressurisation methods involving either pressurisation (or depressurisation) of whole buildings or part of it, or involving the use of pressurisation test facilities (the so-called test boxes).

Whilst there have been many full-scale studies of wind loading effects at high windspeeds on tall buildings (Eaton and Mayne, 1969, Tamura and Wilson, 1967) and low buildings (Eaton and Mayne, 1974, Eaton et al, 1976) and many full-scale infiltration studies employing various tracer-gas techniques for (see for example, reviews by Sherman et al 1980, Hunt, 1980, Harje et al, 1981, Pitts and Ward, 1983, Lagus and Persily, 1985, and such recent studies as Sandberg 1987, Roulet and Scartezzini, 1987, Dietz et al, 1985 and Prior et al, 1985) reviewing them is not within the scope of this thesis. Therefore in this part of the work, attention would be concentrated on pressurisation techniques, especially with respect to methods involving the use of pressurisation test facilities on sections of the building or on specific building components.

3.5.8.2 Application of Pressurisation Methods

There is always some degree of *natural* pressurisation of building which takes place as a result of the combined effects of the speed and direction of the wind at the building site and pressures caused by air buoyancy due to the difference between the indoor and outdoor temperatures (ASHRAE, 1981, 1985). These wind and stack effects induce air leakage through tiny openings in the building envelope. However as a result of the unpredictability of the wind and stack effects it is not possible to use them to adequately quantitatively document these flow and building air tightness. So some form of *artificial* pressurisation by means of one or more fans has been used for many years to measure infiltration and air tightness of buildings.

One of the earliest of such studies include that of Thomas and Dick (1953), which investigated airflow characteristics through gaps around windows and Hopkins and Hansford (1974) which studied airflow through cracks and its dependence on Reynolds Number, using a pressurisation test box (Figure 3.5) to draw air through the cracks. Three types of cracks were studied, namely (1) "straight-through", (2) "L-shaped" and (3) Multi-cornered cracks. The authors developed a theory relating discharge coefficients to the crack dimensions for a given Reynolds Number and then incorporated the experimental results into a semi-empirical equation. From this work it can be deduced that Reynold's Number is an important consideration with respect to measurement of flow through cracks.

Air leakage through component openings including cracks around windows and background leakage areas can be determined by *pressurisation and selective sealing* of the components (Hunt, 1980). This method has been used to determine the component of air leakage in single family houses (Caffey, 1979; Harrje and

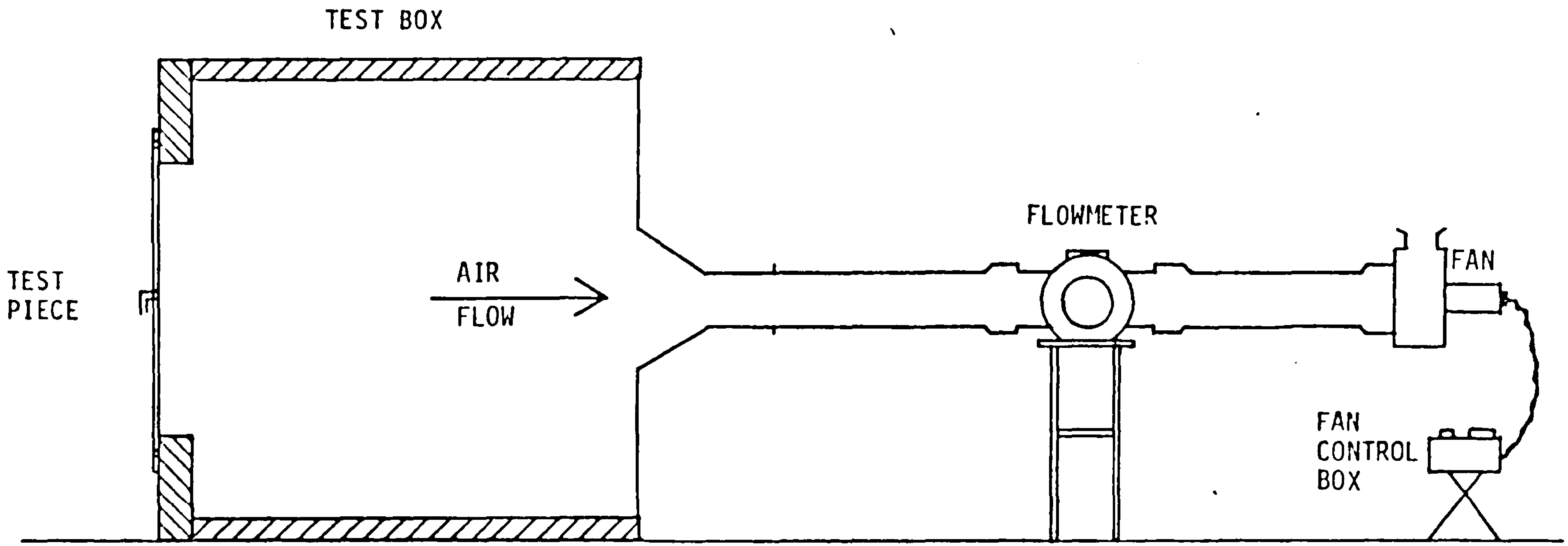
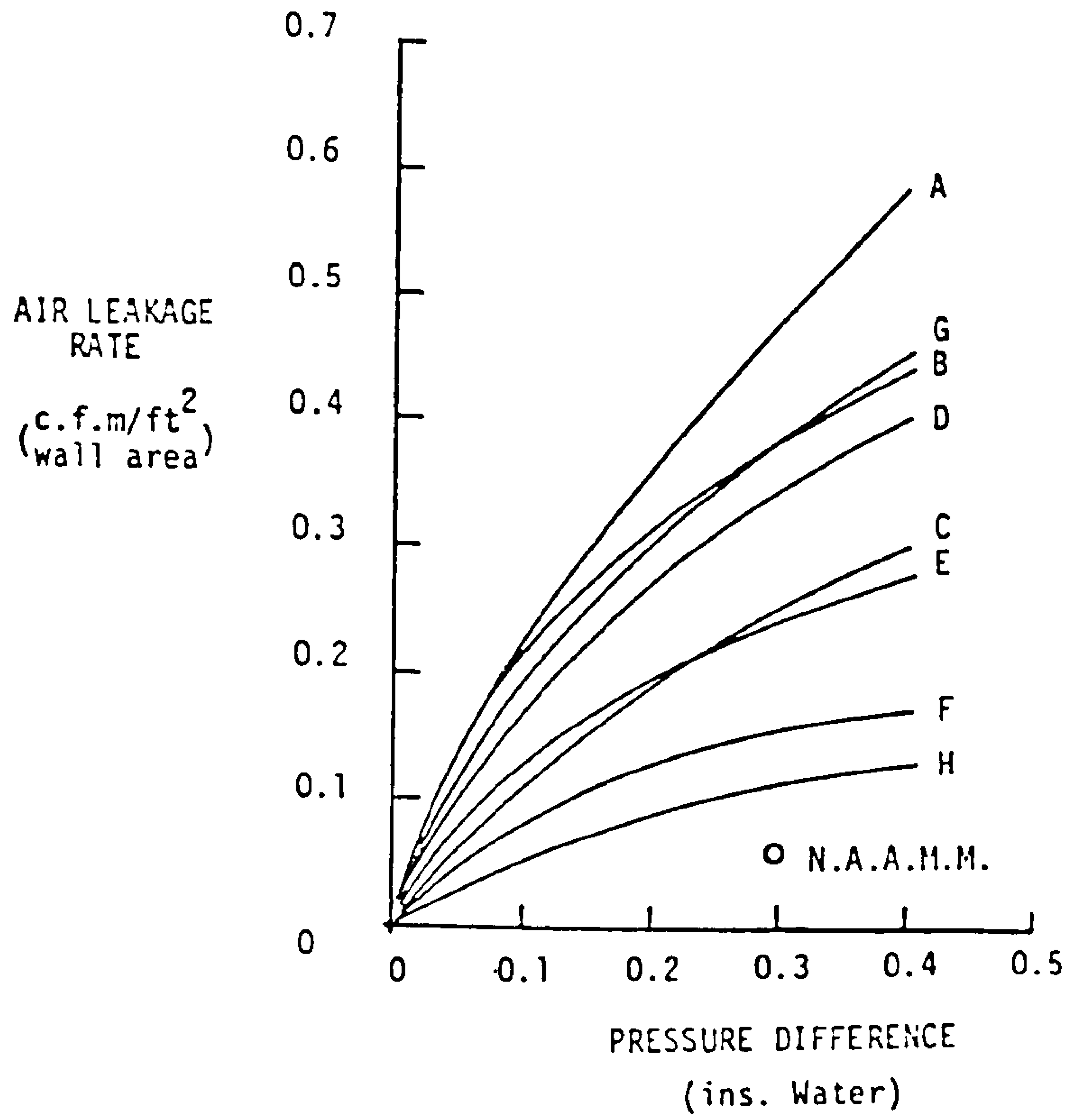


Figure 3.5: The use of pressurisation test box (After Hopkins and Hansford, (1974))

Born, 1982; Reinhold and Sonderregger, 1983). Sometimes *suction* rather than pressurisation, is used in conjunction with the component sealage, as in Shaw and Jones (1979), who use this method in their infiltration study in school buildings. They assessed the leakage through individual components by taking measurements with the individual components' leakage areas sealed and unsealed. Their studies showed that infiltration due to stack effect was significant even for single storey buildings.

Another approach is to pressurise the building using its mechanical ventilating plants (Harrje et al, 1982). This is most convenient for buildings with central air distribution system and without too many interior partitions. Shaw et al (1973) used this method in a study to determine the leakage areas in the walls of tall buildings. Results from the study were used to formulate a mathematical model which calculates the leakage rate for a wall area given the overall leakage figures. A computer simulated validation of this model for a specified building showed agreement between calculated and simulated values to within $\pm 10\%$. However actual validation against four real buildings indicated poor prediction with the model, giving higher leakage rates. In a similar study using the same mathematical model (Tamura and Shaw, 1976), pressurisation was done with buildings air supply system with their extracts shut down and the test were carried out during unoccupied periods as well as when there was little winds, in a bid to offset unpredictable effects. Their results as show in Figure 3.6, showed that leakage through walls may be far higher than the recommended standard.

The use of portable fans for small-scale pressurisation studies (Shaw, 1980) has the advantage of enabling a comparison, in situ, of real building leakage values with those of laboratory tests. This method entailed using the portable fan to produce positive or negative pressure for a small test chamber that was sealed around a test area such as an external wall, window or door. These small scale tests are then used to predict leakage values for whole buildings. The problem with this method is that leakage can occur from the test chamber to adjacent rooms rather than to the outside. Shaw overcame this problem by also pressurising all the adjoining rooms to the test room containing the test chamber (Figure 3.7), a sort of *pressure balancing act.* Results from tests using this technique were found to have very good agreement with the whole building leakage tests than results obtained without the pressure-balancing technique.



(N.A.A.M.M. = National Association of Architectural Metal Manufacturers Standard = 0.06 c.f.m/Sq.ft. wall area at 0.3 ins. H_2O pressure)

Figure 3.6: Air leakage rates of exterior walls (After Tamura and Shaw, (1976))

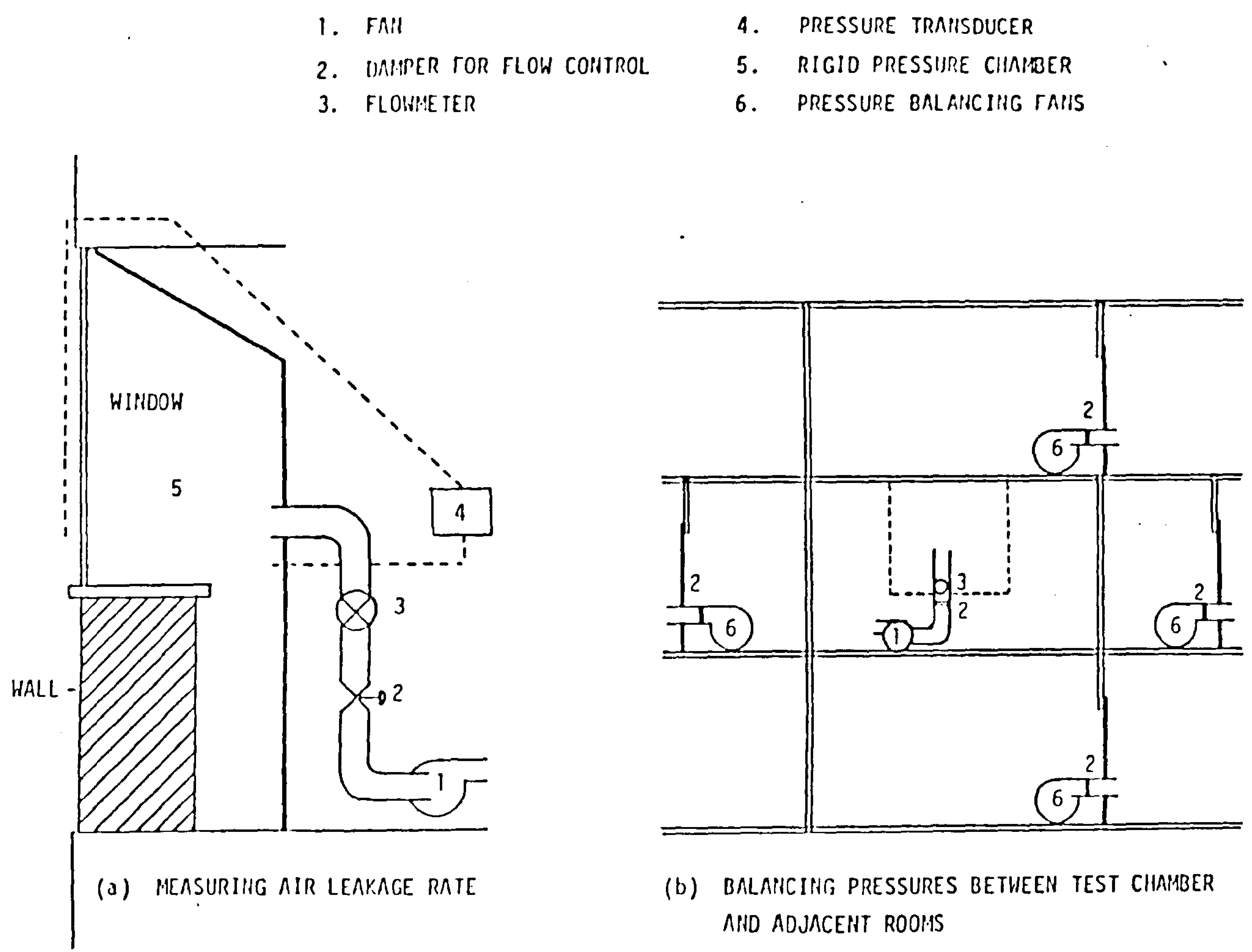


Figure 3.7: Experimental set-up for measuring air leakage rate through wall assembly (after Shaw, (1980))

The "reciprocity" method proposed by Swedish researcher Per Olof Nylund (Nylund, 1980(a)) eliminated this problem of leakage paths to adjacent rooms, enabling easy calculation of the flow through the external wall. With this method, all adjoining rooms into which there may be leakage from the room under test, must also be pressurised and the flow measured, thereby integrating the tightness tests from a number of individual interconnected zones to arrive at individual air tightness levels. Air leakage to or from adjacent rooms can also be evaluated by means of multiple portable fans or blower doors, enabling pressurisation to take place in unison, or by estimating flows based on pressure measurements taken in the adjoining space as has been demonstrated by Nylund, 1980(b) and (Lundin, 1981). This technique has been effectively used to evaluate leakage flow between adjacent row, houses. Nylund, 1980(b), and Lundin, 1981 have reported additional leakage rates of 6% to 25% from adjacent row houses to the row house under study. This issue of inter-row house leakage communication is also being investigated in the United States where the application of the fan pressurisation method is being used to study the phenomenon in the infiltration program of U.S. military family housing (Gadsby and Harrje, 1985). An alternative method of correcting for party wall leakage has been proposed by Love and Passmore, (1987), which involves computation based on measurement of indoor - outdoor pressure differentials in dwelling adjacent to the test room while the later is pressure tested. Results from a pilot test using the method was compared with that of pressure equalisation similar to Nylund's indicated an average agreement within 6.5%.

The most glaring of the limitations of pressurisation techniques include the fact that in order to offset the adverse effect of the vagaries of prevailing conditions, rooms or elements under test necessarily have to be pressurised or depressurised to a much higher level than would happen in reality (De Gids, 1980). For example, although natural (weather-induced) pressures are only between -5 Pa and 5 Pa in broad terms, the pressure differences induced by fan pressurisation may typically range between ± 10 *Pa* to ± 50 *Pa*. Using higher than normal pressures and flow rates alter the flow (e.g. from the usual laminar flow for cracks to turbulent one) and the size and formation of leakage areas.

Some alternatives to using higher than normal pressures is the *alternating* low pressure and suction technique as in (Sherman et al, 1979) which has claimed high accuracy levels since the adverse effect due to vagaries of the weather and weather-induced pressures at low pressures are eliminated by the averaging effects of the technique. The other is the *infrasonic* low pressure method of Card et al (1978) in which fluctuation of room pressures was attained by sequentially compressing and rarerifying the air in an oil drum through a pumping mechanism. The pressures set up by this method were within the range that naturally occur in buildings but its use has been limited due to several weaknesses inherent in the method. For example resonance effect have to be allowed for which greatly limits the size of the building for which it can be used, and the range of frequencies that can be used. Moreover it has not been found to be more accurate than normal pressurisation methods.

A different technique that can measure building air tightness directly *at small pressure difference.* The so-called "AC pressurisation", was suggested by Modera and Sherman (1985). It differs from the normal fan pressurisation in that it creates a periodic pressure difference across the building envelope that can be differentiated from naturally occurring pressure fluctuations. The method is based on the concept that the airtightness of a building affects the pressure change in the building due to *periodic volume change*, including both the amplitude and the phase of the pressure change. Therefore provided there are no leaks and that the structure is rigid, then the pressure change can be precisely determined from the structure's volume and piston's displacement. Hence any deviation from this predicted pressure can be attributed to leakage through the envelope. The measured volume change and pressure response are used to calculate the airflow through the envelope.

A comparison of measurements made with AC pressurisation with those by normal fan pressurisation in six houses were shown to agree reasonably well but that AC values were consistently lower (an average of approximately 14%) than the latter values. This was attributed to the presence of large leaks which the AC pressurisation did not detect easily since they require the movement of relatively large masses of air and can only be more closely approximated by resistances and inductances in series. However the AC method is thought to be inherently more accurate since it operates at the natural pressures that actually drive infiltration.

With application to large apartment buildings especially those without central air distribution systems it is always necessary to use multiple fan systems or blower doors for the infiltration studies. For example as many as six blower doors have been used to study a six apartment building (Modera et al, 1985). Some multizone airflow models have been developed in the recent past (Feustel and Kendon, 1985) application of which generally requires empirical parameters such as leakage areas and wind induced pressure differences specific to the building. The difficulties associated with measurement of these parameters for large multicell apartment buildings has limited the determination of these parameters and consequently the validation of these models. Bohac et al (1987) have recently put forward some experimental approaches of the application of the multizone pressurisation concept, namely (1) The "constant pressure" method and (2) The Guarded pressurisation method. The object of both methods is the separation of inside and outside leaks.

With the "constant pressure" method each apartment was pressurised using a single blower door and its gross leakage was measured. Then all the apartments were pressurised simultaneously so that each apartment was at the same pressure (in which case there is no flow between apartments and all the flow through the fan in or out of the apartment is outside leakage). Thus there is a breakdown between inside and outside leaks.

With the guarded pressurisation method a single blower door, as usual, measured the gross leakage of the apartment. Neighbouring apartments were then pressurised to the same pressure, which gives the gross leakage less the leakage between the test apartment and its neighbours. If all the adjacent zones to the test apartment can be pressurised then the net leakage from the test apartment to the outside can be determined.

3.5.8.3 Models for Infiltration Prediction

The guide to the choice of the appropriate calculation techniques for air infiltration and ventilation prediction has been presented by the AIVC Applications Guide (Liddament, 1986, 1988). The various generic forms of calculation techniques are arranged in the order of their level of complexity and applicability namely; (1) "Air change" method (2) Reduction of pressurisation data (3) Regression techniques (4) Theoretical network methods and (5) Simplified theoretical methods.

From the menu of methods, specific applications can be selected to meet the needs of individual situations. The basic calculations are handled by the first three which are of more limited application while the last two are relatively more versatile and are expected to fulfil the needs of most applications. The choice of the calculation technique would also depend on the required level of accuracy, the availability of data and the type of building involved. However no single method can be deemed as being universally appropriate or absolutely accurate. Only the empirical and some basic theoretical models are considered relevant, within the scope of this study.

A. **Empirical Models**

These being the most basic of all infiltration models, they are only loosely based on the physical concepts of air flow. Empirical techniques may be said to consist of the first 3 methods above and taking them in turn, we have:

(1) "Air change" methods

These are generally used to estimate air change rate (ACR) for specific design conditions for use in *simple* heating and cooling calculations for which intricate details of flow are not required. Such methods can be found in Handbooks/Guides such as CIBSE Guide (1976) and ASHRAE (1981, 1985). The CIBSE Guide for example outlines two approaches. In the first approach infiltration is calculated by graphical means using local wind speed, building heights and window characteristic data. The second approach makes use of tables of expected values for buildings of typical construction under average weather conditions. Similar approaches are used in the ASHRAE Handbooks.

(2) **Reduction of pressure test data**

This technique which is based on the concept of artificial pressurisation of a building as a means of assessing air leakage performance merely expresses the "leakiness" of a building in terms of its air change rate at 50 *Pa* pressure difference (Q_{50}). This does not usually indicate the distribution of openings or the effects of wind, temperature, terrain or shielding. The general rule of this technique is that the *the rule of thumb* approximate air infiltration is of the order of one-twentieth of the measured air change rate at 50 *Pa*, i.e.

$$Q_{inf} = \frac{Q_{50}}{20} \tag{3.6}$$

where Q_{inf} is the infiltration rate (h^{-1}) and Q_{50} is the airchange rate at 50 Pa.

(3) Regression Techniques

This is based on statistical linear regression fit to long-term time-series data of infiltration rate measurements and associated climatic data and is usually expressed in its most basic form, as a linear function of wind speed and temperature, i.e.

$$Q_{inf} = a + b\Delta T + cV^2 \tag{3.7}$$

where Q_{inf} is the infiltration rate (h^{-1}), ΔT is the internal/external temperature difference ($°C$), V is the wind speed (m/s) and a, b and c are regression constants. With known values of ΔT and V, the regression constants can be obtained by the method of least squares analysis.

B. <u>**Theoretical Models**</u>

As explained earlier, the magnitude of the infiltration through a building envelope is influenced by building airtightness and the magnitude of pressure regimes across the envelope penetrations as well as by the distribution of the leakage, the flow characteristics of the various openings, and the internal impedances to air movement. Models of air infiltration and ventilation predictions are based on the fundamental concept of the balance of mass flow (i.e. that the air entering the building displaces an equivalent mass of internal air). The models represent a theoretical underpining to the mathematical representation of air infiltration. It may be pointed out however that mathematical representations of infiltration is extremely complex and that the number of acceptable representations of the flow process have been formulated with underlying simplifying assumptions. It is the degree of these assumptions that determines the applicability of a model and its level of sophistication and data requirements.

The flow through relatively large openings such as purpose-defined vents and large cracks around windows is considered as turbulent in nature and can be represented by the orifice flow equation such as

$$Q = C_d A \left[\frac{2}{\rho}\Delta p\right]^{1/2} \tag{3.8}$$

where Q is the airflow rate, (m^3/s), C_d is the discharge coefficient, ρ is the air density (kg/m^3), Δp is the pressure difference across the opening (Pa) and A is the area of the opening (m^2).

The flow through very tight openings with relatively long flow paths as in mortar or tightly fitted components is dominated by the effects of viscosity and is therefore laminar with the flow rate being directly proportional to the applied pressure difference. With analogy to pipe flow, it is represented as

$$Q = \frac{\Delta p}{8\mu L}\pi r^4 \tag{3.9}$$

where μ is the dynamic viscosity, L is the length of the flow path (m), r is the radius of the opening (m) and Δp is the pressure difference (Pa).

A combination of the above two situations is what normally obtains in reality, and the flow is usually represented by the power law equation in the form

$$Q = K(\Delta p)^n \tag{3.10}$$

where K is the flow coefficient (m^3/s at 1 Pa), which is related to the size of the opening, n is the flow exponent which characterises the flow regime (ranges between 0.5 for fully turbulent flow to 1.0 for laminar flow) and Δp is the pressure difference across the opening (Pa).

Where the exponent n in the above equation is approximated to be 0.5 then the square law equation is said to apply as suggested by Dick (1950) and Sherman et al (1979); and hence

$$Q = K\sqrt{\Delta p} \tag{3.11}$$

In situations in which there is need to meet the requirements of dimensional homogeneity such as where the turbulent and laminar flow components are separated, a quadratic formulation of the flow equation has been suggested. It takes the form

$$\Delta p = aQ^2 + bQ \tag{3.12}$$

where a and b are constants.

For airflow through ducts and chimneys, the duct flow equation applies and is represented as

$$Q = A\left[\frac{2A}{E}.\frac{1}{fl\rho}.\Delta p\right]^{1/2} \tag{3.13}$$

where A is the cross-sectional area of opening (m^2), E is the cross-sectional perimeter (m), f is the friction coefficient, l is the length of the duct (m) and ρ is the air density (kg/m^3).

In most airflow studies one or more of these models are used. The *power law* (equation 3.10) and the *quadratic* (equation 3.12) relations seem to be the most widely used to describe the flow through cracks and other small openings. However many studies have shown that the quadratic relation gives a better description of the flow (Thomas and Dick, (1953), Etheridge, (1984), and Baker *et al, (1987))* and may soon replace the ubiquitous *power law*.

3.6 Conclusion

One might say by way of concluding this section that whilst it is possible to obtain good results from wind tunnel modelling, there are stringent criteria which must be met to realise this objective. Hence the reliability of the data obtained would depend on the ability of the researcher to meet these criteria.

It has also been observed that not much validation of data seems to have been done in the field in spite of the proliferation of papers in recent times. For example comparisons of modelling results with those of computer simulations or, where possible, full-scale results would be helpful in evaluating the accuracy of internal flow estimates deduced from external pressure distribution studies on solid or sealed models.

Furthermore whilst the external pressure distributions on low-rise buildings have been studied extensively for a long time, the data generated have not been suitable for ventilation predictions, as emphasis had been on maximum values to meet the objective of determining the wind loads on buildings. Hence studies of pressure distribution for passive ventilation prediction is a relatively recent development. Unfortunately however, only a few researchers have been consistently engaged in such studies. This has resulted in the paucity of comprehensive and validated data and/or information required for ventilation prediction.

In addition although pressurisation techniques have been applied extensively to studies of airflow through small openings not much attention has been paid to flow characteristics through external shading devices such as louvres and screens, the use of which reduce direct solar penetration but may adversely affect airflow through the opening.

All in all this chapter has provided some useful background while laying a good foundation for the experimental stage of this study, which is presented in the next section of the thesis. The section begins with the full-scale field measurements presented in the next chapter.

Chapter 4

Full Scale Field Measurements

4.1 Introduction

The fieldwork was undertaken to measure and collate data on temperature in a full scale contemporary residential building which incorporates some degree of solar shielding of it's fabric in a hot semi-arid climate. It was carried out in Kano, a historic and commercial city in northern Nigeria. The building selected for the study is a contemporary residential building built with modern construction materials and techniques.

The main consideration for the choice of a relatively modern building rather than a traditional mud house is that as we have seen in chapter 2, there is presently a great shift of emphasis from traditional to modern buildings and it was considered that the great challenge directly facing the designer in the present times is how to incorporate passive cooling techniques in the design process in order to achieve indoor comfort at a minimum cost. In the context of the climate under study, this can be achieved if the building not only rejects as much solar radiation heat as possible but also find means of protecting itself against direct solar rays. This is an era in which the designer must seek means of integrating modern techniques with traditional thermal control strategies which had evolved in the hot-dry climates through the ages.

Secondly, the building has elements which are directly relevant to the theme of the study. In addition to this, it is unoccupied and unconditioned and is therefore most suitable to give a good representation of the parameters under study without the complexities that would otherwise have arisen in an occupied and/or air-conditioned building and which may have adverse bearing on the results. Furthermore there is a large pool of literature dealing with the virtues of building traditional mud houses with their legendary massive walls and roofs. It was considered that a survey of a contemporary building would also provide some useful information and some level of understanding of the thermal dynamics of a building fabric in the context of energy and environmental control.

Furthermore the quantum jump in the development of modern technology has had a tremendous impact on architectural design and on the development of the human shelter in all it's ramifications, especially in the developed countries, but also in the developing nations where it is having a profound and spontaneous impact. In the latter countries, it has, ironically, had an adverse effect on the quality of design, resulting in inappropriately designed "modern" buildings and an almost total neglect of the long-tested and enduring principles by which a good level of indoor comfort had been attained in this climate in the past. Though there are a few cases where conscious effort is being made to improve the adaptive qualities of modern houses (or lack of it) to the realities of our climate, the general practice presently is the impulsive tendency to copy western designs and impose it on the climate **either** as a result of lack of understanding of the serious implications (which may imply that there is little knowledge of the principles involved) **or** as a result of total disregard for coherent application of design principles that would foster the harmony that should exist between man and his indoor environment, **or** both. Therefore it was considered pertinent that conscious efforts be made now to provide design data, and investigate relevant parameters that would establish the framework for a potential design strategy by which contemporary residential buildings in this climate could reduce indoor thermal discomfort by passive means.

4.2 The Building Case Study

The building is a one-storey residential duplex and is one of several units in a private family estate in "Goron Dutse", and is one of the relatively 'modern' developments in the north-western periphery of the ever-growing Kano metropolis. It is designed as a five-bedroom medium sized family unit, including two self-contained guest bedrooms. The building is in two parts, the living zone and the sleeping zone. The living zone incorporates a large sitting/dining space, a double garage, two guest bedrooms, and a kitchen, and is mainly located on the ground floor.

The living zone is also surrounded by landscaped courts and flowers and there is adequate provision of guest parking spaces. The sleeping zone which is located on the first floor above comprises a large master bedroom with a bath/exercise room and two other self-contained bedrooms and a spacious family living room. All the bedrooms and the bath/exercise room have both an open balcony and a shielded space where people can relax and not be seen by the curious eyes of passers-by and/or visitors.

The design philosophy of the building was a deliberate deviation from the central courtyard concept which generally harmonises with the socio-religious idiosyncrasies of the people. Rather, an attempt was made to create some "mini-courtyards" in the periphery of the building in the form of covered spaces. The main purpose for covering these spaces was to prevent passers-by or visitors from seeing the women (an Islamic practice) while allowing the women to have a visual command of the external environment whenever desired. It is apparent however that the covering may have a thermal function in that it helps to forestall the adverse effect of direct and diffuse solar radiation, and to maintain a little buffer zone between the inner habitable spaces and the rather severe external climate. In this way, an attempt may be said to have been made to keep away beam and diffuse solar radiation as much as possible, from the building fabric especially in the sleeping areas. The shielding material is "luxalon flex" which is basically thin slats of treated aluminium with a fine plastic coating. The architects actually wanted to use treated wooden slats water proofed by a fine plastic coating. But this material was not agreeable to the client.

The building form is that of a "rising pyramid" which alludes more to a status symbol of the "nouveau riche" than a bioclimatic design strategy. In fact the walls sloping inwards at 75° is a disadvantage since it provides little shading to direct radiation. However the pyramidal shape has a symbolic significance in the historical context. In the days gone by, Kano was famous for her huge groundnut pyramids which was then one of Nigeria's main agricultural exports. As in Ancient Egypt where the *Great Pyramids* symbolised a great civilization, leaving an enduring footprints in the sands of time, the pyramids of Kano symbolised a quintessence of commercial success. Every effort was used to reflect this status symbol in the building form and it is said to be liked by the client because it kindles his gone-by days as a youth in "Kano city".

In order to ameliorate the thermal hazard of this constraint, the architects tried to ensure that little or no direct solar radiation is incident on window glazing by providing some form of shadings with deep recesses, overhangs and projections)

The building is basically a concrete structure since the material was used freely for the floors, roof beams and columns for which the concrete was made *in-situ*. For the walls, concrete blocks are used while the floors had a marble finish. All the windows are of the sliding type and doors on the external walls are made of translucent glass. The roof has an unventilated airspace which is bordered by the reinforced concrete roof deck and the celotex ceiling. The roof deck was weatherstriped with bituminous felt and sprayed with sand and stone chippings. As at the time the measurements were taken, the building had been completed and ready for occupation except for electricity supply that was yet to be connected and the site that was yet to be properly landscaped. Graphic details of the building are shown in Plates 4.1 to 4.5.

4.3 Criteria for Temperature Measurement

4.3.1 Introduction

The major considerations undertaken for temperature measurements in the field work was the issue of what measurement device should be used and what temperature should be measured. Experience in the field seem to indicate that electrically based methods which entails the use of electrical sensors are most suitable for continuous logging of temperature data though in some situations, techniques based on thermal expansion may be preferred (SERC, 1983). In this study the former was considered suitable since a continuous recording of temperature with respect to time variation was required. As to what temperature to measure, what needed to be bourne in mind was the fact that the measuring sensor records it's own temperature as well as the temperature it is required to measure and that the relationship between these two values would depend on the complex heat exchange between the sensor and its surrounding environment and how far the environment represents the specific temperature it is intended to observe. The air temperature (dry bulb) was measured in this study since the heat balance calculations are done using the air temperature as the standard temperature and it seems to be the most

Plate 4.1: The building case study.

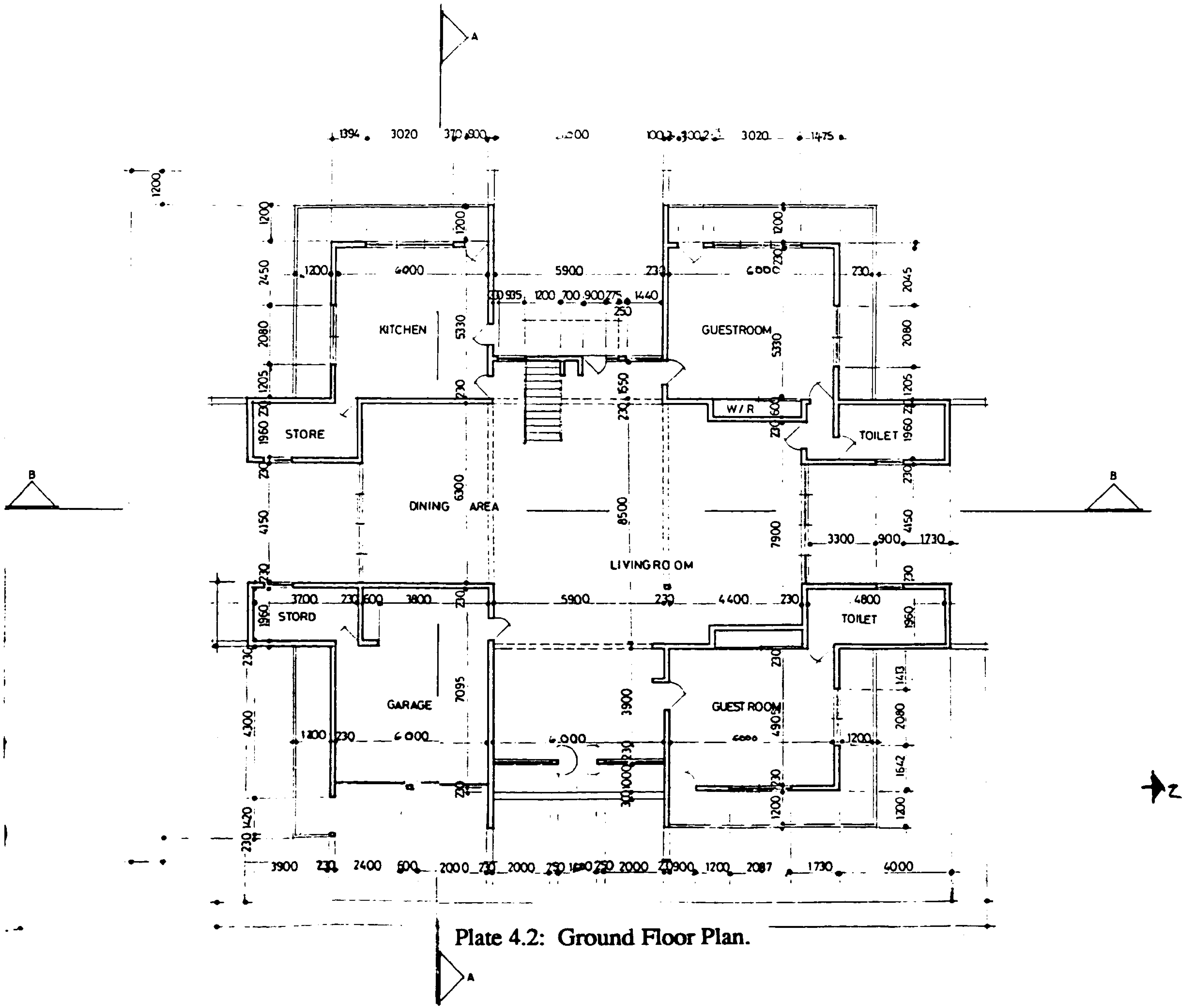


Plate 4.2: Ground Floor Plan.

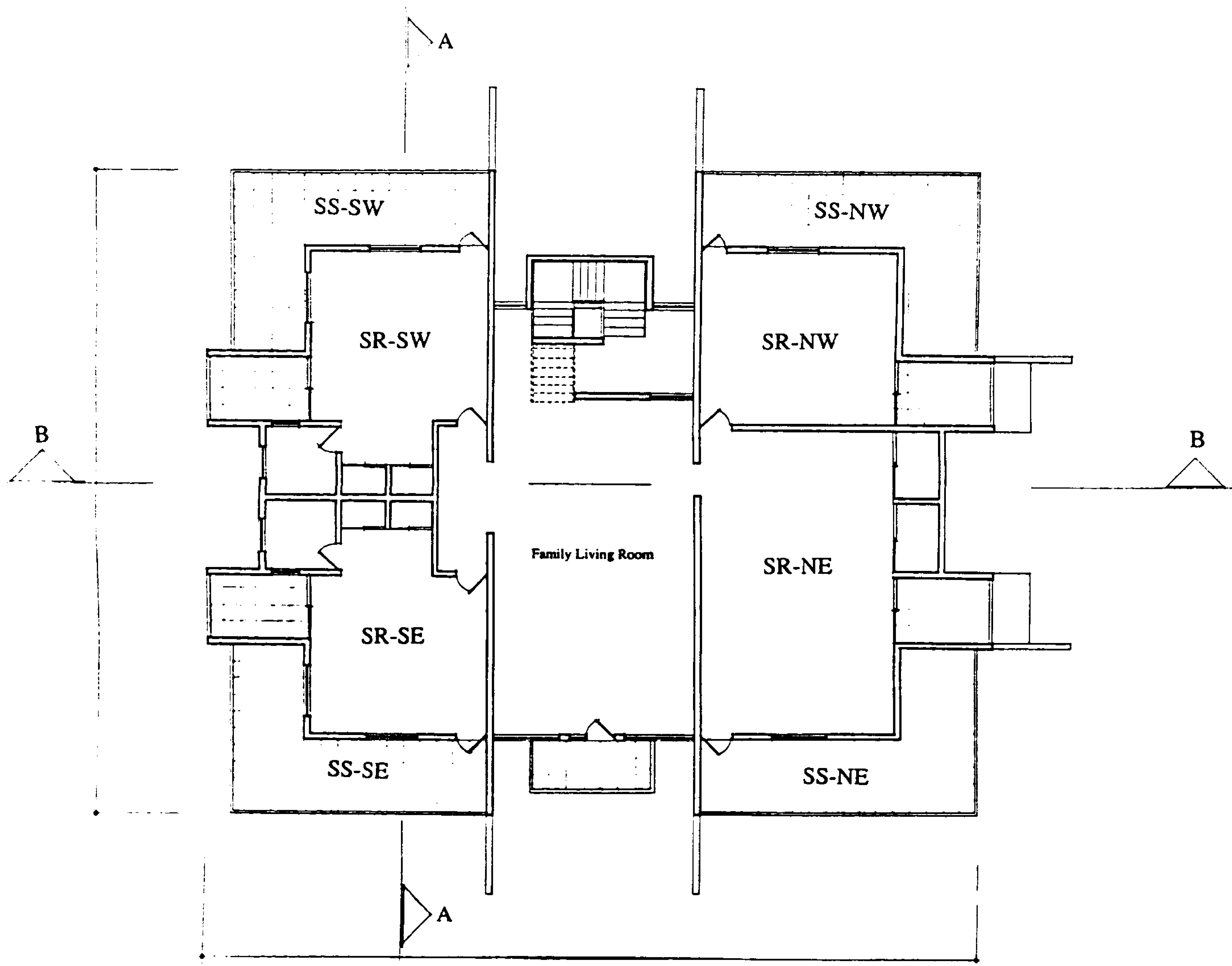
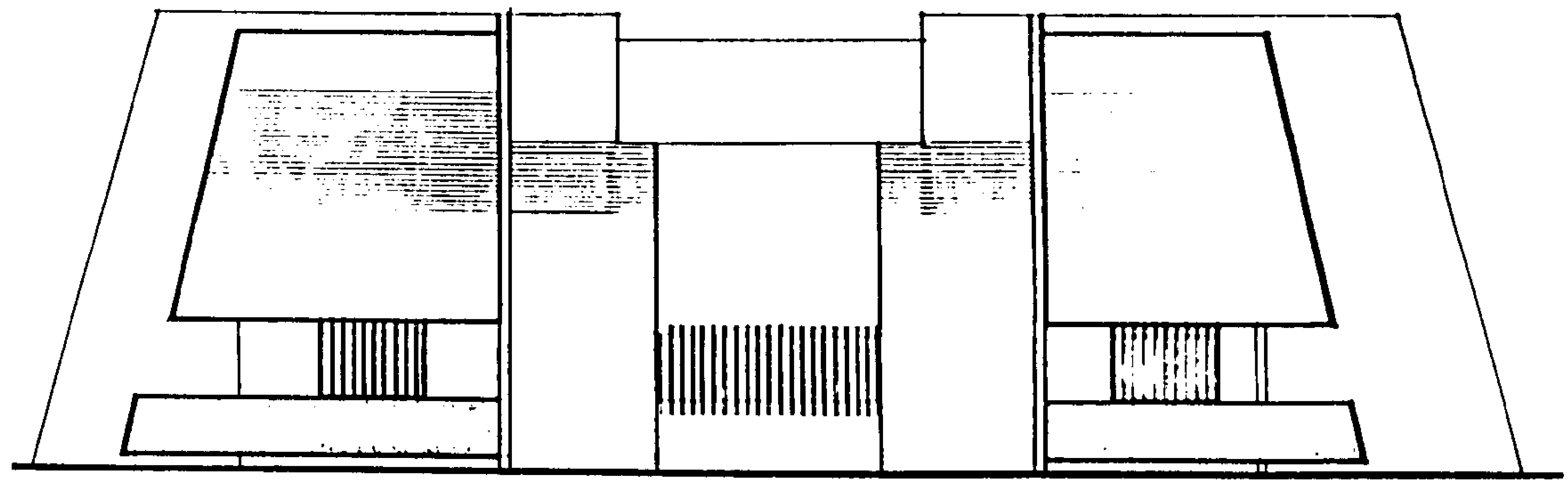
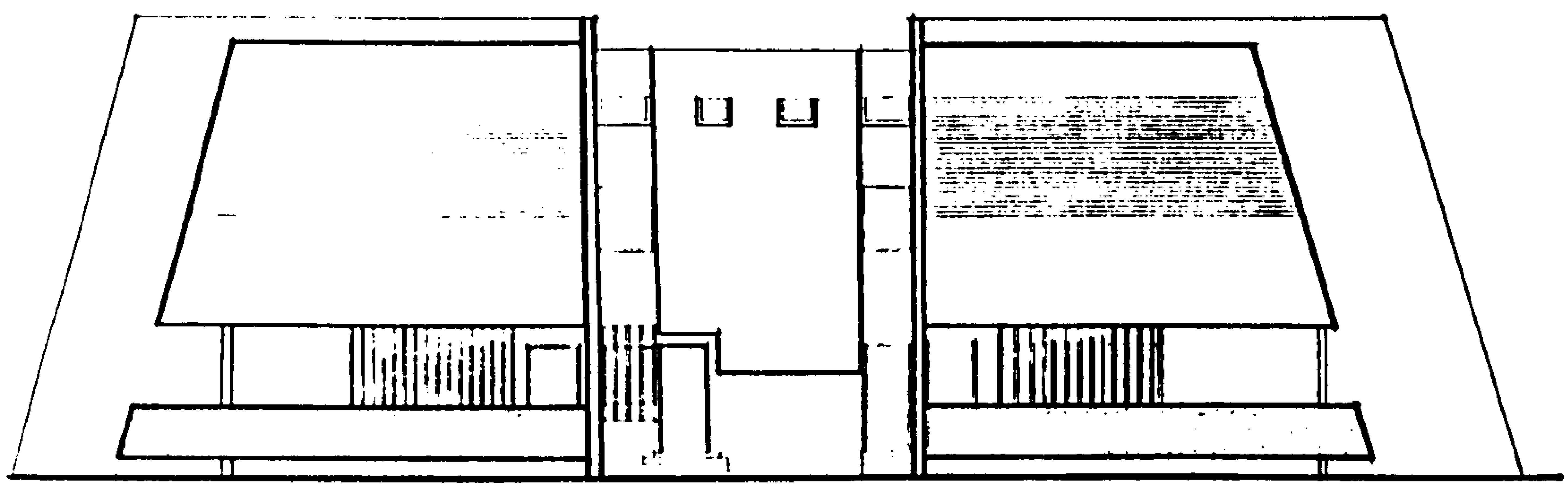


Plate 4.3: First Floor Plan.



SIDE ELEVATION



BACK ELEVATION

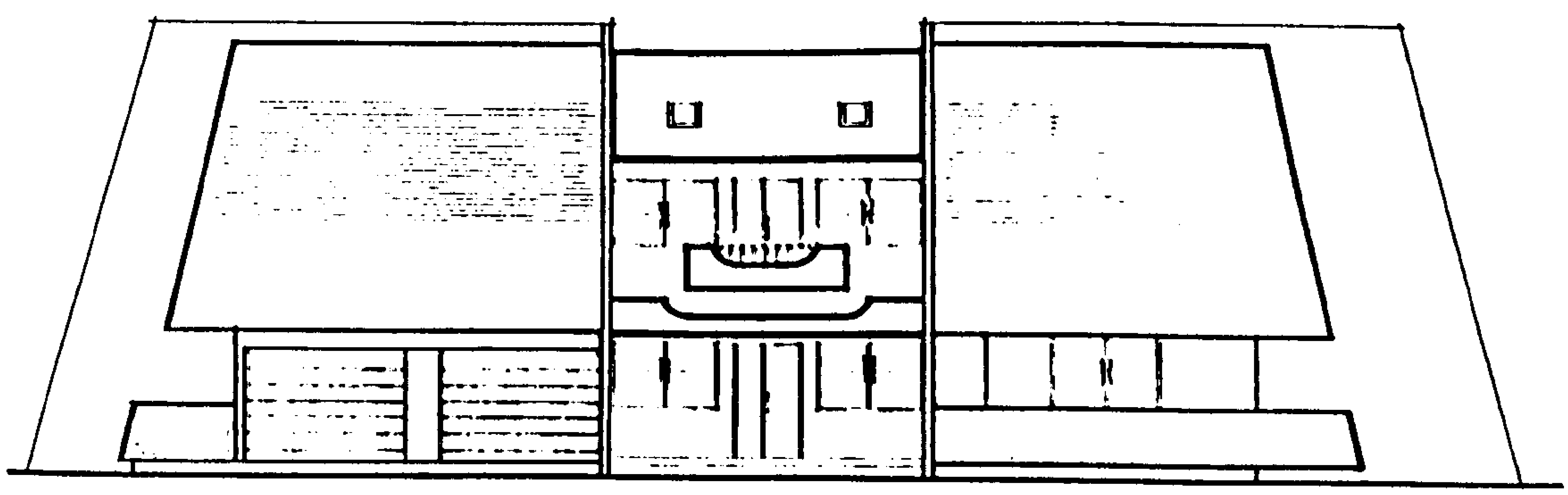


Plate 4.4: Elevations.

FRONT ELEVATION

Plate 4.5: A part of the site under study showing the aggregation of identical buildings

relevant temperature with respect to occupants thermal comfort considerations.

4.3.2 Sensor Type

As far as temperature measurement is concerned the choice of an appropriate sensor type is vital and is usually made with full considerations of the available instrumentation, skills, costs, reliability, resistance to weathering, permanence and accuracy. For temperature sensors, there are two main groups, namely those that need some form of excitation to give an output voltage and those that do not. The first group consists mainly of resistive sensor types such as platinum resistance thermometers and thermistors and other semi-conductor devices. In this group only platinum film thermometers and thermistors are widely used. The second group consists of thermocouples and thermopiles and of these, copper-constantan or nickel-based thermocouples have been generally preferred. The following extract from SERC, (1983) presents a resume of some of the properties of thermocouples. From the properties considered it was apparent that thermocouples (copper-contantan type) were a good choice for the field measurement.

4.3.3 Data Recording Equipment

The other main preliminary consideration was the type of data recording (and possibly storage) equipment to be used with due considerations of such factors as cost of equipment, its weatherability, the amount of data to be collected and at what frequency, the mode of data recording and storage by the equipment, facilities available for reading and for retrieving the data afterwards, whether the equipment is compatible with other equipments such as a personal or mini computer, and so on.

Eventually a data logging equipment was purchased for the project from Delta-T Devices Ltd., Cambridge. The logger is a portable instrument which can automatically scan and record data from up to 62 sensor channels (though it is upgradable to take far more channels) and can accept inputs in the form of voltages, resistances, counts, frequencies or digital levels (see Delta-T, 1987). It came with its own software, may be operated manually or via a computer and can store recorded data in its own RAM (Random Access Memory) located in its

Table 4.1a: Properties of thermocouples.
Source: SERC, (1983)

Basic Principles: If a circuit is made up of two lengths of wire of dissimilar metal with one junction kept at a higher temperature than the other, a small voltage appears, driving current around the circuit. The size of this voltage and the way it changes with temperature depends on the constitution of the metals or alloys used in the wires, as well as the temperature difference.
Cost: "Home-made" junctions cost practically nothing being formed simply be a welded joint between two wires. However, these wires must be lead right back to the logger, preferably without a break. Copper Constantan wire costs about 14p per metre, so that a typical sensor with five metres of cable may cost one pound sterling. A commercially made sensor in encapsulation may cost about 2 pounds sterling and may be advisable since "home-made" welds are sometimes unreliable. If the costs of a connecter box and reference junction are added, it may be that the costs are comparable to PRTs.
Range: Copper Constantan thermocouples cover the range from $50^{\circ}C$ to $+300^{\circ}C$ although they are non -linear in this range. Other materials will cover other ranges.
Typical Output: 40 micro-volts per K is typical of Copper Constantan and relative to the temperature difference between hot and cold junctions. If the multiple wiring can be accepted junctions can be placed in series to form a thermopile to give a higher output.
Wiring: Special two-wire cable is required, preferably without joints. Very thin wires can be used, except for provision of robustness.

Table 4.1b: Properties of thermocouples (cont'd). Source: SERC, (1983)

Estimated Practical Accuracy: .2°C can be achieved with care including encapsulation of junctions in epoxy resin and freedom from mechanical stress.
Long Term Accuracy and Stability: .2°C is achievable, provided a good table zero reference is provided in the data logging equipment.
Problems: There is a catastrophic loss of data if the zero reference fails. It is, therefore, essential to monitor some sort of stable sub-referece temperature to guarantee that this has not happened. Another problem is the possibility of corrosion of the junction in water if it is not sheathed.
Advantages: These are the cheapest sensor once the amplification system has been bought, and provided wore runs are not too great. They are very useful for measuring temperature differences using multiple junctions in series. This does not require the use of a zero reference, although the junctions should be carefully checked to ensure that there is no off-set voltage generated. They also have a very low thermal inertia and can be used for measuring rapidly changing temperatures of surface temperature.
Disadvantages: The cost of the wiring required is very high because of the special purpose wire necessary, and amplification may be expensive because of the low signal level. Great care must be taken in forming the junction to be used that spurious voltages due to stress or corrosion are not generated.

main board. During an experiment, data can be read out to a computer and even stored on floppy disk and then erased from the RAM of the logger in order to make room for more readings, and current readings of sensors can be examined without interrupting the logging process. Readings are either "timed", in which case data is recorded at regular preset intervals (with intervals being optionally different for each channel) or "triggered" in which case a sequence of readings, optionally repeated a number of times, is recorded in response to specified "event-trigger" channels. Both modes of recording can be used in the same logging configuration.

4.3.3.1 Data Logger Configuration

Table 4.2 shows the configuration of the data logger. Readings were logged every hour which implies that the "timed" mode of recording was selected rather than the "event-triggered" mode. The first channel was configured as the "cold junction" for the temperature measurements while all other channels were to record values of air temperature in different annotated spaces inside or outside the building.

4.4 The Measurement Procedure

Having cleaned the building to rid it of excessive dust in order to create a fairly good working environment, the data logger was centrally located in the first floor living room (in order to cut down the cost of wiring all the spaces) and the wiring network connecting the various sensors in the annotated spaces to the data logger was done. Luckily the building was unoccupied and so there was no issue of the wiring network disturbing anyone. The logger came with channels which has facilities for easy connection of the copper-constantan thermocouples. Sometimes purpose-made thermocouple wire junctions were used to connect multiple sensors all the way from the point of measurement to the data logger. Care was taken to avoid dirty connections, bending of the wires or unnecessarily stressing them or any forced movements which may lead to fatigue cracking of the wires, or any mechanical straining which may generate spurious effects.

As for the measurement of the air temperature outdoors, the sensor probe was 'encased' with aluminium foil to prevent direct sunlight on it, without necessarily isolating it seriously from the environment in which it is measuring. The sensor probes inside the building were centrally positioned in each annotated space, sus-

Table 4.2: The data logger configuration.

INPUT CHANNELS:

Ch	Label	Snsr Type	VRCFD [uA]	Sample Store		Conv-Factor Zero-Offset	B-Unit/E-Unit	Min Max	Reference Space
1	**CJ**	TM1	R	10m		Table	Kohms/deg °C	-19.99	**Cold Junction**
			20	1h	A			60	of data logger
2	**TSS-SW**	TCT	V	10m		Table	mVolts/deg °C	-120	**Shielded Space**
			V	1h	A			200	South-West
3	**TSR-SW**	TCT	V	10m		Table	mVolts/deg °C	-120	**Shielded Room**
			V	1h	A			200	South-West
4	**TSR-SE**	TCT	V	10m		Table	mVolts/deg °C	-120	**Shielded Room**
			V	1h	A			200	South-East
5	**TSS-SE**	TCT	V	10m		Table	mVolts/deg °C	-120	**Shielded Space**
			V	1h	A			200	South-East
6	**TSS-NE**	TCT	V	10m		Table	mVolts/deg °C	-120	**Shielded Space**
			V	1h	A			200	North-East
7	**TSR-NE**	TCT	V	10m		Table	mVolts/deg °C	-120	**Shielded Space**
			V	1h	A			200	North-East
8	**TLR-FFL**	TCT	V	10m		Table	mVolts/deg °C	-120	**First Floor**
			V	1h	A			200	Living Room
9	**TLR-GFL**	TCT	V	10m		Table	mVolts/deg °C	-120	**Ground Floor**
			V	1h	A			200	Living Room
10	**TAO**	TCT	V	10m		Table	mVolts/deg °C	-120	**Outdoor**
			V	1h	A			200	

pended in air and away from any surface contact and from any other source of heat or excessive thermal inertia. The centralisation of the temperature sensor in the rooms was done in order to position the probe at the point which was considered would give a representative temperature value of the average room temperature, since air temperature varies from point to point in the room. Apart from this reason, some evidence suggests (SERC, 1983) that the boundary layer thickness of air at a wall surface is about 6 inches (152.4 mm), and that sensors should be placed at least this distance from the wall, though this has been found impractical consequent upon which a compromise distance of 60 mm has been adopted.

Having positioned all the sensor probes the logging process was programmed to start at 30 minutes past the hour such that readings are averaged on the hour (for example 10.30 - 11.30, 11.30 - 12.30, etc).

4.5 Discussion of Results

The temperature profiles indicate a fairly even distribution of average daily temperature values in the different rooms and shielded (buffer) spaces, with slight variations according to orientation. (Table 4.3). It will be observed that the average indoor temperatures are slightly less than the average outdoor temperatures. This is probably due to the attenuation of the ambient thermal conditions by both the building structure and the shielding system. Most parts of the building's external fabric (both opaque and transparent parts) are not directly exposed external ambient energies. Furthermore, the building is unoccupied, and there is consequently little or no casual gains from people, equipments, cooking/laundary or from artificial lighting.

What also readily comes to mind is the close proximity between the indoor and outdoor mean daily air temperatures (Figure 4.1). The results indicate that a contemporary "modern" building in an a hot semi-arid environment can be inefficient in tempering the climate in which it is built, when it's materials have been specified purely on aesthetic and "prestigious" grounds rather than on the basis of their thermophysical properties. The difference between the indoor and outdoor average daily temperatures are often less than 2°C.

The ground floor is relatively cooler than the first *floor*, due to the longwave thermal input from the roof. The roof space with its unventilated air cavity and

TABLE 4.3A: MEAN DAILY TEMPERATURE VALUES

	16 JUN	17 JUN	18 JUN	19 JUN	20 JUN	21 JUN	22 JUN	23 JUN	24 JUN	25 JUN	26 JUN	27 JUN	28 JUN	29 JUN	30 JUN
COLDJ	32.3	31.4	32.1	32.4	31.0	30.3	29.3	30.6	31.5	32.1	29.0	28.5	26.8	25.7	26.3
TSS_SW	31.5	30.2	31.2	31.6	30.0	27.5	27.1	30.5	31.1	30.2	27.8	27.6	23.5	24.5	25.9
TSR_SW	31.4	30.8	31.4	31.6	30.5	29.0	27.8	30.0	31.1	30.9	28.4	27.9	24.8	24.8	25.9
TSR_SE	31.1	30.4	31.3	31.4	30.0	28.1	27.1	29.8	30.7	31.8	28.5	27.7	24.8	24.8	25.9
TSS_SE	31.6	30.7	31.7	31.9	30.4	27.4	27.5	30.1	31.2	30.3	27.7	27.8	23.8	24.2	25.7
TSS_NE	32.3	31.1	32.1	32.7	31.3	28.3	28.3	30.7	31.8	31.2	27.9	28.3	24.4	25.0	26.0
TSR_NE	32.7	32.1	32.4	33.0	31.5	30.2	29.5	30.6	31.9	31.3	29.2	28.7	26.9	26.0	26.4
TLR_FFL	32.0	31.3	32.0	32.2	30.8	29.9	29.0	30.4	31.2	31.9	28.6	28.2	26.0	25.4	26.2
TLR_GFL	31.2	30.4	31.3	31.3	30.1	29.7	28.3	29.9	30.8	30.1	28.4	27.9	26.6	25.7	26.2
TAO	32.3	31.3	33.2	33.2	30.5	27.7	28.8	31.5	31.9	31.0	27.5	28.1	22.9	25.1	26.5

COLDJ = Cold Junction of the data logger
TAO = Temperature of air outside

TABLE 4.3B: MEAN DAILY TEMPERATURE VALUES

	1 JUL	1 JUL	3 JUL	4 JUL	5 JUL	6 JUL	7 JUL	8 JUL	9 JUL	10 JUL	11 JUL	12 JUL	13 JUL	14 JUL	15 JUL
COLDJ	28.2	27.9	27.8	28.3	26.5	27.0	28.3	29.1	27.9	28.4	27.2	26.3	27.1	27.6	27.9
TSS_SW	28.0	25.9	26.1	27.7	25.1	27.0	28.2	28.5	27.3	27.6	25.6	25.6	27.2	26.9	27.5
TSR_SW	28.0	26.8	26.9	27.6	26.1	26.8	28.2	28.7	27.4	27.9	26.4	25.9	27.3	27.2	27.7
TSR_SE	27.6	27.4	26.7	27.4	27.5	27.7	28.2	28.9	28.3	27.9	26.5	25.6	26.7	27.4	27.5
TSS_SE	27.9	26.2	26.0	27.8	25.1	26.7	28.1	28.8	27.7	28.0	25.7	25.6	27.1	27.3	27.7
TSS_NE	28.2	26.5	26.6	28.4	25.5	27.4	28.7	29.7	28.2	28.7	25.8	28.6	34.2	29.4	28.0
TSR_NE	27.9	28.1	27.6	28.3	27.3	27.1	28.6	29.4	28.1	28.6	27.3	26.4	27.3	27.6	28.0
TLR_FFL	28.0	27.7	27.6	27.9	26.2	26.9	28.1	28.9	27.7	28.2	26.8	26.1	27.0	27.4	27.8
TLR_GFL	27.3	27.4	27.3	27.8	25.7	26.6	27.2	28.0	27.1	27.3	26.1	25.8	26.9	27.1	27.3
TAO	28.6	26.1	27.2	28.3	24.8	28.5	29.1	29.0	28.6	28.9	26.2	25.9	28.2	27.1	28.1

COLDJ = Cold Junction of the data logger
TAO = Temperature of air outside

TABLE 4.3C: MEAN DAILY TEMPERATURE VALUES

	16 JUL	21 JUL	22 JUL	23 JUL	24 JUL	25 JUL	26 JUL	27 JUL	28 JUL	29 JUL	30 JUL	1 AUG	2 AUG
COLDJ	27.6	29.0	28.1	26.1	26.0	27.4	27.9	27.7	27.7	25.0	24.7	25.3	26.0
TSS_SW	25.4	29.1	26.9	25.1	25.7	27.1	27.1	26.6	27.3	23.0	24.4	25.2	25.8
TSR_SW	26.7	28.7	27.3	25.6	25.6	27.1	27.2	26.9	27.5	23.5	24.3	25.0	25.9
TSR_SE	26.6	28.4	27.4	25.6	25.6	26.9	26.9	27.1	27.6	24.2	24.5	25.0	25.8
TSS_SE	26.5	28.9	27.5	24.8	25.5	27.0	27.4	26.8	27.5	22.9	24.0	25.0	25.7
TSS_NE	26.1	29.3	28.0	28.5	26.7	27.9	27.6	27.4	28.5	26.8	25.5	25.4	26.5
TSR_NE	27.7	28.9	28.3	26.3	26.4	27.8	28.0	27.8	28.3	25.3	24.9	25.5	26.4
TLR_FFL	27.3	28.5	27.8	25.8	25.7	27.2	27.5	27.2	27.5	24.5	24.7	25.1	25.7
TLR_GFL	26.6	27.5	27.0	25.9	25.8	26.7	27.0	26.9	27.0	25.3	25.1	25.3	25.8
TAO	25.3	29.7	27.6	25.2	26.7	27.9	27.9	27.3	28.7	22.1	25.1	25.8	26.7

COLDJ = Cold Junction of the data logger
TAO = Temperature of air outside

TABLE 4.4: MEAN HOURLY TEMPERATURES (^{o}C) ON JULY 15

TIME	COLDJ	SS-SW	SR-SW	SR-SE	SS-SE	SS-NE	SR-NE	LF-FFL	LR-GFL	TAO
00.30	27.95	26.42	27.18	27.37	27.05	26.63	27.97	27.67	27.03	25.98
01.30	27.81	26.09	26.82	27.21	26.83	26.49	27.84	27.51	26.90	25.50
02.30	27.60	25.53	26.57	26.79	26.40	25.94	27.67	27.28	26.55	25.00
03.30	27.45	25.09	26.42	26.51	25.99	25.60	27.46	27.13	26.28	24.61
04.30	27.28	24.79	26.25	26.20	25.78	25.25	27.28	26.92	26.12	24.41
05.30	27.12	24.54	25.97	26.00	25.45	25.01	27.14	26.67	25.99	24.27
06.30	26.90	24.23	25.57	25.53	25.05	24.70	26.91	26.29	25.71	23.95
07.30	26.68	24.43	25.62	25.57	25.08	25.55	26.60	26.36	25.73	24.32
08.30	26.71	25.24	26.01	25.90	25.73	27.54	26.80	26.57	26.07	25.43
09.30	26.87	26.17	26.49	26.48	26.47	28.63	27.01	26.76	26.55	26.92
10.30	27.13	27.18	27.21	27.04	27.27	29.10	27.34	27.13	27.03	29.95
11.30	27.52	28.32	28.16	27.75	28.22	29.88	27.86	27.60	27.60	30.83
12.30	27.95	29.57	28.89	28.27	29.17	30.17	28.29	28.12	27.98	32.16
13.30	28.40	30.38	29.32	28.53	29.68	30.20	28.63	28.63	28.38	32.20
14.30	28.77	31.57	29.81	29.05	30.26	30.85	29.02	29.03	28.67	33.57
15.30	28.98	32.16	29.91	29.36	30.47	30.77	29.21	29.19	28.60	34.04
16.30	29.08	31.07	29.50	29.47	30.34	30.97	29.19	29.26	28.62	32.50
17.30	29.00	29.56	29.09	29.03	29.44	29.68	28.86	28.90	28.31	30.92
18.30	28.78	28.91	28.74	28.77	28.95	29.23	28.77	28.68	28.19	29.80
19.30	28.66	28.32	28.45	28.44	28.44	28.69	28.63	28.43	27.96	28.53
20.30	28.47	27.76	28.10	27.99	28.01	28.28	28.48	28.16	27.72	27.81
21.30	28.40	27.43	27.88	28.02	28.09	28.02	28.51	28.14	27.59	27.50
22.30	28.38	27.62	28.00	28.05	28.05	27.94	28.55	28.17	27.64	27.57
23.30	28.36	27.28	27.92	27.85	27.87	27.67	28.45	28.11	27.52	27.19

chippings does not seem to be effective in attenuating the thermal gain through the massive concrete roof structure. A generalisation of this finding would imply that if there was another floor above the first floor, thereby isolating the impact of the roof, then the first floor may be cooler than it presently is, and that the temperatures in that upper level would also be higher than the first floor temperatures.

A careful look at the average hourly temperature values (Table 4.4) indicate that in the afternoon, the indoor air temperature are often close to the ambient temperature. This indicates that when comfort is most needed, discomfort is maximum.

Furthermore, the building is endowed with some of the widest overhangs and sidefins that could be found in a contemporary building in the tropics. Yet the attenuation of the harsh outdoor conditions is very little. However it is believed that with an appropriate design philosophy and use of materials, the building's climatic control capability would be highly enhanced.

The impact of shielding is apparent from the results. The average daily temperatures in the shielded spaces were found to be, in most cases, less than the outdoor average daily values, in spite of the inappropriate choice of the shielding material and pyramidal inclination of the shielding structure (Figure 4.1). The inner rooms are therefore surrounded by a buffer zone whose temperatures are lower than the ambient temperatures which it would otherwise have had to cope with.

Furthermore, and most interesting, the average daily temperatures in the buffer zone are also lower than the temperatures in the inner dwelling spaces, although the temperature differences are not very pronounced because of the long-wave thermal transfer from the metallic shielding elements into the buffer zone. This development indicates that heat transfer can be encouraged between the inner spaces and the buffer, while appropriate measures are taken to discourage thermal transfer from the ambient into the buffer space during the day-time. The hourly temperature values show the same pattern of results.

4.6 Conclusions

The following conclusions may be drawn from the above results.

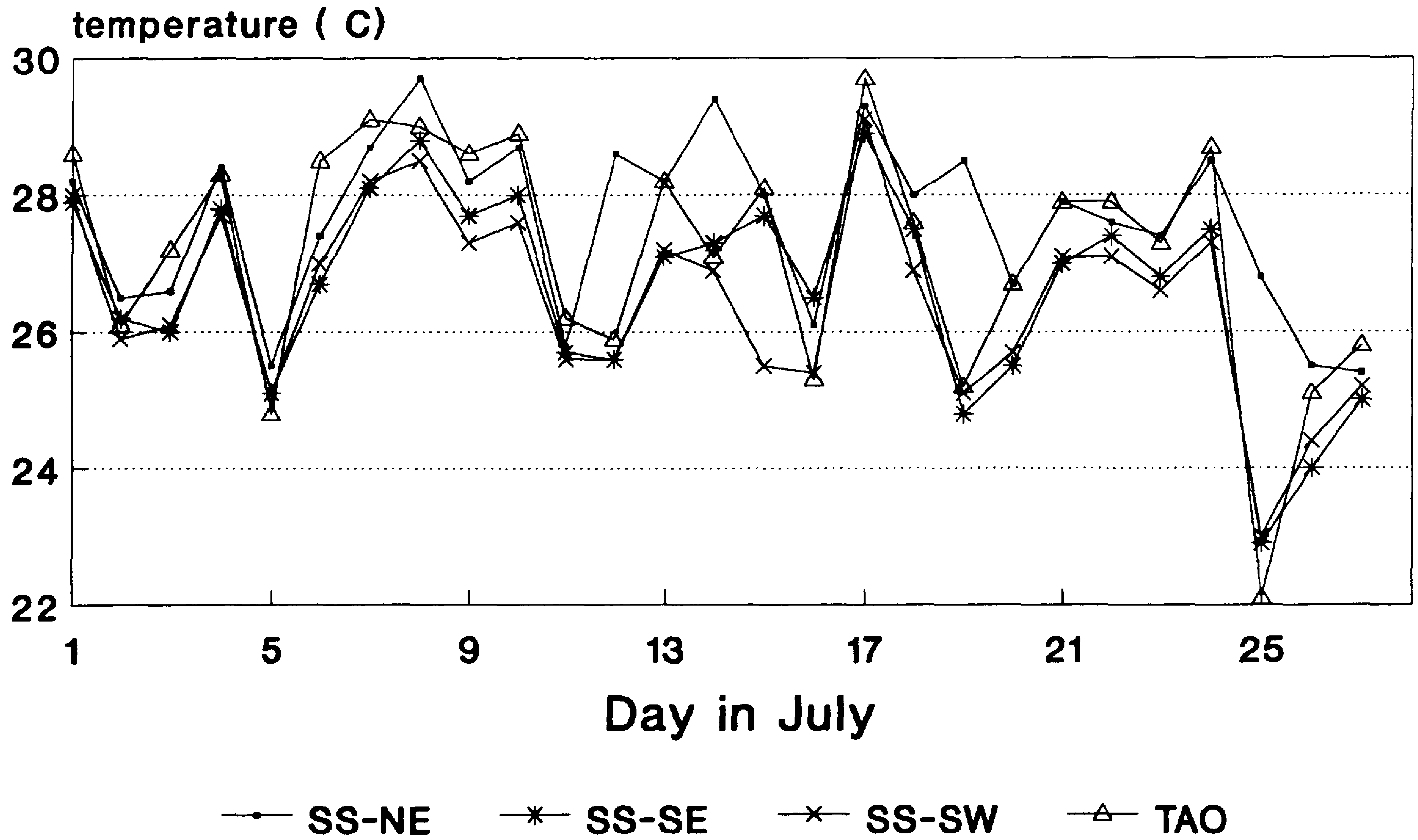
(1) The attenuation of the harsh ambient thermal conditions by a concrete-

built dwelling, (even with sidefin and overhang shading) in a hot semi arid climate is quite low. This is exemplified by the little difference between the indoor and outdoor mean daily air temperatures.

(2) The use of a structural semi-porous membrane to protect the external fabric of a building has a bearing on the microclimatic characteristics of the building and its immediate environs. The impact, favourable or unfavourable, of shielding the external facade may be dependent upon the material used.

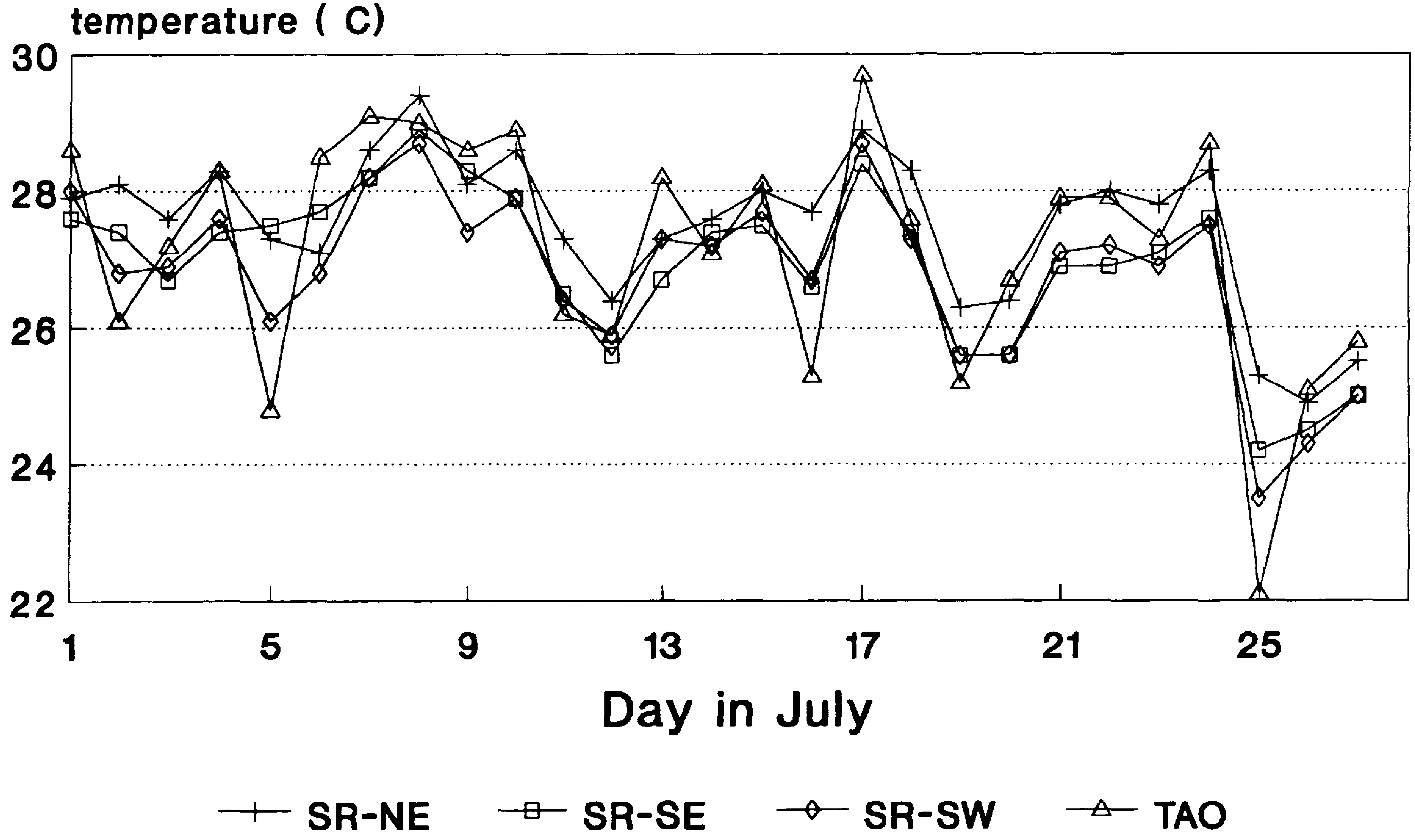
(3) Spaces that are shielded tend to be bounded by a buffer space whose temperature level is lower than both the ambient and the indoor temperatures. Also such a buffer space may offer opportunities for further passive cooling measures for the building to be taken.

Fig 4.1a: Mean Daily
Temperature Profiles



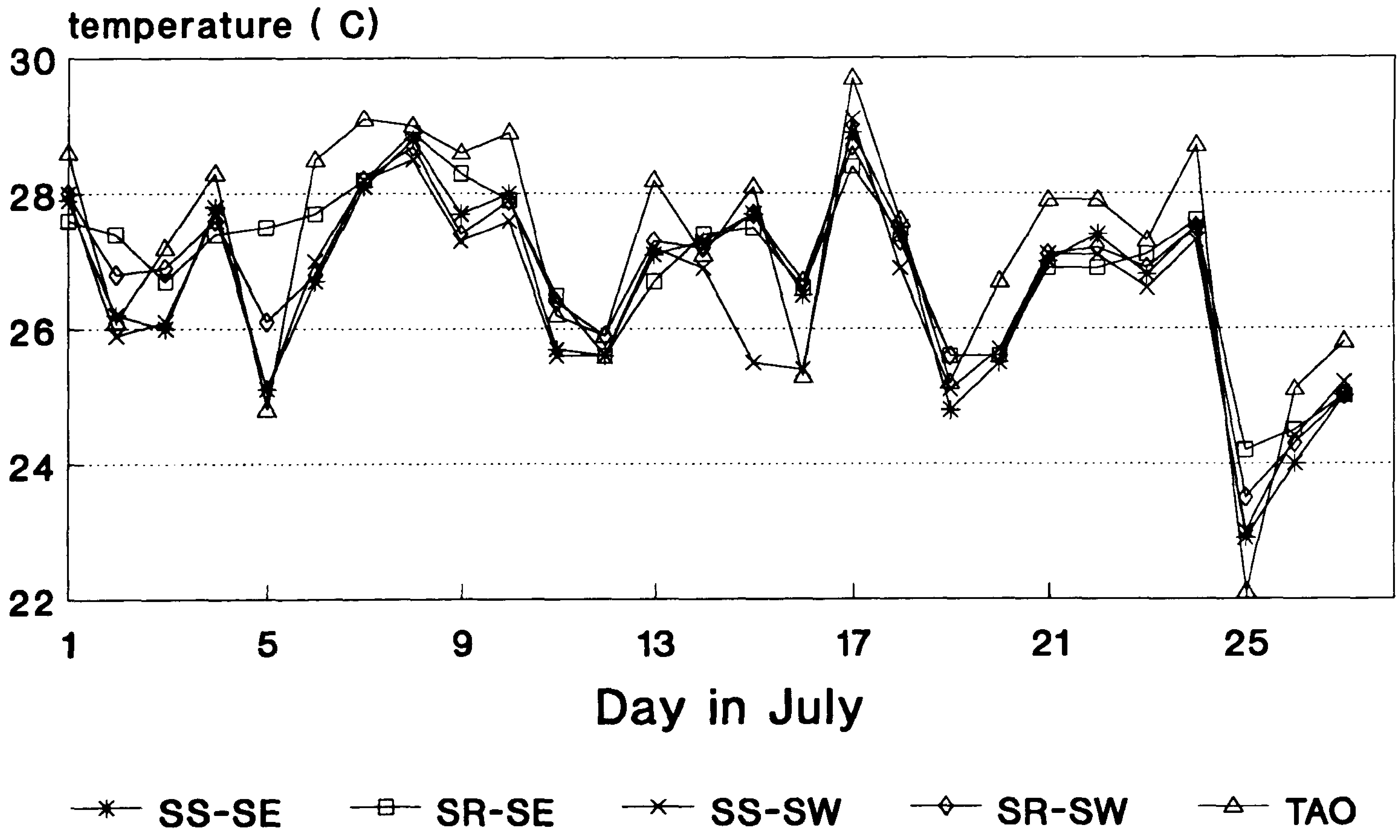
(Shielded buffer spaces)

Fig 4.1b: Mean Daily
Temperature Profiles



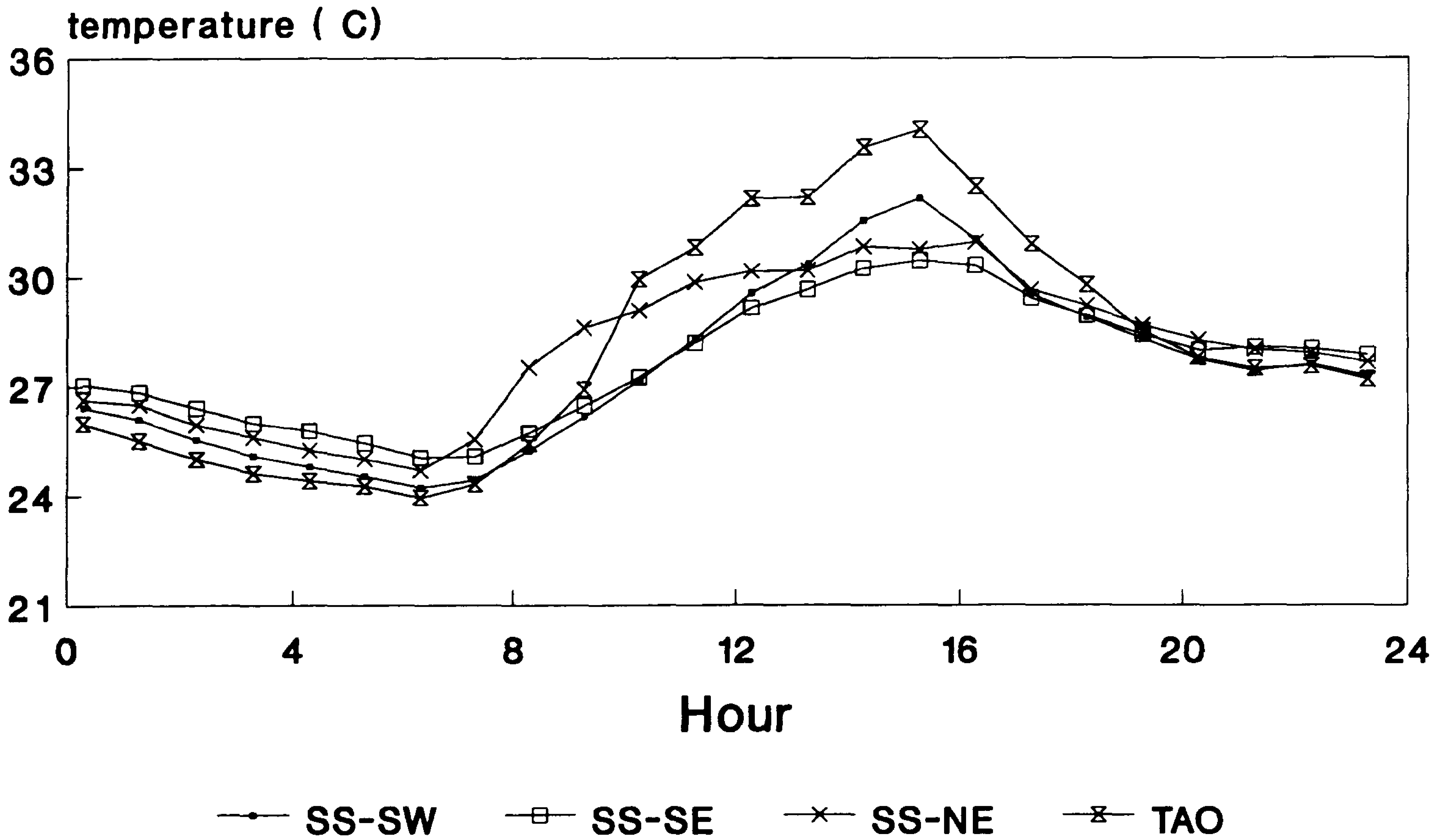
(Shielded Rooms)

Fig 4.1c: Buffer and Room
Temperature Compared



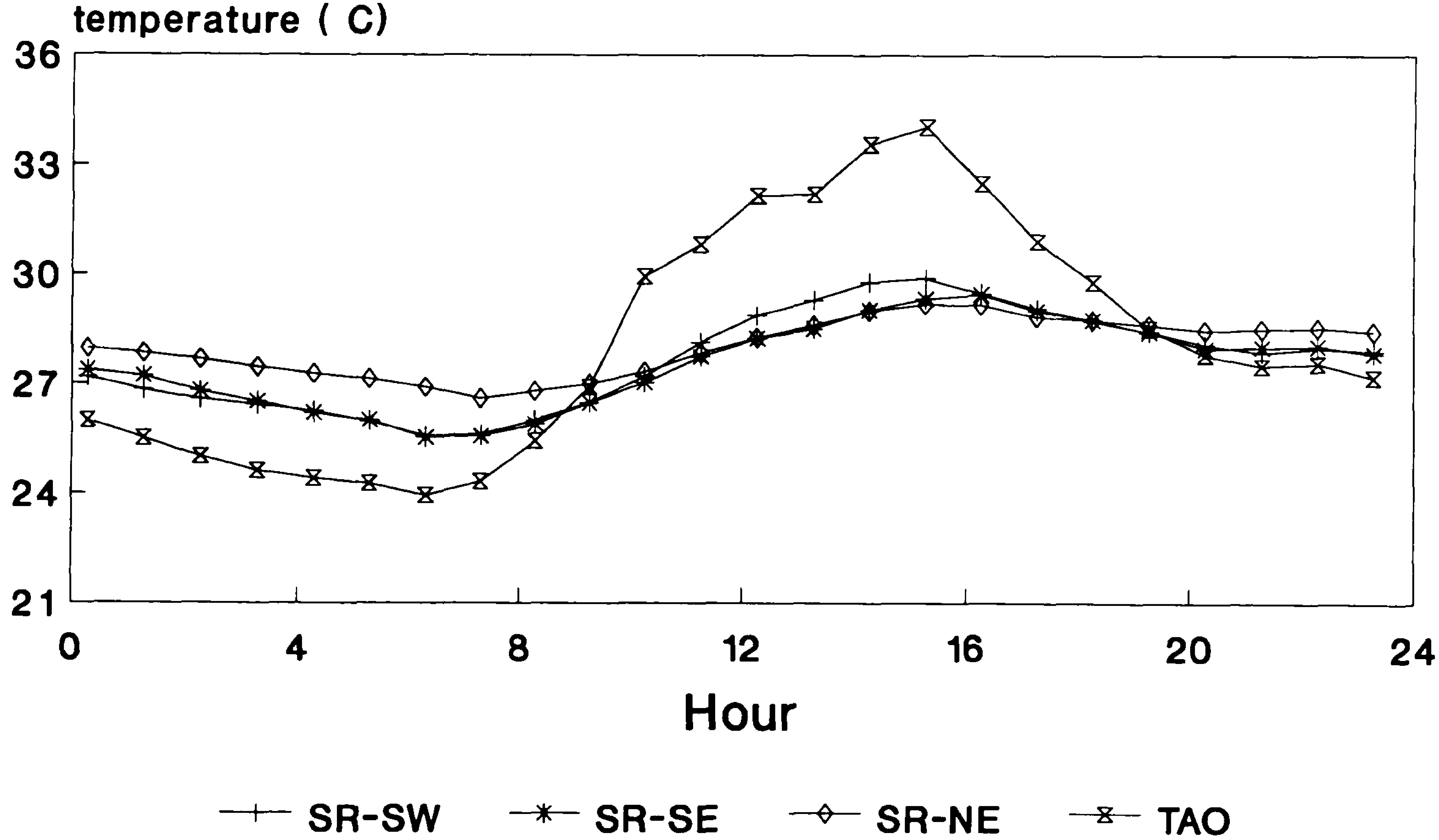
(Shielded Rooms)

Figure 4.2a:Mean Hourly
Temperature profiles



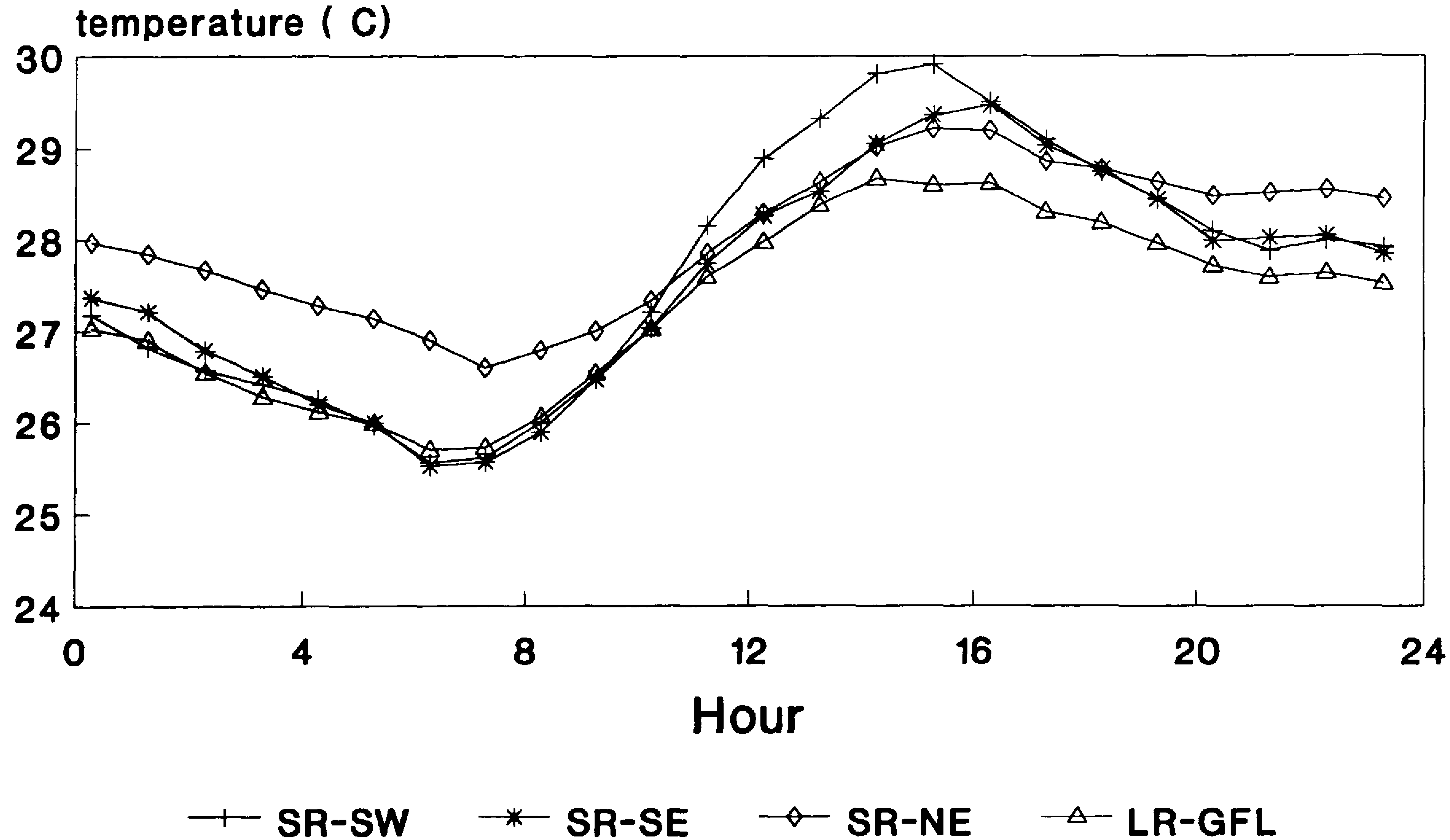
shielded buffer spaces

Figure 4.2b:Mean Hourly
Temperature profiles



shielded Rooms

Fig 4.2c: First fl. v. Ground fl.
Temperature Profiles



The grd fl. has lower temperatures

Chapter 5

Wind Tunnel Model Test

5.1 Introduction

The important role played by ventilation as one of several means by which the indoor climate of a building is controlled, as earlier discussed, has generated renewed interest in the investigation of air movement and wind effects on buildings. It has also been stated earlier that in spite of its relatively minor shortcomings, physical scale modelling in wind tunnels remains invariably, the principal means of contemporary investigations of ventilation and air movement in and around buildings. Many studies that have been carried out have tended to be mainly on buildings with simple forms, for which much data and other information have been consequently generated. Since the building under study has a different philosophy of form it was suggested that a wind tunnel study of it would provide some useful data and other information.

Moreover, since we are dealing with the shielding of the building fabric as a solar radiation control strategy, it calls to mind the need to investigate the implications of this strategy for ventilation. It became necessary therefore to make a model of the building and carry out measurements of the external pressure distribution around the building surfaces which would enable the derivation of other parameters.

Under most situations air movement is turbulent in nature, except where very small apertures are involved (e.g cracks in walls, interstices around various openings) in which case the flow is laminar. It was considered that the use of a turbulent flow in the investigation was important since the openings under consideration were not of small aperture. Not only that, the investigation should be done in a *turbulent* boundary layer following the Jensen, 1958, 'model' law. The availability of the Sheffield University Boundary Layer Wind Tunnel which would not only enable a turbulent flow to be generated but would also enable the modelling of the natural environment around the building, was extremely useful. Many model tests have been carried out in this wind tunnel in the past with results that have been generally accepted as accurate. It was envisaged therefore that provided the experiment was well carried out, a set of reliable data would be obtained.

The investigations were carried out at two levels of detail that involved two separate experiments. The first level which was carried out in the wind tunnel involved the construction of a detailed model of the building at a scale which would enable important architectural features to be modelled. Full details of the experiment including the results are discussed in this chapter.

For the second level, an element of the building, namely the shielding element in the form of louvres, made of smooth wooden slats, was studied in more detail. A model of the louvres system was made to full scale. The aim was to investigate the flow characteristics across a typical shielding element such as a louvre system. The experiment was carried out using pressurisation techniques and is fully presented in the next chapter.

5.2 Experimental Objective

The main objective of the experiment was to carry out an investigation that would determine the magnitude and distribution of external wind pressures over the building surfaces. This was to enable the evaluation, or more precisely, estimation, of the airflow and its distribution around the building.

The need for the measurement was inspired by the multi- dimensional parameters (such as projecting walls, slopes, recesses and cantilevers) inherent in the building form and the subsequent quest to know the implications of these parameters for airflow in the building. Also the entire building is such that the aggregation of the various planes apparently divides it into separate zones, unique in themselves, but essentially an inextricable part of the whole. It was thought that the results would be instructive on the impact of such dynamics of planes and projections on the flow pattern around the building.

5.3 Experimental Instrumentation

5.3.1 Experimental Apparatus:

In addition to the boundary layer wind tunnel and the model of the building which are the primary facilities for the experiment, the other necessary apparatus for the measurements are the micromanometers, a scanning box and a static tube all of which are described below.

5.3.2 The Wind Tunnel:

The Sheffield University Boundary Layer Wind Tunnel (see Plate 5.1) in which the test was carried out has an exhaustive description in Lee (1977). It has a large working section of 1.2 x 1.2m module size, with an overall length of 7.2m incorporating a 1.1m-diameter turntable whose centre is 5.4m downstream of the entry point. It has a fixed roof section frame with side walls consisting of a series of 1.2 x 1.2m panels, six of which are framed 12.5mm-thick clear accrylic sheets while the other six are 25mm-blockboard sheets painted matt black on the inside. The side walls are constructed to be interchangeable and removable to permit easy access. The tunnel has a flow straightener made of a honey combe, 150mm thick with 15mm cell size, and positioned at the inlet flare.

The large working section of the tunnel is said to have a maximum mean speed of about 25 ms^{-1} when empty with a side wall boundary layer growth of 125mm at the turntable centre position. The longitudinal r.m.s. turbulence intensity is constant across the central 80% of the width and has a value of approximately 2% of the mean velocity. The transition section down stream of the 1.2 x 1.2m working section acts as a 4:7 area contraction ratio to the small working section which has two 1.5m-long access panels which may be used for mounting models. Its longitudinal r.m.s. turbulence intensity varies between 0.25% and 0.5% of the mean velocity across the section. The scale factor for the boundary layer produced in the tunnel was 1:350 for urban conditions and 1:500 for rural conditions.

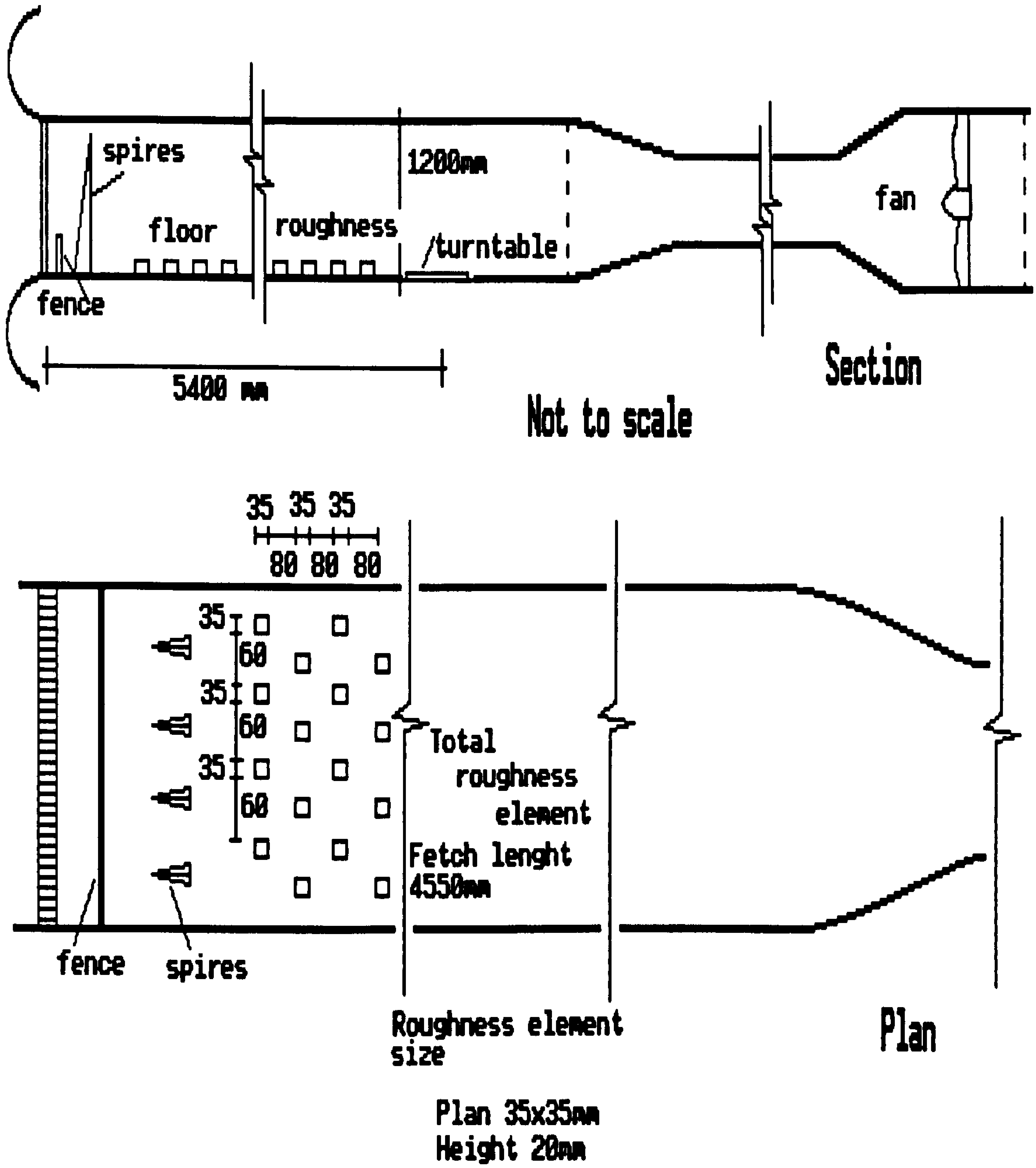
5.3.3 The Model:

The building model was constructed mainly of aluminium though some smooth plywood blocks were also used in a few places to enhance areas of wide horizontal

Figure 5.1: The Sheffield University Boundary Layer Wind Tunnel

Figure 5.1: The Sheffield University Boundary Layer Wind Tunnel

Figure 5.2: The wind tunnel simulation arrangement.



projections. Both these materials produced smooth sharp edges to the model and smooth surfaces to the planes. Aluminium has a relatively high density and combining this with its strength makes it very durable. Secondly it is easy to cut and though not too heavy, it has enough weight to be at rest solely on its own weight within the turbulent flow in the wind tunnel. However it was held down with a few screws solely as a precaution. Another quality was the ease with which the pressure tapping were fitted into place, flush with the model surface, neat and free of any blockage.

The model was constructed at a scale of 1:75 and when finished, it measured 300 x 290 x 118mm including its aluminium rest pad. The outermost external walls were inclined at 75° to the vertical as they are in reality (Figure 5.3 is a photograph of the model and Figure 5.4 shows its layout and the positions of the pressure tappings.

5.3.4 The Manometers:

The two micromanometers used for pressure measurements were of the series manufactured by Furness Controls Limited, Bexhill. They were of model type FC012 with ranges 0-19.99mm H_2O and a self calibrating device to ensure compensation for zero drift, making them accurate enough to measure little pressure differentials. Recalibration before use is recommended and their manufacturer's quoted accuracy is less than $\pm$ 1%. They both have the capability to measure velocity (in m/s) as well because they are fitted with a function switch which introduces a square root extractor, converting the instrument to an anemometer.

5.3.5 The Scanning Box:

A 20-channel scanning box was used to provide the ability to read up to 20 differential pressure positions without disconnecting the pneumatic couplings. The model of the scanning box which was also from Furness Controls Limited, Bexhill, is FC091, manual selection type.

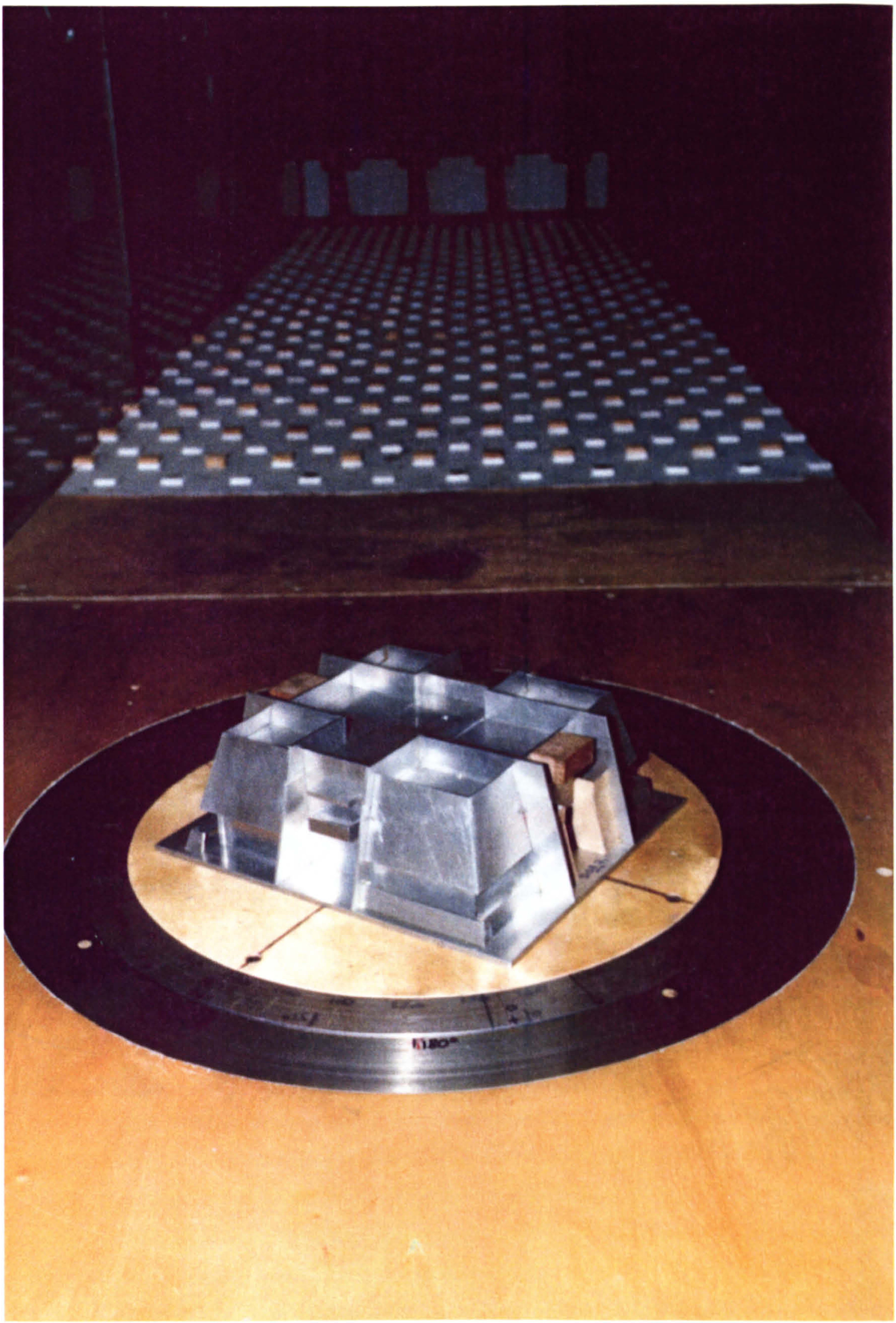


Figure 5.3: The building model

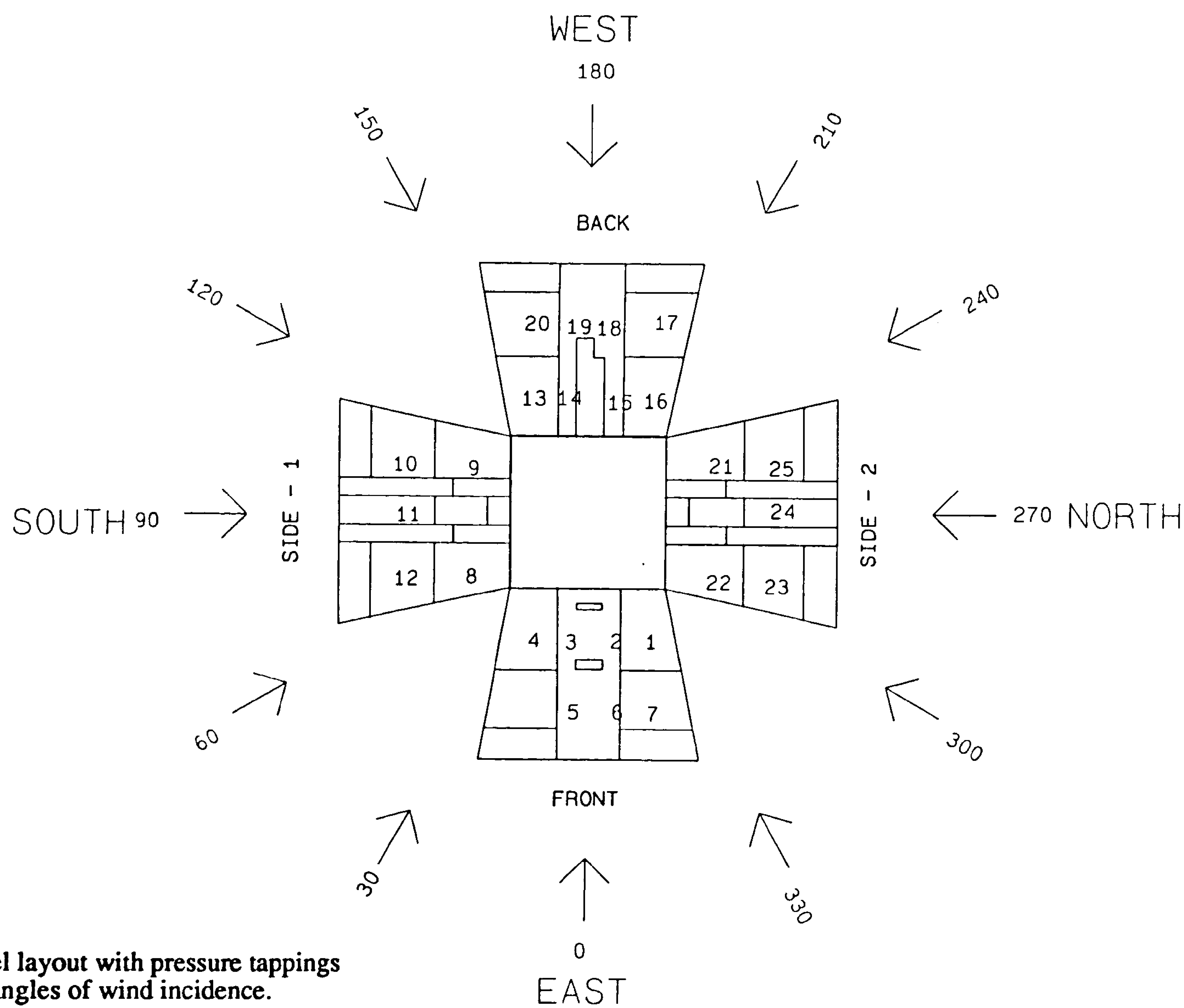


Figure 5.4: The model layout with pressure tappings and angles of wind incidence.

5.4 Preliminary Modelling Criteria

Before carrying out the investigation, it was necessary to certify certain preliminary modelling criteria that would enhance the reliability of results such as:
(a) Simulating the natural boundary layer of Kano which is essentially a suburban boundary layer;
(b) Measuring the velocity profile; and checking
(c) the wind tunnel blockage and length scale; and
(d) The influence of certain dimensionless flow parameters (in this case, it is mainly the Reynolds Number that is considered)

5.4.1 Simulating the suburban boundary layer:

Following the terrain description in Aynsley et al (1977) and correlating with the city of Kano's natural terrain and environmental form, it was obvious that Kano has a suburban terrain boundary layer. In order to carry out the simulation of the suburban terrain boundary layer characteristics, a methodology that utilises the fence, spires and floor roughness element approach suggested by Counihan (1973) was used. This method has been used by many previous researchers (e.g. Hussain (1978), Lee (1977),) with reliable results and has specifically been shown to give adequate representation of the mean velocity and the turbulence characteristics appropriate to the flow over suburban terrain conditions.

The method entails the use of a castellated fence, a row of spires and a regular array of roughness elements all on the wind tunnel floor. The castellated fence spans the width of the wind tunnel working section, with heights of 195mm and 230mm while the actual width of the castellations and the gaps is 150mm each. With the position of the fence at 320mm downstream from the honeycomb at the working section inlet, it precedes a row of triangular spires which are placed 200mm downstream of the fence. The spires which are 200mm x 65mm at the base and 900mm high, are tappered to a point at the top and thus helping to promote mixing at the upper part of the boundary layer.

What follows next is the array of roughness elements each of which measures 35mm x 35mm in plan, 20mm in height, alternated with a row of height 10mm and arranged in staggered format extending up to the leading edge of the turntable. The total fetch length of the layout is 4.55mm. Figure 5.2 shows interior views of the wind tunnel and the flow simulations arrangement. The gap between the roughness elements in the flow direction is 65mm and 80mm in the transverse direction.

5.4.2 Measurement of the velocity profile:

Table 5.1 shows the results of the velocity profile measurements of the suburban boundary layer. Figure 5.6 and Figure 5.7 show the power law and the mean velocity profiles respectively, measured at the turntable centre. The mean velocity profile shows a maximum velocity of 11.27 m/s was at a height of 800mm which is the physical thickness of the suburban boundary layer above which an area of constant velocity exists that extends to the roof boundary layer. As earlier stated it is assumed that the variation of mean velocity profile with height can be represented by a power law of the form

$$\frac{V_h}{V_g} = \left(\frac{h}{g}\right)^{\alpha} \tag{5.1}$$

where

V_g is the gradient windspeed at height g, say, (in this case, g = 800mm)(in m/s);
V_h is the mean speed at some height, h say, from the ground (m/s);
and α (and g) are functions of the ground roughness.

The best value of α that fits the data using the power law function was 0.245, with a coefficient of correlation of 0.978 a value which is in harmony with similar results from full scale studies by such previous research workers as Davenport (1963), Shiotani (1962), Shellard (1963), Kamei (1955), Jones et al (1971), Caton (1975) and previous wind tunnel measurements [e.g Lee et al (1979)] who all had the value of α varying from 0.40 to 0.21 for different types of terrains. The value of 0.245 was therefore regarded as being an adequate description of the suburban mean velocity profile.

An application of the power law concept for the eaves height of 96.66mm, we have

$$\frac{V_{96.66}}{V_{800}} = \left(\frac{96.66}{800}\right)^{0.245} = 0.5958$$

Giving

$$V_{96.66} = 0.5958 V_{800} = 0.5958 \times 11.0 = 6.55 ms^{-1}.$$

Table 5.1 Results of mean velocity profile measurements

h (mm)	**Vh** (m/s)	**h/g**	**Vh/Vg**
30.00	5.15	0.037	0.457
50.00	5.55	0.062	0.492
100.00	6.35	0.125	0.563
150.00	6.55	0.187	0.581
200.00	7.00	0.250	0.621
250.00	7.42	0.312	0.658
300.00	7.83	0.375	0.695
350.00	8.36	0.437	0.742
400.00	8.90	0.500	0.790
450.00	9.23	0.562	0.819
500.00	9.75	0.625	0.865
550.00	9.95	0.687	0.883
600.00	10.25	0.750	0.909
650.00	10.57	0.812	0.938
700.00	10.88	0.875	0.965
750.00	10.91	0.937	0.968
760.00	11.00	0.950	0.976
780.00	11.10	0.975	0.985
800.00	11.27	1.000	1.000
820.00	11.28	1.025	1.001
840.00	11.05	1.050	0.980
860.00	11.18	1.075	0.992
880.00	11.19	1.100	0.993
900.00	11.18	1.125	0.992
920.00	11.10	1.150	0.985
940.00	11.05	1.175	0.980
960.00	10.97	1.200	0.973
980.00	10.99	1.225	0.975
1000.00	10.95	1.250	0.972
1020.00	10.93	1.275	0.970
1040.00	11.00	1.300	0.976
1060.00	11.06	1.325	0.981
1080.00	11.06	1.350	0.981
1100.00	10.90	1.375	0.967

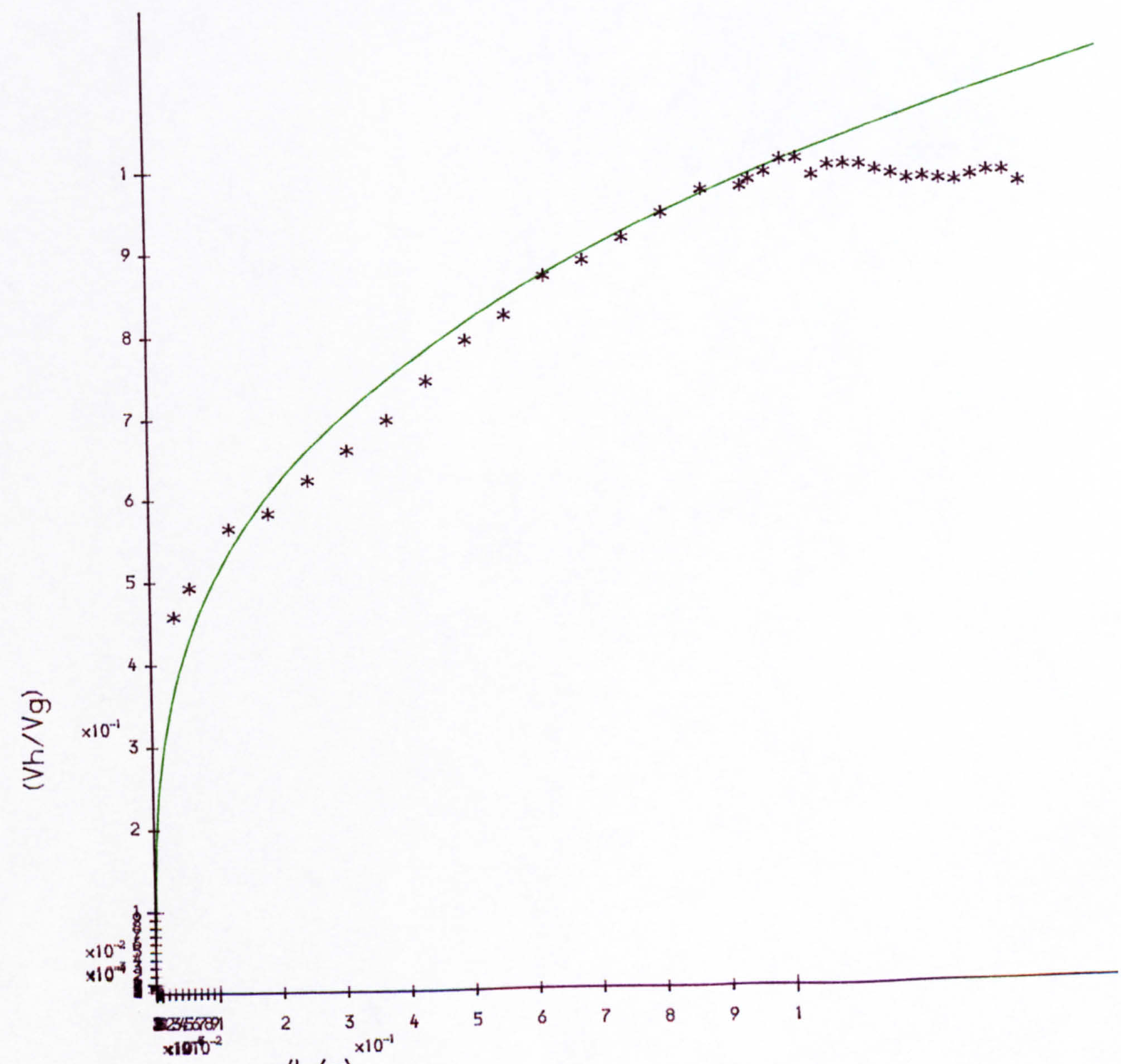


FIG. 5.6: POWER LAW VELOCITY PROFILE

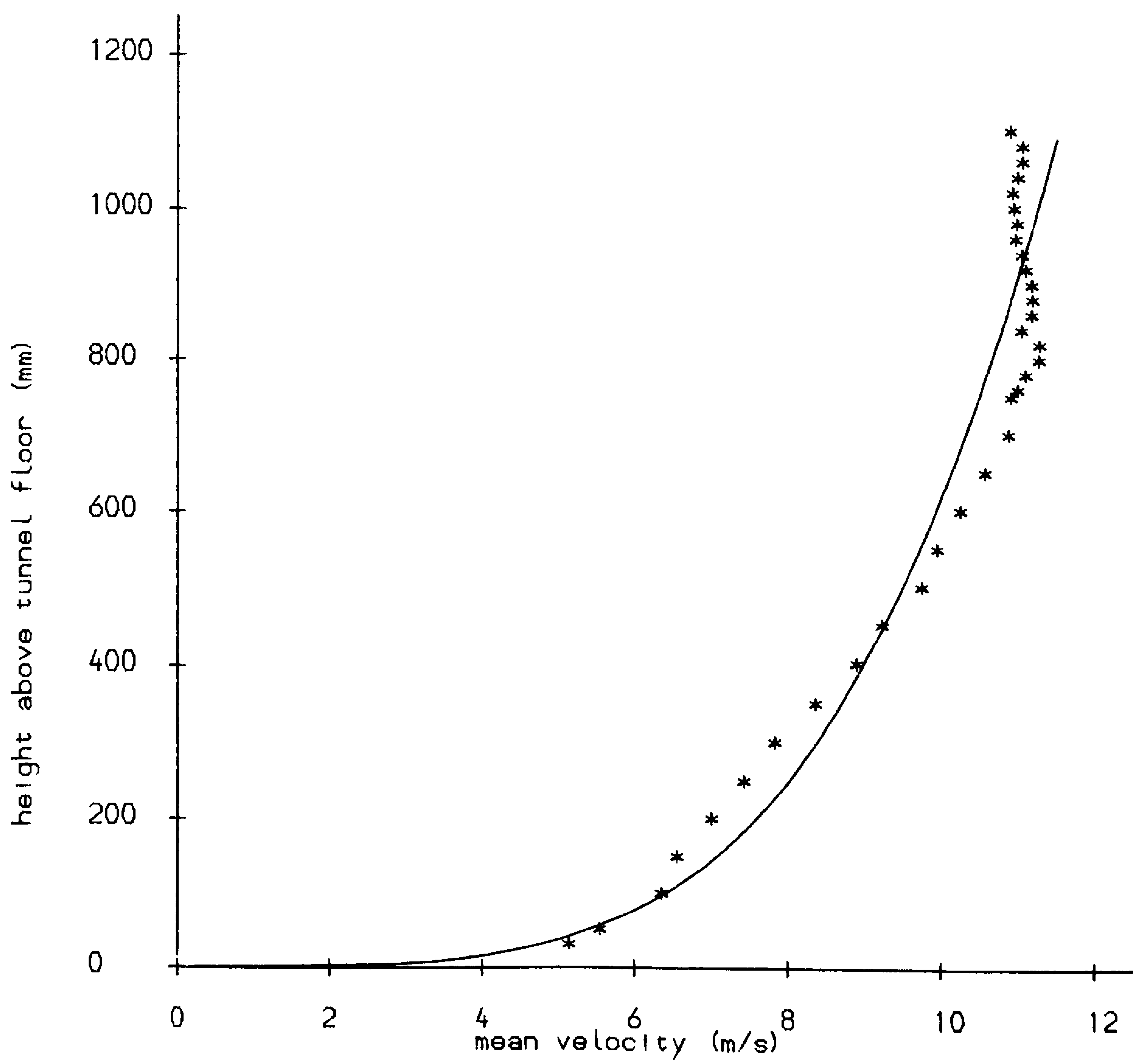


FIG. 5.7. THE MEAN VELOCITY PROFILE

5.4.3 The wind tunnel blockage and length scale:

The wind tunnel blockage refers to the ratio of the maximum cross-sectional area of the model to that of the working section of the wind tunnel. A maximum blockage of 5% is generally recommended. In this study the model measures 300 x 290mm and the maximum blockage is given by the ratio of the area of the diagonal of the model to the 1.2 x 1.2m^2 cross-sectional area of the tunnel's working section. This was given by the following, with reference to Figures 5.5(a,b) The diagonal equals

$$[(0.3)^2 + (0.29)^2]^{\frac{1}{2}} = 0.417$$

Hence, the blockage

$$= \frac{[(0.417 \times 0.118) - ((0.118)^2 \tan 15^\circ)]}{1.44}$$

which approximates to 3%. The ratio of the model height to the boundary layer height was 1:6.8, i.e almost 1:7.

Therefore with the building model constructed at a scale of 1:75 both the maximum blockage and the height ratio values were within acceptable limits of normal wind tunnel measuring practice while the model was also big enough to accommodate proper positioning and the number of the pressure tappings and their associated tubings. Also details of the turbulence intensity, Reynolds stresses, scale factors and turbulence spectra are considered to adequately represent the full scale suburban boundary layers, Lee (1977).

5.4.4 The influence of Reynolds number:

It had earlier been explained that it is often impractical to achieve the same values of Reynolds number for both the scale model and the full scale building due to the fact that the reduced linear dimensions imply an unacceptable level of flow rate to compensate. It has however been found that models with sharp edges and plane faces usually have the same flow pattern over a wide range of airspeeds and the measurements are considered valid if the Reynolds number is above a certain "critical value" though this could be a value much less than at full scale (e.g see Smith, 1951).

In the case of our model, the Reynolds number which is usually expressed

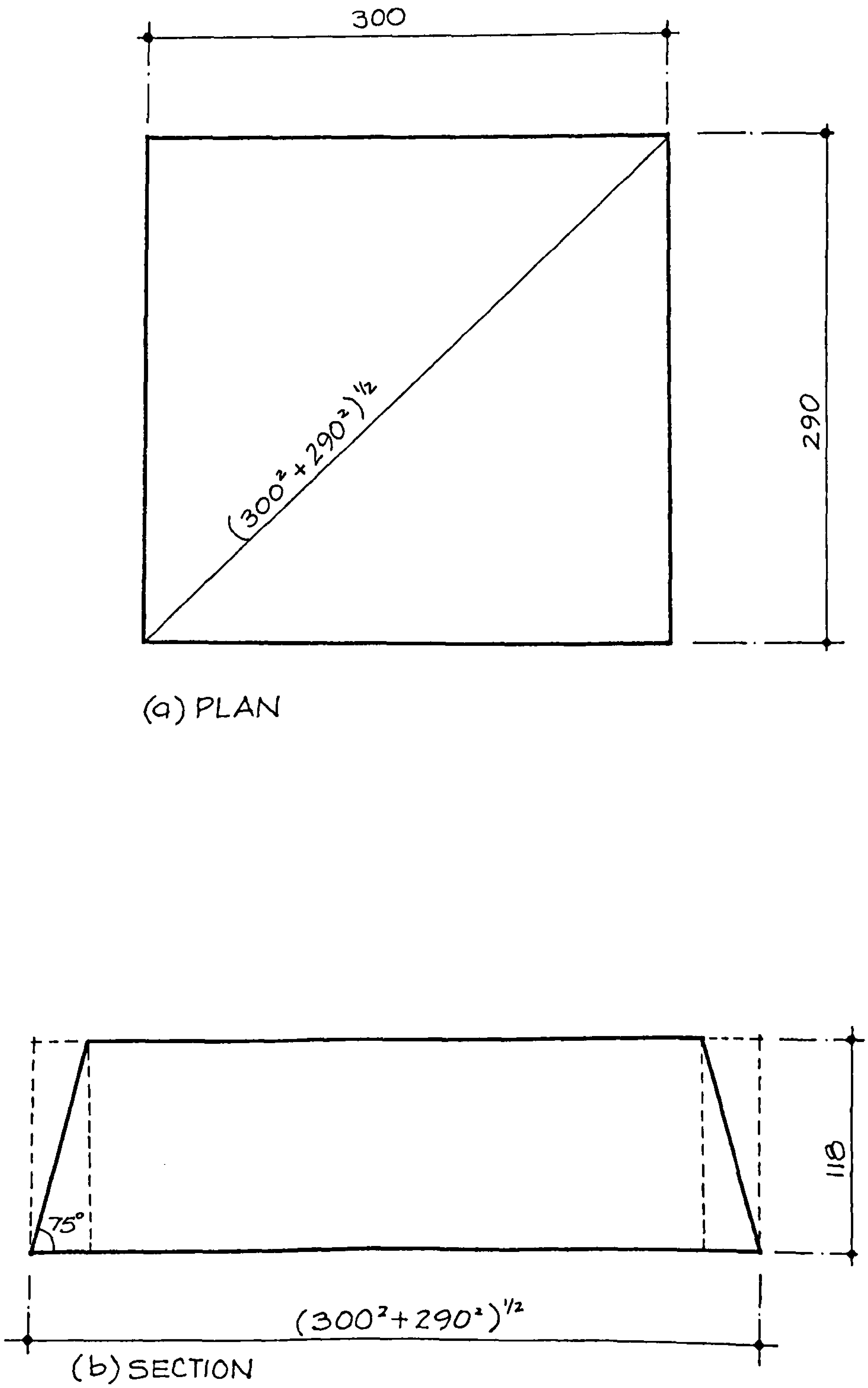


Figure 5.5: The model diagonal dimensions.

Table 5.2 Pressure coefficients for all angles of incidence

pressure tapping	ANGLES OF WIND INCIDENCE (deg) 0	30	60	90	120	150	180	210	240	270	300	330	
1	0.95	0.60	0.23	-0.17	-0.50	-0.31	-0.32	-0.44	-0.86	-0.72	0.37	0.89	
2	1.0	0.90	0.16	-0.33	-0.61	-0.39	-0.26	-0.36	-0.60	-0.46	-0.14	0.51	
3	1.0	0.49	-0.17	-0.46	-0.62	-0.36	-0.26	-0.40	-0.58	-0.34	0.16	0.87	
4	0.96	0.94	0.38	-0.90	-0.84	-0.41	-0.32	-0.32	-0.51	-0.18	0.19	0.59	FRONT
5	0.89	0.46	-0.10	-0.43	-0.59	-0.34	-0.24	-0.37	-0.54	-0.29	0.15	0.73	
6	0.88	0.75	0.10	-0.32	-0.61	-0.39	-0.24	-0.35	-0.58	-0.43	-0.10	0.47	
7	0.75	0.55	0.24	-0.16	-0.41	-0.26	-0.29	-0.43	-0.85	-0.54	0.43	0.88	
8	-0.51	0.71	1.0	0.94	-0.09	-0.69	-0.52	-0.37	-0.36	-0.27	-0.40	-0.81	
9	-0.53	-0.75	-0.06	0.99	0.97	0.71	-0.66	-0.80	-0.41	-0.25	-0.37	-0.39	
10	-0.41	-0.66	-0.18	0.79	1.0	0.67	-0.43	-0.76	-0.35	-0.23	-0.34	-0.34	SIDE 1
11	-0.61	-0.13	0.70	0.90	0.69	-0.15	-0.58	-0.52	-0.31	-0.17	-0.30	-0.52	
12	-0.36	0.67	1.0	0.67	-0.27	-0.61	-0.42	-0.32	-0.34	-0.24	-0.36	-0.77	
13	-0.31	-0.48	-0.86	-0.87	0.34	0.86	0.89	0.49	0.15	-0.19	-0.46	-0.29	
14	-0.23	-0.34	-0.63	-0.54	-0.33	0.19	0.93	1.0	0.58	-0.17	-0.58	-0.37	
15	-0.24	-0.42	-0.65	-0.20	0.67	1.1	0.87	0.12	-0.29	-0.46	-0.57	-0.30	
16	-0.20	-0.21	-0.39	-0.10	0.31	0.71	1.0	0.96	0.44	-0.72	-0.72	-0.33	
17	-0.26	-0.25	-0.40	-0.16	0.30	0.68	0.87	0.96	0.45	-0.59	-0.79	-0.41	BACK
18	-0.22	-0.38	-0.61	-0.29	0.24	0.89	0.90	0.58	-0.01	-0.38	-0.55	-0.29	
19	-0.22	-0.35	-0.59	-0.45	-0.08	0.60	0.92	0.86	0.17	-0.24	-0.55	-0.34	
20	-0.29	-0.46	-0.79	-0.54	0.54	0.95	0.87	0.63	0.28	-0.18	-0.35	-0.23	
21	-0.49	-0.35	-0.39	-0.29	-0.42	-0.87	-0.51	0.73	1.0	0.94	-0.07	-0.74	
22	-0.63	-0.77	-0.40	-0.26	-0.36	-0.41	-0.50	-0.70	0.02	0.94	0.96	0.64	
23	-0.29	-0.66	-0.31	-0.23	-0.34	-0.35	-0.42	-0.60	-0.22	0.70	1.0	0.66	SIDE 2
24	-0.57	-0.49	-0.33	-0.18	-0.30	-0.55	-0.60	-0.12	0.71	0.90	0.84	-0.14	
25	-0.35	-0.31	-0.37	-0.24	-0.35	-0.79	-0.30	0.72	1.0	0.66	-0.25	-0.60	

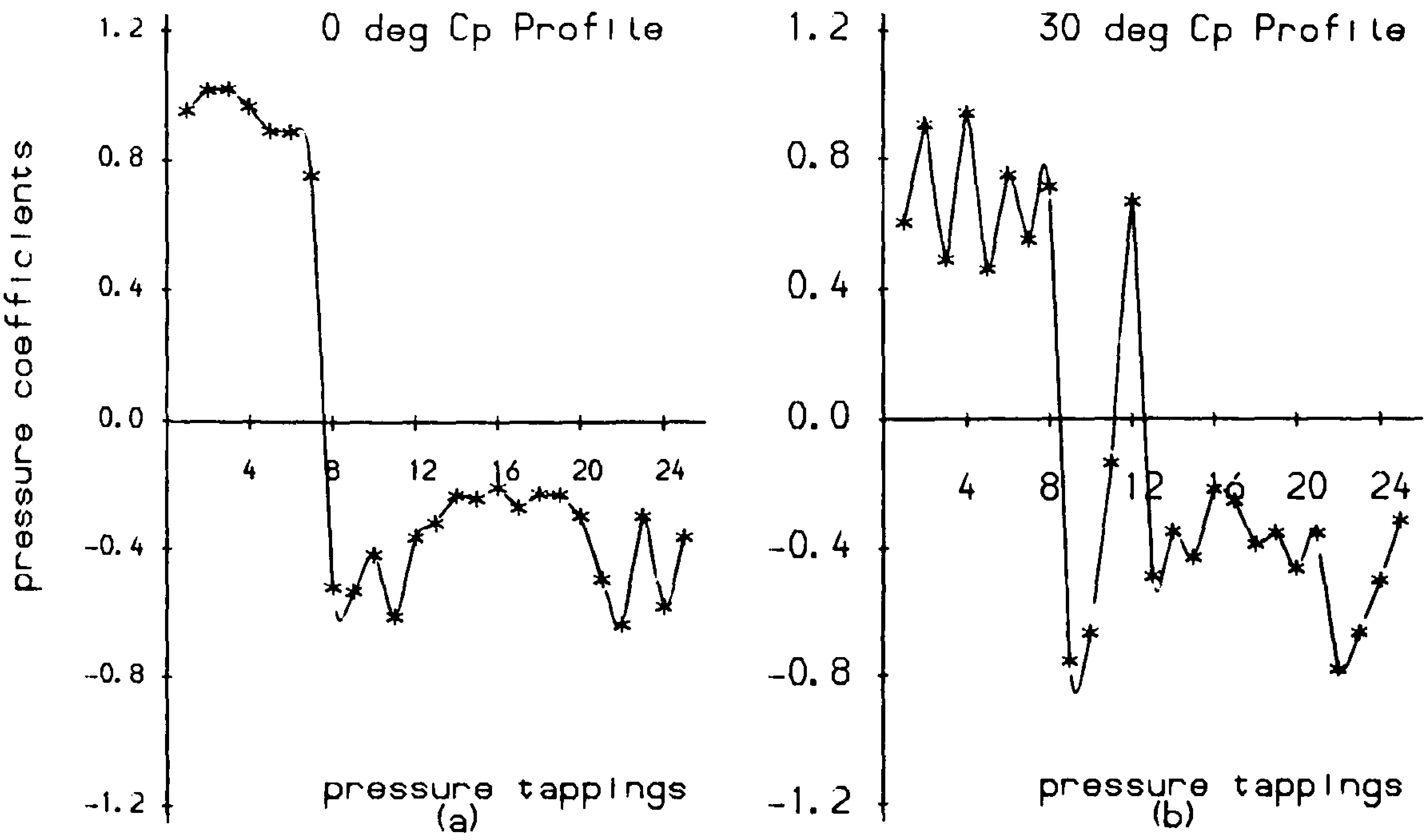


FIGURE 5-8: Cp PROFILES (0 + 30 deg)

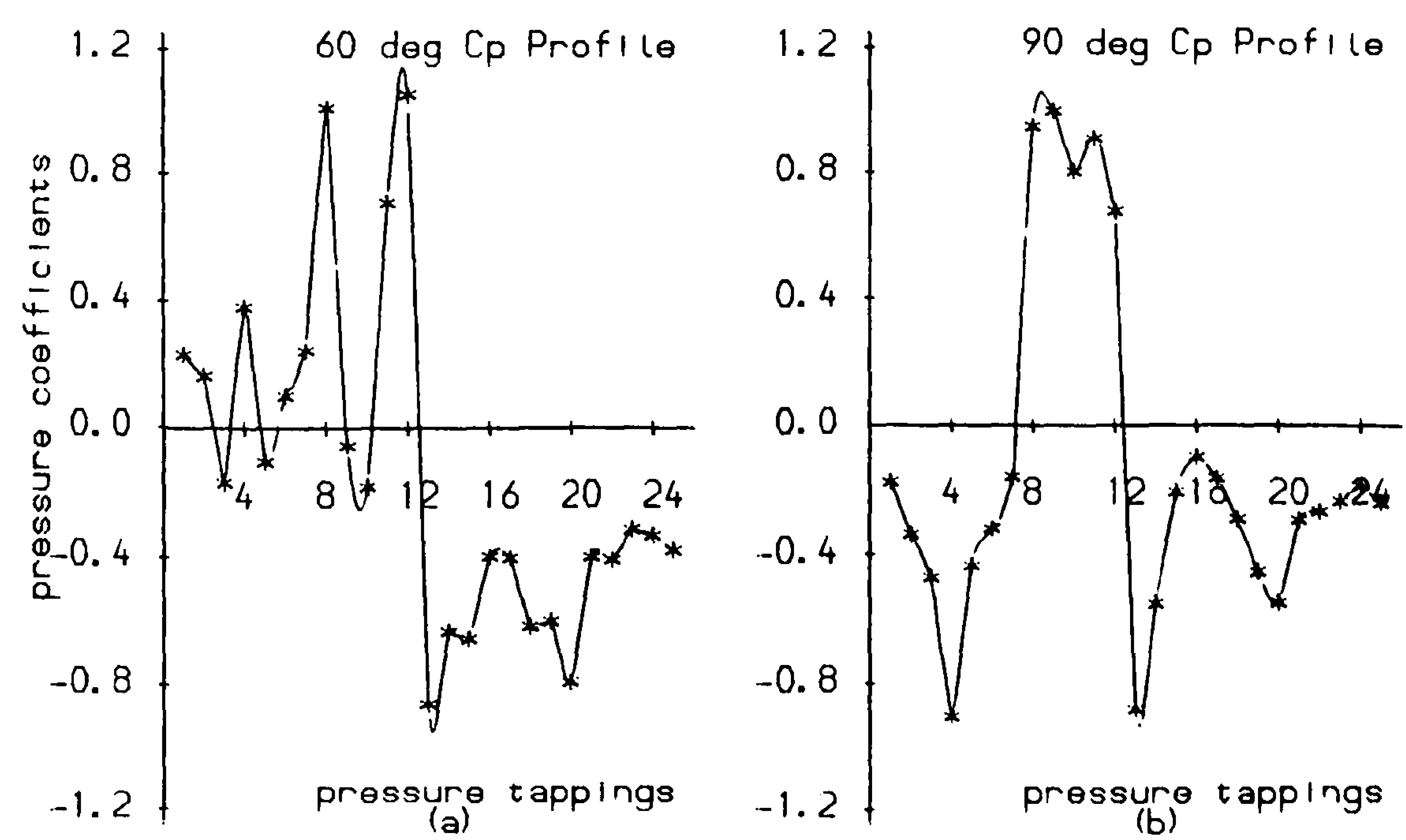


FIGURE 5-9: Cp PROFILES (60 + 90 deg)

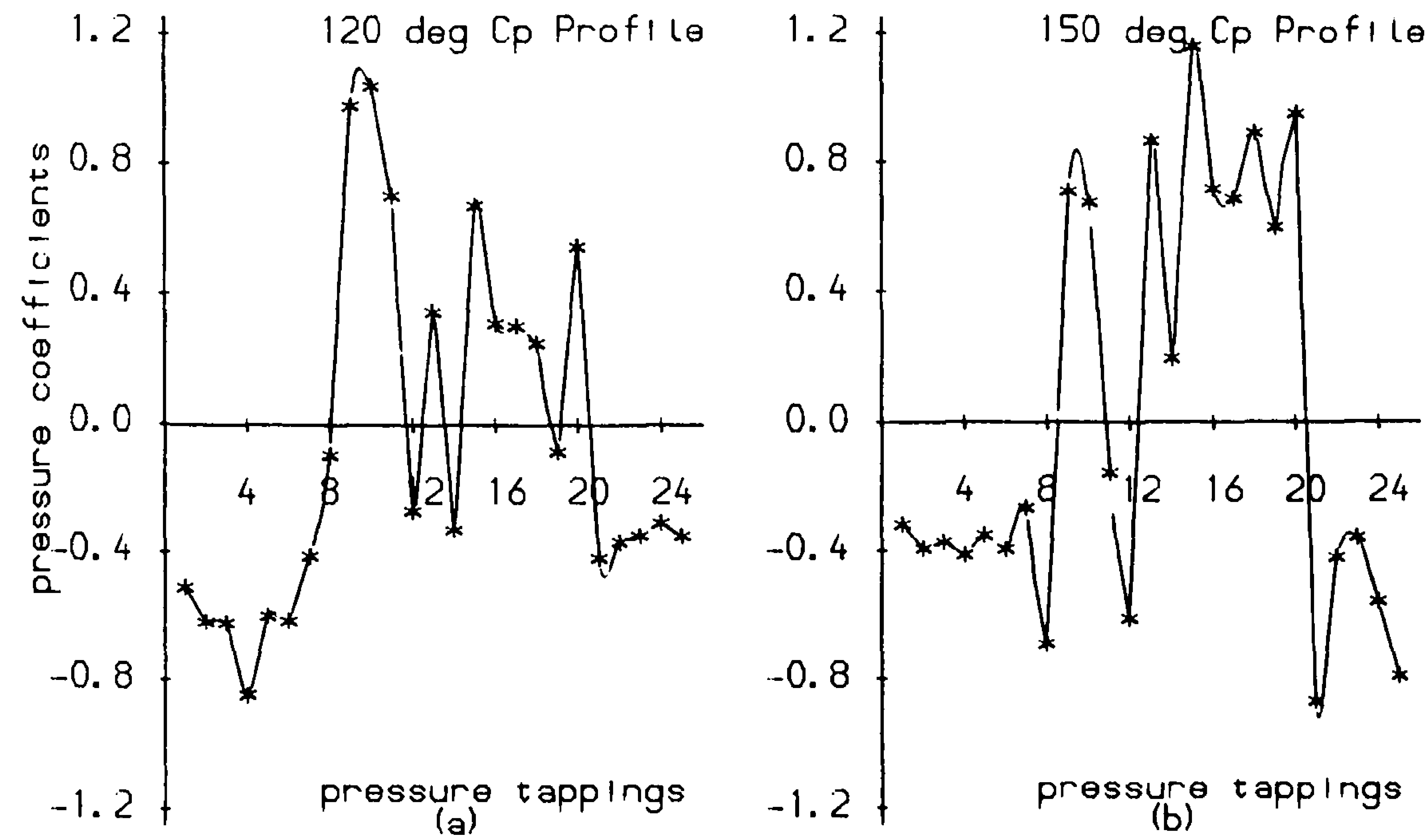


FIGURE 5-10: Cp PROFILES (120 + 150 deg)

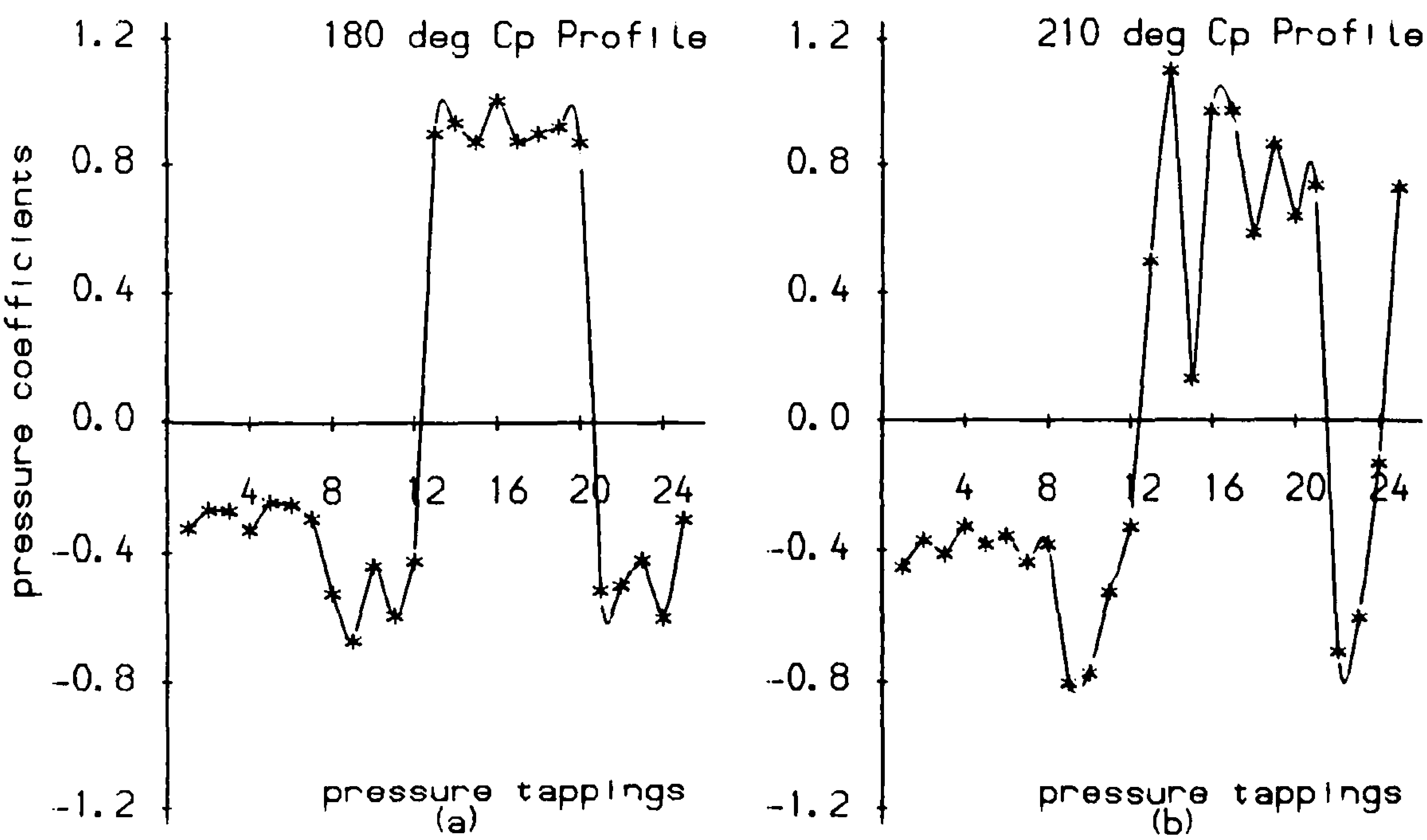
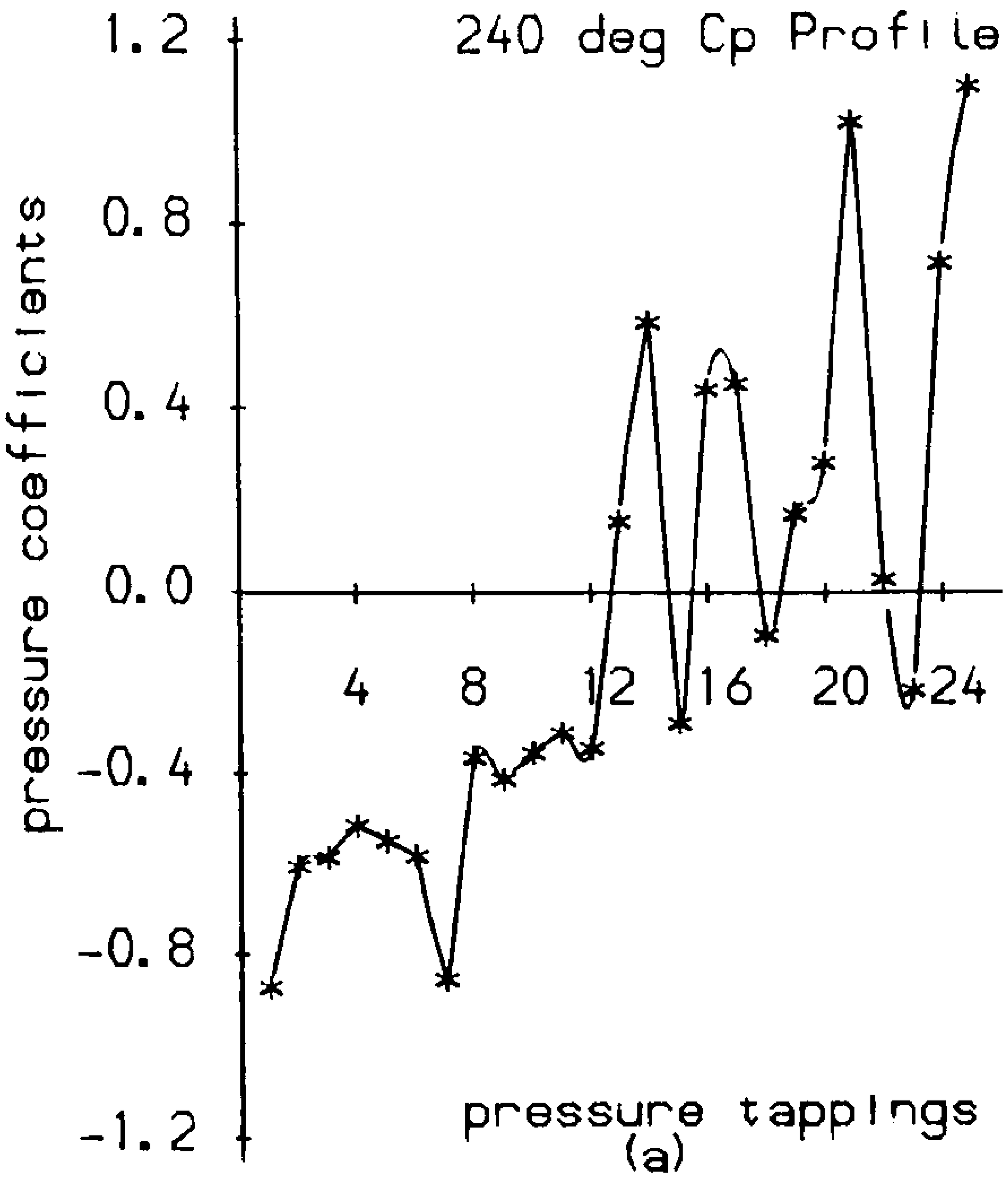


FIGURE 5-11: Cp PROFILES (180 + 210 deg)



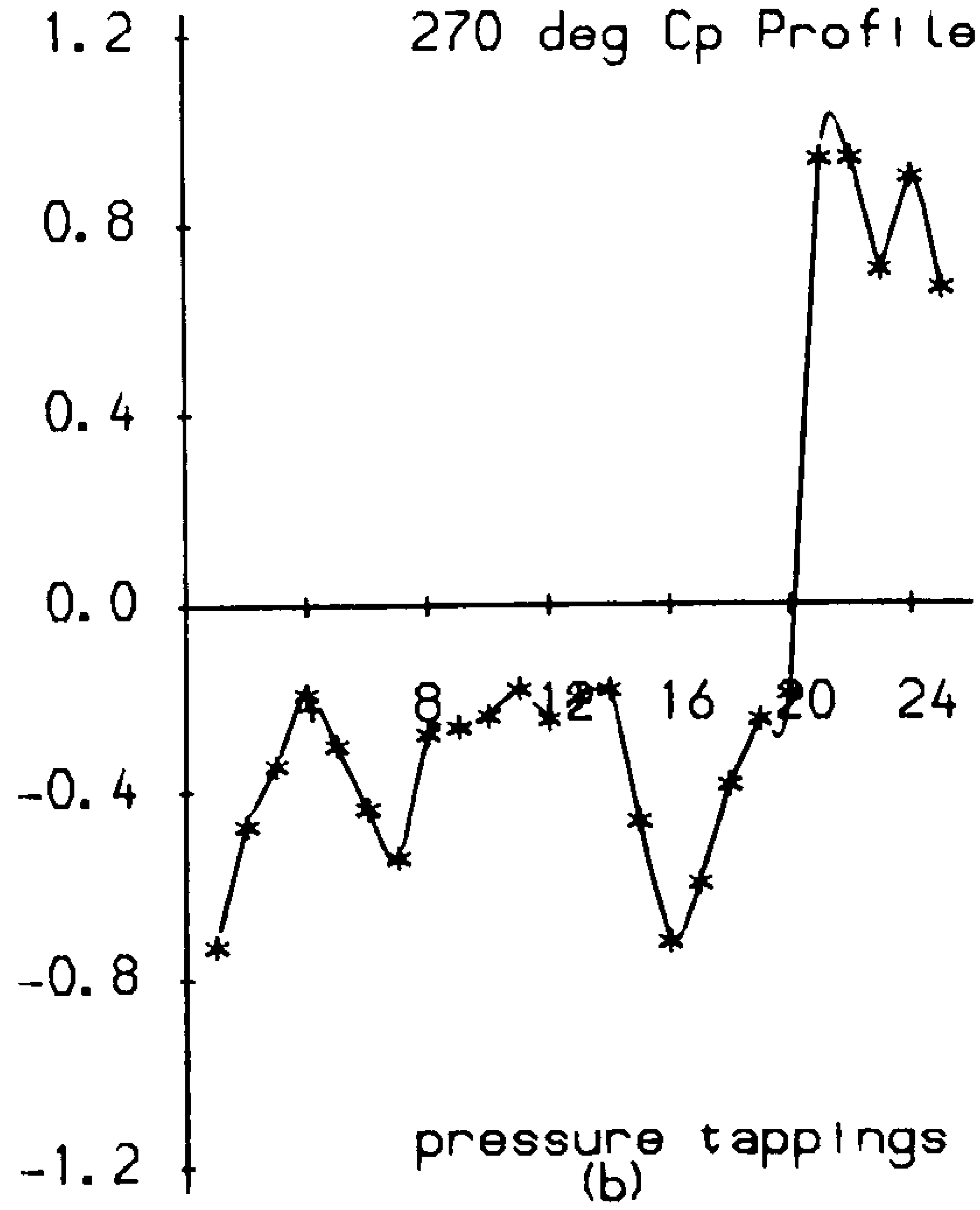
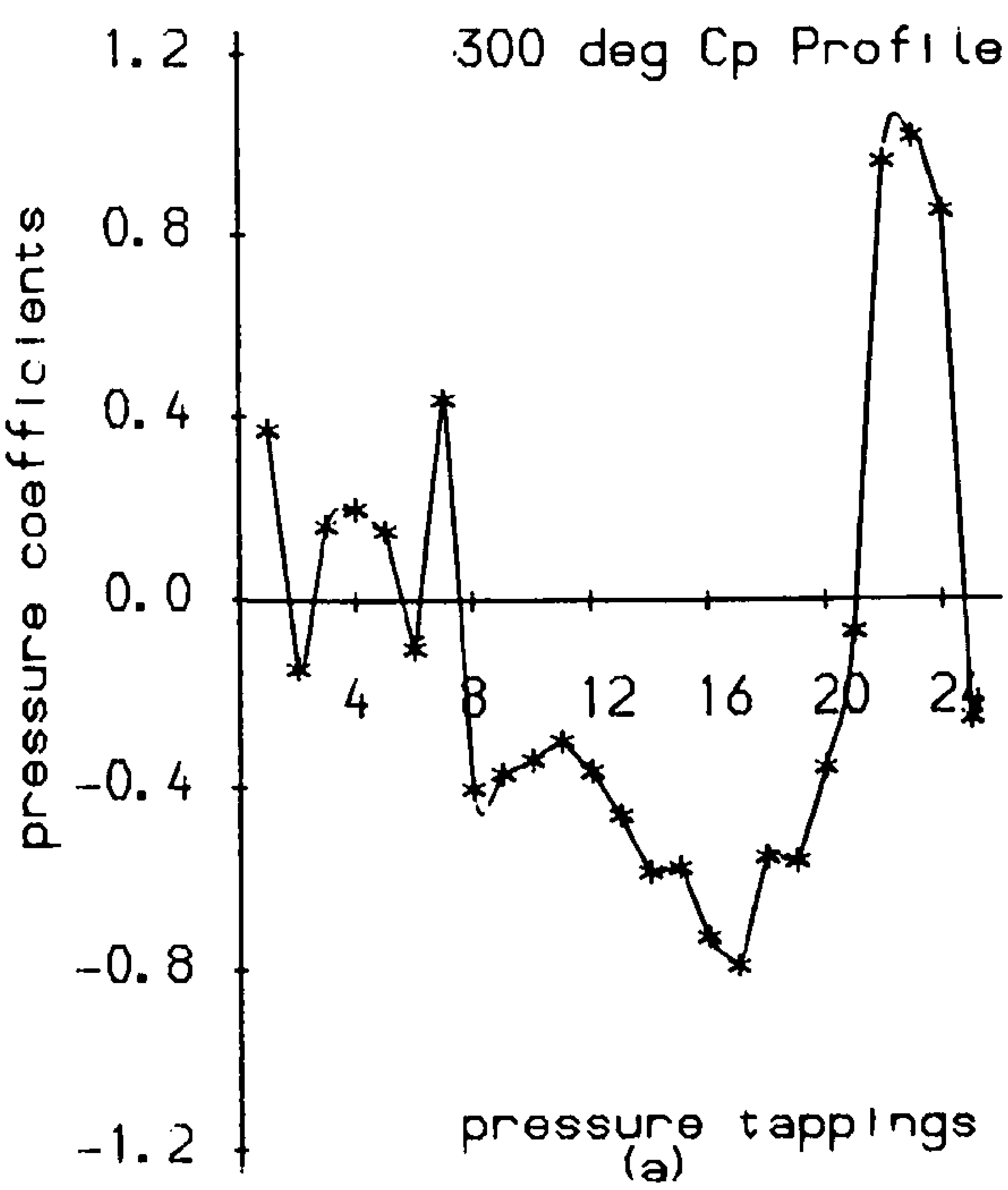


FIGURE 5-12. Cp PROFILES (240 + 270 deg)



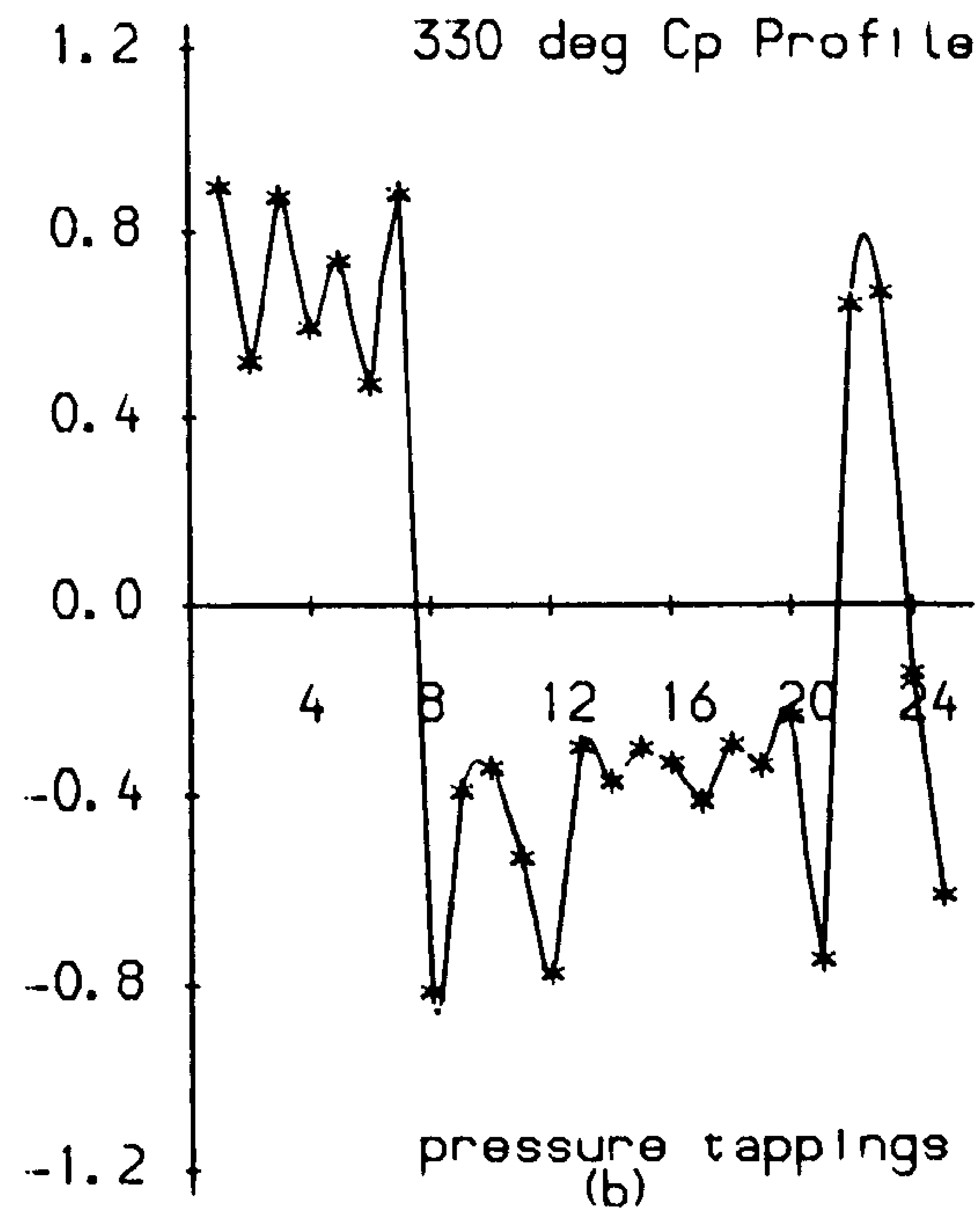


FIGURE 5-13. Cp PROFILES (300 + 330 deg)

as

$$Re = \frac{\rho V d}{\mu} \tag{5.2}$$

where

ρ is the density of the air, (kg m^{-3}) V is the reference windspeed, (ms^{-1}) d is the width of the structure, (m) and μ is the kinematic viscosity of the air, (m^2/s) is calculated to be

$$\begin{aligned} Re_{max} &= \frac{1.19 \times 11.0 \times 0.417}{1.694 \times 10^{-6}} = 3.22 \times 10^6 \\ Re_{min} &= \frac{1.19 \times 11.0 \times 0.290}{1.694 \times 10^{-6}} = 2.24 \times 10^6 \end{aligned} \tag{5.3}$$

Using a scale model of 1:75 linear scaling ratio in a turbulent boundary layer flow with a linear scale factor of 1:350 has the benefit of greatly increasing the Reynolds number at which the experimental modelling was made.

5.5 Measurement Procedure

Having certified that all the necessary pre-modelling conditions have been met, the test was carried out and this entailed the following procedure:

The model was mounted on the turntable which is positioned centrally in the working section of the windtunnel and the pressure tappings were connected, via tubings, to annotated channels on the scanning box with adequate labelling to prevent any mix-ups and/or errors arising therefrom. Special arrangements had been made that enabled a model mounted on the turntable to be rotated to any angle, θ say, from under the wind tunnel floor. Therefore, starting from 0°, which is made to align with the wind direction, the complete circle of the turntable was divided into equal sectors of any desirable angular magnitude (in this test 30° is used). The joints between the turntable and the tunnel floor structure were made as air tight as possible.

The two micromanometers, adequately labelled for clarity, were connected such as to enable one manometer to measure the pressure differential between the total and the static pressure of the free-stream pitot static tube placed 800mm above the centre of the turntable (i.e free stream dynamic pressure) while the other manometer measured the differential pressure between the total pressure at the building surface measured by the pressure tapping, and the static pressure measured by the free stream pitot static tube. The latter manometer is connected to the scanning box.

After switching on the manometers and doing the zero setting, the wind tunnel was switched on and allowed to warm up for at least 60 minutes with the model secured in place on the turntable and the doors of the wind tunnel firmly shut. Then a trial test run was made which involved the following routine:

(i) The reference side of the model was made to coincide with the 0° wind incidence (i.e normal to the view) and measurements of each pressure tapping was taken by scanning through the channels in the scanning box at a reasonable interval. At the same time the reading of the free-stream dynamic pressure in the other manometer was recorded.

(ii) After taking all the readings for 0° wind incidence, step (i) was then repeated for $\theta = 30°$, $60°$ etc. until all the sectors have been traversed.

(iii) All results were cross-checked to ensure that there were no blocked pressure tappings, no disconnections or leakages in the tubing systems. Any necessary corrections were made and then steps (i) and (ii) were repeated until everything was working correctly before proceeding to the next step.

(iv) The wind tunnel test was carried out which was essentially done by repeating steps (i) and (ii) after the wind tunnel has warmed up for at least 60 minutes. At least 2 readings per channel and were taken and then averaged.

5.6 Discussion of Results

5.6.1 Introduction

As mentioned earlier results obtained from wind tunnel tests are usually expressed as a set of pressure coefficients which relates the pressures measured on the building surface to the free stream (dynamic) wind pressure in the tunnel. The pressure coefficients were calculated from the equation

$$C_p = \frac{P - P_o}{\frac{1}{2}\rho V_h^2} \tag{5.4}$$

where

P is the total pressure measured at each pressure tapping on the building model surface, (Pa);

P_o is the static pressure measured by the free stream pitot static tube at the gradient height in the wind tunnel, (Pa); ρ is the density of air at the working conditions, (kg/m^3; and
V_h is the mean wind speed at the eaves height of the building which is h metres, say, from the ground, (m/s).

The expression $\frac{1}{2}\rho V_h^2$ which is the free stream dynamic pressure at the eaves height, H metres above the ground, is related to the free stream dynamic pressure measured at the gradient height (i.e $\frac{1}{2}\rho V_g^2$) of the wind tunnel. This relationship becomes apparent by examining equation 5.1 from which

$$V_h = V_g(\frac{h}{g})^\alpha \tag{5.5}$$

Therefore,

$$\frac{1}{2}\rho V_h^2 = \frac{1}{2}\rho V_g^2(\frac{h}{g})^{2\alpha} \tag{5.6}$$

Table 5.2 shows the results of the pressure coefficient, cp, values obtained from the test for angles of wind incidence from 0° to 360° inclusive, at 30° intervals. Negative values indicate suction which means the pressure tapping is a leeward point at that angle or within a flow separation zone.

5.6.2 Analysis of results

The results are presented in terms of the prevailing seasons in Kano taking into consideration the wind directions during these different periods.

5.6.2.1 Hot season

The severe hot season is from about the middle of March to the end of June and during this period the wind directions are variable. In March it is mainly due North-East (which is correspondent to wind incidence angle of 330° in the wind tunnel test), in April it is due South-West (150° wind tunnel angle) and for May and June, it is due West (about 180° wind tunnel angle). Please note that numbers indicate pressure tapping locations.

Therefore in March which is the beginning of the hot season, the wind is incident on both the front and side-2 of the building on which all the pressure coefficients should be positive, and negative for all the other faces. But as can be seen from Figure 5.13(b) positions 21 and 25 are suction points due to the shielding effect of the projecting side wall while the deep recess also makes 24 a suction point, (and a very poor one at that, since the C_p is only 0.143). In this month it is apparent that the airflow through the back windows may be relatively poor except at 17 which is close to Side-2. Every other part of the building receives a good measure of airflow. At the end of March, the wind direction changes to South West and this lasts throughout the month of April. Examining results for 150° wind tunnel angle (Table 5.2 and Figure 5.10(b) shows that the wind is now incident on both the back and side-1 faces. But except for points 9 and 10 on side-1 all other points are suction points due to the combined effect of the side wall projections and recesses. Also the stagnation point which was at 10 (the kitchen) on side-1 at wind incidence 120° moved up to 15 on the back face near the roof eaves. Every part of the building has a good ventilation airflow in April.

For the rest of the hot season (May and June) when the wind direction is due West, and throughout the rainy season (July to September) for which the wind direction is also due West, the stagnation point is to the left side of the back face to which the wind is mainly incident. There is a well distributed pattern of airflow except for the North East guest room on the ground floor and the South East bedroom upstairs whose ventilation rate would be relatively lower. However for the last months of the rainy season, (September) a good proportion of flow also comes from due North West the effect of which is relatively different from the rest of the season (Figure 5.12(a)): The wind is incident on both the back and side-2 and yet 15 and 18 on the back face and 23 on side-2 are suction points. Though the airflow distribution is good in this month, the North East guest room may receive little or no air even though two stagnation points (21 and 25) are on side-2 which is one of its sides.

5.6.2.2 The *Harmattan* season

For the dry and dusty 'harmattan' season which extends from around October to February, the airflow is as follows. The wind direction changes from due West to East till December after which it is due North East till March. Therefore in November, December and early January, the C_p values for wind tunnel test angle of 0° shows a well distributed airflow except at the back, due among other factors, to the great depth of the building (Figure 5.8). The side projecting walls and the deep recesses would enhance the airflow in the building, especially on the ground floor that is open-plan, since they help to create useful suction zones on the windward side of the building and increase the effect of suction zones on leeward sides.

During the months of February and March the wind direction is due North East for which the C_p values for 330° indicate that the airflow may be generally poor. However during this period ventilation requirements are quite low since the ambient temperatures are relatively low and many people keep openings closed due to the dusty weather.

It can also be observed that highly recessed areas (11 and 24) may have relatively higher air flow for most wind directions and that, as should be expected, the airflow on the first floor is slightly but not significantly better than the ground floor for all wind directions, due to height effect (e.g. C_{p1} is always greater than C_{p2} directly below it, C_{p8} is always greater than C_{p12} and so on). This seems to indicate that for low rise buildings in Kano there is no significant difference between the airflow in the upper and the lower levels.

5.7 Conclusion

The results indicate that the use of side projections on the North and South sides seems to be detrimental to the airflow around the building in Kano and nearby locations with similar climates. This is especially more precarious in the hot-dry season, especially in April, and at the end of the rainy season (September).

Deep recesses and side projecting walls would enhance ventilation flow in the building as designed, and this is mostly felt in the hot-dry season, They are also useful for solar shading of buildings in this climate.

Building orientation should be such as to catch as much of the evening breeze as possible during the critical months of March to June during which the wind directions are mostly North East (March) south West (April) and due West (May and June). This implies orientation of the maximum-opening sides to the North East - South West (or even West) direction which may not be very favourable for thermal control in view of the difficulties involved in adequately shading South West - or West - facing windows with ordinary affordable shading devices. In this regard, modulated solar shielding may play a vital role since it would not only give the needed flexibility in window location and/or orientation to take the best advantage of the prevailing wind directions but would also fulfil its other thermal control objectives.

While this part of the work has generated C_p values which would enable the determination of other parameters such as airflow rate and the air change per hour for the different parts of the building and has given an insight into the seasonal airflow distribution throughout the year, it would be instructive to investigate, to a relatively higher level of detail, the effect the shielding elements (such as wooden louvres) would have on the ventilation rate in the building. The results of such a study is presented in the next chapter.

Chapter 6

Airflow Through Modulated Louvre Systems

6.1 Introduction

In order to investigate the airflow characteristics through a potential shielding system such as that of modulated louvres, an experimental study with the aid of a pressurisation test facility was carried out in the Sheffield University Building Science Research Laboratory. The details of the experiment including the analysis of the results are presented in this chapter.

6.2 Experimental Objective

The main objective of this experiment was the investigation of the flow characteristics of air through a louvre system especially with respect to establishing some understanding as to what extent shielding elements such as louvres can impede the airflow across them. The secondary aim was to give, through the measurement system, a fundamental understanding of the impact of optimising the vertical inclination of the slats of a modulated louvre system on airflow.

6.3 Experimental Instrumentation

6.3.1 Equipment

The main apparatus required for the experiment were the pressurisation chamber, digital micro-manometers, volume flow meters, fans, orifice plate and pressure tappings. The pressurised chamber is made of glued and taped plywood, finished with polyurethane varnish. It has a small drilled opening on top to enable the insertion of pressure tapping and is mounted on wheels for easy motion though provision is made to stabilize it in position when necessary. The other equipments were:

6.3.1.1 Micromanometers:

The micromanometers used were those of Furness Controls Limited, Bexhill. They were of model FC012 with ranges 0 - 19.9 Pa and 0 - 19.99mm H_2O both of which incorporate a self-calibrating device to ensure compensation for zero-drift, making them accurate enough to measure small pressure differences. However it is recommended that recalibration of the manometers be made by the user to forestall unwanted errors. The manufacturers quoted an accuracy of less than $\pm 1\%$ error for the devices.

6.3.1.2 Volume Flowmeter:

The flowmeter used to validate the orifice plate calibration was the TSI model 2014 flowmeter, which has a range of 0.0001 to 0.01 m^3/s and a signal output of range 1 to 5 volts. It has a manufacturers quoted accuracy of a reading of $\pm 2\%$ error.

6.3.1.3 Fans:

Four fans connected in series, made by Woods of Colchester Limited, were used for the depressurisation. Each fan has a diameter of 480mm (19 inches) with blades of 14° pitch capable of 1440 r.p.m. and can perform well under fluid temperature of up to 40°C. Each fan is fitted with a fan speed control to enable speed alterations.

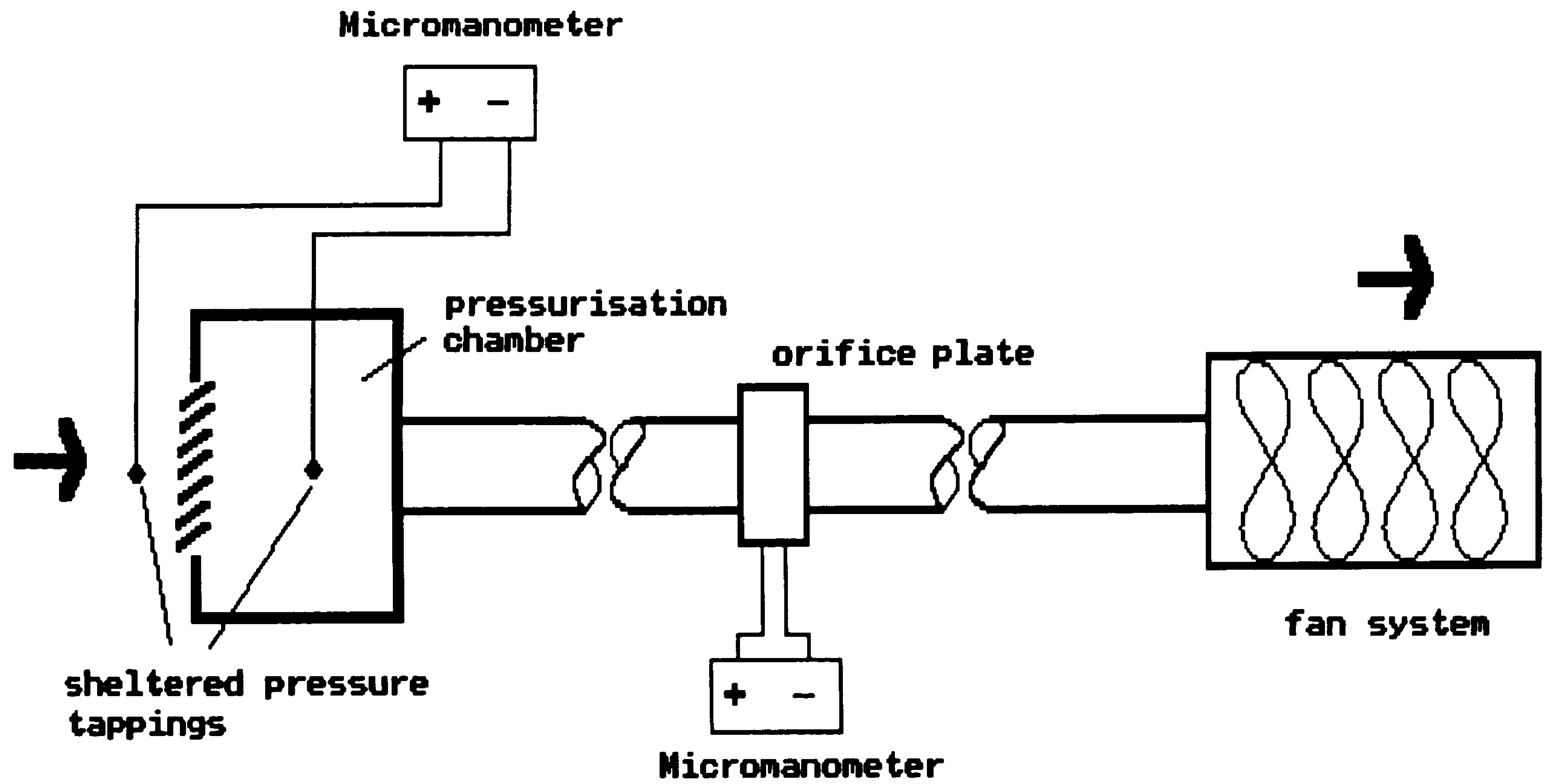


Figure 6.1:

The experimental setup.

6.3.2 Experimental Setup

The schematic layout of the experimental arrangement is shown in figure 6.1.

A louvre system of thin plywood slats was constructed and fitted as a detachable unit onto the front of the pressure chamber. There were 5 louvres in all each measuring 450mm by 5mm thickness (full size dimension) and were all so fitted as to allow adjustment of the louvres to align with pre-determined vertical angles clearly marked on the side board. The pressure chamber was then stabilised in position and then connected via a 6 inches (150mm) diameter tubing to the orifice plate which itself was then connected to the fan system. The pressure tapping which was connected to the manometer, was enclosed in a small multi-porous cylinder with a hemispherical base and was centrally positioned on the pressure chamber. The pressure tappings of the orifice plate which is located downstream of the test system, were connected to a Furness Control micromanometer capable of measuring above 19.99mm H_2O, to measure pressure differential across the orifice plate.

All connections in the set-up were so made as to meet adequate considerations for the dynamic nature of flow, especially with respect to streamlined points along the piping to prevent sharp diameter differentials. Also all the joints were sealed with draught-proof materials to prevent or minimise leakages or infiltrations. In this case layers of self-adhesive polythene-coated silver cloth tape was used to seal minute holes and other joints in the connections.

6.4 Experimental Procedure

The need to obtain a higher volumetric flow rate which would induce greater pressure drop across the louvre system necessitated the use of an orifice plate of 1.5 inches (38.1mm) diameter instead of the TSI flowmeter. The orifice plate was made and calibrated in accordance with BS 1042 sections 1.1 and 2.1 respectively (BS 1042, 1981, BS 1042, 1983). The details of the calibration which was done before the measurements were made is herein presented.

6.4.1 Calibration of the Orifice Plate

Writing the full details of all that was involved in the calibration of the orifice plate would be unnecessarily voluminous. Full details of the instructions and guide-lines can be found in BS 1042 sections 1.2 and 2.1 respectively, to which further reference can be made. Below is a short summary of the calibration process.

6.4.1.1 Assumptions:

The calibration was done with the assumptions that,
(1) The fluid (air) was under a substantially constant density of Mach number not exceeding 0.25 and that the fluid was running full in the conduit under steady flow conditions.
(2) The stagnation temperature across the measuring section was constant.
(3) The compressibility correction factor was negligible and was therefore ignored since the fluid density was constant under the flow conditions. (for air speeds below 60 ms^{-1}, with error of measurement of the airspeed not greater than 0.5%, compressibility effects can be ignored (Ower and Pankhurst, 1977).

6.4.1.2 Procedure:

It was certified that the orifice plate, the conduit, pipe, the fluid, and the pitot tubes conform with British Standards and that the measuring conditions and other requirements in comformity with BS 1042 sections 1.1 and 2.1 respectively. Then the following steps were taken in order:
(1) The area of the cross-section of the circular conduit pipe was determined from the measurement of the diameter.
(2) The measuring points in the cross section were defined such as to ensure that they are sufficient to enable adequate determination of the velocity profile.
(3) Corrections to the measuring points positions were carried out from the equation

$$\Delta Y = d\left[\left[K_g - 0.195K_g\left(\frac{d}{Y}\right)\right]\left[1 - \frac{1}{\sqrt{1+\left(\frac{10.24}{K_g}\right)\left(\frac{Y}{d}\right)^2}}\right]\right] \qquad (6.1)$$

for measurements of differential pressure ΔP recorded at real distance Y from the wall which are considered for calculation as being carried out at distance $(Y + \Delta Y)$, where ΔY is the fictitious displacement of the measuring point. Kg is a constant which depends on the nose shape of the measuring pitot tube of head diameter d.
(4) Having established the actual measuring points, the differential pressure between the total and static pressures at the measuring points were measured using a pitot-static tube connected to the manometer. Seven points of measurements were determined, of which the seventh was at the centre of the conduit (i.e. the conduit axis). Six other measuring points were determined on the same straight line across the conduit section at corresponding distances as the first set of six so as to cross-check the accuracy of the measurements. So there were a total of thirteen measuring points through the conduit diameter. For each flow rate measured by differential pressure across the orifice plate, ΔP is measured on all the 13 points across the conduit.
(5) Corrections to the differential pressures were made from the expression

$$\delta(\Delta P) = 0.7K_b\left(\frac{S}{A}\right)\Delta P_{max} \tag{6.2}$$

where
ΔP is the recorded differential pressure at the measuring point *(Pa)*;
ΔP_{max} is the corresponding value of ΔP at the conduit axis *(Pa)*;
S is the frontal projected area of the portion of the pitot stem inside the conduit;
K_b is the blockage coefficient of a cylindrical pitot stem.
(6) The local velocity of flow at each measuring point was determined from the equation

$$v = \alpha(1-\varepsilon)\sqrt{\frac{2\Delta P}{\rho}} \tag{6.3}$$

where
v is the local velocity of flow, m/s;
α is the calibration factor of the pitot tube; (dimensionless)
$(1-\varepsilon)$ is the compressibility factor; (dimensionless)
ΔP is the differential pressure at the measuring point (P_a),Pa and
ρ is the local density of the fluid (Kg/m^3).
ρ is taken as unity under normal conditions, and $(1-\varepsilon)$ is also taken as unity since compressibility correction was not necessary.

(7) Then the discharge velocity was determined. Three methods are available for this calculation:

1. by graphical integration of the velocity area.

2. by numerical integration of the velocity area.

3. by arithmetical methods.

The method of graphical integration of the velocity area was chosen for the simple reasons that in this method, the measuring points do not have to be on a rigidly defined positions and is not subject to the various errors induced by the weighting coefficients and the assumptions inherent in mathematical formulations and the numerous calculations involved in the other methods.

The graphical integration method is based on the understanding that for flow velocity v at a point on the circle of polar co-ordinates (r,θ), for a conduit section of mean radius R, the discharge velocity U is given by

$$U = \frac{1}{\pi R^2}\int_o^{2\pi}\int_o^R v(r,\theta) r dr d\theta = \int_o^1 u d\left(\frac{r}{R}\right)^2 \tag{6.4}$$

$$= \int_o^{\left(\frac{r_n}{R}\right)^2} u d\left(\frac{r}{R}\right)^2 + \int_{\left(\frac{r_n}{R}\right)^2}^1 u d\left(\frac{r}{R}\right)^2 \tag{6.5}$$

where

u is the spatial mean velocity along the circumference of radius r;

r_n is the radius of the circle defined by the measuring points closest to the wall.

In order to carry out the graphical integration it was necessary to

(a) plot the mean value of the velocities on the measuring points located on the circle of radius r against $\left(\frac{r}{R}\right)^2$ between $r = 0$ and $r = r_n$,

(b) graphically determine the value of the area in enclosed by the curve, and

(c) adding to this value the calculated term for the area enclosed within the peripheral zone which is approximately equal to

$$\frac{m}{m+1} U_n \left(1 - \frac{r_n^2}{R^2}\right) \tag{6.6}$$

where

U_n is the mean velocity at the measuring point on the circle closest to the wall, and

(7) Then the discharge velocity was determined. Three methods are available for this calculation:

1. by graphical integration of the velocity area.

2. by numerical integration of the velocity area.

3. by arithmetical methods.

The method of graphical integration of the velocity area was chosen for the simple reasons that in this method, the measuring points do not have to be on a rigidly defined positions and is not subject to the various errors induced by the weighting coefficients and the assumptions inherent in mathematical formulations and the numerous calculations involved in the other methods.

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$$U = \frac{1}{\pi R^2}\int_o^{2\pi}\int_o^R v(r,\theta) r dr d\theta = \int_o^1 ud\left(\frac{r}{R}\right)^2 \tag{6.4}$$

$$= \int_o^{\left(\frac{r_n}{R}\right)^2} ud\left(\frac{r}{R}\right)^2 + \int_{\left(\frac{r_n}{R}\right)^2}^1 ud\left(\frac{r}{R}\right)^2 \tag{6.5}$$

where

u is the spatial mean velocity along the circumference of radius r;

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(b) graphically determine the value of the area in enclosed by the curve, and

(c) adding to this value the calculated term for the area enclosed within the peripheral zone which is approximately equal to

$$\frac{m}{m+1}U_n\left(1 - \frac{r_n^2}{R^2}\right) \tag{6.6}$$

where

U_n is the mean velocity at the measuring point on the circle closest to the wall, and m is a coefficient depending on the wall roughness which is usually between 4 (for rough walls) and 10 (smooth walls).

In this calibration, m was found to be 8.74 approximately when determined according to BS 1042 section 2.1.

(8) The volume flow rate (m^3/s) were then determined from the product of the values of discharge coefficients and the cross-sectional area of the conduit. Table 6.1 shows the results of the calibration values.

(9) The next step was to plot the calibration curve, as shown on Figure 6.2. The equation of the calibration curve was

$$Q = 0.00282(\Delta P)^{0.467}$$

where

Q is given in m^3/s and ΔP is in mmH_2O. The curve was an excellent fit to the data, as shown by the coefficient of determination of 0.9953, and as was observed by examining the residuals of the least square fit. The calibration was then checked for accuracy over a limited range of flows 100 - 600 *litre/min* (0.0001 - 0.01 m^3/s) by making simultaneous measurements of the orifice plate and a factory calibrated TSI flow meter connected in series. The flows measured agreed to within 3% and hence the calibration was then certified satisfactory within reasonable limits and was therefore suitable for use in the experiment.

6.4.2 Measurement Principle

The main principle of the experiment was to depressurise the chamber by adjusting the circuit controls of the fan system. As a result of the decreased pressure, air flows into the chamber through the louvres which are pre-set at a particular vertical angle θ. The volume flow readings and pressure drop readings are recorded from the TSI flowmeter and the micro-manometers respectively when the readings have stabilized. The measurement procedure which involves the following steps, is repeated over a range of pressure drops up to the maximum that is obtainable from the combined power of the 4 axial fans.

Table 6.1: Calibration Results for Orifice Plate

ΔP (mm H_2O)	Q (m^3/s)	Q (L/min)
3.80000	0.00508	334.791
6.45000	0.00709	437.389
7.85000	0.00728	472.788
9.70000	0.00813	523.786
11.6000	0.00883	565.785
12.8000	0.00943	617.984
13.9000	0.00978	647.983
17.8000	0.01090	725.981
18.9000	0.01110	749.980
20.4000	0.01150	779.980
23.7500	0.01220	839.978
25.2000	0.01260	893.977

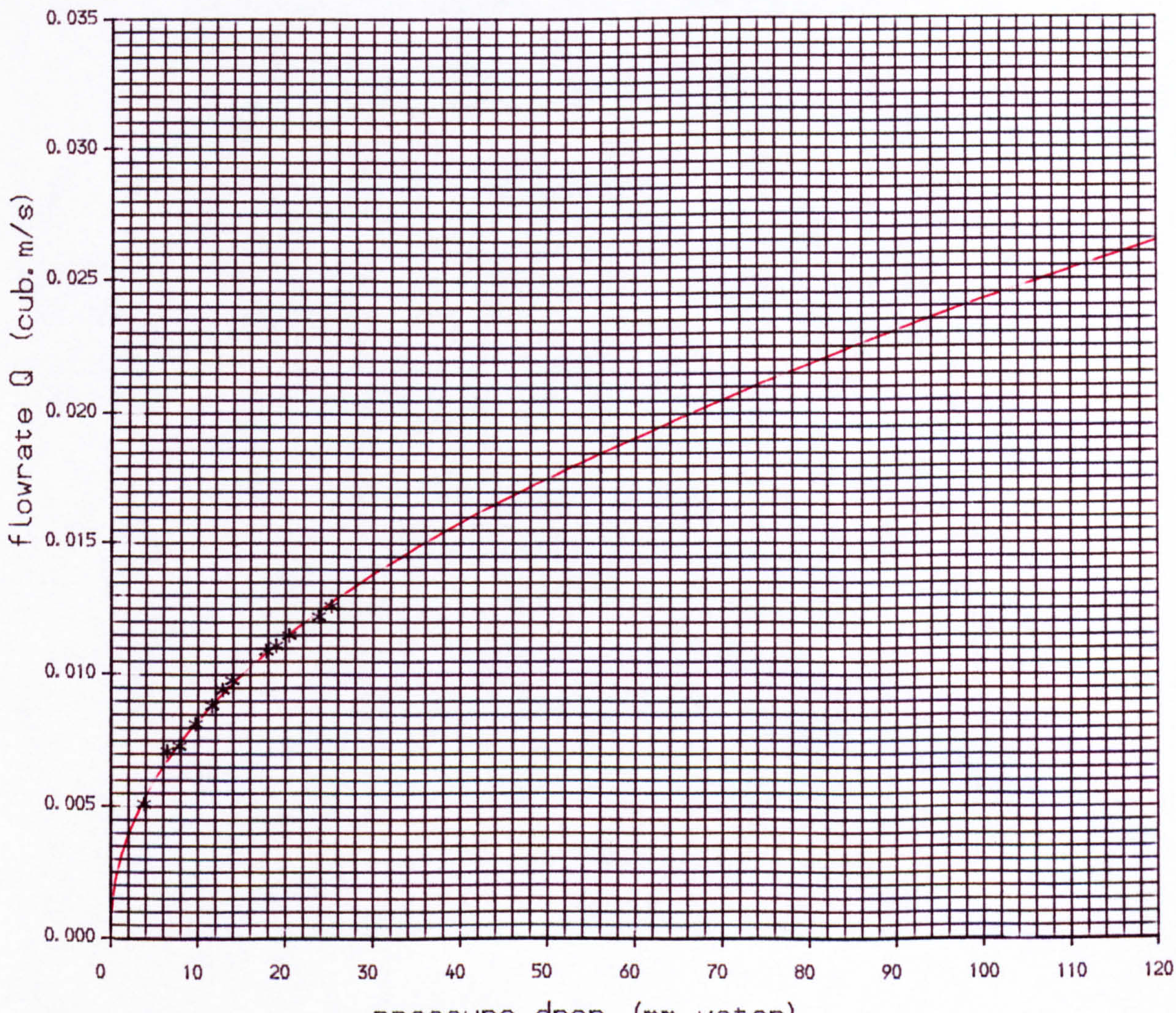


FIG. 6.2: CALIBRATION OF ORIFICE PLATE

6.4.3 The sequence of a Test Measurement

After ensuring that the laboratory temperature is about 20^0C, then
(i) The TSI Flowmeter and the FC012 micro-manometers were switched on and allowed to warm up;
(ii) The zero settings were performed on the micromanometers
(iii) The louvres were adjusted to the desired angle, as fitted onto the pressure chamber;
(iv) The fans were switched on and the controls were adjusted to the desired setting;
(v) The volume flow and pressure drop readings were allowed to stabilize before making a recording of both the pressure differential across the orifice plate and the louvre system respectively;
(vi) The fan speed was increased to different ranges of pressure differentials and step (v) was repeated in each case, up to and including the maximum obtainable from the fan system at that particular angle. At least 10 settings were made. Two readings at least were taken per fan control setting and the average taken;
(vii) After setting the controls to zero, the fans were switched off and the louvres were set to another desired angle (increment of 15° from 0° through 90° were desirable). Steps (iv) to (vi) were repeated for each setting.

6.5 Discussion of Results

6.5.1 Introduction

Generally the Power Law has been widely used to describe the relationship between the pressure drop, and the volumetric flow rate through defferent ranges of apertures in buildings (e.g. cracks, slits and gaps around windows and doors etc.) (Swami and Chandra, 1987; Sherman and Grimsrud, 1982; ASHRAE, 1987). The Power Law takes the form

$$\Delta P = aQ^n \tag{6.7}$$

where
ΔP is the pressure drop in Pa and Q is the volume flow rate in m^3/s while a and n are constants.

Under the umbrella of Power Law applications, some authors in the field (e.g. Dick, 1950) have suggested as far back as the early fifties that the flow rate is almost proportional to the square root of the pressure drop; i.e.

$$Q = a(\Delta P)^{1/2} \tag{6.8}$$

'*a*' being a constant proportional to the effective leakage area of the aperture. This relationship is called the Square Law for convenience.

However, it has been pointed out that the Power Law equations expressed above in (equation 7), are not dimensionally homogeneous since they do not obey Reynolds law of similitude (Etheridge, 1977) and that the **square law** approximation is not strictly true for all types of cracks and their different geometries and pressure differentials (Hopkins and Hansford, 1984).

A polynomial relationship of the type

$$\Delta P = AQ^2 + BQ \tag{6.9}$$

has been found to give the best fit to the data obtained from the pressurisation testing of different types of cracks (Baker, Sharples and Ward, 1987) with evidence that the quadratic equation is dimensionally homogenous and that it had some theoretical validity by using the basic flow equation for laminar flow through infinite parallel plates as found in (Fox and MacDonald, 1978). Their results, combined with previous results and earlier suggestions (Etheridge, 1984; Thomas and Dick, 1953) led the authors to conclude that the quadratic relationship

$$\Delta P = AQ^2 + BQ$$

be used as a practical fit to pressurisation data "to replace the ubiquitous "**power law**" adding that

> "although the quadratic disregards the existence of a critical velocity of transition between streamline and turbulent flow, it has the practical advantage that at both extremes, i.e. $Q \rightarrow 0$ and $Q \rightarrow \infty$, it gives correct forms corresponding respectively to laminar flow and to complete turbulence. The coefficients A and B remain independent of the rate of flow".

The theoretical foundation upon which the validity of the quadratic relationship is based was also shown, as derived from the parallel plate theory of laminar flow. It culminated in the equation

$$\begin{aligned}\Delta P &= C.\frac{\rho}{2}\left(\frac{Q}{d.L}\right)^2 + \frac{Q}{L}.\frac{12\mu z}{d^3} \\ &= \frac{C\rho}{2d^2L^2}Q^2 + \frac{12\mu z}{Ld^3}Q \qquad (6.10)\end{aligned}$$

where

ΔP is the total pressure drop, allowing for edge effects, due to skin friction along the dimension z in the direction of flow,*(Pa)*;

d is the gap thickness between the plates *(m)*;

L is the breadth of the plates *(m)*;

μ is the dynamic viscosity *(Pa.s)* and

ρ is the fluid density (Kg/m^3)

From equations (6.9) and (6.10) it is clear that

$$A = \frac{\rho C}{2d^2L^2} \qquad (6.11)$$

and

$$B = \frac{12\mu z}{Ld^3} \qquad (6.12)$$

With this background, it may be shown as hereby presented, that the pressure drop is also a function of the vertical angle of the louvre blades:

Let the initial position of 2 louvres be 0^o, say, (i.e. perfectly horizontal) as shown in Figure 6.3(a) and let the louvres be turned through angle θ to the new position as in Figure 6.3(b). If the breadth of louvre is L and gap thickness between them is d, then it can be seen that as the louvres are turned through any angle, say θ, both the effective breadth in the direction of flow L_θ and the effective gap thickness d_θ decrease.

From the interplay of the angles, it can be seen that

$$\begin{aligned}\frac{d_\theta}{d} &= \cos\theta \\ d_\theta &= d\cos\theta \qquad (6.13)\end{aligned}$$

Also

$$\begin{aligned}\frac{L_\theta}{L} &= \cos\theta = \sin(90-\theta) \\ L_\theta &= L\cos\theta \qquad (6.14)\end{aligned}$$

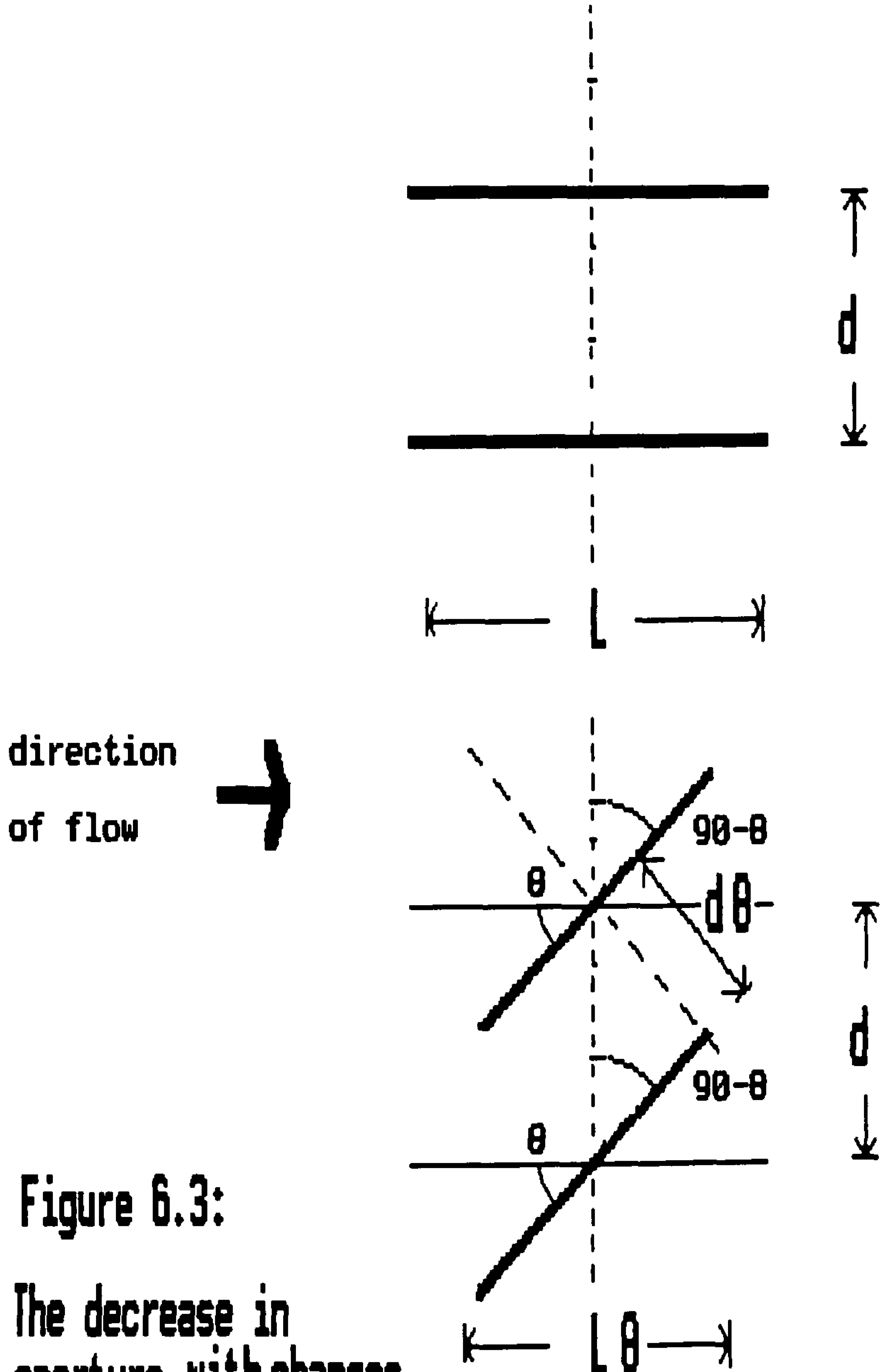


Figure 6.3:

The decrease in aperture with changes in louvre inclination

As in equation (6.10), following the parallel plate theory, the total pressure drop across the louvres at vertical angle θ is

$$\begin{aligned} \Delta P &= \frac{\rho C}{2d_\theta^2 L_\theta^2} Q^2 + \frac{12\mu z}{L_\theta d_\theta^3} Q \\ &= A_\theta Q^2 + B_\theta Q \end{aligned} \tag{6.15}$$

in which case

$$A_\theta = \frac{\rho.C}{2d_\theta^2 L_\theta^2} \tag{6.16}$$

$$B_\theta = \frac{12\mu z}{L_\theta.d_\theta^3} \tag{6.17}$$

Substituting for L_θ and d_θ in equations (6.16) and (6.17) would give

$$\begin{aligned} A_\theta &= \frac{\rho C}{2L^2\cos^2\theta.d^2\cos^2\theta} \\ &= \frac{\rho.C}{2L^2d^2}.\frac{1}{\cos^4\theta} \end{aligned} \tag{6.18}$$

and

$$B_\theta = \frac{12\mu z}{L\cos\theta d^3\cos^3\theta} = \frac{12\mu z}{Ld^3}\frac{1}{[\cos^4\theta]} \tag{6.19}$$

But we know that it is when the louvres are perfectly horizontal (i.e. $\theta = 0°$) that we have the relation

$$A_0\& = \&\frac{\rho C}{2d^2L^2} \tag{6.20}$$

and

$$B_0\& = \&\frac{12\mu z}{Ld^3} \tag{6.21}$$

(renaming A as A_0 and B as B_0, say) as given by equations (6.11) and (6.12). So that $\Delta P_0 = A_0Q^2 + B_0Q$ as in equation (6.9). It follows therefore that equation (6.18), for a perfectly ideal situation should be

$$A_\theta = A_0\frac{1}{\cos^4\theta} \tag{6.22}$$

and equation (6.19) should be

$$B_\theta = B_0.\frac{1}{\cos^4\theta} \tag{6.23}$$

Hence ΔP_θ is given by

$$\begin{aligned}\Delta P_\theta &= A_0 \cdot \frac{1}{\cos^4\theta} Q^2 + B_0 \frac{1}{\cos^4\theta} Q \\ &= (A_0 Q^2 + B_0 Q)\frac{1}{\cos^4\theta} \\ &= \Delta P_0 \frac{1}{\cos^4\theta} \qquad (6.24)\end{aligned}$$

showing that the pressure drop is also a function of the vertical angle of the louvres, along with other parameters which are embodied in the constants A_o and B_o. However this relationship, though theoretically consistent, can only be true if the friction along the dimension z in the direction of flow is assumed constant for all louvre inclinations.

6.5.2 Analysis of Results

The experimental results are shown on Table 6.2. Least square fits of both the Power Law and the quadratic relationship were tested on the data obtained from the experiment. The following points of interest were highlighted:

1. The data obtained in the experiment were found to have good least square fits for both the Power Law and the quadratic relationships.

2. The coefficient of determination (r^2) for the Power Law least square fits ranged from 0.5868 for 0° to 0.9754 for $\theta \approx 90°$ showing that the Power Law least square fits gradually improved from 0° to near perfect as the angle approaches 90°

3. The quadratic fits were much better than those of the Power Law, with coefficients of determination ranging from 0.9993 for 0° to 0.9999 for 90° (see Table 6.3). By examining both the coefficients of determination for both relationships it is evident that the quadratic least square fit was better in most of the cases. As the angle of the louvre approaches 90°, the quadratic relation was found to be only slightly better than the Power Law. Table 6.4 presents the details of the polynomial least square fits including the levels of significance and other details. Figure 6.4 shows the curves of the polynomial fits to the data for louvre angles of 0° through 75°.

4. There was a marked linear correlation between the coefficients A and B of the quadratic relationship, and the angle of the louvre (see Table 6.4). The plots of the coefficients A and B against $\frac{1}{\cos^4\theta}$ gave a coefficient of determination of 0.9923 for A and 0.9965 for B indicating a strong proportionality of the pressure differential and the flow rate, to the louvre angle. Though the number of points were few (only 6 cases) this result is 99% significant. A plot of A and B against $\frac{1}{\cos^4\theta}$ are straight lines (Figure 6.5 and 6.6).

   Computed values of the airflow were obtained from the quadratic relationship by the expression

$$Q_\theta = \frac{-B \pm \sqrt{B^2 + 4A(\Delta P)}}{2A} \tag{6.25}$$

   The computed and measured data for the different angles of louvre inclinations are presented in Table 6.6 together with the residuals.

5. It can be observed from the results that there is no significant decrease in airflow at louvre angles of up to 45° at which angle the decrease in flow is just over 30%. (Tables 6.6 and 6.7). In precise terms, the average reductions were found to be 4.76% for 15°, 13.10% for 30°, 34.19% for 45°, 56.45% and 72.90% for 75°. This indicates that the decrease to air flow begins to increase *significantly* from 60° louvre angle at which the flow is reduced by over 50%. At 75° louvre inclination, the reduction can be expected to be about 70%.

Table 6.2(a): Experimental Results

0^o		15^o		30^o	
Q (m^3/s)	ΔP (Pa)	Q (m^3/s)	Δ P (Pa)	Q (m^3/s)	Δ P (Pa)
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0048	0.0020	0.0053	0.0040	0.0048	0.0050
0.0063	0.0040	0.0065	0.0060	0.0062	0.0090
0.0098	0.0120	0.0102	0.0170	0.0099	0.0190
0.0124	0.0210	0.0124	0.0260	0.0125	0.0300
0.0133	0.0240	0.0133	0.0280	0.0133	0.0360
0.0142	0.0270	0.0142	0.0300	0.0142	0.0400
0.0173	0.0420	0.0172	0.0480	0.0173	0.0580
0.0187	0.0480	0.0186	0.0550	0.0186	0.0690
0.0213	0.0670	0.0214	0.0740	0.0212	0.0880
0.0224	0.0730	0.0222	0.0840	0.0221	0.0990
0.0248	0.0960	0.0248	0.1050	0.0249	0.1200
0.0258	0.1040	0.0258	0.1160	0.0258	0.1310

Table 6.2(b): Experimental Results (cont'd)

45°		60°		75°	
Q(m^3/s)	ΔP(Pa)	Q(m^3/s)	ΔP(Pa)	Q(m^3/s)	ΔP(Pa)
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0048	0.0080	0.0047	0.0130	0.0049	0.0760
0.0064	0.0130	0.0062	0.0270	0.0065	0.1350
0.0101	0.0350	0.0099	0.0760	0.0104	0.3820
0.0125	0.0550	0.0125	0.1270	0.0125	0.5510
0.0133	0.0620	0.0133	0.1440	0.0133	0.6220
0.0142	0.0650	0.0142	0.1530	0.0142	0.6550
0.0173	0.1050	0.0171	0.2440	0.0173	1.0720
0.0185	0.1190	0.0185	0.2810	0.0182	1.1880
0.0214	0.1600	0.0212	0.3700	0.0213	1.6700
0.0221	0.1680	0.0220	0.4050	0.0219	1.8100
0.0247	0.2160	0.0245	0.4900	0.0248	2.4500
0.0258	0.2450	0.0256	0.5350	0.0255	2.5700

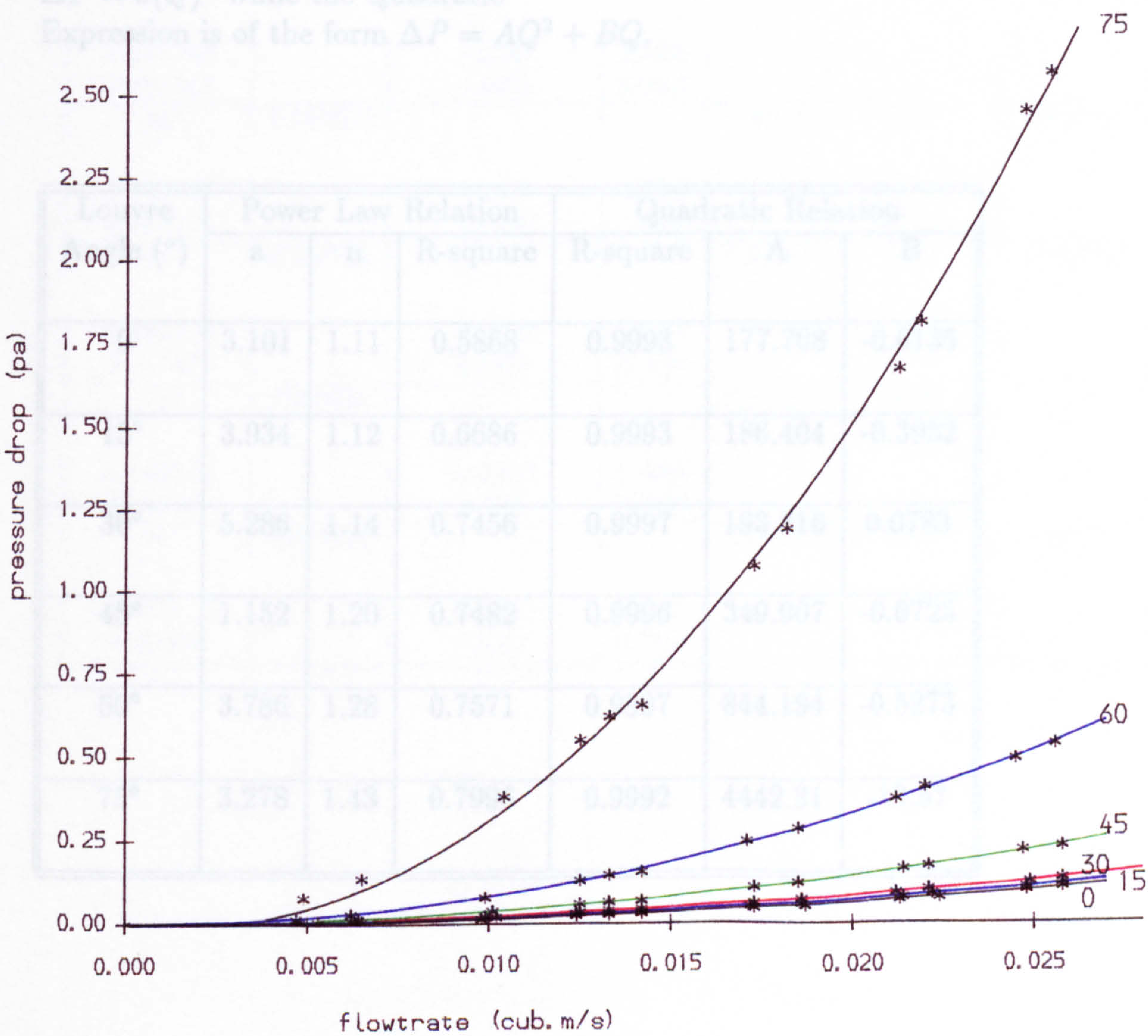


FIGURE 6.4. PRESSURE DROP V. FLOWRATE
FOR DIFFRENT LOUVRE ANGLES (degrees)

Table 6.3: Comparison between Power Law and Quadratic Fits to the data. The Power Law relation is of the form $\Delta P = a(Q)^n$ while the Quadratic Expression is of the form $\Delta P = AQ^2 + BQ$.

Louvre Angle (^{o})	Power Law Relation			Quadratic Relation		
	a	n	R-square	R-square	A	B
0	3.101	1.11	0.5868	0.9993	177.708	-0.6135
15°	3.934	1.12	0.6686	0.9993	186.404	-0.3952
30°	5.286	1.14	0.7456	0.9997	193.316	0.0783
45°	1.152	1.20	0.7482	0.9996	349.907	-0.0723
60°	3.786	1.28	0.7571	0.9997	844.194	-0.5273
75°	3.278	1.43	0.7996	0.9992	4442.31	-13.57

Table 6.4: Details of Polynomial Least Square Fits in the quadratic expression $\Delta P = A.Q^2 + B.Q$

	R-square	Standard Error of Estimate	PRT	Root MSE	Significance Level	Sum of SQ Resid.
0°	0.999325			0.00148	99.9	0.000024
A:177.708		4.9886	0.0001			
B:-0.6135		0.1054	0.0001			
15°	0.999303			0.00168	99.9	0.000031
A:186.404		5.6480	0.0068			
B:-0.3952		0.1190	0.0001			
30°	0.999717			0.00125	99.9	0.000017
A:193.316		4.2365	0.3996			
B:0.0783		0.0893	0.0001			
45°	0.999657			0.00243	99.9	0.000065
A:349.907		8.2174	0.0001			
B:-0.0723		0.1729	0.6838			
60°	0.999745			0.00489	99.9	0.000263
A:844.194		16.8653	0.0001			
B:-0.5273		0.3525	0.1628			
75°	0.999248			0.03924	99.9	0.0169
A:4442.31		133.892	0.0001			
B:-13.57		2.799	0.0005			
90°	0.999974			0.0602	99.9	0.0254
A:57,439.232		506.889	0.0001			
B:20.846		7.5537	0.0281			

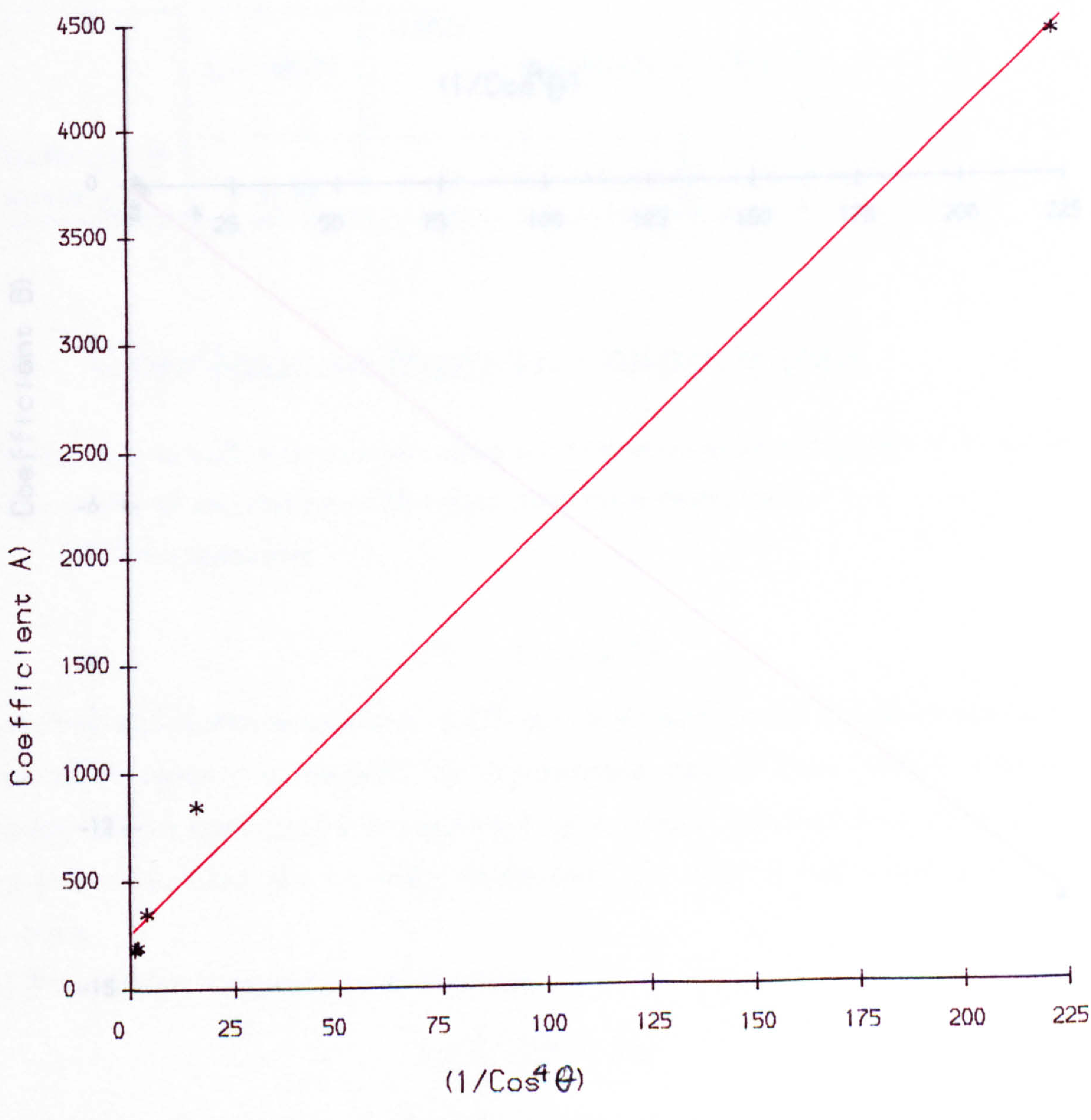


FIG. 6.5: COEFF. A VERSUS $(1/\cos^4\theta)$

FIG. 6.6: COEFF. B VERSUS (1/Cos$^4\theta$)

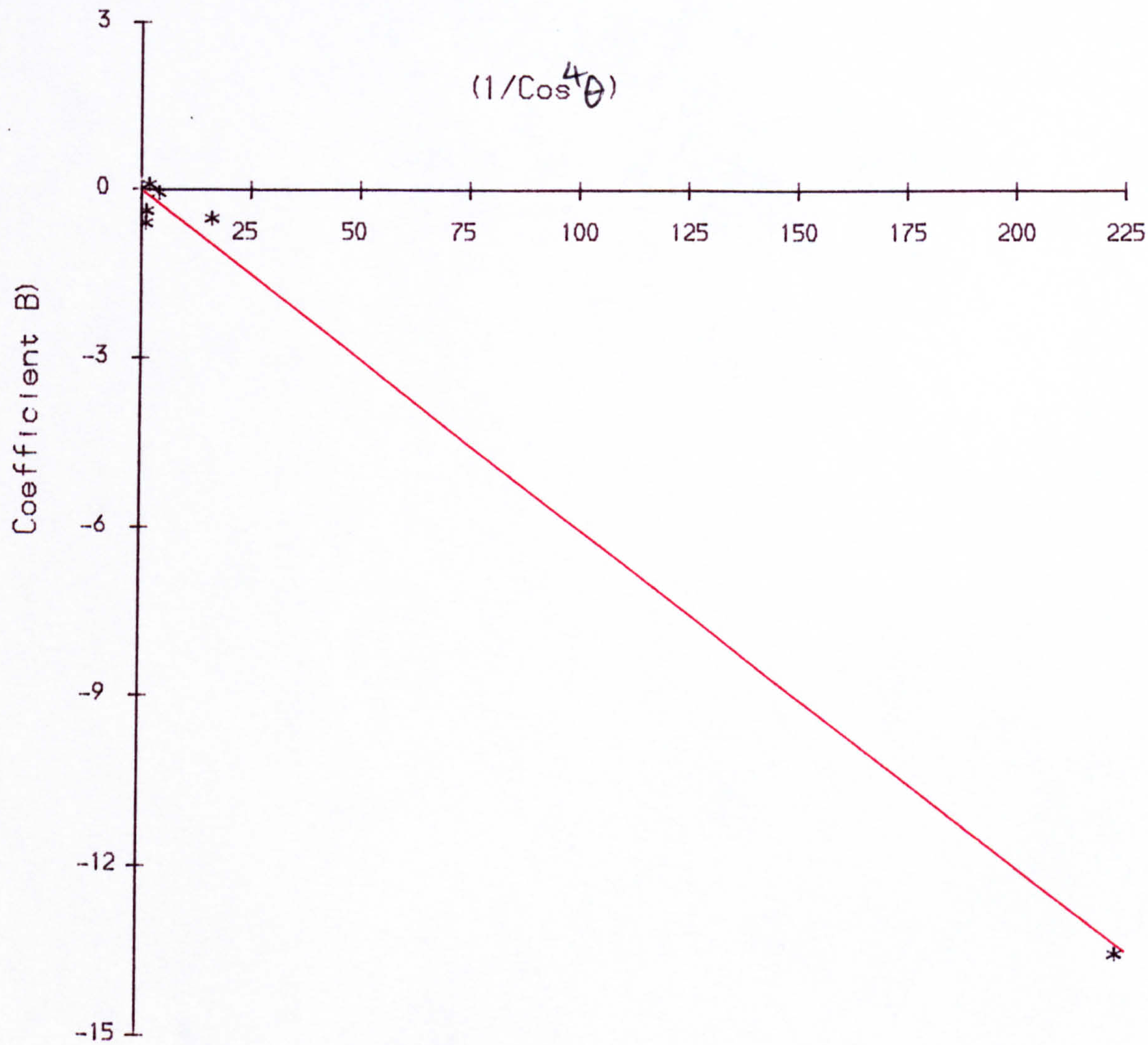


Table 6.5: Details of the coefficients A and B.

	Linear Regression Constants	R-Square	Standard Error of Estimate	PRT:
Coefficient A versus $\frac{1}{\cos^4\theta}$	K:18.870	0.99232	0.830	0.0001
	C:256.166		75.73	0.0277
Coefficient B versus $\frac{1}{\cos^4\theta}$	K:0.06075	0.99655	0.00160	0.0001
	C:0.00			

6.6 Conclusions from the experiment

Models relating airflow to pressure drop across a wooden louvre system with respect to the angles of inclination of the slats have been developed.

(i) The expression

$$\Delta P_\theta = \Delta P_o \cos^{-4}\theta$$

as derived and shown in equation (6.22), which is based on the parallel plate theory, is found to adequately describe the experimental data of flow through a smooth wooden louvre system and is suggested as a simple practical tool since all the parameters involved can be easily estimated by quadratic regression analysis of the data.

(ii) The quadratic expression of the form

$$\Delta P = AQ^2 + BQ$$

was found to describe the relationship between the pressure drop and the airflow rate through the louvre system better than the Power Law of the form

$$\Delta P = a_o(Q)^n$$

TABLE 6.6 COMPUTED AND MEASURED VALUES OF AIRFLOW (cub.m/s)

0 degree				15 degrees				30 degrees			
Qm	dP	Qc	Resid	Qm	dP	Qc	Resid	Qm	dP	Qc	Resid
0.0048	0.0020	0.0055	-.0007	0.0053	0.0040	0.0059	-.0006	0.0048	0.0050	0.0049	-.0001
0.0063	0.0040	0.0068	-.0005	0.0065	0.0060	0.0069	-.0004	0.0062	0.0090	0.0066	-.0004
0.0098	0.0120	0.0101	-.0003	0.0102	0.0170	0.0108	-.0006	0.0099	0.0190	0.0097	0.0002
0.0124	0.0210	0.0127	-.0003	0.0124	0.0260	0.0131	-.0007	0.0125	0.0300	0.0123	0.0002
0.0133	0.0240	0.0135	-.0002	0.0133	0.0280	0.0135	-.0002	0.0133	0.0360	0.0134	-.0001
0.0142	0.0270	0.0142	0.0000	0.0142	0.0300	0.0139	0.0003	0.0142	0.0400	0.0142	0.0000
0.0173	0.0420	0.0172	0.0001	0.0172	0.0480	0.0173	-.0001	0.0173	0.0580	0.0171	0.0002
0.0187	0.0480	0.0183	0.0004	0.0186	0.0550	0.0185	0.0001	0.0186	0.0690	0.0187	-.0001
0.0213	0.0670	0.0212	0.0001	0.0214	0.0740	0.0212	0.0002	0.0212	0.0880	0.0211	0.0001
0.0224	0.0730	0.0221	0.0003	0.0222	0.0840	0.0226	-.0004	0.0221	0.0990	0.0224	-.0003
0.0248	0.0960	0.0250	-.0002	0.0248	0.1050	0.0251	-.0003	0.0249	0.1200	0.0247	0.0002
0.0258	0.1040	0.0260	-.0002	0.0258	0.1160	0.0263	-.0005	0.0258	0.1310	0.0258	0.0000

45 degree				60 degrees				75 degrees			
Qm	dP	Qc	Resid	Qm	dP	Qc	Resid	Qm	dP	Qc	Resid
0.0048	0.0080	0.0049	-.0001	0.0047	0.0130	0.0042	0.0005	0.0049	0.0760	0.0059	-.0010
0.0064	0.0130	0.0062	0.0002	0.0062	0.0270	0.0060	0.0002	0.0065	0.1350	0.0072	-.0007
0.0101	0.0350	0.0101	0.0000	0.0099	0.0760	0.0098	0.0001	0.0104	0.3820	0.0109	-.0005
0.0125	0.0550	0.0126	-.0001	0.0125	0.1270	0.0126	-.0001	0.0125	0.5510	0.0128	-.0003
0.0133	0.0620	0.0134	-.0001	0.0133	0.1440	0.0134	-.0001	0.0133	0.6220	0.0135	-.0002
0.0142	0.0650	0.0137	0.0005	0.0142	0.1530	0.0138	0.0004	0.0142	0.6550	0.0138	0.0004
0.0173	0.1050	0.0174	-.0001	0.0171	0.2440	0.0173	-.0002	0.0173	1.0720	0.0171	0.0002
0.0185	0.1190	0.0185	0.0000	0.0185	0.2810	0.0186	-.0001	0.0182	1.1880	0.0180	0.0002
0.0214	0.1600	0.0215	-.0001	0.0212	0.3700	0.0212	0.0000	0.0213	1.6700	0.0210	0.0003
0.0221	0.1680	0.0220	0.0001	0.0220	0.4050	0.0222	-.0002	0.0219	1.8100	0.0218	0.0001
0.0247	0.2160	0.0249	-.0002	0.0245	0.4900	0.0244	0.0001	0.0248	2.4500	0.0251	-.0003
0.0258	0.2270	0.0256	0.0002	0.0256	0.5350	0.0255	0.0001	0.0255	2.5700	0.0256	-.0001

TABLE 6.7A COMPUTED AIRFLOW (cub.m/s) FOR DIFFERENT LOUVRE ANLGLES FOR THE SAME RANGE OF PRESSURE DROP (Pa)

PRESSURE DROP	AIRFLOW RATE					
	0 deg	**15 deg**	**30 deg**	**45 deg**	**60 deg**	**75 deg**
0.0040	0.0068	0.0059	0.0044	0.0035	0.0025	0.0033
0.0060	0.0078	0.0069	0.0054	0.0042	0.0030	0.0034
0.0170	0.0117	0.0108	0.0092	0.0071	0.0048	0.0040
0.0260	0.0139	0.0131	0.0114	0.0087	0.0059	0.0044
0.0280	0.0144	0.0135	0.0118	0.0090	0.0061	0.0045
0.0300	0.0148	0.0139	0.0123	0.0094	0.0063	0.0045
0.0480	0.0183	0.0173	0.0156	0.0118	0.0079	0.0052
0.0550	0.0194	0.0185	0.0167	0.0126	0.0084	0.0054
0.0740	0.0222	0.0212	0.0194	0.0146	0.0097	0.0059
0.0840	0.0235	0.0226	0.0206	0.0156	0.0103	0.0061
0.1050	0.0261	0.0251	0.0231	0.0174	0.0115	0.0066
0.1160	0.0273	0.0263	0.0243	0.0183	0.0120	0.0069

TABLE6.7B PERCENTAGE REDUCTION OF FLOW FROM THAT AT ZERO DEGREES FOR THE SAME RANGE OF PREESURE DROP

PRESSURE DROP	**15 deg**	**30 deg**	**45 deg**	**60 deg**	**75 deg**
0.0040	13.28	35.78	48.54	62.93	50.91
0.0060	11.32	31.02	45.48	61.52	55.74
0.0170	7.49	21.28	39.32	58.74	65.61
0.0260	6.36	18.27	37.44	57.90	68.53
0.0280	6.18	17.80	37.14	57.77	68.98
0.0300	6.02	17.37	36.88	57.65	69.38
0.0480	5.06	14.77	35.26	56.94	71.77
0.0550	4.82	14.11	34.85	56.76	72.36
0.0740	4.34	12.80	34.04	56.41	73.50
0.0840	4.16	12.29	33.73	56.27	73.93
0.1050	3.86	11.46	33.22	56.05	74.62
0.1160	3.74	11.12	33.01	55.96	74.90

and is recommended for use as a practical fit to pressurisation data.
(iii) The relationship between the pressure differential and the louvre angle is established and presented. ΔP is found to be proportional to $\frac{1}{\cos^4 \theta}$ and not directly proportional to the value of θ *per se*. It was also established that for $0^\circ \leq \theta \leq 45^\circ$, there is no appreciable pressure drop across the louvre system.
(iv) It can be deduced from the experiments that the flow through a small proportion of a louvre system area is representative of the flow through the louvre system as a whole, the main discrepancies being the magnitude of the values obtained from the data rather than the principles involved.

6.7 Limitations of the Experiment

(i) The measurements are only for wind incidence of approximately 90° (i.e. normal) to the plane of the wall on which the louvres are placed.
(ii) The measurements are restricted to smooth wooden louvres with dimensions of 100mm in breadth and 5mm in thickness with a gap of 95mm between the louvres when they are perfectly horizontal (i.e. 0°).
(iii) The measurements for 90° vertical angle is only approximate at best due to the fact that there is always a small overlap between the louvres as θ approaches 90°. Therefore the angle is never exactly 90°. Secondly there is always a small gap between the louvres through which infiltration takes place and this is what gives rise to the high pressure drop at low flow rate. In any case if the angle is exactly 90° and there are no gaps between the louvres, then the situation is a wall opaque to airflow and there would be nothing to measure. Usually louvres are not used at this angle except to keep out rains and cold winds at night especially during the harmattan season.

6.8 Conclusion

This chapter presented an investigation of the airflow characteristics through a modulated louvre system and culminated in the development of some airflow models through louvres, bringing to a conclusion the section of the study dealing with scale model experimentation. The next chapter presents the planning and backgrounds to the thermal simulation studies.

Chapter 7

Thermal Simulation Studies

7.1 Introduction

In this chapter the details of the planning and layout of the thermal simulation studies are presented. The chapter begins by touching upon the basic modes of heat transfer as relevant principles upon which the thermal considerations of a building are based. Thereafter the need for thermal modelling of buildings was established and some existing thermal models were briefly looked at with a view to selecting a suitable model for the study. Some details of the chosen thermal model were also presented especially with regard to its thermal and solar control and/or shading concepts. The realities of shielding in terms of solar control were discussed and a simulation methodology developed for the study taking due cognisance of the weaknesses of the model. Finally the main parametric studies that were undertaken were highlighted.

7.2 The Modes of Heat Transfer

Heat transfer through a building fabric and within the enclosed living spaces takes the form of one or more of three basic modes, namely conduction, convection and radiation. These are covered in many basic heat transfer texts such as Holman (1976), Kreith (1973), Incropera and DeWitt (1981). Whatever the heat transfer mode, temperature difference is the main reason for the flow of heat between one point and another. No detailed study of any of these modes of heat transfer is intended here. This area of study is so vast and complex that only a little glimpse can be given in order to stay within the scope of this study.

7.2.1 Conductive Heat Transfer

Conduction is the mode of transfer of heat energy within a body, or between bodies in contact, or within stagnant fluids, by virtue of the *interaction* between the constituent particle, (molecules or free elections) which are in different pedestals of energy as a result of temperature gradient. The rate of conductive energy transfer per unit area is proportional to the normal temperature gradient i.e. according to Fouriers Law,

$$q = -kA\frac{\delta T}{\delta r} \tag{7.1}$$

where q is the heat transfer rate (W),
K is the thermal conductivity of the material (W/m°C),
and $\frac{\delta T}{\delta r}$ is the temperature gradient in the direction of the heat flow. The minus sign enables the second principle of thermodynamics to be satisfied i.e. heat must flow down hill on the temperature scale.

An efficient estimation of the conductive heat transfer through the building fabric, the heat storage in massive elements, the heat flux at their surface and the corresponding surface temperatures are vital for both the design of new passive solar buildings and the analysis of measured performance of existing ones. The quantity of heat stored in the massive elements influences the building's long term performance, and the heat flux at the surfaces of high thermal capacitance elements and the corresponding surface temperatures has a great impact on the efficiency with which the stored heat is used to warm the living spaces (e.g. heat stored in massive adobe walls, during the day being radiated into the indoor environment during the cold nights).

7.2.2 Convective Heat Transfer

Convection may be considered as a mixed mode mechanism which can be best referred to as *conduction with fluid flow*, because in addition to the molecular motion within the fluid, energy is also being used as a result of the bulk motion of the fluid. The convective heat transfer process is very complex which makes its accurate computation very challenging (Bejan, 1984). The overall effect of convective heat transfer from a plate in contact with air (fluid) in freestream motion, is aptly expressed by Newton's Law of cooling which is expressed as

$$q = hA(T_p - T_f) \tag{7.2}$$

where q = rate of heat transfer (W),
h = heat transfer coefficient W/m^2 ^{o}C),
T_p = temperature of the plate (^{o}C),
T_f = temperature of fluid, (^{o}C) and
A = surface area of plate (m^2).
Thus the heat transfer rate is a function of the overall temperature difference between the plate and the fluid and the surface area. The convection heat transfer is also dependent upon the viscosity of the fluid (which influences the velocity profile and hence the rate of energy transfer in the region near the wall) and the thermal properties of the fluid (its thermal conductivity, specific heat capacity and its density).

Although the analysis of convective heat transfer is complex generally, the case of convective heat transfer from enclosed building surfaces is even more so due to the spatial complexity and time dependences of the boundary conditions. The convective heat transfer models in most building thermal simulation models have been developed for idealised surfaces and geometries, (smooth surfaces are mostly used), while one or more simplifying assumptions are employed. In reality however, surfaces within enclosures are neither always smooth isothermal nor adiabatic. Their boundary conditions change temporarily and spatially, (see Kawaji, 1987). Also many models use a combined convective and radiative coefficients which may introduce substantial errors in some particular situations (Buchberg, 1971). The absorption of energy through objects in the space is very difficult to model, and only close approximations can be made in such cases.

7.2.3 Radiative Heat Transfer

Radiation can simply be said to be the transfer of energy in the form of electromagnetic waves. In this process, the internal energy is converted into electromagnetic waves at the surface of a body (solid or fluid) and then these waves travel through one or more media until the energy is again converted, whole or in part, back into internal energy at the surfaces of an intercepting media. Electromagnetic radiation that is propagated as a result of a temperature difference is called thermal radiation. It has been shown (Holman, 1974) that a perfect or ideal radiator or *blackbody* emits energy at a rate proportional to the fourth power of its absolute temperature. Hence when there is radiation heat exchange between two bodies, the net heat exchange rate is proportional to their temperature difference raised to the fourth power (Stefan - Boltzmann law of thermal radiation) and is expressed as

$$q = \delta A(T_1^4 - T_2^4) \tag{7.3}$$

where δ is the Stefan Boltzmann constant and is equal in value to 5.669 x 10^{-8} W/m^2K^4, and A is the area (m^2).

For "*non blackbodies*" like glossy painted wall surfaces or polished metals which do not radiate as much energy as the blackbody, the emmissivity factor F_E is introduced into equation 7.3 to take account of the "gray" nature of such surfaces. Also account is taken of the loss of some radiation to the surroundings by introducing the "geometric view factor" F_G because not all the radiation leaving one surface will reach the other since electromagnetic radiation travel in straight lines. Introducing both these factors to equation 7.3 would give

$$q = F_E F_G \delta A(T_1^4 - T_2^4) \tag{7.4}$$

However, these functions are not independent of one another as the above equation seemingly portrays. The methods of solving for radiative heat transfer, the implementations of which are tedious and time-consuming have been published for a relatively long time, unlike the case of convective heat transfer, (see for example the ray tracing and radiosity network methods in Siegel (1973), Siegel and Howell (1981), and Hottel and Sarofim (1967).

All the above modes of heat transfer have been briefly touched upon and may be found detailed in many standard texts of heat transfer. In most cases, all three modes of heat transfer are present in any one situation. For example, the heat conducted through a wall may be removed from the surface by a combination of both convection and radiation (Figure 7.1). The energy balance equation would give:

$$\left(-KA\frac{dT}{dY}\right)_{wall} = hA(T_w - T_f) + F_E F_G \delta A(T_w^4 - T_s^4) \tag{7.5}$$

where T_w = wall surface temperature (°C),

T_f = fluid temperature (°C), and

T_s = surrounding temperature (°C).

Practical situations such as this call for a thorough knowledge of all three modes of heat transfer for accurate modelling of the thermal performance of a building.

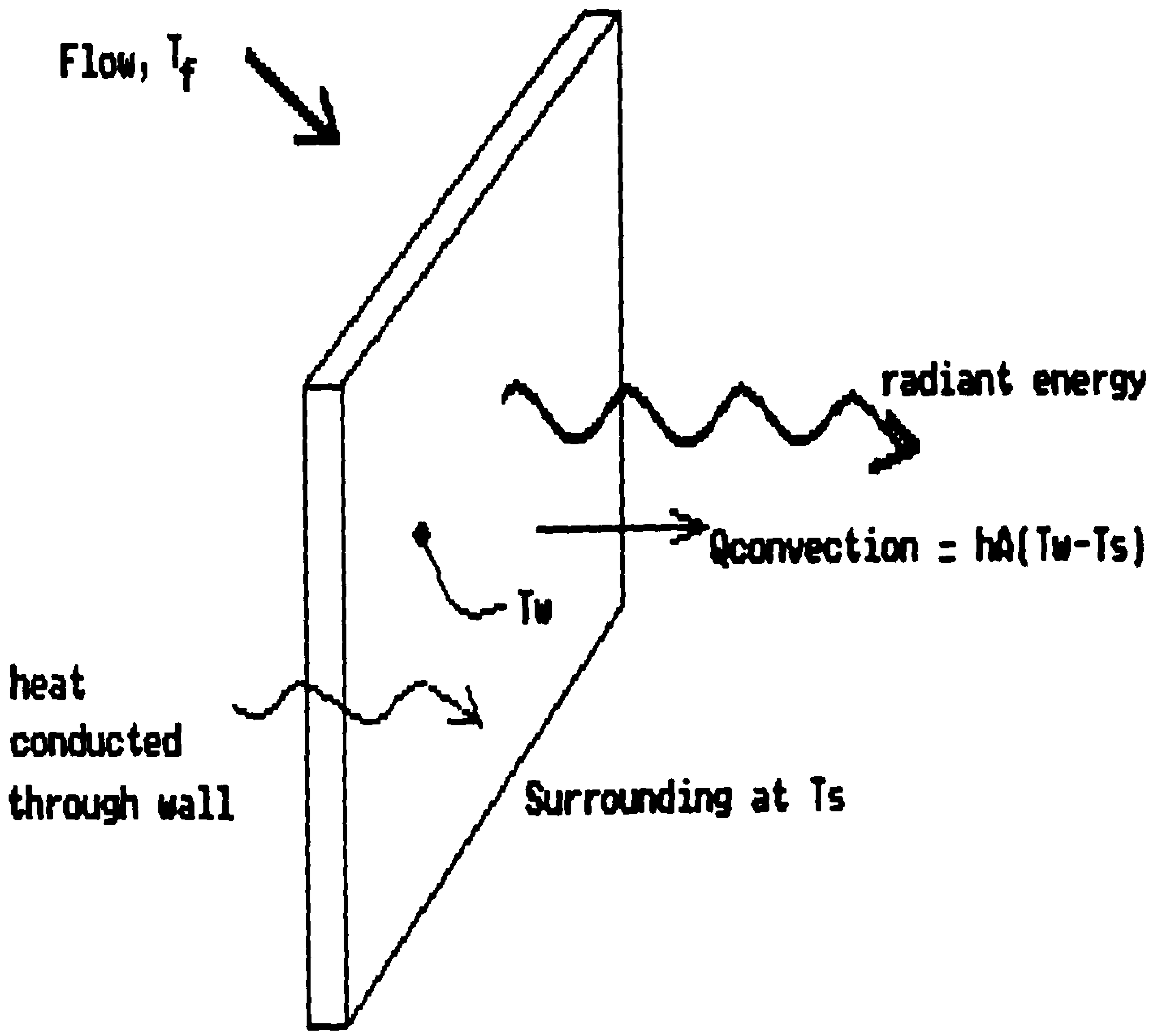


Figure 7.1: Heat flow through a wall.

7.3 Building Thermal Modelling

7.3.1 The need for Thermal Modelling of Buildings

To achieve the objective of designing energy-efficient passive solar buildings, designers must be able to relate the physical properties of the building to its thermal performance via accurate energy transfer models. Since low-energy buildings are designed to be used with a minimum of mechanically powered systems, it is imperative that every detail of heat transfer within the building be properly accounted for, at the design stage since the task of ameliorating poor performance after the building has been built is not only difficult but very costly. The *knowledge* of the performance of existing and proposed designs of passive solar buildings in terms of energy and cost, is therefore a very essential information for the design team. This information can be obtained by several means.

The first, and the most expensive and the least feasible approach, is to construct each passive solar design full scale, in a chosen climate and monitor its performance under varying weather conditions and other parameters. In any case, apart from the cost, it is impracticable to substantiate the thermal performance of low-energy buildings by basing the facts on a small number of constructed and monitored buildings which do not represent the extensive matrix of building types, occupancy and climatic variations. Building thermal modelling is therefore recommended for assessing thermal performance (Lebens, 1981).

The second and much less costly approach is the use of reduced scale models, such as the Los Alamos Test Cell variety which measures about 2m x 2m x 3m high. This cannot obviously be expected to give as realistic and reliable results as for the first approach above.

The third approach and least expensive is the use of computer-based accurate, realistic, reliable and validated thermal models to simulate the energy performance of the building with desired changes of variables such as climate location, occupancy, and options of design typology, building form, use of materials and so on. Such thermal simulation models should be capable of accurately and dynamically handling the following processes (Clarke, 1985):

(i) The transient conduction of heat through the enclosure envelope and therefore the associated lag and thermal storage effects.

(ii) The time-dependent sensible and latent gains from occupants, lights, process-

ing equipment etc and the relative split of these gains into radiant and convective portions which will dictate how they are delayed in time by the system.
(iii) Infiltration, natural and controlled ventilation, and inter-zone air movement.
(iv) The effects of shortwave solar radiation impinging on exposed external and internal surfaces.
(v) The longwave radiation exchange between exposed external surfaces and the sky vault and the surroundings.
(vi) The corresponding longwave radiation exchange between internal surfaces.
(vii) The shading of external opaque and transparent surfaces as caused by surrounding buildings as well as a variety of facade obstructions.
(viii) The mapping of moving insolation patches from windows to internal receiving surfaces.
(ix) Time varying convection and, perhaps, other system thermophysical properties.
(x) The essential link between controller location and type, plant characteristics and interaction point(s), and properties and operation of the building system.
(xi) Effects of moisture.

7.3.2 Types of Thermal Simulation Models

Common to most if not all thermal simulation models are the following caveats which must be borne in mind:
(a)assumptions of simplifying boundary conditions,
(b) the use of idealised geometries and surfaces,
(b) the use of combined and/or fixed value coefficients and other assumptions that would enhance the flexibility of the model.

The main differences between existing thermal models lies partly in the manner in which they mathematically treat the complex thermal network of a building (which embodies convective, conductive, radiative and heat storage processes) and partly on the degree of sophistication and realism imbibed in the thermal computation methods. These methods may broadly be classified (Clarke, 1985(b)) as (a) steady-state; (b) simple dynamic; (c) response function; numerical; and (d) electrical analogue.

The **steady-state** methods are those in which variation in the value of parameters *with time* is not considered and therefore cannot *realistically* deal with the *dynamic* thermal response of a building and with many of the energy flows occurring within it, nor can they accurately model the effect of solar gains, casual gains, longwave radiation exchanges operation of equipments etc. (see Clarke, 1977). Consequently these models are being increasingly "out-classed" by the more realistic dynamic simulation models which address the dynamic performance of a building, and of which there are several categories.

The **simple dynamic** methods are based on regression techniques applied to the results of multiple parametric runs of more powerful models. Their results are often reducible to simple relationships or presented in graphical or tabular form.

The **response function** method uses time-domain response function, or frequency-domain response function methods with specified boundary conditions to solve the partial differential heat equations that govern the flow of heat within the building.

The **Numerical** methods use finite difference and finite element techniques to solve the complex differential thermal equations. The finite difference method is the one that is used in most building thermal simulation models. They have been used to first estimate the effective thermal properties of high thermal capacitance elements (Balcombe and Hedstrom, 1980) and then to calculate surface heat flux and at storage. Finite difference formulations have found extensive thermal analysis codes because they have the advantage of ease of coding, and compatibility with simulations techniques used in simulation codes. The main drawback of the method is that it is a **discretization** technique. Both time and space must be discretized with the questions of accuracy, stability and computation time. The temperature distributions must be calculated at each time step in order to advance to the next step and there are inherent errors in obtaining the surface heat flux from the calculated temperature. Furthermore, the view is commonly held that a finite difference algorithm is specific to the problem for which it was developed (Kahwaji, 1987(b)).

The **electrical analogue** methods use electrical analogue devices which apply the analogy between electrical flow and heat flow) to study complex heat flow phenomena. Used mainly as a research tool, they enable long-time simulations to be done within a short elapsed time.

7.3.3 Selection of a Thermal Model

In general terms, and as a consequence of the preceding discussions, the extant building thermal simulation models represent a wide range of flexibility, complexity and accuracy levels. Many models exist. As far back as 1979, Burgess (1979) reviewed 46 thermal models. Table 7.1 shows details of models which participated in the 1978-1980 validation exercise of the International Energy Agency. Only a few of the lot could stand as contenders as *"passive solar"* models. Based on results of a SERI (1980) studies and some other reviews, Littler (1982) derived a table of some of the widely used models that could, as at that time, be considered as prime contenders as *passive solar* models (Table 7.2) and the attributes of several short-listed models namely ESP, BLAST, DEROB, and SUNCODE which were considered as potentially capable of handling passive systems accurately.

BLAST was based on the response factor method, which would not be suitable for simulating large diurnal changes of conductance in massive elements. However version 3.0 of BLAST was written to meet the demands of the US Passive Solar Programme and had been validated against the Los Alamos Test Cells. But its simulations are very slow, and it ran on CDC machine.

As for **DEROB**, some of the over shadowing routines were unreliable for *large areas* of glazing and its predictions were reassuring for energy but poor for temperature (with errors greater than 5K). Also it was expensive to run.

ESP which was developed at ABACUS in Strathclyde University was written as a very versatile but nevertheless a general-purpose building thermal simulation model and not particularly for passive solar design. The multizone version is costly to run. Moreover the model was not validated against very good experimental data from test cells. However it has very good graphics output facilities and through continuing improvements, is definitely going to be greatly enhanced.

SUNCODE was specifically written for passive applications but was designed to fit on a minicomputer and therefore has self-imposed restrictions. However SUNCODE and the one-zone model SUNCAT were to be later refined, enhanced and extended to produce an entirely new program, SERI-RES which thereafter was enthusiastically in use in the United States. Based on excellent reports from Solar Energy Research Institute (SERI) on SERI-RES, the model was selected as one of those to be evaluated and possibly selected for the UK passive

Table 7.1: The IEA Annex 1 and 4 participant programs (1978-1983) (From Clarke, 1985)

Program Name	**Organisation**
Annex 1	
ATKOOL	W S Atkins Group, UK
OFFICE	Electricity Council Research Center, UK
THERM	British Gas Corporation, UK
HTB	UWIST, UK
ENPRO	Faber Computer Operations, UK
ESP	University of Strathclyde, UK
ANTS	Pilkington Flat Glass Ltd, UK
ECBE'75	American Gas Association, USA
SCOUT	Gard Inc, USA
DOE2	Lawrence Berkeley Laboratory, USA
ECUBE3	American Gas Association, USA
MS	Reid Crowther & Partners, USA
JULOTTA	Swedish Council for Building Research, Sweden
VENTAC	AB Svenska Flaktfabriken, Sweden
DOE2	EMPA, Switzerland
WTEO1	TNO, Holland
LPB1	University of Liege, belgium
Annex 4	
AMBER	Faber Computer Operations, UK
ATKOOL	W S Atkins Group, UK
DOE2	EMPA, Switzerland
ENCO2	Pilkington Flat Glass Ltd, UK
ESP	University of Strathclyde, UK
LPB1	University of Liege, Belgium
TEMPER	CSIRO, Australia
THERM	British Gas Corporation, UK
WTEO1	TNO, Holland

Table 7.2: Features of energy modelling and features of four energy models (from Clarke, 1985)

TOPIC	ESP	BLAST	DEROB	SUNCODE
Designs				
Direct gain	Y	Y	Y	Y
Attached sun space	Y	Y	Y	Y
Thermosiphon	Y	Y	Y	Y
Roof space collector	Y	Y	Y	Y
Double envelope	Y	N	1	N
Mass wall (vented)	Y	Y	Y	Y
Mass wall (unvented)	Y	Y	Y	Y
Under floor rock bed	Y	Y	Y	Y
Physical problems				
Air/heat movement by convection or by fans	Y	Y	Y	Y
Infiltration	Y(2)	2	2	2
Solar radiation mapping around spaces	Y	Y	Y	N
Variable glass emissivity	Y	N	Y	Y
Variable room colour	Y	Y	Y	Y
Effect of furnisings	1	1	1	N
Air/temperature stratification	Y	N	Y	N
Movable window insulation	Y	Y	Y	Y
Isothermal and non-isothermal storage	Y	Y	Y	Y
Phase change walls	Y	Y	N	Y
Isolated storage	Y	3	Y	Y
Adequate handling of beam radiation	Y	Y	Y	Y
Adequate treatment of sky temperature	N	N	N	N
Weather input Complete 'set' supplied	Y	Y	Y	Y
Daylighting	Y	Y	Y	N
Surface temperatures for comfort assessment	Y	1	Y	Y
Validation	4	4	4	4
Documentation	V	P	G	V
Graphics input	V	N	V	N
Building input via digitising tablet	Y	N	N	N
Building input format	5	5	6	3
Continuing improvement	Y	Y	Y	Y

1: with difficulty 2: by schedule 3: see reference 4: tested in a number of validation exercises 5: Cartesian 6: standard shapes Y: yes N: no V: very good P: poor G: good.

solar energy program. Within the comparative studies by the Commission for European Community Passive Solar Program and that of the Energy Technology Support Unit (ETSU) of the UK Department of Energy, it soon became apparent that SERI-RES was

(a) easily transferable between different computer types,

(b) well-documented, fast, easy to use, and does not require too large a memory space,

(c) well written, coherent and potentially easily modifiable.

The program was therefore selected and refined for the Performance Analysis Project set up by the ETSU. The refined and enhanced version of SERI-RES (version 1.2) was a versatile thermal model which was found to be capable of handling the issues involved in this study to a reasonably high degree of reliability. Moreover it was *available* and fairly well documented.

7.4 Strengths and Weaknesses of the Enhanced Model

7.4.1 Strengths

The advantages of SERI-RES over other multizone dynamic simulation models include the following:

(a) Speed - SERI-RES remains the only model that is fast enough for annual simulation parametric studies on a small main frame or mini computer.

(b) The input is *simple*, though not "user friendly" by the going standards

(c) The outputs are flexible and a variety of *very specific* output may be selected by the user.

(d) It has a portable code, has been implemented on a number of different machines and is accessible for scrutiny.

(e) It has been included in validation studies in both the USA and the UK, ranging from analytical tests at SERI (Wortman, *et al*, 1981) comparison between measured and predicted data in a SERI test house (Judkoff et al, 1983) and a Canadian test room (Judkoff, 1985) to the BRE-SERC Joint Validation Project (Allen and Bloomfield, 1985) and extensive use on the IEA Task VIII on Passive and Hybrid Solar and Low Energy Buildings.

Although comparisons between models does not necessarily indicate which models are more accurate, the presence of significant discrepancies may help to identify model errors or limitations. No significant problems have been reported with SERI-RES to date.

7.4.2 Weaknesses

Just like any other model, SERI-RES has its limitations and these include the followings:

(a) The input process is slow and error prone. Maximum care has to be taken and checking of building descriptions is a difficult and slow process.

(b) The output is produced only in tabular form whereas graphical outputs are required for presentations.

(c) In the actual simulation, there is more approximation in SERI-RES than in more detailed models. The effects of sky radiation and ground conduction are not treated in detail and there are limitations in the modelling of window systems (especially internal windows) and shading. The main approximations include that of energy flow within the building envelope. The *distribution* of solar radiation within each zone is assumed to remain constant with time and the user has the option of specifying the distribution. The use of a single star network to model the convective and infra-red radiation heat transfer in each zone may lead to errors in the temperature predictions.

Furthermore air movement through zones and its thermal implications are not treated, and there is no explicit treatment of *comfort* as such, although the zone air temperature which is essentially an environmental temperature, is a reasonable indicator of thermal comfort.

In comparison to other *more detailed* models such as BLAST, DOE-2, ESP, HTB2, NBSLD and TAS which model convection and radiation separately SERI-RES has the advantage of its speed over these other models that are relatively much slower and non of which, explicitly includes such facilities as Trombe walls and rockbins as does SERI-RES.

And in comparison to simpler models such as BREDEM (Building Research Establishment), CALPAS (Berkeley Solar Group, California), the Solar Load Ratio Method (Los Alamos Scientific Laboratories) and SPIEL (Ecotech Design, Sheffield), one finds that non of these models are intended primarily as design tools and that non of them has the facilities and flexibility of SERI-RES more details of which are presented in the subsequent section.

7.5 The SERI-RES Thermal Simulation Model

7.5.1 Introduction

SERI-RES is a building thermal simulation model originally developed mainly for residential buildings but can also be used for light commercial buildings. It was written by Larry Palmitter and Terry Wheeling of the Ecotope Group, Seattle, Washington on contract to the US Solar Energy Research Institute (SERI). Although SERI-RES was an outgrowth of a series of earlier thermal analysis programs written by the authors such as SUNCAT and SUNCODE the large number of enhancement included in the program makes it an entirely new product unique in itself.

The method of analysis used in the program is simulation. A thermal model of the building created by the user is translated into mathematical form by the program and the required mathematical equations are then solved repeatedly at time intervals of one hour for the period of simulation, which is usually one year. The mathematical representation of the building is a thermal network with non-linear, temperature dependent controls and the mathematical equations are solved by a combination of forward finite differences, Jacobian iteractions and constrained optimisation techniques.

7.5.2 Limitations of the Original Version of SERI-RES

Perhaps the main limitation of the original version of SERI-RES (Version 1.0) was its lack of detailed treatment of heating and cooling equipment. This was probably a deliberate choice since the program was designed mainly to simulate the dynamic performance of the *building envelope* in great detail and generate the heating/cooling loads for the equipments to supply in order to maintain comfort conditions without any attempt to simulate the actual performance of the heating/cooling units. SERI-RES was not aimed at commercial buildings where the most pressing issue is the *types and combination of equipments* that would provide the best comfort for the lowest operating costs. The energy requirements of residential buildings is dominated by the performance of the building itself. This is particularly true for passive solar buildings.

Secondly, neither the accurate and/or realistic analysis of earth-sheltered or underground buildings nor the accurate analysis of air envelope or double-shell structures are fully addressed. Although it is possible for the sophisticated user to obtain reasonable results for these cases with the constructs provided. To do this would require analysis of experimental data to provide values for the parameters which the program uses.

Furthermore the program does not model the longwave or infra-red radiation transfer in between surfaces nor does it model the actual distribution of incoming solar radiation to the various surfaces in a room, although the user may allocate the solar gains among the different surfaces.

Lastly, the shading of external surfaces and windows were treated mainly for a general situation. Assumptions are made of overhangs of infinite length with finite dept and vertical offsets, and of side fins of infinite length, with finite dept and height both of which may shade a surface of any tilt or orientation. Provision is also made for shading by far away objects which obstruct the skyline but no provision was made for specular or diffuse reflectors.

These limitations have been addressed but enhancements and refinements have been made to the original version of SERI-RES in the new versions 1.1 and 1.2 which were developed within the UK Passive Solar Program.

7.5.3 SERI-RES For The UK Passive Solar Program

The current version of SERI-RES (version 1.2) which is one of the main thermal simulation models adopted for use in the UK Department of Energy's Passive Solar Research and Development Programme is essentially the original version with enhancements and refinements (Haves and Littler (1987), Haves (1987)). The enhancements and refinements were carried out to meet the specific needs of the Passive Solar Design Programme and to improve the use of the model, the realism of its predictions and therefore its credibility. Before version 1.2 was released, there was the interim version 1.1 which contained some level of enhancements but version 1.2 is the final document which may therefore be regarded as the UK version of SERI-RES. Both of them were produced by the Polytechnic of central London under contract to the Energy Technology Support Unit (ETSU) of the Department of Energy.

Some of the enhancements include the addition of menu-driven full-screen editing facilities, additional modelling facilities such as daylighting, artificial lighting (Haves, 1986), interior windows between conservatories and conventional zones, the use of reduced weather data sets of 3,5, or 7 days per month (Short Reference Years) (Loxsom, 1986) enhanced scheduled output, and an expanded shading facility. Also the geometrical input to SERI-RES may be optionally generated by SCRIBE-MODELLER, an architectural modelling program written by Ecotech Design Group of Sheffield. SCRIBE was originally developed to generate graphical input to another thermal simulation model, SPIEL, written by Cedric Green at Sheffield University (Green, 1983). Hence no significant changes to the original program was necessary for its use with SERI-RES. In addition the generated output file of SERI-RES may be viewed graphically by VIEW, a program also developed by Ecotope Group. Selected parts of the output may also be reformatted to be read by Lotus 1-2-3 and symphony micro computer spreadsheet programs, including the use of *macros* to facilitate the ease of use of the program (Huddy, 1985).

7.5.4 Thermal Calculations in SERI-RES

SERI-RES thermally conceptualizes a building as one or more zones with each zone having independent solar inputs and independent heating, cooling, and ventilation equipment, rockbin and thrombe wall. Zones may be connected by walls, pure conductances or even by thermostatically controlled fans. The program uses a single zone temperature mode which is centrally located within the specified zone. All heat transfer paths are connected to this central temperature mode, and walls are connected by a constant heat transfer coefficient to the central mode. This heat transfer coefficient includes both radiative and convective heat transfer enabling the program to avoid the calculation of radiation view factors and the solution of radiosity matrix at each time step.

The central zone temperature is not the air temperature as referred to by the program but is rather a conductance - weighted average of the surface temperatures or, in effect, a close approximation of mean radiant (environmental) temperature. The central zone temperature may differ significantly from the true air temperature.

For each specified zone and its idealised HVAC system with its specified capacities and setpoint SERI-RES calculates the envelope heat flows by conduction and infiltrations, calculates solar gain and accounts for casual gains. Then it determines whether the specified temperature setpoints can be satisfied and then calculates the zone temperatures and loads. These calculations are performed sequentially a number of times per hour, unlike several other models which essentially generate simultaneous solutions per hour.

Walls are coupled to the zone central air node as explained earlier, by a constant heat transfer coefficients which include the combined effects of convection and radiation heat transfer. In each timestep, the wall heat fluxes are updated and then the zone temperatures and HVAC loads are calculated by means of a heat balance equation on the central node of each zone. New node temperatures are calculated in each wall independently by means of explicit finite difference approach. Conduction through the walls is calculated using explicit finite differences while convective and longwave radiative transfer within each zone is modelled using single star network which yields a zone temperature that is as explained earlier, the environmental temperature. HVAC operation is controlled on the basis of the nodal temperature of each zone. Where there are pure resistance connections between zones, then iteraction is used to attain consistency between the zone temperatures and the interzone heat flows at each timestep.

The choice of a sequential solution technique necessitated the use of the explicit (forward) finite difference method for the calculation of wall conduction, since this require fewer arithmetic operations per timestep than other methods. This is essential for the speedy execution of simulation runs. However SERI-RES owes most of its speed advantage over other multi-zone models to the modelling of internal convective and longwave radiative transfer by a single star network in each zone. The star network approach avoids the need to simultaneously solve the heat balance equations for each inside surface of a zone. In addition, the combination of star networks for radiation and convection into a single star network whose central node temperature is the environmental temperature further simplifies the calculation of the zone temperatures and HVAC loads. In spite of this simplification, no significant errors have been reported in modelling heat inputs which are either purely radiative or convective. Errors due to combining convective and radiative transfer is small unless a substantial purely radiative or convective heat is accompanied by a high ventilation rate (greater than 15 air changes per hour) (Haves, 1985 (b)).

7.5.4.1 The Order of Thermal Calculations

Table 7.3 shows a fragment of the core of the calculations order which are performed for each hour of the simulation run. First the solar energy received on the exterior surfaces and transmitted into the building are calculated from the values of solar intensity in the weather data files. These solar intensity values are held constant for each timestep within the hour. The solar gains are then distributed within the specified zones and, where required, infiltration rates are calculated for each zone as a function of current windspeed and the difference between ambient air temperature and zone air temperature at the end of the previous hour.

Then for each timestep within the hour, new nodal temperatures are first calculated for each main wall defined, based on the node temperature on either side at the end of the previous timestep. Then the energy flows from each zone air node to the elements considered as having "fixed" temperatures are accumulated.

Next, if direct energy flow paths (e.g. non-mass walls or loss coefficients) are defined between any interior zones, iteraction is used to calculate new zone temperatures. In this case energy flows between zones are first calculated based on the old zone air temperatures after which the HVAC and fan controls setpoints are used to set equipment operations and calculate new zone 'air' temperatures. This process is repeated until the new air temperature for each zone differs from the previous value by less than a user-defined constant. When no iteraction is required, the equipment controllers calculate the new air temperature directly.

A second level of iteration is used when Trombe walls with natural convection air flow is specified. Here the airflow rate through the Trombe is calculated as a function of the most recent temperatures for the zone air node and the Trombe air gap node. A new air gap temperature is then calculated based on the old zone air temperature can be held constant by iteracting this calculation of airflow rate and air gap temperature.

Table 7.3: The core of thermal calculations in SERI-RES.
(Source: SERI-RES Manual, Version 1.0)

```
For hour:- 1 to 24 do

  begin
  calculate solar input variables;
  distribute solar gains within zones;
  calculate infiltration rates for each zone;
  For timestep:- 1 to number of timesteps do

    begin
    calculate new wall node temperatures;
    accumulate fixed energy flows: to mass walls,
    passively to rockbins, and to ambient and ground;
    Repeat

      For zone:- 1 to number of zones do

        begin
        If zone has Trombe then

           Repeat

              calculate Trombe thermocirculation;
              calculate Trombe air gap temperature;

           Until air gap temperature converged;

        accumulate interzone energy flows;
        end;

      set fan and rockbin charge fan operation;
      set HVAC equipment operation;
      calculate new zone air temperatures;

    Until zone air temperatures converged;
    calculate wall surface temperatures;
    set rockbin discharge operation;
    calculate rockbin node temperatures;
    end;

  calculate zone humidity ratios and cooler latent
  loads;
  end.
```

After determining new air temperatures for all zones, new wall surface temperatures are calculated. For mass walls, these are based on the new air and new wall node temperatures. When a mass wall has a node at the surface of the wall, (i.e. no thermal resistance from the mass wall surface to the first node), the surface temperature is taken as the first node temperature. For massless walls, the surfaces temperatures are calculated as a function of the new air temperatures on either side of the wall.

Then, if *rockbins* are defined, they are checked to find out if all or part of the zone's heating load can be supplied by the rockbin. After the operational state of the rockbin's change and discharge fans are determined, new node temperatures for the rockbin are calculated.

Finally, if requested for, new zone humidity ratios and cooler latent loads are calculated once at the end of each hour.

7.5.4.2 Zone Air Temperature

The Energy balance equation defining the zone air temperature is stated as:

$$\begin{aligned} Q_{wall} + Q_{pass} + Q_{tc} + Q_{zone} + Q_{window} &\quad + \\ Q_{amb} + Q_{grd} + Q_{inf} + Q_{solzon} + Q_{appli} &\quad + \\ Q_{fan} + Q_{rock} + Q_{heat} - Q_{vent} - Q_{cool} &= 0 \end{aligned} \tag{7.6}$$

where Q_{wall} = energy flow between zone and enclosing mass wall (including Thrombe wall);

Q_{pass} = passive (non-controlled) energy flow between zone and rockbins connected to it;

Q_{tc} = Trombe wall thermocirculation energy flow;

Q_{zone} = energy flow between zones through explicitly defined interzone loss coefficients or through massless walls between zones or through internal windows between zone;

Q_{window} = energy flow through windows;

Q_{amb} = energy flow to ambient air through explicitly defined loss coefficients to ambient or through massless walls between the zone and ambient;

Q_{grd} = energy flow to user-specified "ground" node through explicitly defined loss coefficients to ground or through mass-less walls between zone and ground;

Q_{inf} = energy flow due to infiltration;
Q_{solzon} = total solar gain to zone;
Q_{appli} = user-specified appliance gain;
Q_{fan} = energy flow between zones by fans;
Q_{heat} = heating energy supplied to zone;
Q_{vent} = energy removed from zone by venting;
Q_{cool} = energy removed from zone by cooling.

7.5.4.3 Thermal Flow Through Walls

The wall thermal response is determined by approximating the wall construction with thermal network, which is then solved by explicit finite differences or Eulers method. Various constant coefficients which define the nodal network layout and additional precalculation coefficients are determined within the program. Several nodal layout are considered and these include:
(1) a pure thermal resistance,
(2) a single node with internal thermal resistance (i.e. finite conductivity),
(3) a single node without internal thermal resistance (i.e. a pure thermal capacitance layer or "infinite" conductivity), and
(4) a multi-node layer with internal resistance.

Various types of combinations of layers to produce the thermal network for each wall are considered within the program.

Interior Node Temperature The thermal network model contains only nodes with heat capacity in the wall interior. The governing equations of these internal nodes is derived from an instantaneous heat balance on the node, given by the expression:

$$dS = dL + dR \tag{7.7}$$

where dS = rate of heat storage,
dL = rate of heat gain from left node, and
dR = rate of heat gain from right node.

The differential equations (one for each) are solved by explicit finite differences or Euler integration. These brief discussions are intended to provide a general overview of the concept of thermal analysis used in SERI-RES and is by no means exhaustive. Detailed algorithms accompanying the discussions can be found in Chapter 6 of SERI-RES version 1.0 user manual.

7.6 Solar Control Concept in SERI-RES

7.6.1 Solar Thermal Effects

The thermal effect of solar energy on buildings is extensively addressed by SERI-RES. The program uses 2 hourly solar intensity values from the weather data file (the global horizontal and the direct normal intensities respectively) to calculate the solar input variables taking cognisance of the solar geometry and other parameters. The solar intensities are held constant at an hourly input value for each time step within the hour. The sun's position is determined for each sunlit hour by calculating its altitude and azimuth angles. The global horizontal radiation is split into direct and diffuse components.

The intensity of the direct component of solar radiation on each exterior surface by calculating the angle of incidence. For the diffuse component the view factors from the building surface to the skydome and to the ground in front of the surface are determined. Sky diffuse radiation was assumed to be isotropic (i.e. evenly distributed) in the original code but in version 1.2, Hay's anisotropic sky model was used. The ground is assumed to be an infinite horizontal plate with a uniform user-defined reflectivity.

For direct and diffuse solar energy incident on each window, the fraction transmitted through the window and the thermal gain due to energy absorbed *within* the window are separately calculated. The window model which the program authors took from Willier (1977) assumes that the window is composed of one or more layers of identical glazing (up to a maximum of 4 layers). The model uses the calculated angle of incidence for the direct solar and a user-defined constant angle for the diffuse component. The transmitted and absorbed fractions for both direct and diffuse components are reduced by any shading coefficient specified for the window.

The fraction of energy absorbed within the window, or longwave radiation, that flows inwards is used as thermal gain to the central air temperature node for the zone in which the window is located. All shortwave window-transmitted solar energy is assumed to be evenly distributed within the zone without consideration of the zones internal geometry. But where there are transparent elements between zones, a fraction of the window-transmitted energy in a given zone may be redirected to another zone to account for interzone solar transfer. The total shortwave solar energy in each zone may be divided into 3 fraction

(a) the fraction which is removed from the zone due to outward reflection from the window;

(b) the fraction which is immediate thermal gain to the zone air temperature node to account for energy striking lightweight surfaces; and

(c) the fraction which strikes the wall defined within the zone.

In the case where solar energy is incident on any interior wall containing one or more main nodes SERI-RES automatically apportions a fraction of the solar energy which is used as an immediate thermal gain the nodal air temperature of the zone while the remainder is absorbed by the first mass node. For solar energy incident on massless walls, the energy is divided into thermal gains to the zones nodal air temperatures on either side of the wall.

7.6.1.1 Internal Distribution of Solar Radiation

The factors that affect the magnitude and distribution of solar radiation in each zone are

(1) the *shading coefficient* for each window in the zone,

(2) the *solar transfer* and *reverse transfer* in the interzone data section,

(3) the *fraction to air* and *fraction lost* in the zone section.

As stated earlier, the solar heat gain has two components:

(a) the shortwave solar radiation transmitted through the window, and

(b) the inward flowing fraction of the solar radiation absorbed in the glazing layers. This goes directly to the zone air temperature node, while the sum of all the transmitted shortwave solar radiation is multiplied by the shading coefficients and the "fraction *lost*" factor. The "fraction lost" lost accounts for the shortwave radiation reflected back through the glazing and lost, and can be regarded as the effective cavity absorptance of the zone, (typical values range from 0.05 to 0.10). The remaining shortwave radiation is then distributed within the zone by several mechanisms, with due consideration for interzone transfer if any. A fraction of the available shortwave solar radiation may be put immediately into the zone air temperature node by using the "*fraction to air*" values in the zones data section. This fraction enables account to be made for that portion of the solar radiation absorbed by non-massive objects and converted more or less instantly into heat. (Typical values of "fraction to air" values range from 0.10 to 0.25).

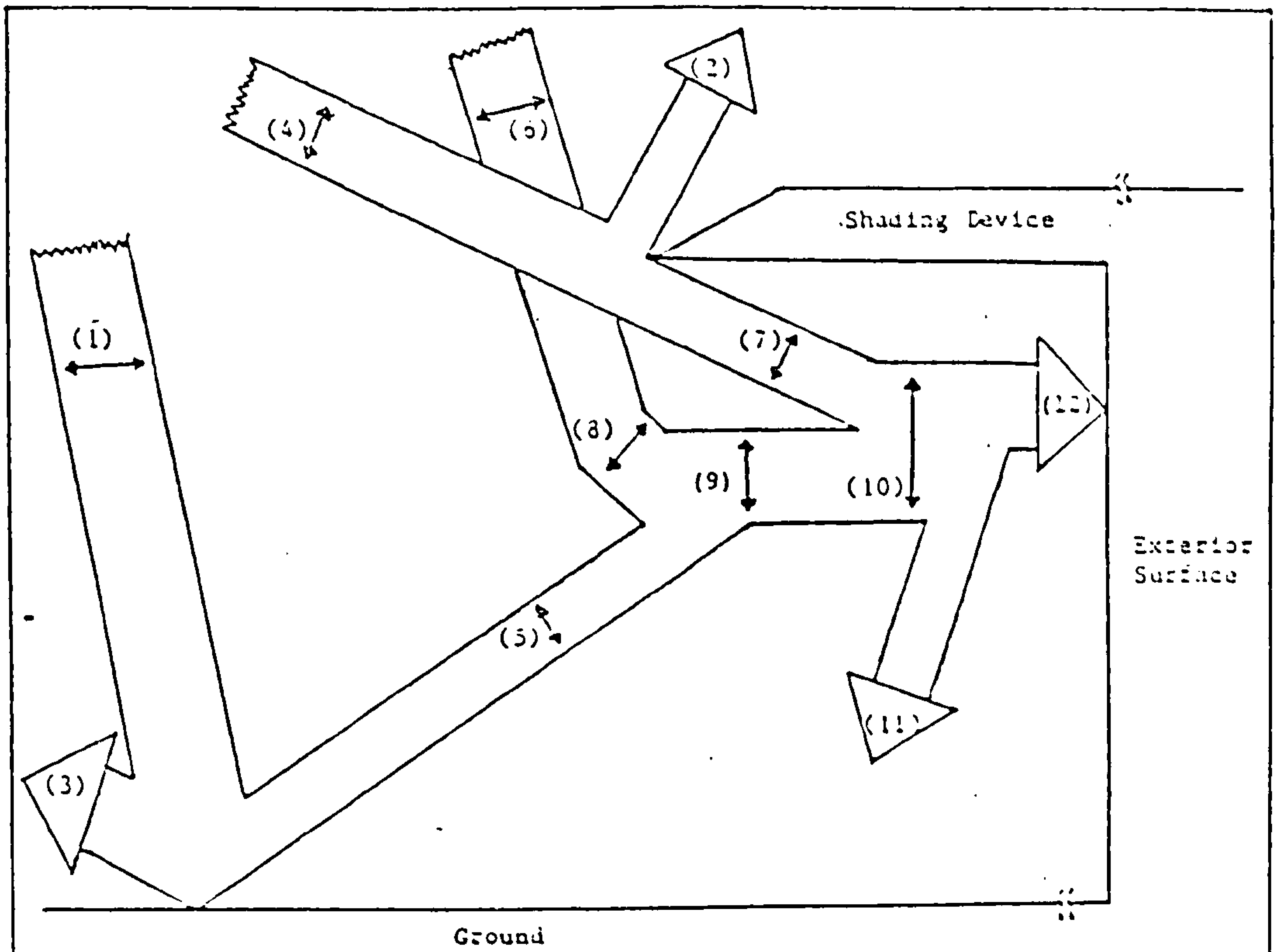
The remaining shortwave radiation after all the above considerations have been met, is distributed onto the walls in 2 ways:
(1) The first method distributes all the radiation in the walls in proportion to their areas, and
(2) If more detail is desired a "fraction absorbed" may be associated with each surface by specifying the solar coefficient for each wall. For this level of detail, the sum of the *solar coefficients* for wall surfaces facing each zone, plus the "*fraction lost*", plus the "*fraction to air*" must be equal to one. The interior distribution of solar radiation is illustrated on figure 7.2

7.6.2 The Shading Concept

SERI-RES version 1.0 only treated simple shading of the direct (beam) radiation by simple overhangs and side fins. Shading of the diffuse sky radiation was not considered. The overhangs are assumed to be of infinite horizontal extent, parallel to the shaded surface while the side fins are assumed to project to infinite height (see figure 7.3). Therefore overhangs that extend only a limited distance on either side of the window cannot be correctly modelled.

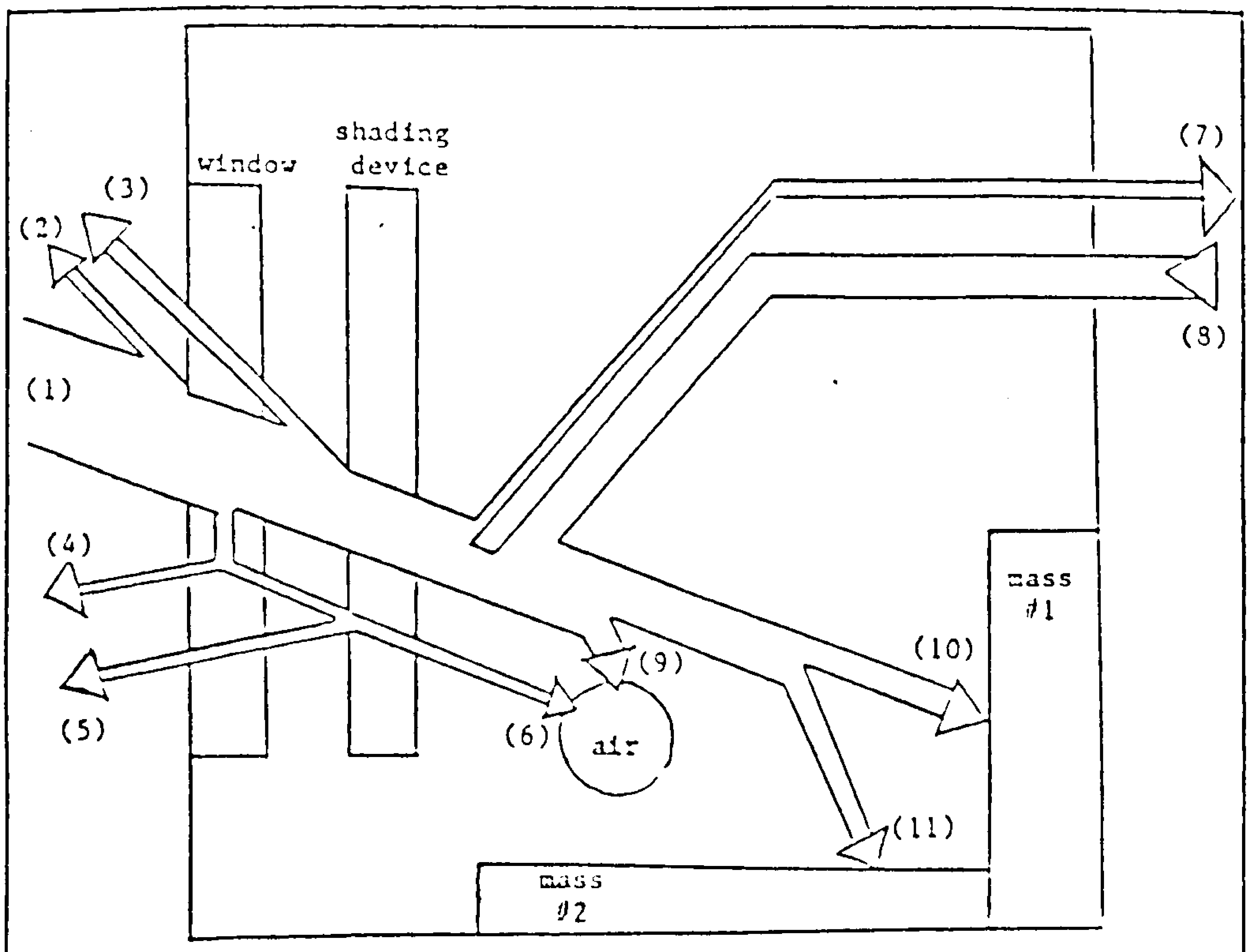
However version 1.2 has extended the shading treatment to enable the modelling of the shading associated with courtyard geometries. This was done by the introduction of 2 new shading elements:
(a) the "*screen wall*" which has a horizontal top running parallel to the shaded surface, and
(b) the "*side screen*" which has a horizontal top running perpendicular to the shaded surface.

The screen wall and the side screen may be of different heights and the side screen may be offset from the edge of the shaded surface. These extensions to the shading algorithm were said to have been tested using the SCRIBE solar projection facility SOLPRO which allows a 3-Dimensional wireframe model to be viewed in projection as seen from the sun. This enabled the correction of errors in



(1) Total Horizontal Radiation. Input from weather data.
(2) Direct Solar Lost by Shading. Calculated by program.
(3) Ground Scattering. Calculated by program.
(4) Direct Solar on Tilted Surface (Unshaded). Calculated by program.
(5) Ground Diffuse on Tilted Surface. Calculated by program.
May also be reduced by sidefin shading (not shown).
(6) Sky Diffuse on Tilted Surface (Unshaded). Calculated by program.
(7) Shaded Direct Solar on Tilted Surface. Calculated by program.
(8) Shaded Sky Diffuse Solar on Tilted Surface. Calculated by program.
(9) Total Shaded Diffuse on Tilted Surface. Calculated as (5)+(8).
(10) Total Incident Solar.
See Fig. 2-5 for further effects on glazing systems.
(11) Reflection Losses. See (13) below.
(12) Solar Absorbed. Specified by user for each exterior wall
as a fraction of Total Incident Solar (10).

Figure 7.2a: Illustration of exterior distribution of solar radiation (Source: SERI-RES User Manual)



(1) Total Solar Incident on window.
(2) Reflection Losses from glazing layers.
(3) Reflection Losses from shading device.
(4) Outward flowing portion of solar absorbed in glass.
(5) Loss of inward flowing portion of solar absorbed due to shading device.
(6) Net inward flowing portion of solar absorbed in glass goes to air node.
(7) Shortwave solar loss to other zones.
(8) Shortwave solar gain from other zones.
(9) Shortwave to air node.
(10) Shortwave to mass #1.
(11) Shortwave to mass #2

Figure 7.2b: Illustration of the interior distribution of solar radiation
(Source: SERI-RES User Manual)

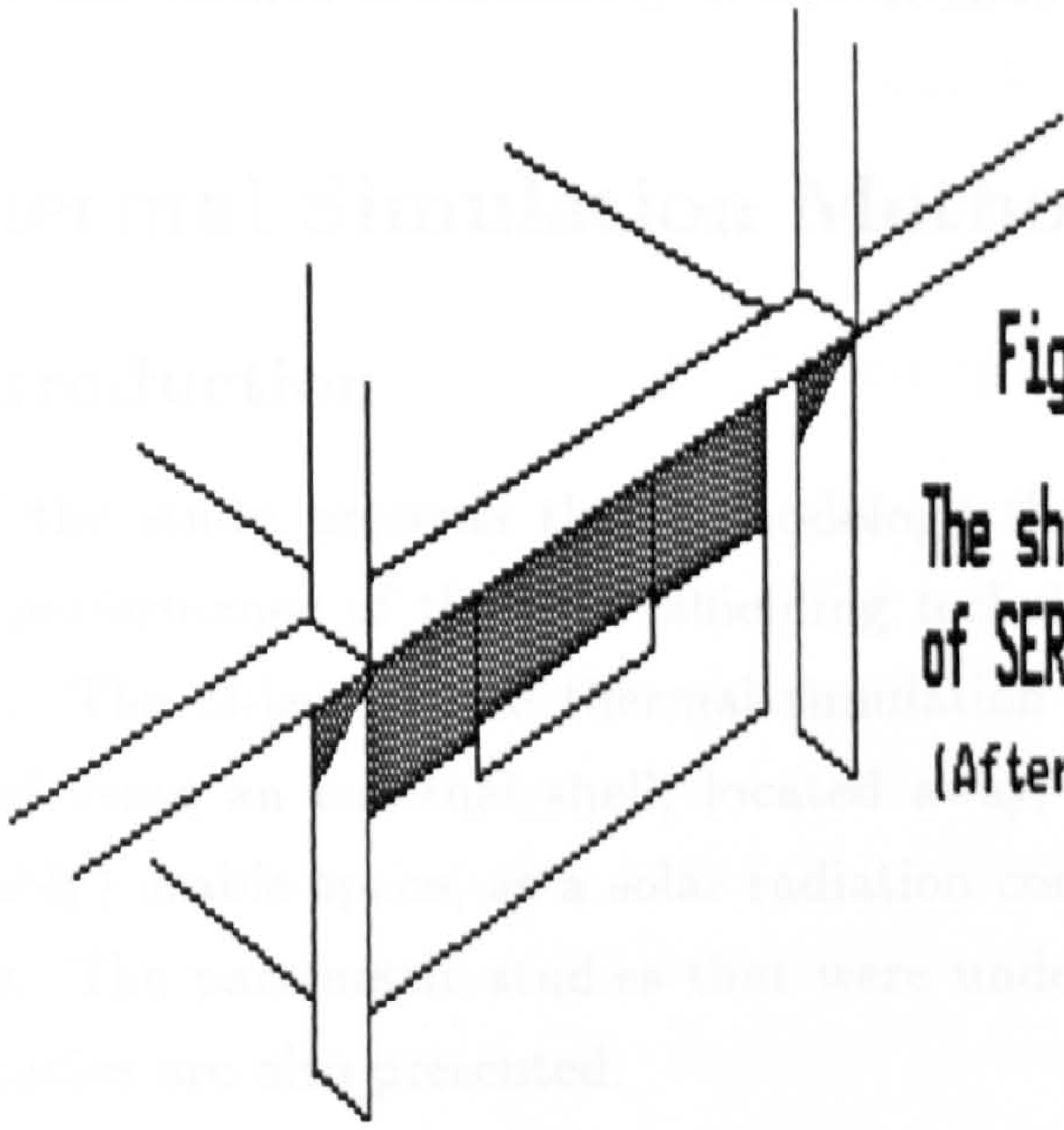


Figure 7.3a

The shading concept of SERI-RES version 1.0.

(After Hawes, 1987)

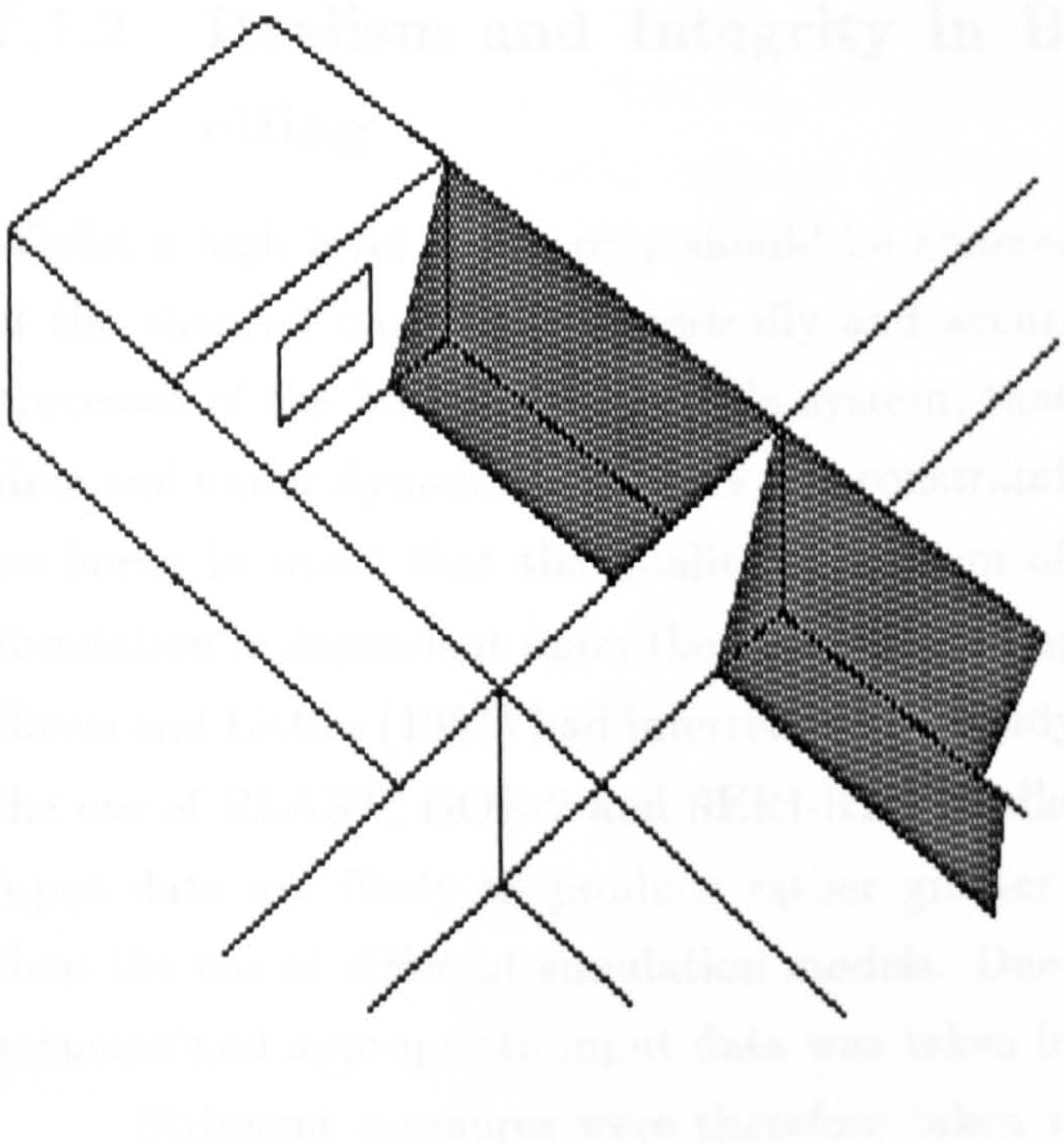


Figure 7.3b

The additional shading elements in the enhanced SERI-RES version 1.2.

(After Hawes, 1987)

the algorithm and verified the accuracy of the extended algorithm.

7.7 Thermal Simulation Methodology

7.7.1 Introduction

This part of the study presents the methodology that was used to investigate the thermal performance of the solar shielding technique as put forward earlier in chapter 1. The object of the thermal simulation was to study the thermal implication of using an external shell, located away, from the present building by a (preferably) usable space, as a solar radiation control strategy for hot semi-arid climates. The parametric studies that were undertaken within the thermal simulation studies are also presented.

7.7.2 Realism and Integrity in Building Thermal Modelling

Whilst a high level of integrity should be adhered to and maintained on the part of the thermal model by numerically and accurately processing all the thermal processes of the building as a single system, that is fully connected in space and time and under dynamic influences and constraints, (Clarke, 1985 (c)) it must also be borne in mind that the quality or realism of the predictions of any thermal simulation is dependent upon the accuracy and appropriateness of the input data. Haves and Littler (1987) had inferred from a study at SERI in 1983 which included the use of BLAST, DOE-2 and SERI-RES (Judkoff *et al*, 1983) that variations in input data are likely to produce rather greater variations in model predictions than the use of different simulation models. Due cognisance of the importance of accurate and appropriate input data was taken in this part of the study.

Stringent measures were therefore taken to certify the accuracy of all relevant input data including the weather data. These included (a) using an accurate correlation s model in the computer program that generated insolation values (chapter 2), (b) certifying the dimensions, locations of building elements and their component parts, and reliability of the data of their thermo-physical properties, (c) a careful and accurate description of the parameters of the shielding technique to the program with fair and realistic assumptions, (d) carrying out *series* of pre-test simulations to correct any possible errors/mistakes before actual simulation runs began.

7.7.3 Description of the Shield to SERI-RES

The important issues to be addressed here were:

(a) How to effectively model the material of the shield if required,

(b) The description of the composition of the shield, its dimensions and configuration, and description of its *openings* in terms of size, distribution and configurations which would determine its porosity to diffuse radiation on the one hand, and to airflow on the other. It was also pertinent to state as to whether the openings on the shield are such that direct (beam) radiation can penetrate.

(c) The Input of the shield in the shading/solar radiation control context. In other words, this aims to provide answers to such crucial questions as

(i) Is the shield just an EXTERNAL WALL protecting the parent building or is it an *external boundary element*, defining a semi-outdoor space around the EXTERNAL WALL of the parent building?

(ii) Should the semi-outdoor buffer space defined by the shield be treated as a "courtyard" and the shield a "screen wall" in accordance with the SERI-RES definition of these terms in its shading facilities?

(iii) Is the shielded space an equivalence of a "courtyard" balcony without the "screen wall"?

7.7.3.1 The shield as an External Wall

SERI-RES does not have facilities for modelling the *material* of the shading device apart from the basic assumption of *concrete* overhangs and side fins. In the enhanced shading facility no provision is made for modelling the material and/or composition of the screen wall. In view of these limitations it was considered that the modelling of the *shielding material* should can only be done by describing the shield as an *external wall* to the program. In this wise, the shield may be specified as being composed of one or more layers of material. In this context, the external wall of the parent building loses its status as an *external surface.*

However, this approach is somewhat contradictory to the concept of shielding as earlier stipulated which primarily infers that the external wall of the parent building are the external surfaces exposed to solar radiation and, the shield is a shading device protecting it.

In any case this option enabled the buffer to be defined as a *separate zone* and the environmental parameters within it determined.

7.7.3.2 Plywood Slats as Shielding Elements

When the external shielding structure is considered as a wall, its openings (input as WINDOWS) are variable in size and dispensation depending on the material that is used and how it is used. For example since the basic material being used for the shield is plywood slats, which may be inclined at any desired angle, then it may either be described to the program as series of small *inclined* overhangs of a relatively small width or an equivalent very wide overhang with the same shading mask (see Figure 7.4).

Two problems arise here

(a) SERI-RES does not have provisions for the *inclination* of the overhang apart from its being perpendicular to the shaded surface.

(b) Describing the slat as an equivalent overhang even if this were possible, would fall short of the shielding concept since the overhang is a mere formal shading technique designed to intercept **direct** solar radiation and not the diffuse.

Betwixt these constraints the ideal option was to describe it as a continuous vertical screen membrane to the program while calculating the total openings between the slats (according to their angles of inclination) and this total openings size is described as a single opening to the program and as a measure of the distance between the screen membrane and the shield. The *'window'* on the shield is very thermally porous and was regarded as a highly ventilated airspace and therefore has a very high U-value (the highest possible U value allowed in SERI-RES, for accurate modelling, was input as the U-value for this 'window'. (see Table 22.9, CIBSE Guide A3). In architectural terms, adequate provision for airflow is therefore made, and since an *equivalent window area* has been exposed to the ambient, there is no discrepancy between actual design and building description input. If this approach was adopted, the notion of an *equivalent window area* would be a basic assumption used to simulate the *reality* of the situation. The distance of the hypothetical screen membrane from the position of the actual window on the

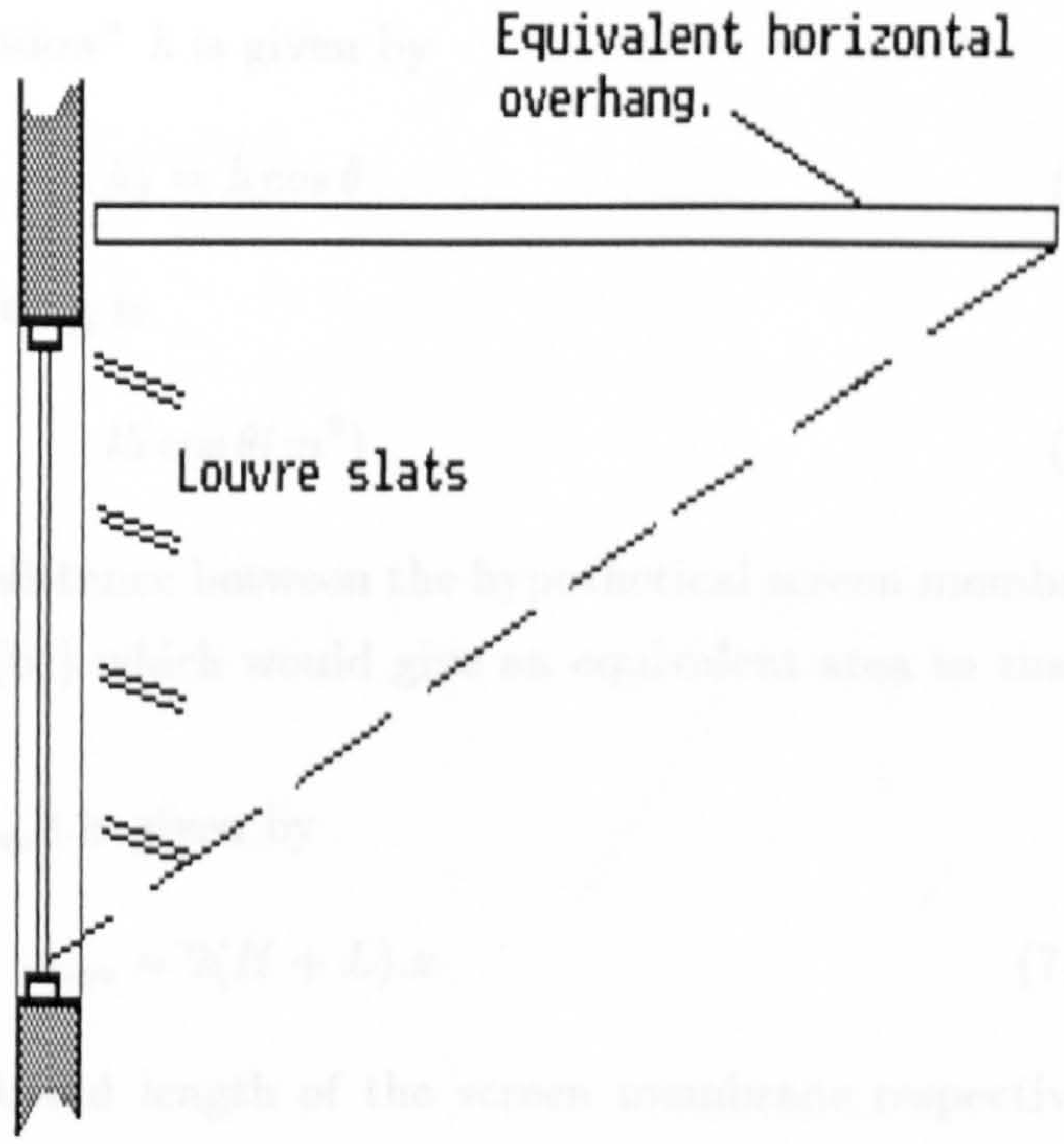


Figure 7.4 : An equivalent overhang to the louvres.

shield is determined as follows.

Let the length of the opening along the shield be l , Let the height of the opening on the shield be h *(m)* and let the louvres be inclined at θ^{o} to the horizontal (see Figure 7.5 (a)). When the Louvres are at inclination θ, from the horizontal, the effective height of the "window" h is given by

$$h_\theta = h\cos\theta \tag{7.8}$$

And hence the area of the opening is

$$lh\cos\theta(m^2) \tag{7.9}$$

Now let x (metres) say, be the distance between the hypothetical screen membrane and the shield (see Figure 7.5(b)) which would give an equivalent area to that of the window on the shield.

The equivalent area (A_{eqv}) is given by

$$A_{eqv} = 2(H + L).x \tag{7.10}$$

where H and L are the height and length of the screen membrane respectively. Therefore,

$$x = \frac{lh\cos\theta}{2(H + L)} \tag{7.11}$$

(with the assumption that the screen does not rest on the ground as in our case which is on the first floor of the building).

Where the screen wall rest on the ground, say on the ground floor, then x is accordingly given by

$$x = \frac{lh\cos\theta}{2H + L} \tag{7.12}$$

Regarding the external shield as a wall naturally enabled the buffer zone to be treated as a separate zone of its own and the internal environmental properties within it determined.

In this context, the shield will have been described as built. The lower and upper parts consists of 100mm thick concrete structure running all through its length. In between them are slats of covering material e.g. Luxalon flex or plywood. The variations in the porosity of the shield was modelled in terms of the variation of the angle of inclination of the louvres.

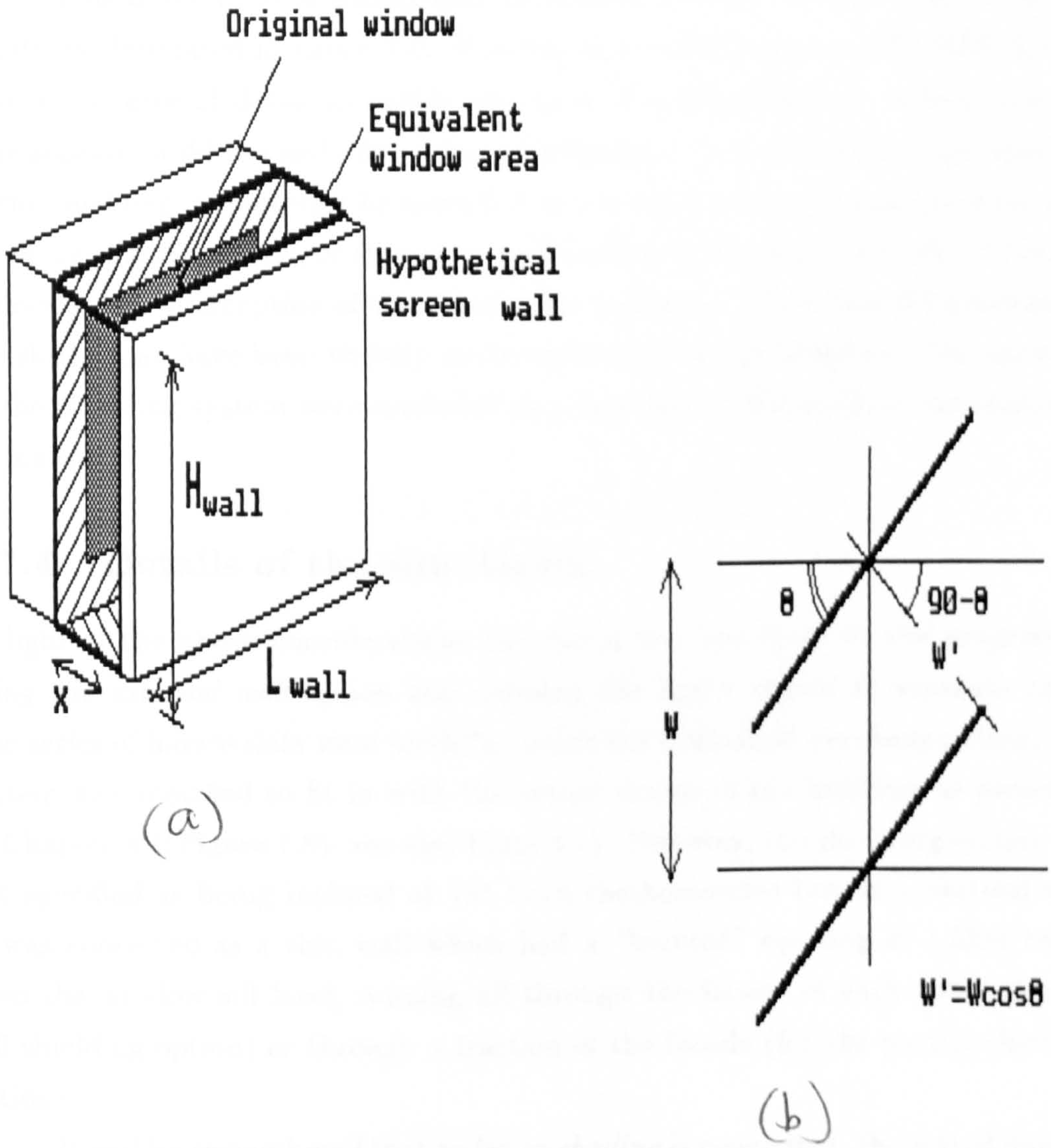


Figure 7.5: The concept of an equivalent window area exposed to the ambient.

This is the ideal situation that accurately models the shielding concept in reality as illustrated in figure 7.6. However it was found that SERI-RES did not have the degree of detail to enable the input of a hypothetical vertical screen to take account of diffuse and inter-reflected radiation. In this situation, the openings in the shielding system may be modelled as a normal window using the equivalent overhang shading option, or the screen wall facility of the thermal model. This only addresses the interception of the direct solar radiation. Therefore the efficiency of the shield may have been slightly under-estimated by the program. The openings in the shielding system were modelled as a function of the angle of inclination of its louvres.

7.7.4 Details of the simulation

In light of the above considerations the shield was described to the program by using the *external wall* option and defining the buffer spaces as separate zones. The series of louvre slats were modelled using the ***equivalent overhang*** option. The system was specified to fit in with the actual design of the building as presented in Chapter 4 ((Figure 7.8)- see also Plate 4.1). However, the shielding system was not specified as being inclined at 75° from the horizontal but as a vertical wall. It was conceived as a thin wall which had a "louvred" opening of 1.35m height from the window sill level, running all through the facade of each room (for the full shielding option) or through a fraction of the facade (for the partial shielding option)

It will be remembered that as far as ***shading*** is concerned, the actual number of the louvres across the opening is insignificant since any number of slats would have the same shading mask. However the number and configurations of the louvre slats is very important for daylighting considerations. In using the equivalent overhang option, the main comsideration was to find an equivalent overhang that can give the same shading mask as the louvres. The size of the derived overhang is a function of the solar altitude (h), the difference between the solar and wall surface azimuth (i.e. the horizontal shadow angle), the inclination of the surface, and the height of the opening.

However, there was the option of dividing the entire opening into a series of smaller openings, each with its own "little" overhang, which is probably a better

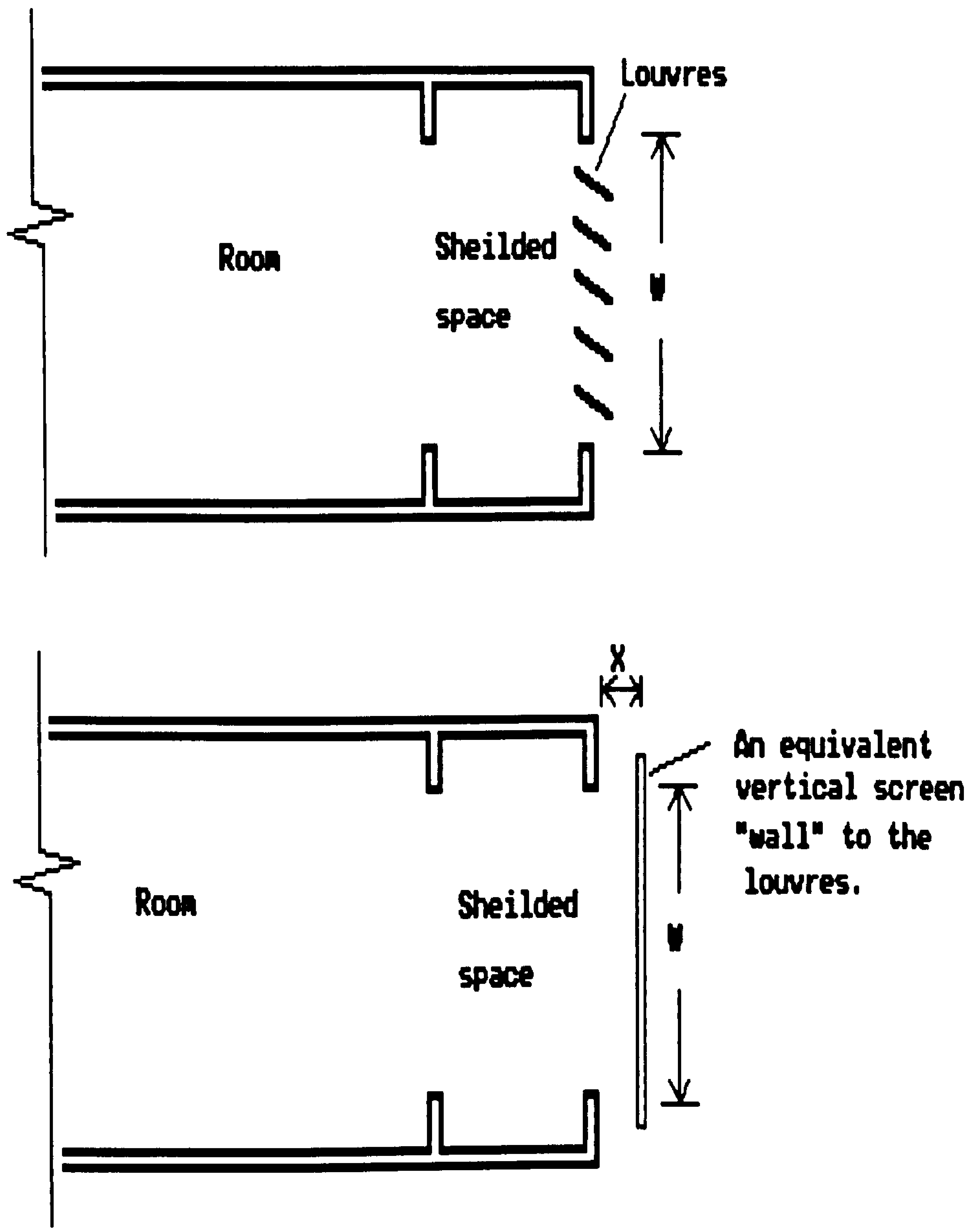


Figure 7.6: The hypothetical screen "wall" equivalent of a louvre system.

design option in reality. It was found that the size of the overhang for the whole opening equals the sum of the little overhangs. The option of the single overhang was adopted to minimise computer time. The shield was modelled at 2.5m away from the building facade, as defined by the buffer space.

7.7.4.1 The complete shielding option

In the case of the complete shielding of the building in which case all the facades and the roof were shielded, a roof buffer zone was created (Figure 7.9). It was bounded by a light roof membrane at the top (which may be regarded as a secondary roof), the usual louvre shielding system on the sides and the main roof of the parent building at the bottom. The roof shielding system was conceived to be 1.75m above the main roof.

Whilst the shielding system on the sides of the roof buffer enabled cross ventilation, the secondary roof membrane is analogous to a louvre system permanently in closed position, and therefore, impervious to both direct and diffuse solar radiation. This also means that maximum radiative heat loss of the parent building was not exploited for reasons explained ealier. In reality the roof shield can be designed as units of louvre systems whose slats can be closed at night and then each unit slided into position for maximum exposure of the parent building to the cool radiant night sky. There are many design options for this system to enable maximum exposure of the parent structure at night.

7.7.4.2 The inputs into the program

The inputs into the program were contained in the **weather file** and the **building description file**. The weather file contains inputs of the ***hourly*** values of direct normal insolation(KJ/m^2), global horizontal insolation (KJ/m^2), dry bulb temperature (°C), dewpoint temperature (°C), and wind speed (m/s).

The building description file contains details of the site and the building. The inputs with regards to these include:

The site:

Its latitude, longitude, elevation above sea level, the skyline profile, the ground surface reflectance, and ground temperature.

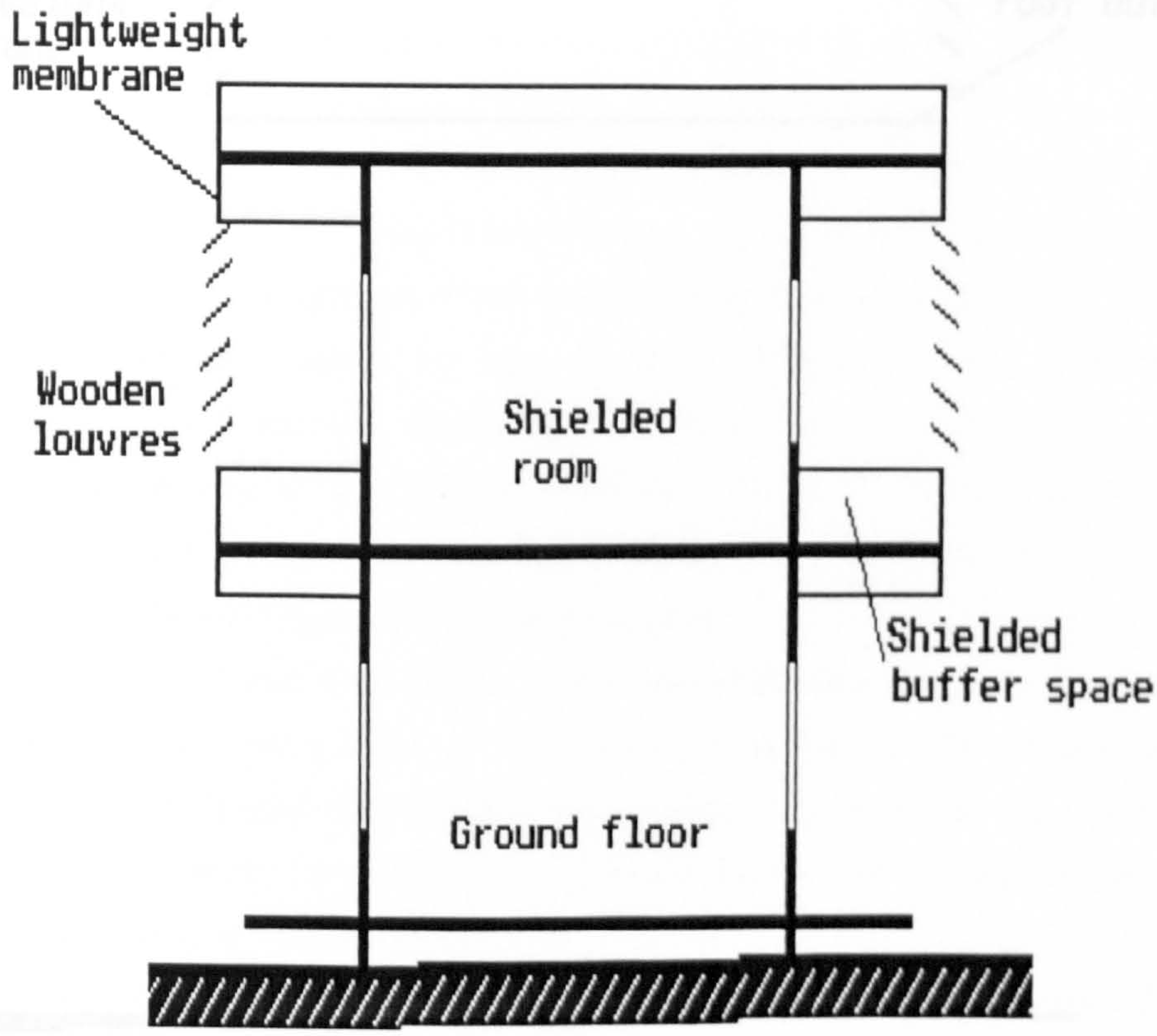


Figure 7.8: Simulation of the sheilding
technique : Full shielding of sides

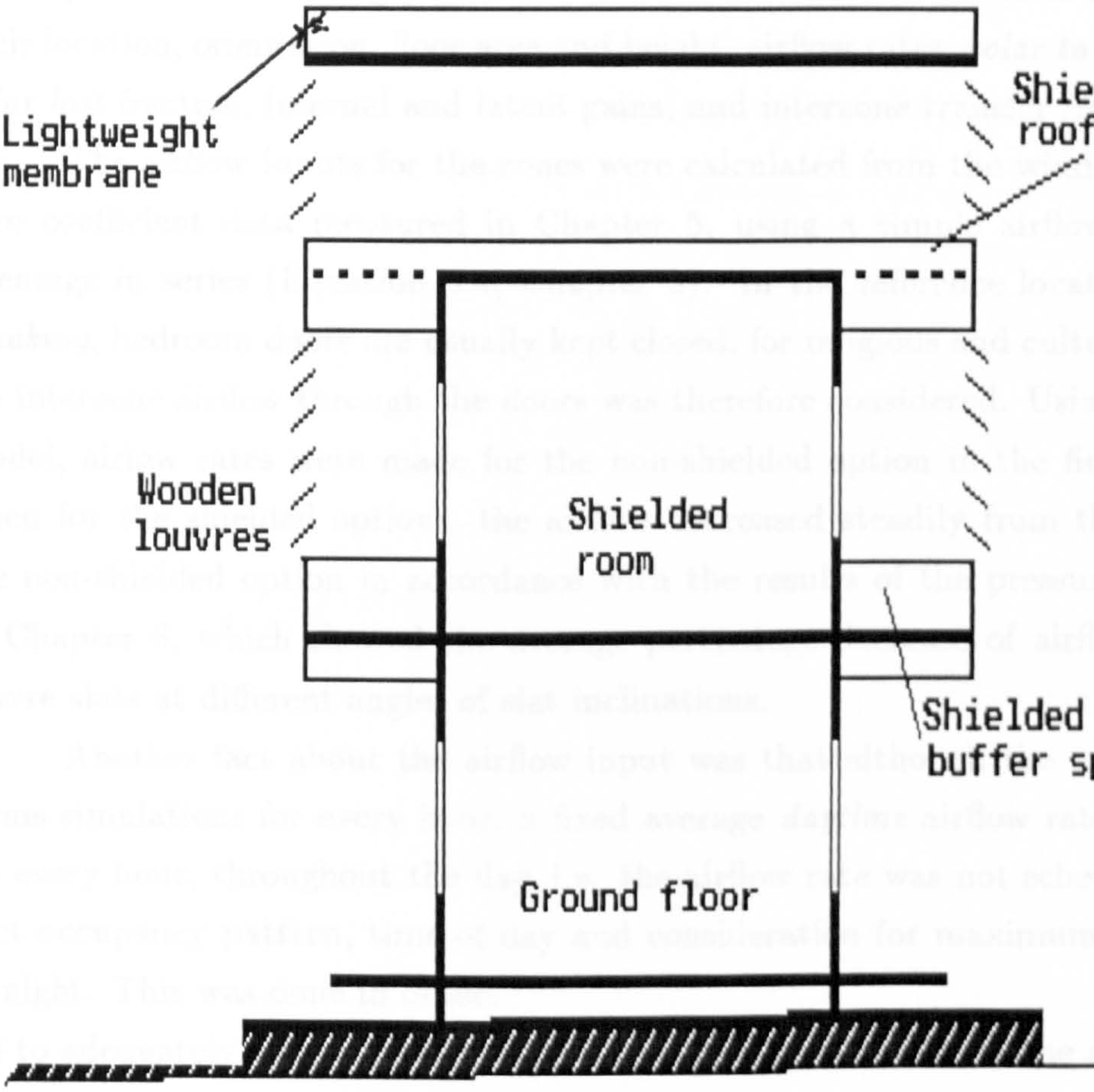


Figure 7.9: Simulation of the sheilding technique : complete shielding of building including the roof

The building:

The inputs of the building parameters include the different *zones* of the building, their location, orientation, floor area and height, airflow rates, *solar to air* fraction, *solar lost* fraction, internal and latent gains, and interzone transfer fraction.

The airflow inputs for the zones were calculated from the windtunnel pressure coefficient data measured in Chapter 5, using a simple airflow model for openings in series (Equation 3.4, Chapter 3). In the reference location, *strictly speaking*, bedroom doors are usually kept closed, for religious and cultural reasons. No interzone airflow through the doors was therefore considered. Using the above model, airlow rates were made for the non-shielded option in the first instance. Then for the shielded options, the airflow decreased steadily from the values of the non-shielded option in accordance with the results of the pressurisation test in Chapter 6, which showed the average percentage decrease of airflow through louvre slats at different angles of slat inclinations.

Another fact about the airflow input was that although the program performs simulations for every hour, a fixed average *daytime* airflow rate was input for every hour, throughout the day, i.e. the airflow rate was not scheduled to reflect occupancy pattern, time of day and consideration for maximum ventilation at night. This was done in order:
(a) to adequately neutralise any effect of the airflow variation on the results;
(b) to adequately isolate the effect of the shielding technique; and
(c) to sufficiently put the shielded building at a disadvantage for passive ventilation cooling at night by using the minimum (daytime) airflow rates for the night time as well. However it must be acknowledged that the *daytime* airflow values would neither indicate the extent of departures from those values nor reflect the actual conditions per hour. But this treatment is unlikely to lead to *significant* errors in the simulations and was therefore considered quite acceptable.

Hence the simulation results would reflect more of the average *daytime* thermal performance of the shielding option than either the night time or the overall 24-hour duration of the day for which natural ventilation was increased at night. It is envisaged that a better overall thermal performance of the system would be obtained if the shielding system's impairment of convective and radiative heat loss is minimised at night by adjusting the louvre slats accordingly.

Other building description inputs include:

1. the **wall, floor** and **roof** *structure*, with detailed specifications of the **material** of *each layer* of construction and their thermophysical properties which include the conductivity, density, specific heat and the thickness.

2. the **windows** and their sizes, location and type of glazing and its thermopysical properties which include the U-Value, shading and extinction coeficients, refractive index, the thickness and number of layers. In relation to the wall surfaces and the windows, a detailed description of the shading characteristics in terms of the types and locations of the shading devices must also be stipulated.

7.7.5 Parametric Studies.

Before full thermal simulation tests were carried out the building under study was simulated as built, for the period of rainy season to enable comparisons with the measured data as presented in Chapter 4. Thereafter studies were made for both the hot and the rainy seasons. These were as follows:
(1) In order to provide a base case, the building was first of all simulated without any form of shading as one would find in many buildings within the ancient city wall of Kano, although there, not concrete, but *adobe*, is used for the walls and roofs. This would provide the base against which all other options would be evaluated.
(2) Then the building was simulated with shading provided by concrete overhangs and sidefins.
(3) Next the building was simulated with shading provided by a balcony.
(4) Then the building was simulated with the shielding option in which the shielded space considered as a separate independent zone with an external shielding system.

Further studies of the performance of the shield by optimising the angle of the louvres were then carried out. Then the variations of the mode of shielding were examined vis-a-vis:
(a) Partial shielding of the facades only;
(b) Full shielding of the facades;
(c) Full shielding of the building including the roof.

7.8 Conclusion

All in all, this chapter presented the details of the planning of the thermal simulation studies while touching upon some relevant principles upon which the thermal considerations of a building are based. Some details of the chosen thermal model were also presented and a simulation methodology developed. The chapter also highlighted the main parametric studies that were undertaken. The results of these studies are presented and compared with the measured field data in the next chapter.

Chapter 8

Results of Thermal Simulation Studies

8.1 Introduction

The results of the thermal simulation studies as presented in this chapter represent in most cases the average daily and sometimes hourly values for the periods of simulation. Thermal modelling was carried out mainly for the hot season which is the most severe in terms of thermal discomfort. However simulations were also done for a part of the rainy season, typically the month of July to enable comparison with the measured data.

For brevity and economy of space only the results of some selected zones namely the shielded rooms within the building, are discussed. The primary attention was paid to the solar heat gain within the respective spaces and the air temperature therein.

Results were presented, for coherence, in accordance with the order of parametric studies carried out in the previous chapter. As mentioned earlier, two levels of thermal simulations were done. The first level dealt with solar radiation control options namely **(a)** overhang/sidefin shading,**(b)** balcony shading and **(c)** the shielding option. The second level dealt with the parametric studies with the shielding option viz-a-viz

1. The variation of the shielding aperture
2. The shielding of all sides of the building instead of just the partial shielding of the different *rooms*

KEY TO THE ABBREVIATIONS USED

NOSH	No Shading
OVH	Overhang
BALC	Balcony
PSS	Partial Shielding of Sides
FSS	Full Shielding of Sides
CSB	Complete Shielding of Building
SS-NE	Shielded Space - (North-East)
SR-NE	Shielded Room - (North-East)
SS-SE	Shielded Space - (South-East)
SR-SE	Shielded Room - (South-East)
SS-SW	Shielded Space - (South-West)
SR-SW	Shielded Room - (South-West)
SS-NW	Shielded Space - (North-West)
SR-NW	Shielded Room - (North-West)

Fig 8.1a: Mean Daily Solar Gain (MJ)
For Different Solar Control Options
(July)

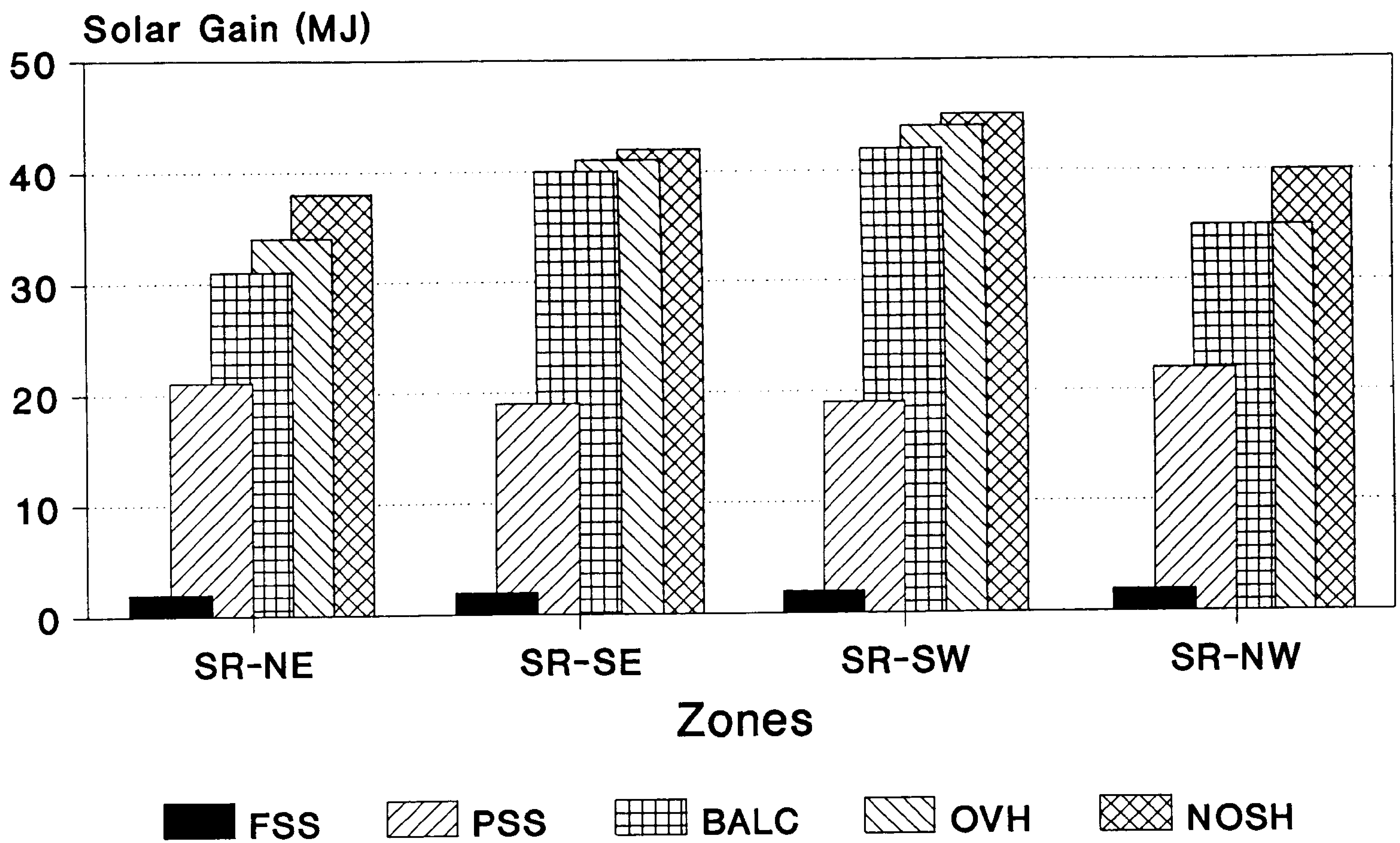
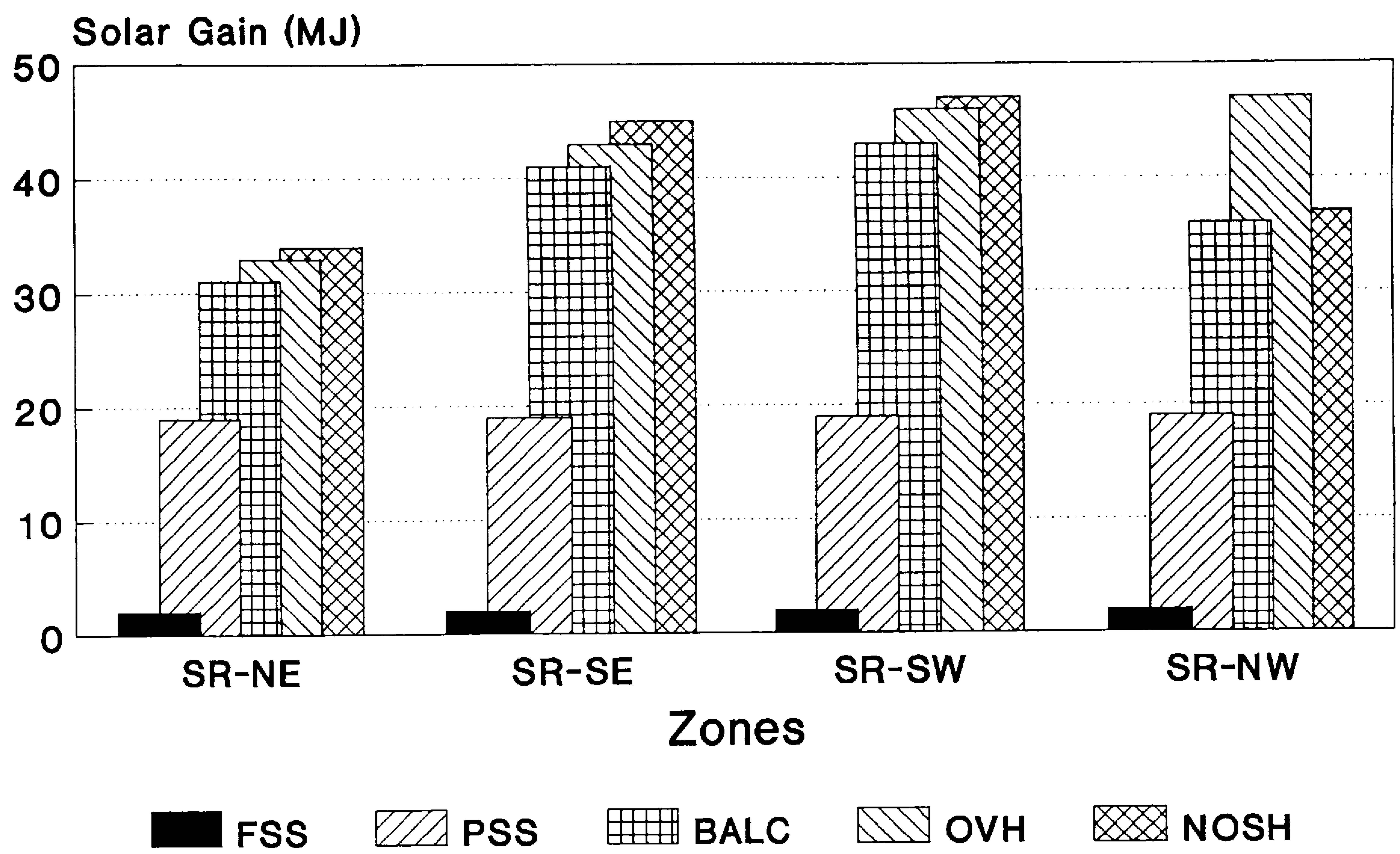


Fig 8.1b: Mean Daily Solar Gain (MJ)
For Different Solar Control Options
(April)



3. The complete shielding of the **whole building** including the roof.

Finally the results of the comparison between the simulated and the measured data were presented. Throughout the chapter, graphic illustrations, *Figures* were used to augment the discussion of the results. Precise details of the results can be obtained from the corresponding *Tables* grouped together at the end of the chapter. Whilst most of the tables are normal standard types, some have been designed specially to facilitate comparison between *groups* of data. Such tables include Tables 8.2(a,b) and 8.4(a,b) to 8.6(a,b) inclusive. In these tables the **base case** with which all other options are compared is centrally located while the various options are located above and below, beginning from the top left corner. This enables the data in the *base case* to be almost equidistant from the data on all the other options.

8.2 Solar Radiation Control Options

8.2.1 The use of overhang and sidefins

The use of overhang and sidefins for shading did not have any *appreciable* decrease in the overall solar radiation transmitted inwards (Figures 8.1(a,b), Table 8.1,). Table 8.1 shows that in July formal shading with overhang and sidefins decreased the average solar transmitted gain in the four rooms by 2.75 MJ (6.7%). They performed relatively poorly in the South-East and South-West oriented rooms. Their performances were relatively poorer during the hot season in which they reduced solar transmitted gain by only 2.5%.

However overhang and sidefin shading with constant ventilation rate throughout the day was found to *slightly* increase the indoor air temperature than if no shading was provided at all (Figure 8.2(a,b), Tables 8.2a and 8.2b,). This is as a result of the combined effect of the shading device. The overhang and sidefins may reduce direct solar radiation and the diffuse sky radiation but may increase the reflected shortwave radiation from the ground. The program calculates the quantity of the reflected shortwave radiation (*Subroutine SOLAR*) from the ground as part of the overall diffuse solar insolation on a surface. A proportion of the reflected ground diffuse insolation onto the lower surface of the overhang is further reflected off the overhang onto both the opaque and transparent parts of the fabric below

Fig 8.2a: Mean Daily Air Temperatures For Different Solar Control Options (April)

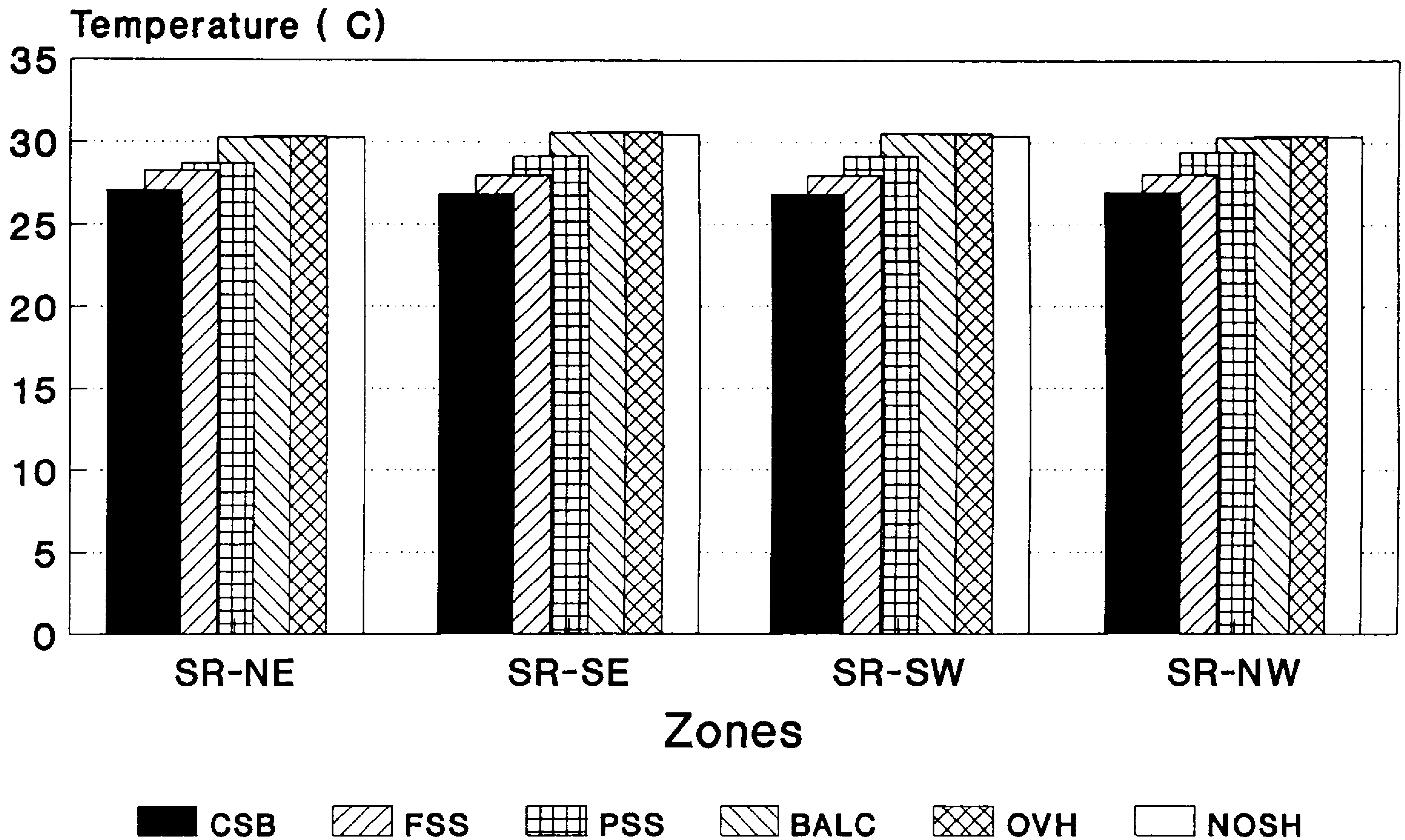
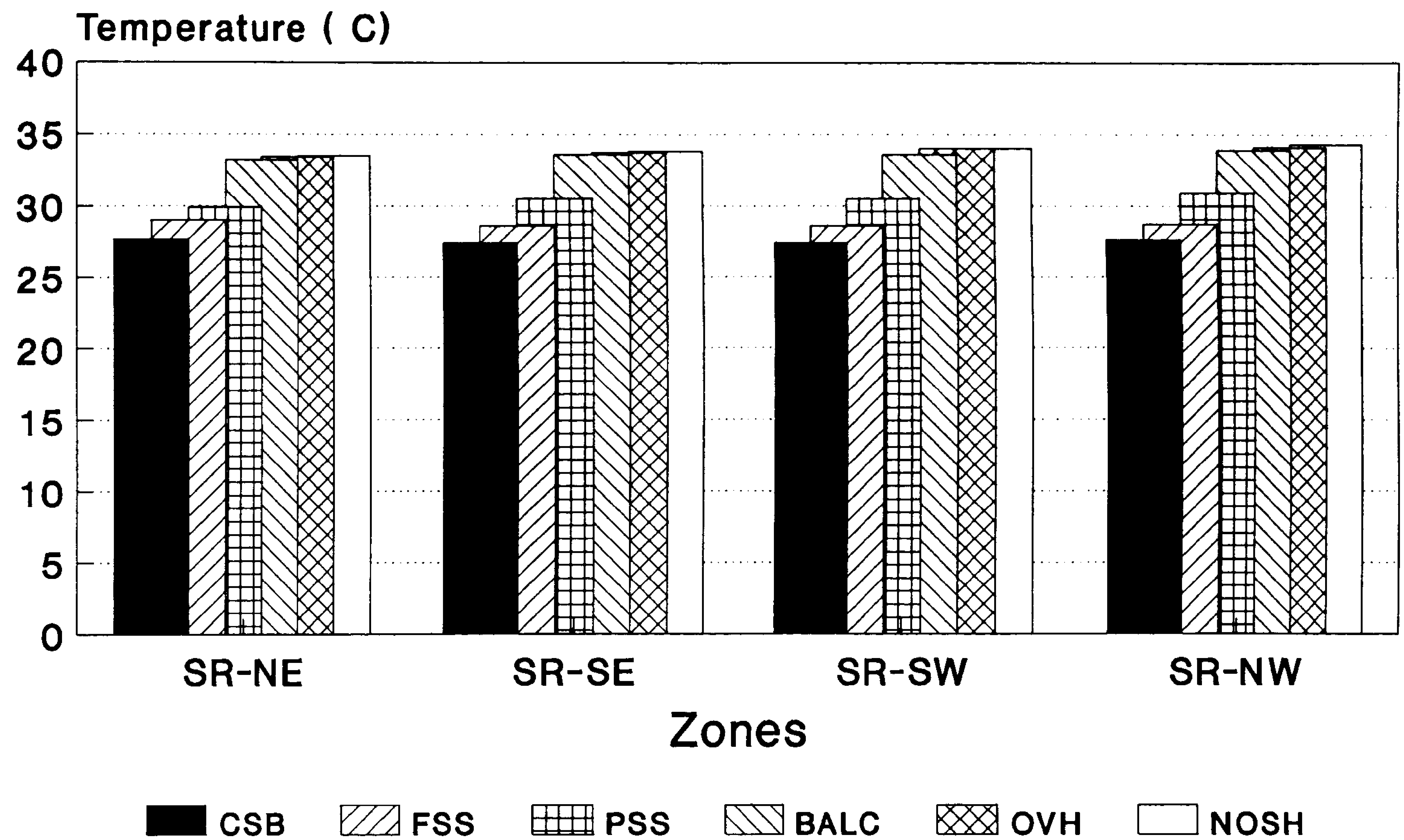


Fig 8.2b: Mean Maximum Air Temperatures for Different Solar Control Options (April)



the overhang. Because this is usually a relatively small quantity, the overall effect should be a net decrease in transmitted solar radiation, although this is dependent upon the proportion of the "direct solar" that the shading device reduces. The *slight* increase in temperature, in spite of the above, is due to the impairment of radiative heat loss by the overhang/sidefins as they reduce the overall area of the radiant sky "seen" by the surfaces of the building than for the case in which no shading device is used at all. Moreover the proportion of direct solar reduced by by sidefins is small since windows cannot be modelled separately. Sidefins can only be specified at the ends of the walls and not for individual windows.

There is another hindrance however, to the use of concrete overhangs and sidefins because concrete structures continue to lose a lot of heat to the ambient long after sunset until the concrete and ambient temperatures equalise some time during the night. This would delay and/or hamper the exploitation of the lower night temperatures for convective cooling of the indoor environment. There is also the longwave conductive heat transfer from the concrete elements. It seems quite apparent that the use of concrete overhangs and sidefins shading has a lot of shortcomings for this climate.

It must be further stated that the counter action of convective heat gain would feature in any shading technique applied, depending on the material used. The vexing issue is that overhangs/sidefins and balconies are often of concrete, and are always in position. As for shielding, if appropriate materials are used, convective gains would be minimised. An added advantage is that the shield can be completely removed *after sunset.*

8.2.2 Balcony Shading

The balcony as used in the study was a combination of the overhang and sidefin all projecting 2.3m normal to the wall surface, with a balustrade of 1.10m above the balcony floor. It was found that the balcony shading was slightly better than the use of ordinary overhang and sidefins but only just so. There is little difference between overhangs/sidefins and the use of balconies which is sometimes being regarded as a better solar protection technique than mere overhangs. In July, balcony shading reduced solar transmitted gain by 4.75 MJ (11.5%) but was much less efficient in the hot season in which the reduction was only 2.75 MJ (6.8%). The results show that there is little difference between this shading and the previous shading options. In reality, the only difference between overhang shading and balcony shading is the floor and the balustrade of the balcony (which do not usually address the shading of the adjacent wall surface and the openings therein) and the subsequent decrease in area of the wall surface exposure.

However as in the previous shading option this option of shading did not have any appreciable reduction in the indoor air temperature in spite of the slight decrease in the values of transmitted direct solar radiation. In fact slight increases in the temperature values were observed. No studies of the effect of increase or decrease of the size of balconies on the indoor thermal conditions were carried out. It is doubtful if any significant difference in results would be obtained from the above which were for a balcony of 2.3m projection. Hence the counteraction of the reduced solar heat gain by an increased convective gain is also a hindrance with balcony shading, coupled with the fact that, like the previous option, it does not address diffuse solar radiation.

8.2.3 The Shielding Option

The shielding option as described in detail in the previous chapter was found to be the most effective in reducing solar thermal gain.

8.2.3.1 Variation of the Shielding Aperture

The solar shielding technique was first simulated with wooden louvres inclined at angle 30^o to the horizontal because it was considered that unless excessively wide louvres are used (which is very unlikely, due to economic and aesthetic constraints), shielding may be said to begin at 30^o at which louvre angle the significance of the view factors come into play. As the louvre angles were increased at 15^o intervals to 45^o, 60^o and 75^o, and for 87^o the following were observed.

(i) Increase in the louvre angle which correspondingly decreases the aperture in the shielding system induced a gradual reduction of the inwardly transmitted solar radiation. In the partial shielding option, (Figure 8.3, Tables 8.3(a,b)) this gradual reduction is shown by the declining **total gain** values as there is a continuously diminishing interzone transfer from the *shielded spaces*. The solar transmitted gain through the unshielded portion of the facades is shown in the "*transmitted*" column

Fig 8.3a: Mean Daily Total Solar Gain For Different Louvre Angles (April) (Partial Shielding Option)

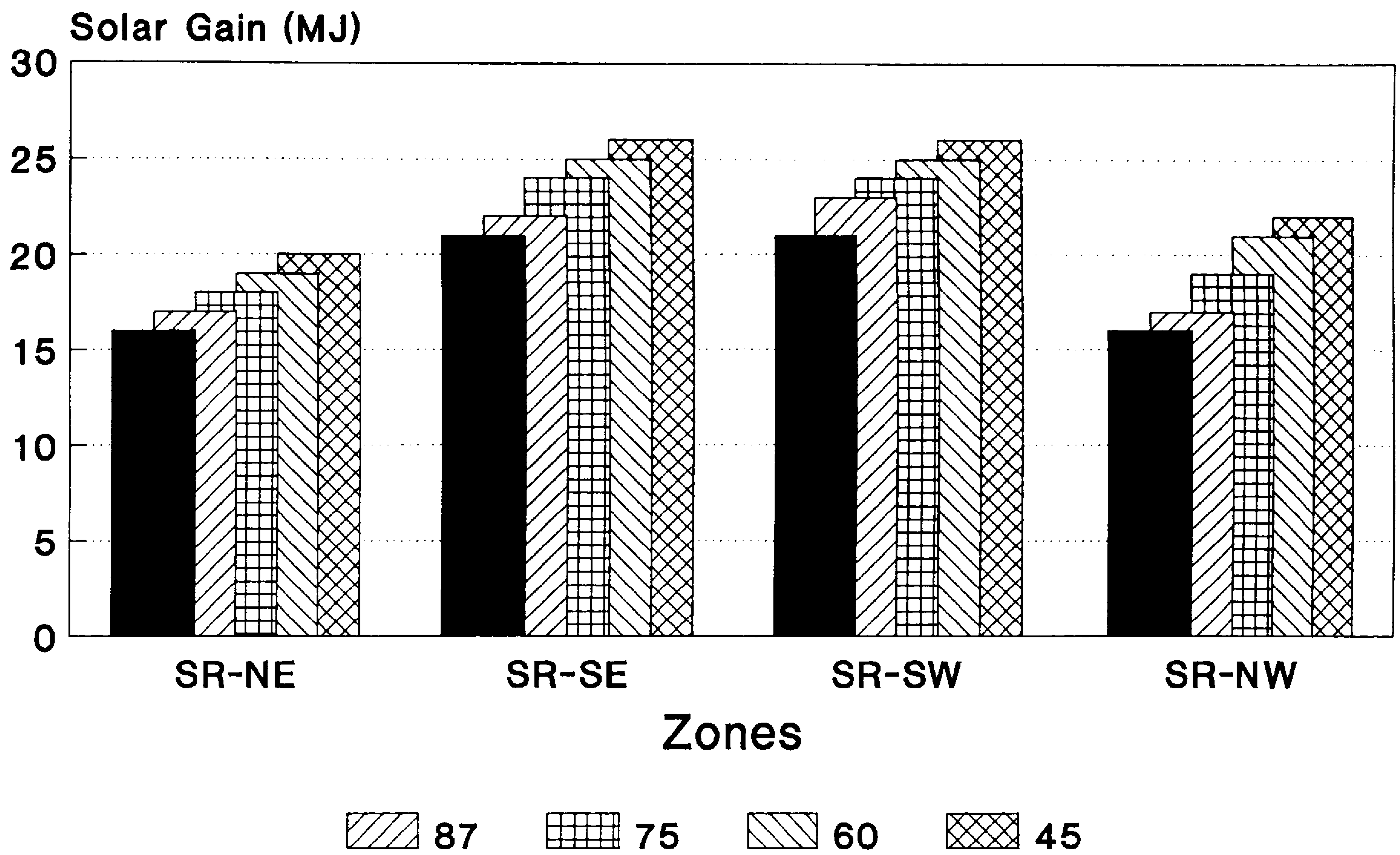


Fig 8.3b: Mean Daily Transmitted Solar Gain For Different Louvre Angles (April) (Full Shielding Option)

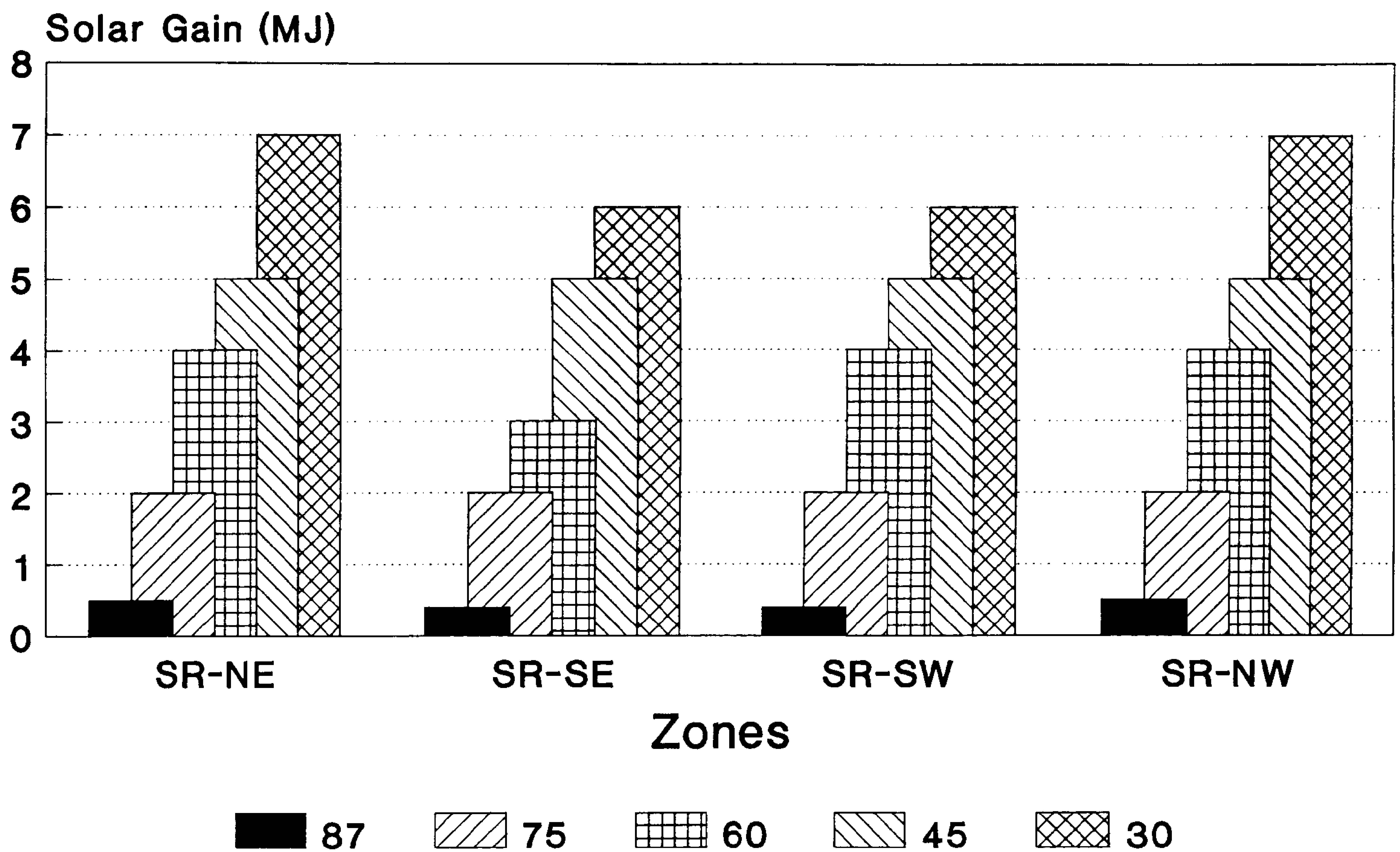
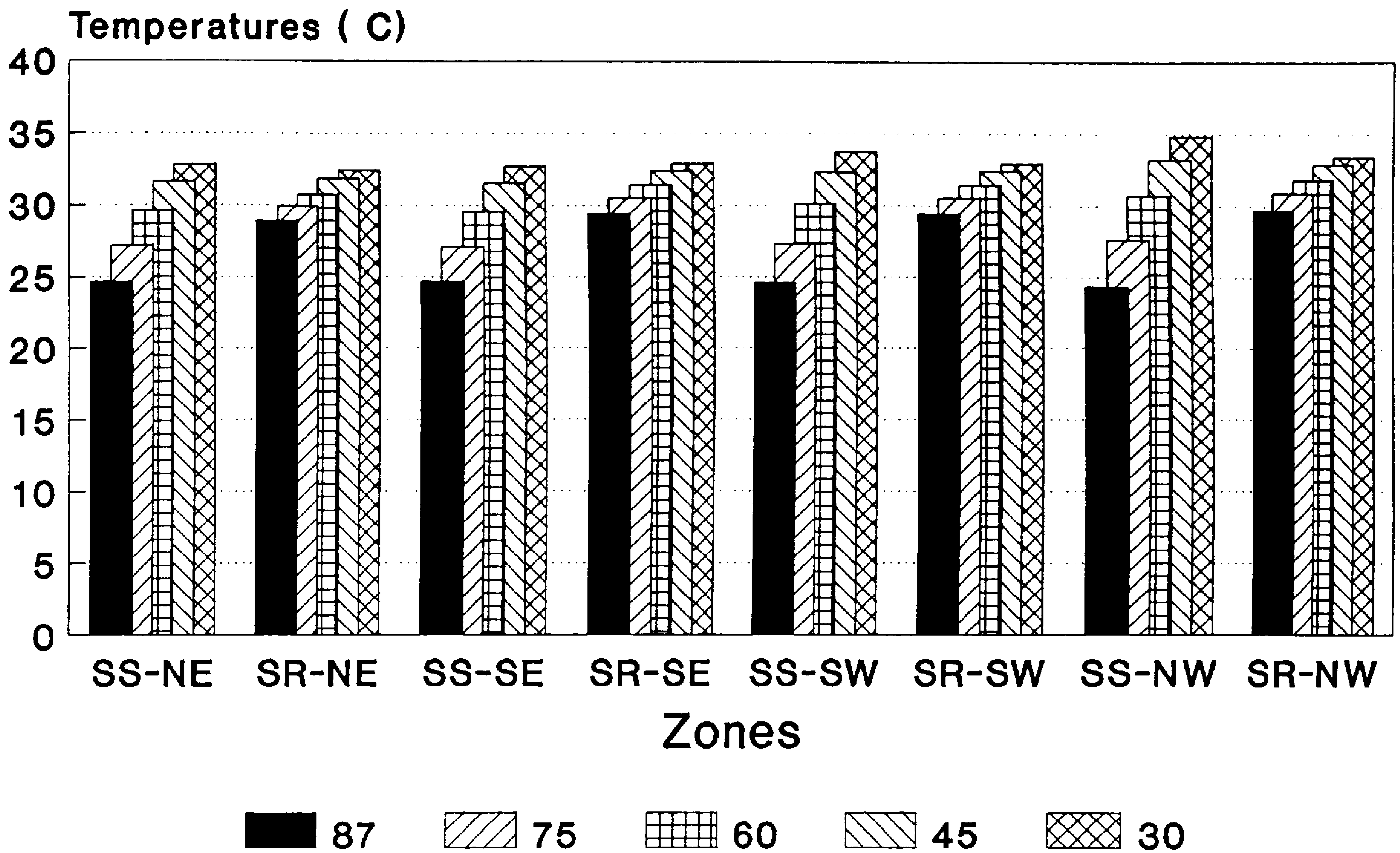


Fig 8.4: Maximum Air Temperatures For Different Louvre Angles (April) (Partial Shielding Option)



and are constant irrespective of the louvre angle. In the full shielding option (Table 8.3b, Figure 8.3) the *"transmitted"* column is solely the interzone transferred solar thermal gain from the shielded spaces.
(ii) A decrease in the aperture of the shielding system results in a gradual decrease in the indoor air temperature due to the combined effect of the decrease in solar heat gain and the corresponding decrease in the airflow. The level of temperature variation according to louvre angle is dependent on whether the building is partially shielded on the sides, fully shielded on all sides or completely shielded on all sides *and* the roof. (Tables 8.4(a),(b) - 8.6(a),(b)). Some of these are graphically illustrated in Figures 8.4 - 8.6) There is a marked improvement in the indoor comfort conditions with a progression from the first shielding option to the last in that order. Although the lowest temperature levels were obtained for 87° louvre angle this option was not regarded as the optimum result as it would admit very little light into the building. Hence the results for the 75° option was regarded as the optimum for shielding.

At 75° louvre angle, the partial shielding of the building sides reduced the solar transmitted gain by 21 MJ (50.9%) while up to 95% reduction can be obtained by completely shielding the facade of the building. Similar results were obtained for the hot season. These are the best results obtained from the shielding parametric studies. At lower louvre angles the louvre system is relatively less efficient.

However these huge reductions are not translated into a proportionate reduction of the temperature profiles into the comfort region due to several factors, namely the impairment of longwave radiative/convective heat loss of the building by the shield, and the longwave thermal transfer from the shield and the roof inwards into the living spaces.

The reduction in transmitted solar gain was also accompanied by a decrease in the values of indoor temperature (as has been observed in Tables 8.5a and 8.5b) principally because apart from the high reduction in solar thermal gain, the use of a shielding system is also accompanied by a corresponding decrease in airflow.

The impact of the shielding system may not be immediately apparent by viewing the daily mean temperature results, because it would be found that they were decreased by the best shielding option (for this building) by an average of 3.2 °C (2.87 °C and 3.45 °C in the rainy and hot seasons respectively. However the mean temperature reduction were generally highest in the south-east and south-

Fig 8.5: Maximum Air Temperatures For Different Louvre Angles (April (Full Shielding Option)

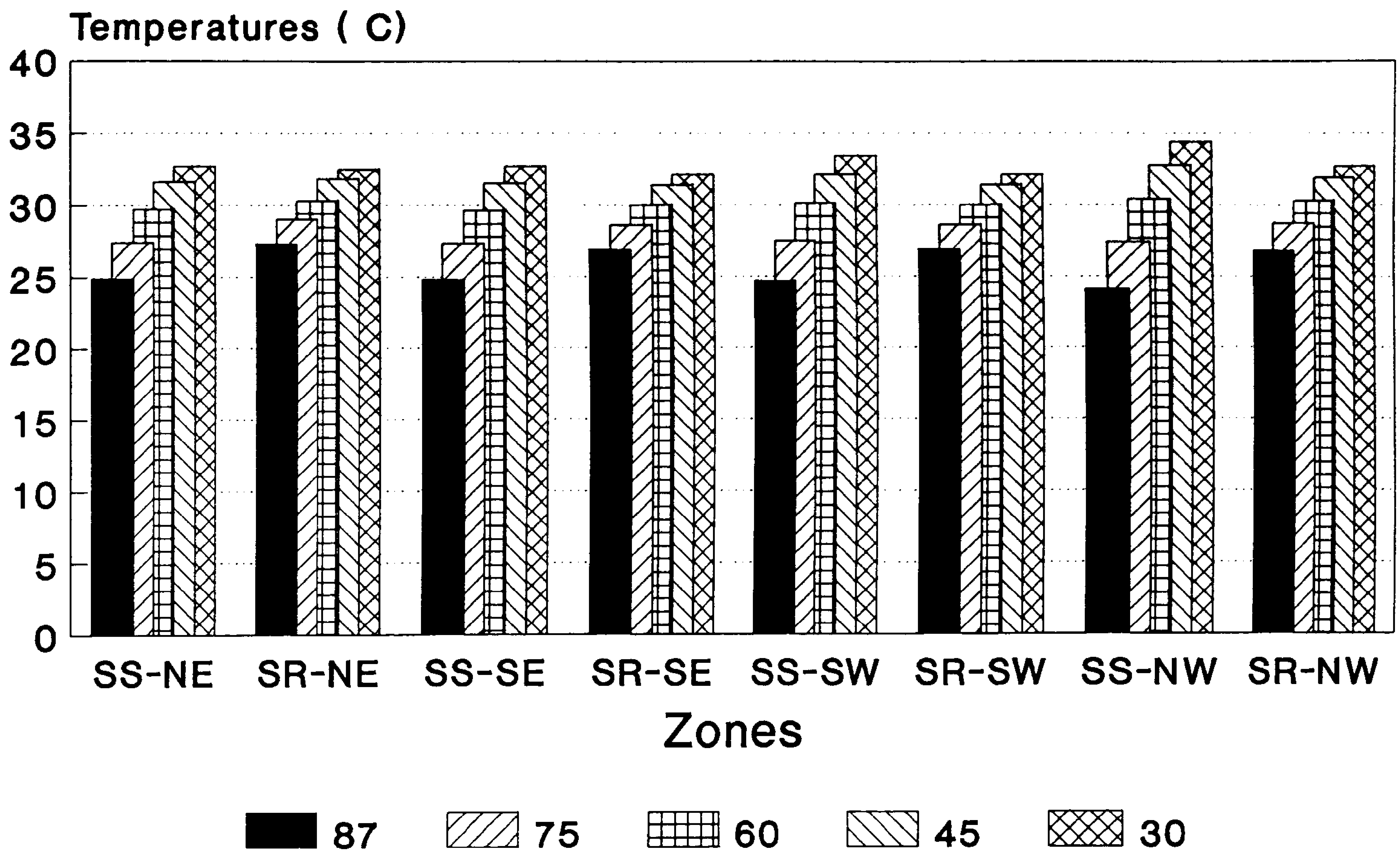
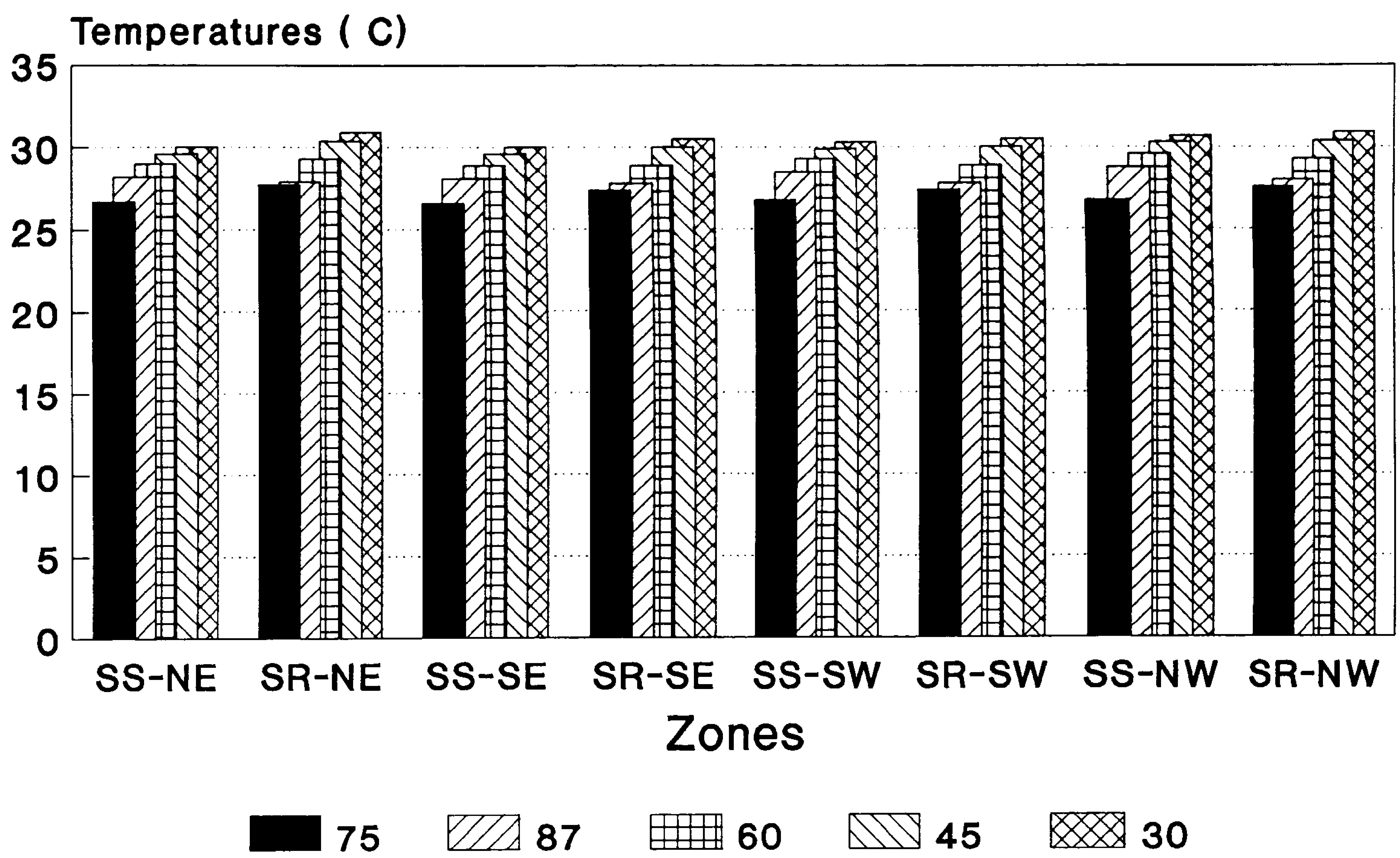


Fig 8.6: Maximum Air Temperatures For Different Louvre Angles (April) (Complete Shielding of Building)



west rooms in both seasons. This is due to the fact that shielding addresses the **daytime** conditions when the sun shines, (and can only be made to address the night conditions, where applicable, by modulation). This implies that it addresses the period of maximum discomfort, when the maximum temperatures occur. It can be observed from Tables 8.2a and 8.2b that the reductions in indoor maximum temperature are relatively higher than those of the mean temperatures while the minimum temperatures varied only slightly. An average of these reduced maximum temperature values and the unaltered night-time minimum temperature values cannot produce a dramatic decrease in the daily average temperature values. In the rainy season shielding reduced the maximum indoor temperature by an average of 4.9 °C but the reductions were higher in the west facing rooms which had an average of 5.3 °C reductions. In the hot season the reductions were slightly higher with an average of 6.4 °C. This implies a good reduction in the peak cooling loads. A more vivid picture of the daytime conditions are presented by the mean hourly values of temperature in the different rooms as presented in Tables 8.7 - 8.10 and graphically only for the south-east and south-west rooms in Figures 8.7 - 8.10. In the south-west room in April during the severe season for example, while the mean outdoor air temperature was 36.00 °C at 15 00 Hours local time, the mean indoor air temperature in the balcony shaded option was 33.44 °C, slightly better than the overhang/sidefin option (33.80 °C), while that in the complete shielding option was 27.38 °C

It can also be observed that the maximum temperature is relatively more reduced by shielding than by any of the other shading options studied while the minimum temperature remains the same in all shading options (Tables 8.2a and 8.2b). Thus shielding has a greater potential to reduce thermal discomfort during this period.

Another feature of the shielding option is the fact that the temperature range in this option is lower than that of the formal shading with overhangs and sidefins and by means of balconies (Table 8.2a and 8.2b). This implies a lower indoor thermal stress than with the other solar protection techniques since apart from the lower temperature values, the difference between the minimum and maximum temperatures is relatively small. This was a common feature in all the shielding options.

A louvre angle of 90° inclination is analogous to a continuous membrane

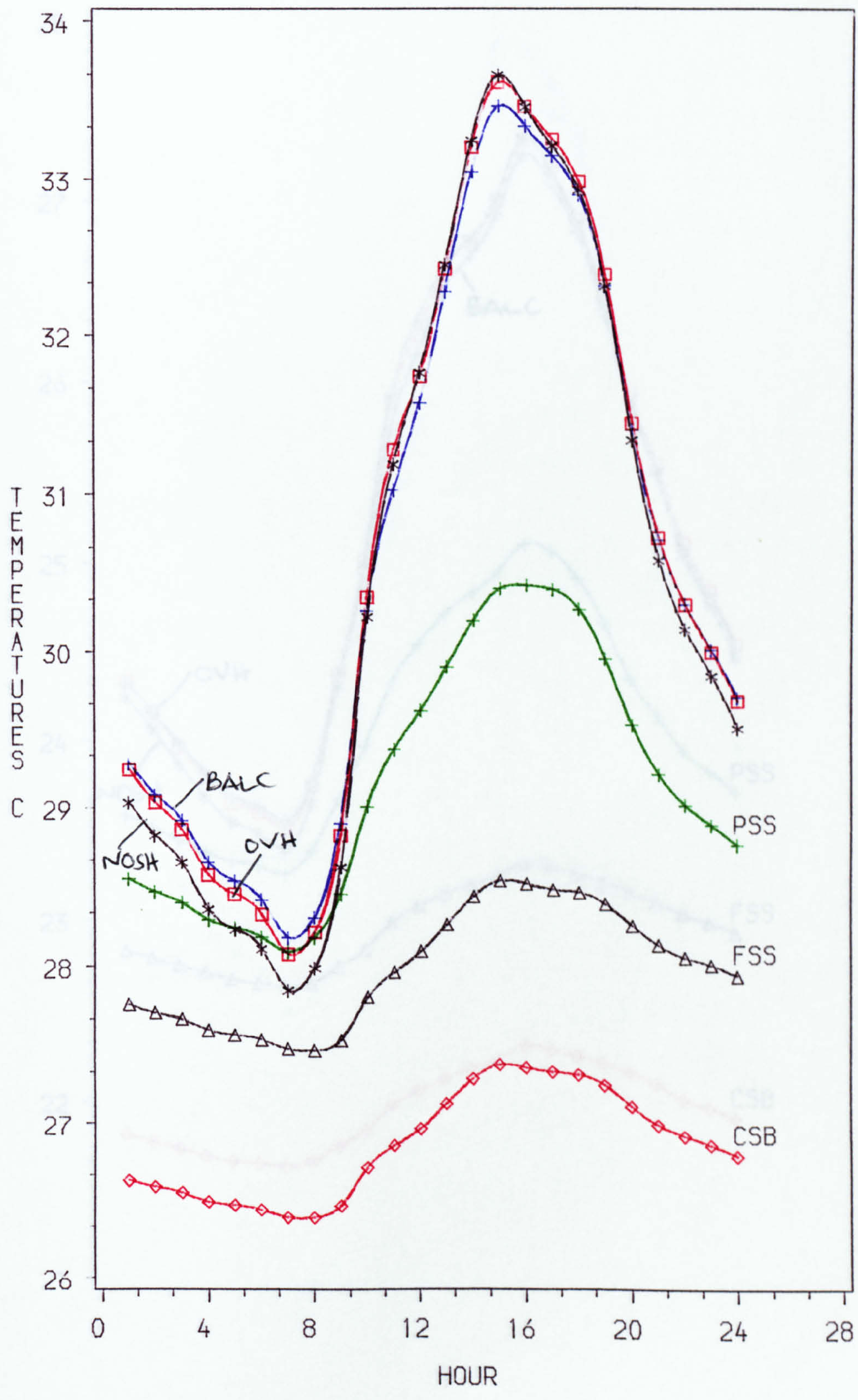


FIGURE 8.7: MEAN HOURLY TEMPERATURE FOR DIFFERENT SOLAR RADIATION CONTROL OPTIONS (SR-SE IN APRIL)

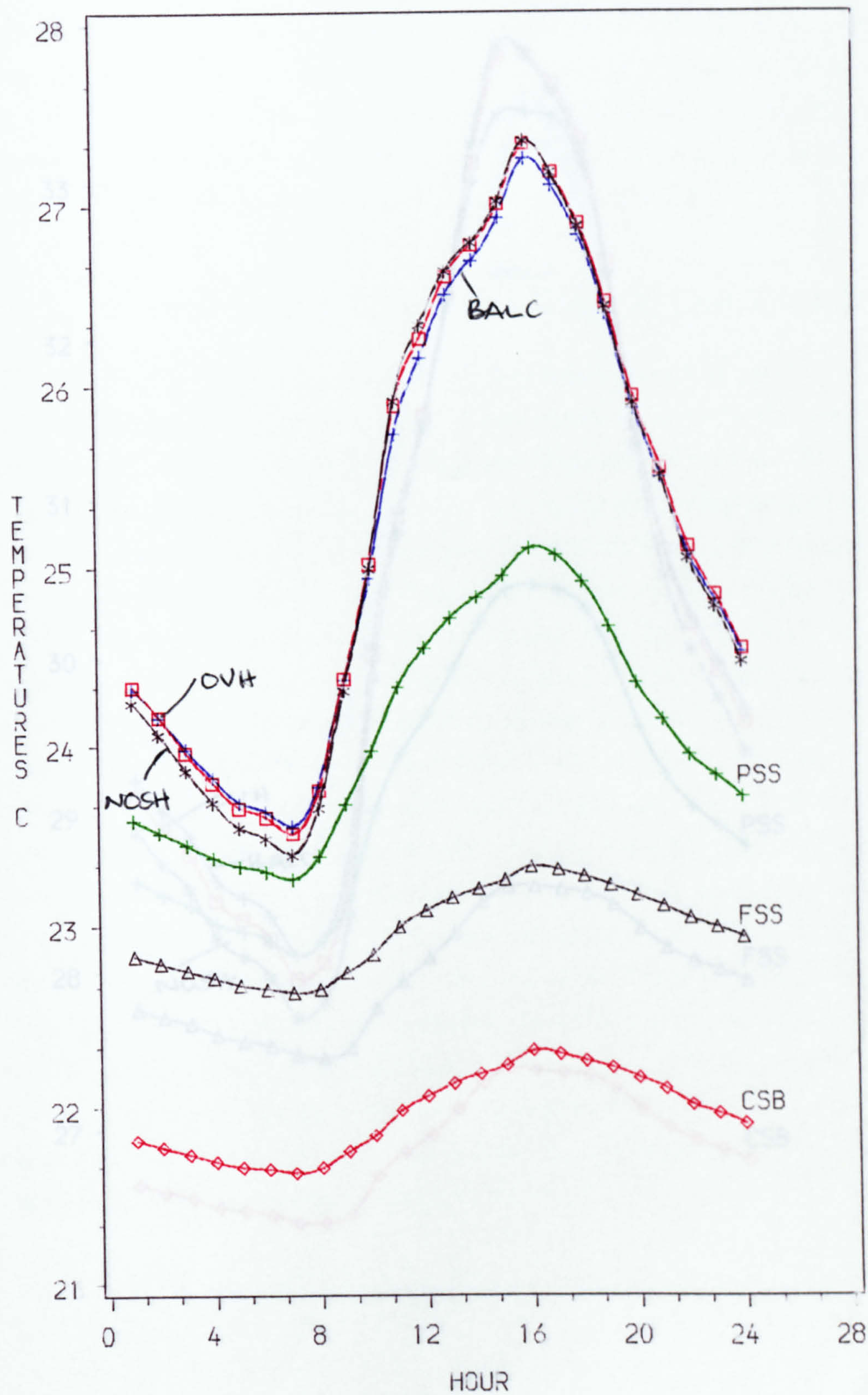


FIGURE 8.8: MEAN HOURLY TEMPERATURE FOR DIFFERENT SOLAR RADIATION CONTROL OPTIONS (SR-SE IN JULY)

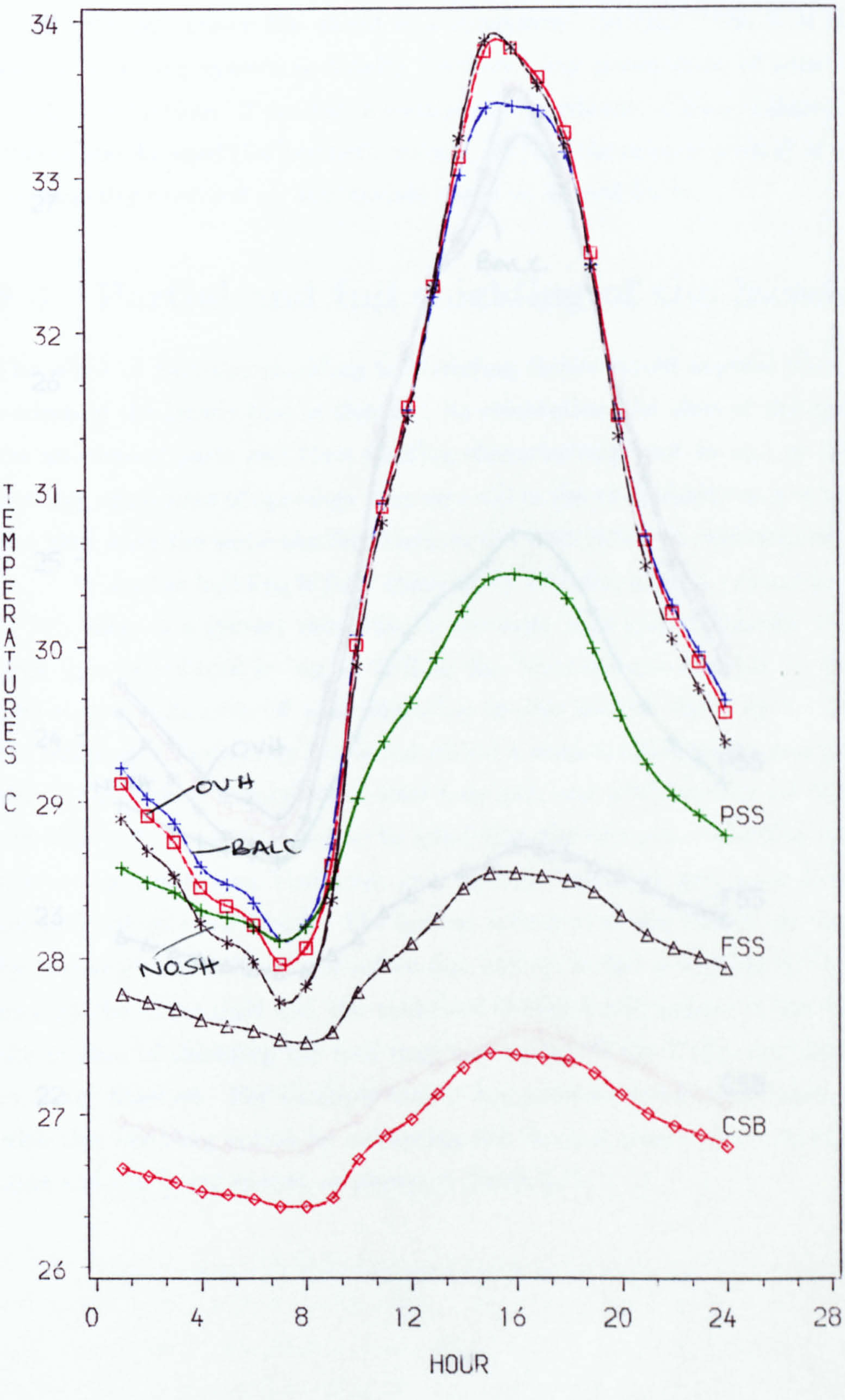


FIGURE 8.9: MEAN HOURLY TEMPERATURE FOR DIFFERENT SOLAR RADIATION CONTROL OPTIONS (SR-SW IN APRIL)

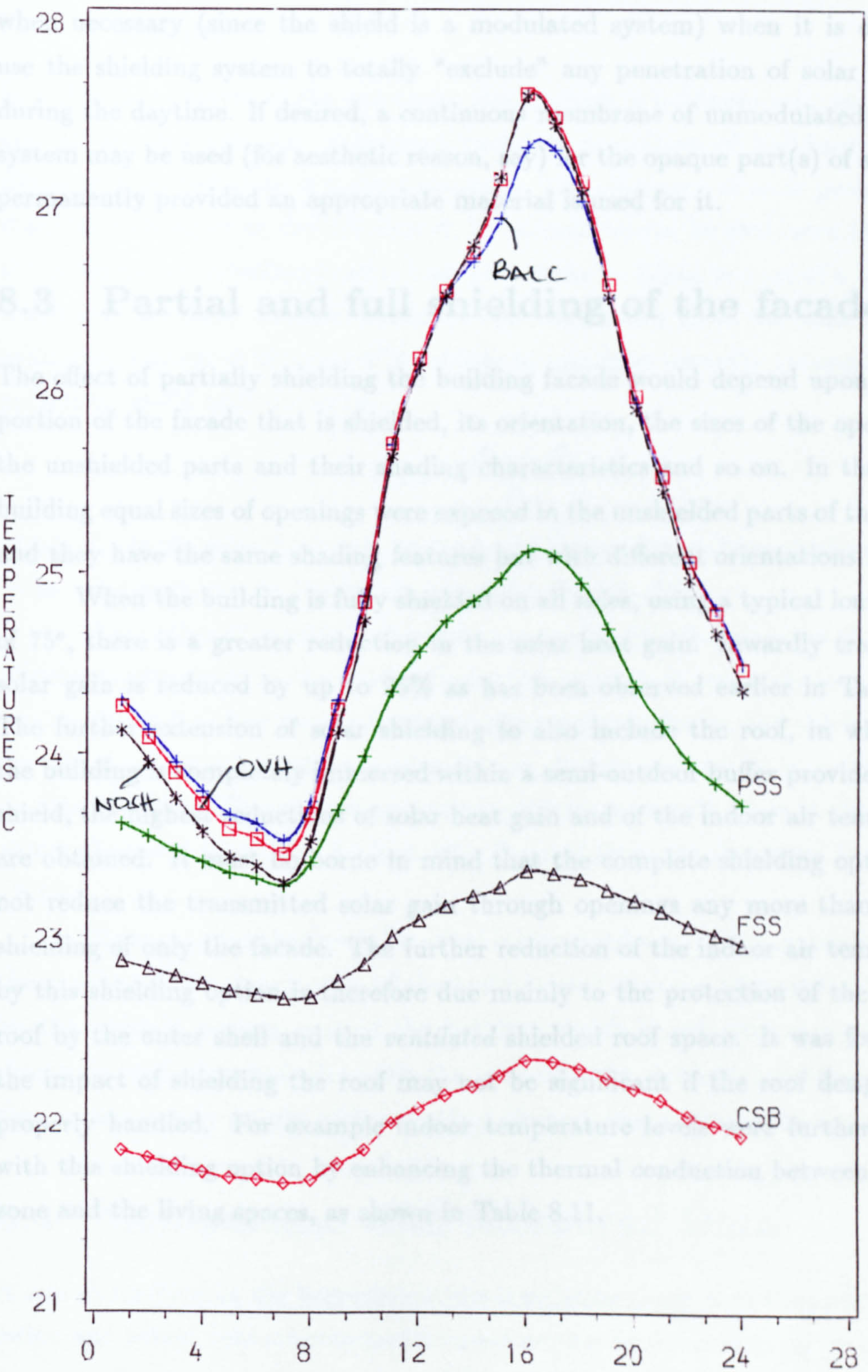


FIGURE 8.10: MEAN HOURLY TEMPERATURE FOR DIFFERENT SOLAR RADIATION CONTROL OPTIONS (SR-SW IN JULY)

covering the facade and totally blocking the view. This situation can only arise when necessary (since the shield is a modulated system) when it is desired to use the shielding system to totally "exclude" any penetration of solar radiation during the daytime. If desired, a continuous membrane of unmodulated shielding system may be used (for aesthetic reason, say) for the opaque part(s) of a building permanently provided an appropriate material is used for it.

8.3 Partial and full shielding of the facade

The effect of partially shielding the building facade would depend upon the proportion of the facade that is shielded, its orientation, the sizes of the openings on the unshielded parts and their shading characteristics and so on. In the present building equal sizes of openings were exposed in the unshielded parts of the facades and they have the same shading features but with different orientations.

When the building is fully shielded on all sides, using a typical louvre angle of 75°, there is a greater reduction in the solar heat gain. Inwardly transmitted solar gain is reduced by up to 95% as has been observed earlier in Table 8.3b. The further extension of solar shielding to also include the roof, in which case the building is completely immersed within a semi-outdoor buffer provided by the shield, the highest reductions of solar heat gain and of the indoor air temperature are obtained. It must be borne in mind that the complete shielding option does not reduce the transmitted solar gain through openings any more than the full shielding of only the facade. The further reduction of the indoor air temperature by this shielding option is therefore due mainly to the protection of the primary roof by the outer shell and the *ventilated* shielded roof space. It was found that the impact of shielding the roof may not be significant if the roof design is not properly handled. For example indoor temperature levels were further lowered with this shielding option by enhancing the thermal conduction between the roof zone and the living spaces, as shown in Table 8.11.

8.3.1 Quality Evaluation of Building Solar Protection Techniques

In a climate as severe as the one under study which is hot/semi-arid, in particular and all hot dry climates in general, excellent protection of buildings from the effects of solar radiation is a great necessity. The efficiency of solar protection (or shading) techniques or devices should, in rational terms, be evaluated in terms of the quantitative reduction in solar heat gain of the building, or part of a building in which they are used. In other words the efficiency factor E_f of the solar protection technique, expressed in terms of its ability to minimise inwardly transmitted solar radiation, would take the form

$$E_f = \frac{E_{ns} - E_s}{E_{ns}} \tag{8.1}$$

where E_{ns} is the solar heat gain in the building or zone without shading; and E_s is the solar heat gain in the building or zone with shading.

This notion of quality evaluation was used in the evaluation of the shading techniques simulated in the study. Under this criteria, it seems obvious from the results (Table 8.1) how poorly formal shading with overhangs and sidefins or even the use of balconies, could be in this climate. It may perhaps be more instructive to view how the different shading options perform on hourly basis in the different rooms (Tables 8.12(a),(b) - 8.15(a),(b)). Some of these are shown on Figures 8.11 - 8.14.

The main issue that must be noted is that overhangs/sidefins merely address the shading of the glazed parts of the building and does not address the heat gain by the exposed opaque part of the building which is not only in contact with shortwave radiation but also with the intensely hot outdoor conditions. Hence they compare very poorly with a shading strategy that protects the entire fabric.

8.4 Comparison with Measured Data

It was understood at the beginning of the simulation study that the thermal simulation and actual field measurements would neither be directly equal to each other nor even directly comparable, since SERI-RES, as explained earlier, outputs environmental temperature rather than air temperature *per se*. However this would

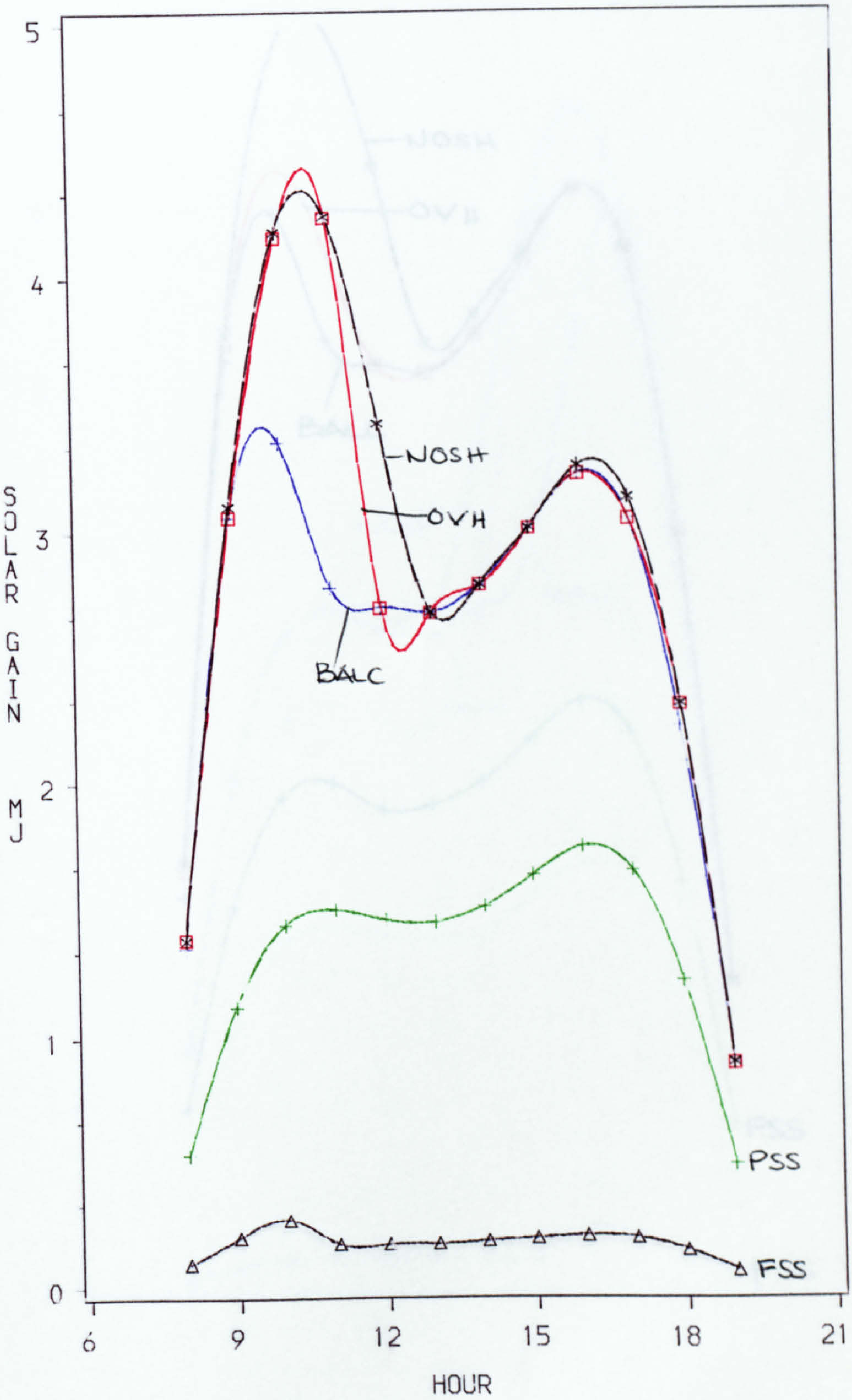


FIGURE 8.11: MEAN HOURLY TOTAL SOLAR GAIN (MJ) FOR DIFFERENT SHADING OPTIONS (SR-NE IN APRIL))

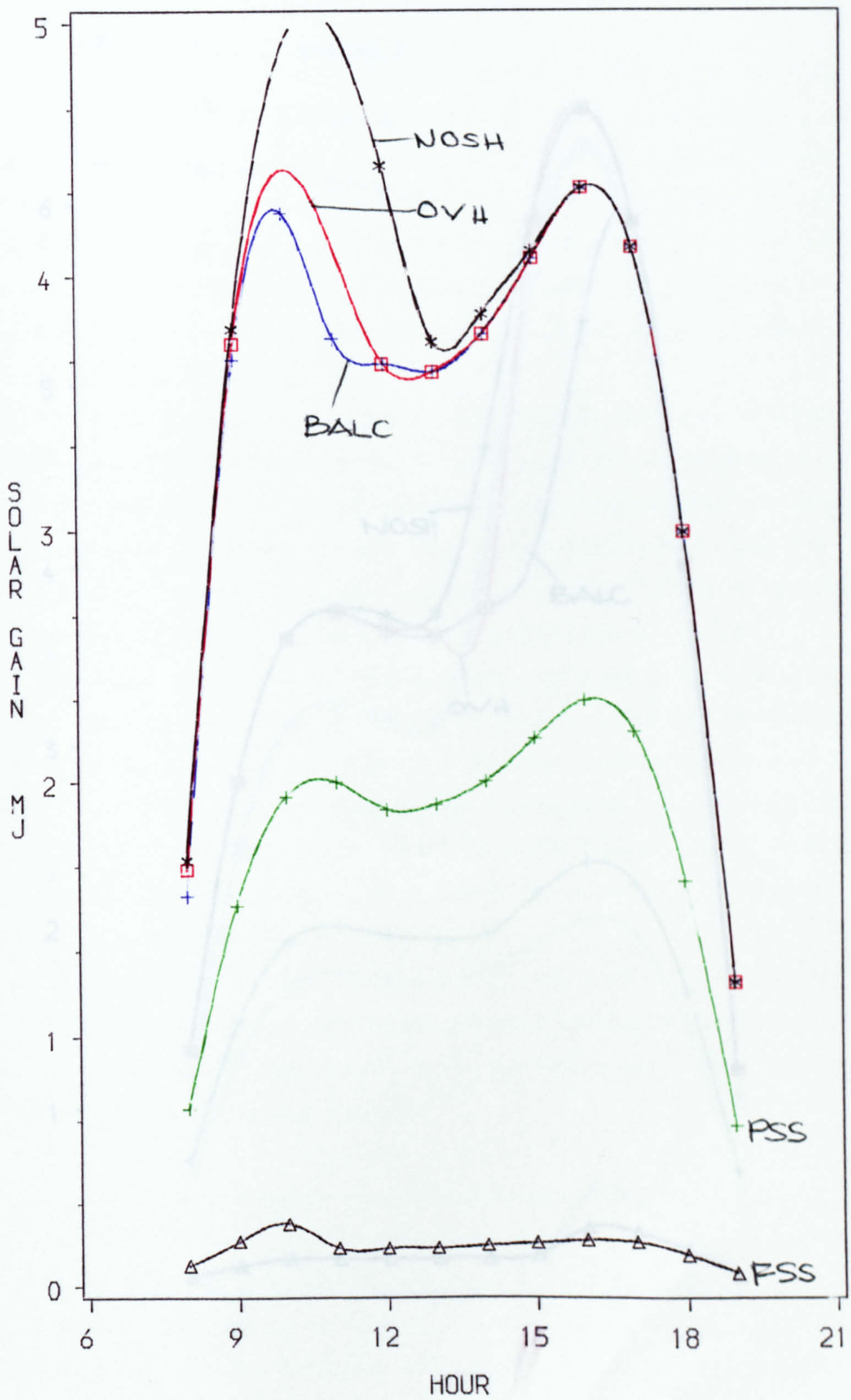


FIGURE 8.12: MEAN HOURLY TOTAL SOLAR GAIN (MJ) FOR DIFFERENT SHADING OPTIONS (SR-NE IN APRIL))

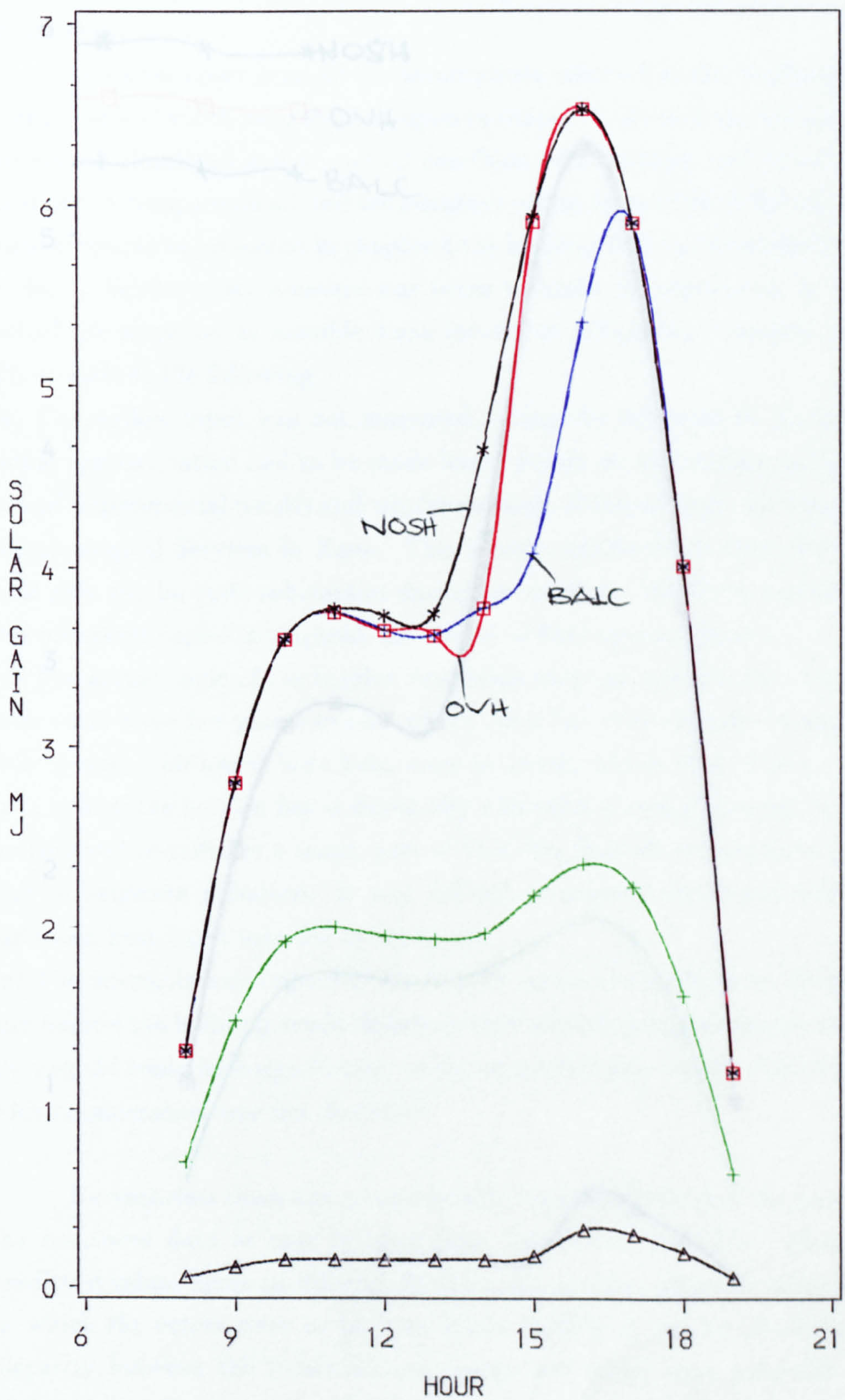


FIGURE 8.13: MEAN HOURLY TOTAL SOLAR GAIN (MJ) FOR DIFFERENT SHADING OPTIONS (SR-SW IN APRIL))

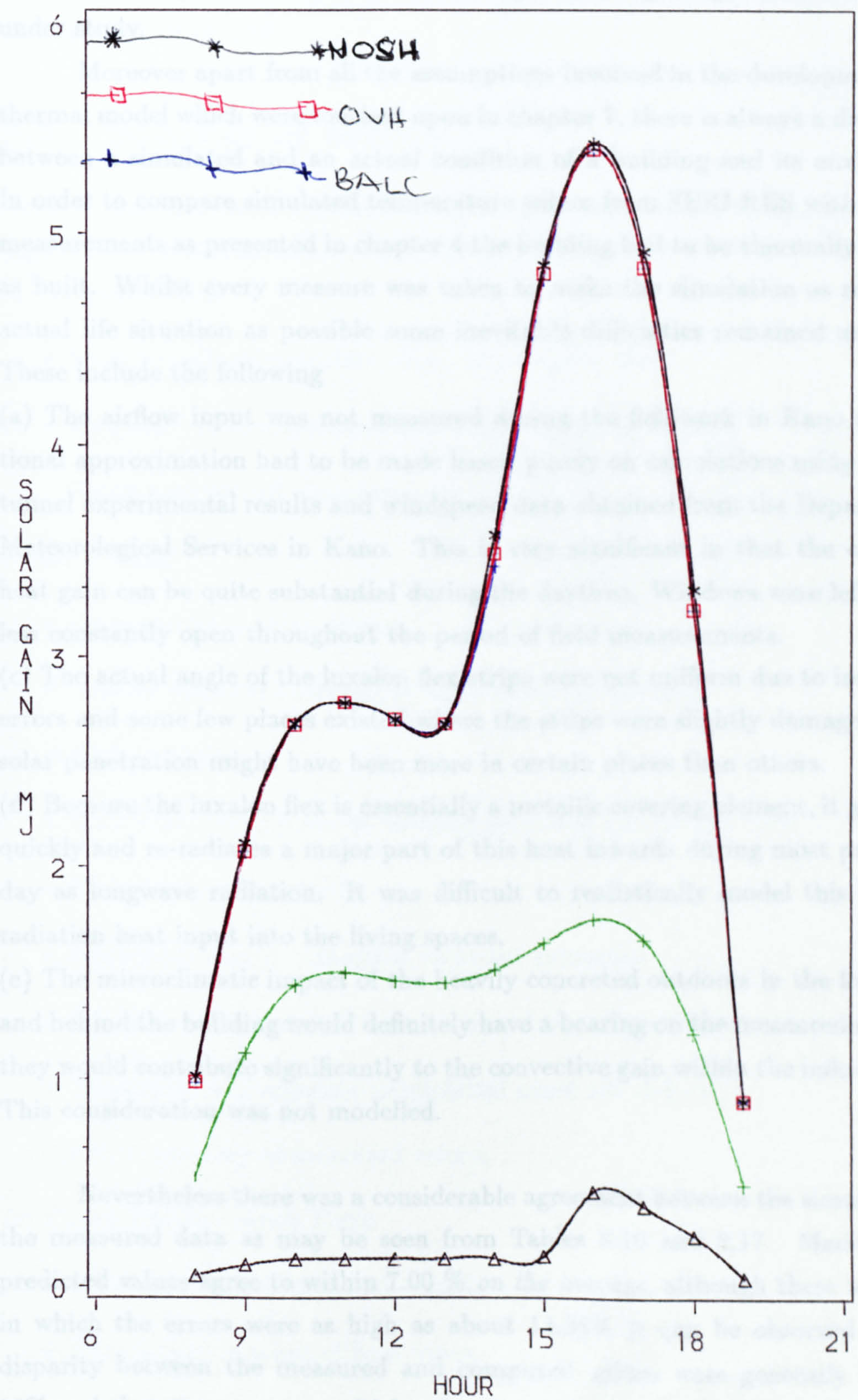


FIGURE 8.14: MEAN HOURLY TOTAL SOLAR GAIN (MJ) FOR DIFFERENT SHADING OPTIONS (SR-NW IN APRIL))

only be very significant where there is a high area of glazing, unlike the building under study.

Moreover apart from all the assumptions involved in the development of the thermal model which were touched upon in chapter 7, there is always a discrepancy between a simulated and an actual condition of a building and its environment. In order to compare simulated temperature values from SERI-RES with full scale measurements as presented in chapter 4 the building had to be thermally modelled as built. Whilst every measure was taken to make the simulation as realistic to actual life situation as possible some inevitable difficulties remained unresolved. These include the following

(a) The airflow input was not measured during the fieldwork in Kano and a rational approximation had to be made based purely on calculations using the wind tunnel experimental results and windspeed data obtained from the Department of Meteorological Services in Kano. This is very significant in that the convective heat gain can be quite substantial during the daytime. Windows were left more or less constantly open throughout the period of field measurements.

(c) The actual angle of the luxalon flex strips were not uniform due to installation errors and some few places existed where the strips were slightly damaged. Hence solar penetration might have been more in certain places than others.

(d) Because the luxalon flex is essentially a metallic covering element, it gains heat quickly and re-radiates a major part of this heat inwards during most part of the day as longwave radiation. It was difficult to realistically model this longwave radiation heat input into the living spaces.

(e) The microclimatic impact of the heavily concreted outdoors in the foreground and behind the building would definitely have a bearing on the measurements since they would contribute significantly to the convective gain within the indoor spaces. This consideration was not modelled.

Nevertheless there was a considerable agreement between the simulated and the measured data as may be seen from Tables 8.16 and 8.17. Measured and predicted values agree to within 7.00 % *on the average*, although there were cases in which the errors were as high as about 14.38% It can be observed that the disparity between the measured and computed values were generally less than 10% and that the errors were higher for the semi-outdoor *shielded spaces* than for the rooms, which had well-defined boundaries. Some of these results are illustrated on Figures 8.16 to 8.18).

8.5 Sources of errors

Some of the sources of external errors in building thermal modelling has been suggested by Bowman and Lomas, (1985, 1986) and they include:

A: Climate Data

- Some (or all) climate data taken at a remote site.
- Frequency of measurement insufficient to define variable.
- Finite accuracy of measurements.

B: Site Data

- Unmeasured shading objects.
- Ground reflected radiation or reflectivity not defined.

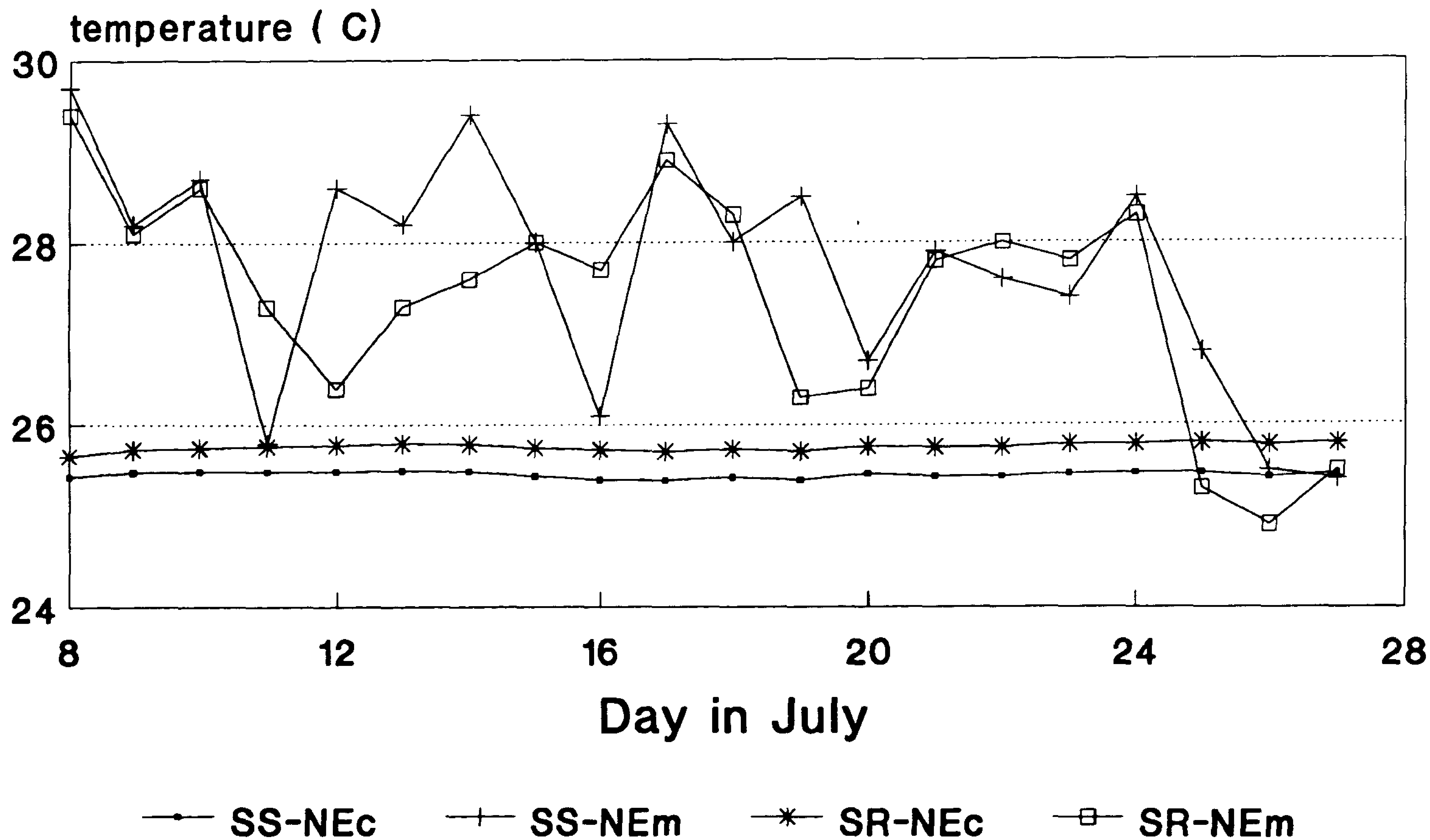
C: Building Data

- Inadequate description of building geometry and construction.
- Uncertain workmanship.
- Infiltration and/or advection rates not measured.
- Use of handbook rather than measured thermophysical properties.
- Temperature of adjacent unmodelled zones not defined.
- Finite accuracy of measured values.

D: Plant Performance Data

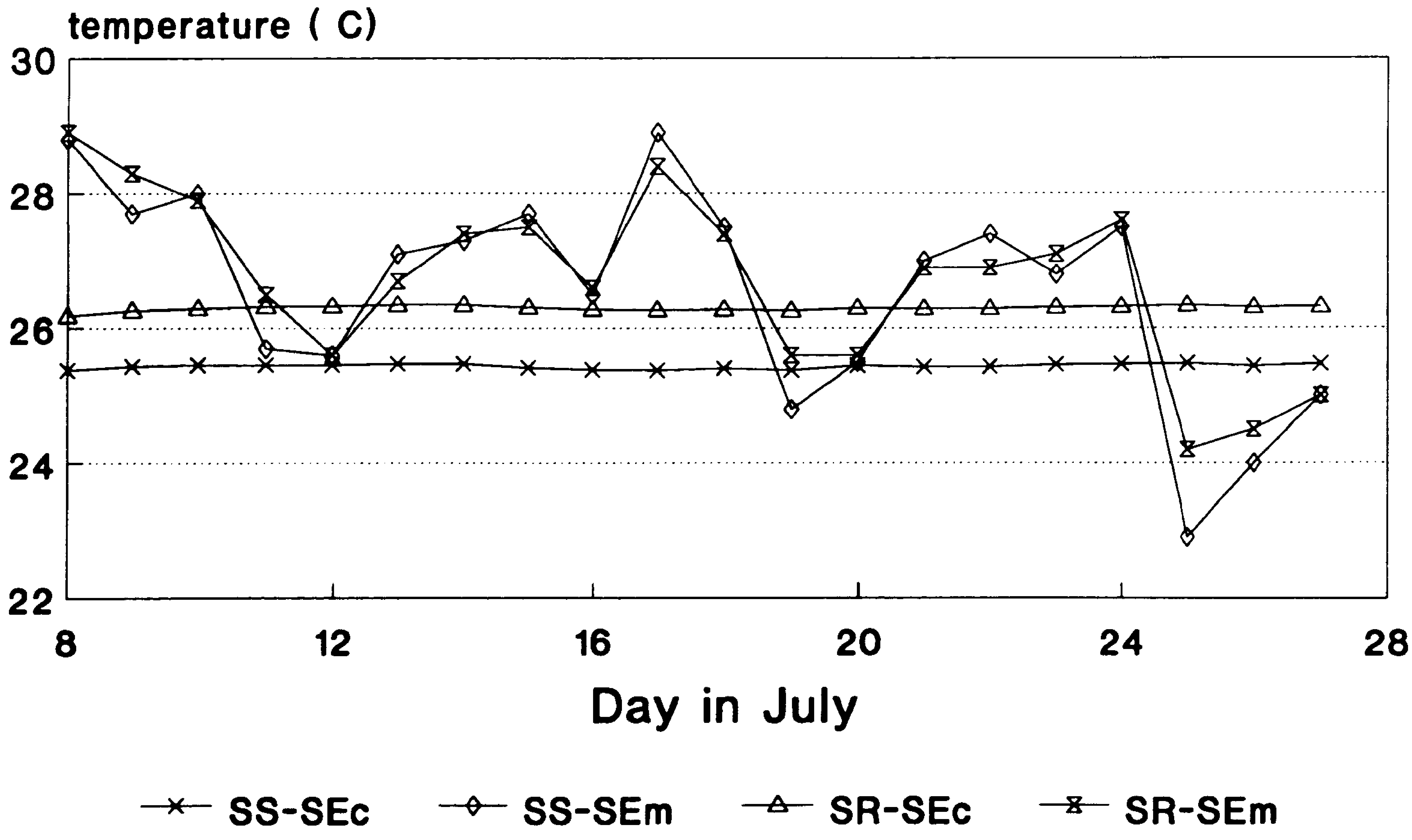
- Uncertain radiant/convective split.
- Uncertainty in point of heat input.
- Uncertain thermostat tolerance.

Fig 8.16: Computed v. Measured
Temperature values



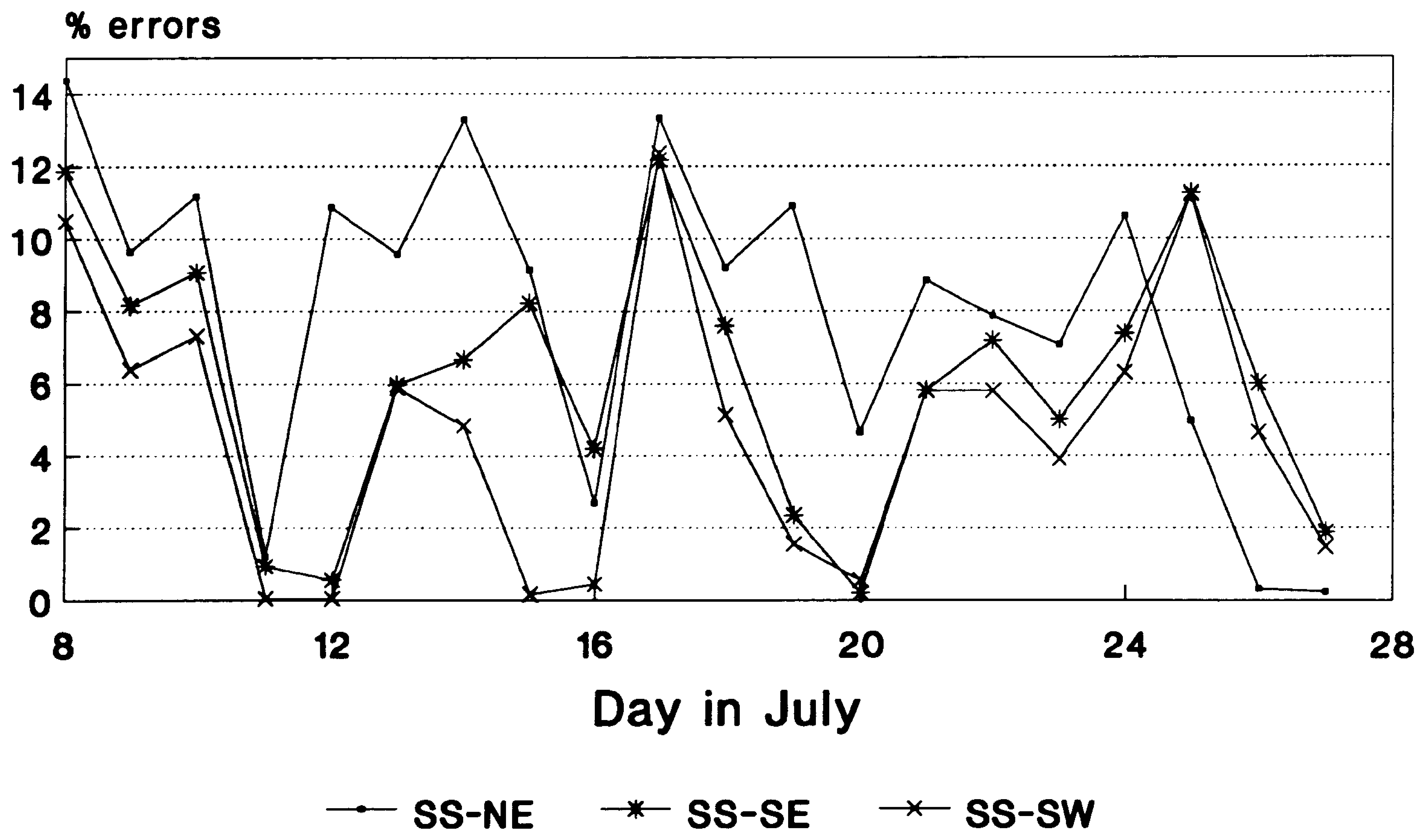
(Subscripts: c = computed; m = measured)

Fig 8.17: Computed v. Measured
Temperature values



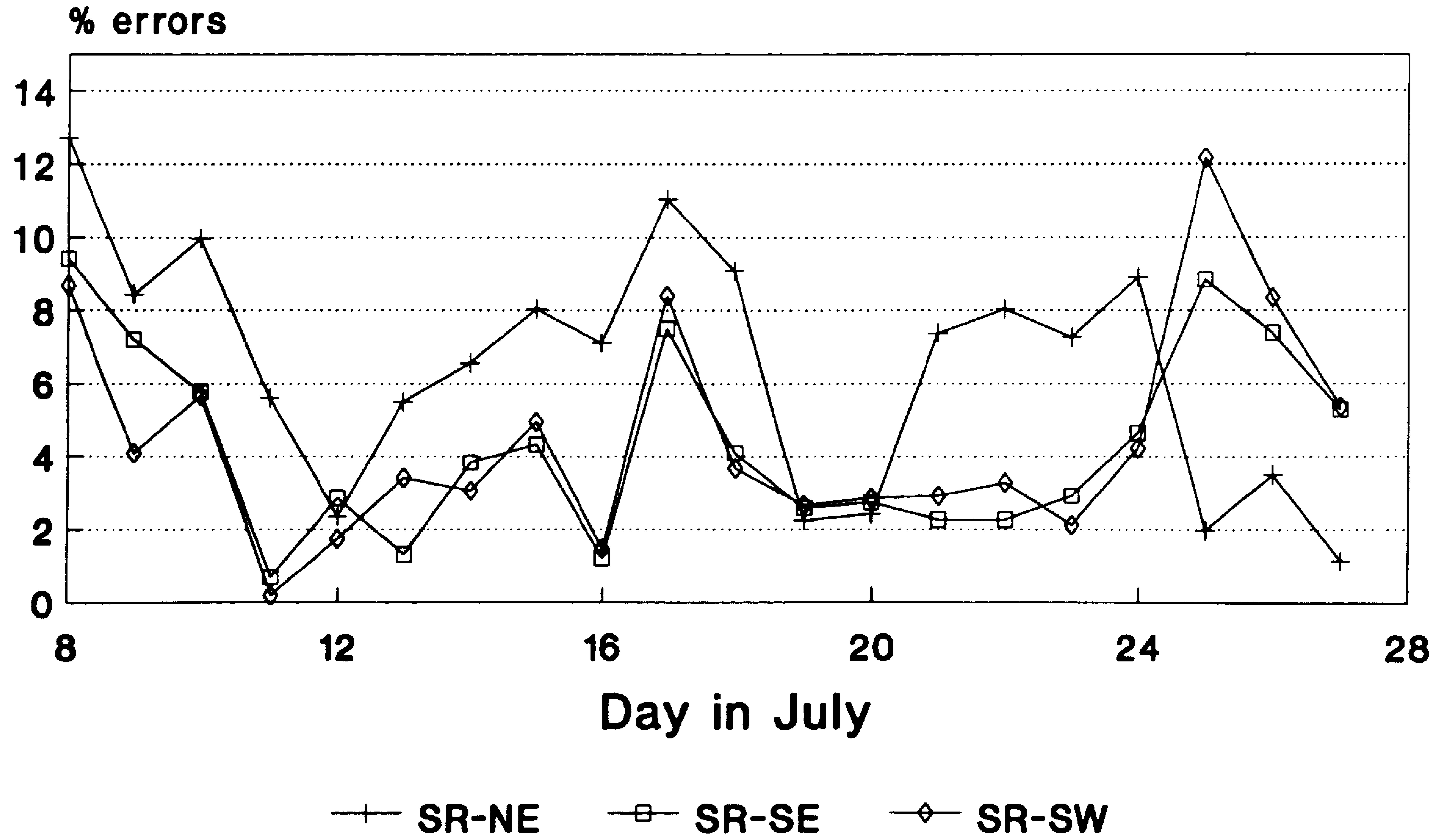
(Subscripts: c = computed; m = measured)

Fig 8.18a: Percentage Errors
in computed temperature values



(Shielded Buffer Spaces)

Fig 8.18b: Percentage Errors
in computed temperature values



(Shielded Rooms)

E: Occupancy

- Interference with the building system.
- Uncertain wild gains from appliances.
- Ill-defined occupancy profile.
- Uncertainty in modelling furnishings.

F: User Interface

- Blunders when entering data.
- Interpretation of poorly documented input data.
- Assuming values to replace missing data.
- Modification to building description so that it can be modelled.
- Amended program coding so that the building can be modelled.

G: Logging

- Noisy, missing or spurious data.
- Frequency of measurement insufficient to define variable.
- Finite accuracy of recording system.

H: Interference

- Internal features of structure altered by monitoring equipment.

I: Data Comparison

- Transcription of measured data from charts etc.
- Differences between measured and predicted parameters.
- Point of measurement and prediction differ.

8.6 Conclusions from the experimental results

- Modulated solar shielding has a higher solar control efficiency than formal shading techniques with overhang/sidefins and the use of balconies. The efficiency factor of a solar control system was obtained by comparing the solar thermal gain by using the shading option to that without any form of shading. The high efficiency of the shielding option stems from the fact that the shielding system prevents most of the shortwave solar radiation from reaching the main shell of the building.

- The high reduction of solar transmitted gain is not translated into a high reduction of indoor temperature. This is due partly to the thermophysical properties of building materials used and partly as a result of the fact that the shielding system's solar thermal gain is re-radiated as longwave thermal transfer partly into the living spaces. Also the inter-reflections of radiation between the slats in the system further reduces its efficiency.

- The efficiency of the shielding system is a function of its porosity to solar radiation. The efficiency can be increased by optimising the inclination of the slats in the system.

- The use of an external shielding system creates a buffer zone around the periphery of a building whose mean daily temperature is lower than both the indoor and the ambient temperatures. (This is also reflected in the measured temperature values in Chapter 4). Thus the building is seemingly *encapsuled* in a microclimate that is less harsh than the ambient.

8.7 Conclusion

This chapter presented the results of the thermal simulation studies. The results indicated that modulated solar shielding could be a better solar radiation control strategy than formal shading methods with shading devices fixed onto glazed areas of the fabric. In the next chapter some of the implications of these results are further discussed, with conclusions and recommendations based on the entire study.

TABLE 8.1: MEAN DAILY INWARDLY TRANSMITTED SOLAR ENERGY (MJ) FOR DIFFERENT SOLAR RADIATION CONTROL OPTIONS

(RAINY SEASON - (JULY))

	NO SHADING		OVERHANG/SIDEFIN		BALCONY		PARTIAL SHIELDING		FULL SHIELDING	
	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain
SR-NE	38.0	31.0	34.0	28.0	31.0	25.0	21.0	17.0	2.00	2.00
SR-SE	42.0	35.0	41.0	34.0	40.0	33.0	19.0	21.0	2.00	2.00
SR-SW	45.0	37.0	44.0	37.0	42.0	35.0	19.0	21.0	2.00	2.00
SR-NW	40.0	33.0	35.0	29.0	35.0	29.0	22.0	18.0	2.00	2.00

(HOT SEASON - (APRIL))

	NO SHADING		OVERHANG/SIDEFIN		BALCONY		PARTIAL SHIELDING		FULL SHIELDING	
	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain
SR-NE	34.0	29.0	33.0	28.0	31.0	26.0	19.0	16.0	2.00	2.00
SR-SE	45.0	37.0	43.0	36.0	41.0	34.0	19.0	21.0	2.00	2.00
SR-SW	47.0	39.0	46.0	38.0	43.0	36.0	19.0	21.0	2.00	2.00
SR-NW	37.0	31.0	37.0	30.0	36.0	30.0	19.0	16.0	2.00	2.00

TABLE 8.2A: MEAN DAILY INDOOR AIR TEMPERATURE VALUES (^{O}C)
FOR DIFFERENT SOLAR RADIATION CONTROL OPTIONS

(RAINY SEASON - (JULY))

OVERHANG/SIDEFIN

	mean	min	max	rng
SR-NE	24.94	23.2	27.0	3.7
SR-SE	25.27	23.5	27.4	3.9
SR-SW	25.25	23.4	27.7	4.3
SR-NW	24.99	23.1	27.6	4.5

BALCONY

	mean	min	max	rng
SR-NE	24.90	23.3	26.8	3.5
SR-SE	25.23	23.5	27.3	3.8
SR-SW	25.24	23.5	27.4	3.9
SR-NW	24.96	23.1	27.5	4.3

NO SHADING

	mean	min	max	rng
SR-NE	24.75	23.0	26.9	3.9
SR-SE	25.22	23.4	27.4	4.0
SR-SW	25.16	23.3	27.7	4.4
SR-NW	24.99	23.0	27.8	4.8

	PARTIAL SHIELDING OF SIDES ONLY				FULL SHIELDING OF SIDES				BUILDING FULLY SHIELDED			
	mean	min	max	rng	mean	min	max	rng	mean	min	max	rng
SR-NE	23.61	22.9	24.5	1.6	23.22	22.8	23.7	0.9	22.16	21.8	22.6	0.8
SR-SE	24.07	23.2	25.1	1.9	22.96	22.6	23.3	0.7	22.42	22.1	22.7	0.6
SR-SW	24.10	23.3	25.2	1.9	22.99	22.6	23.4	0.7	21.97	21.6	22.3	0.7
SR-NW	24.35	23.4	25.5	2.2	23.08	22.7	23.6	0.9	22.11	21.7	22.6	0.8

TABLE 8.2B: MEAN DAILY INDOOR AIR TEMPERATURE VALUES (°C) FOR DIFFERENT SOLAR RADIATION CONTROL OPTIONS

(HOT SEASON - (APRIL))

OVERHANG/SIDEFIN

	mean	min	max	rng
SR-NE	30.34	27.8	33.4	5.6
SR-SE	30.60	28.0	33.7	5.7
SR-SW	30.54	27.9	34.0	6.1
SR-NW	30.44	27.7	34.1	6.5

BALCONY

	mean	min	max	rng
SR-NE	30.26	27.9	33.2	5.3
SR-SE	30.57	28.1	33.6	5.5
SR-SW	30.54	28.1	33.6	5.5
SR-NW	30.31	27.7	33.9	6.2

NO SHADING

	mean	min	max	rng
SR-NE	30.29	27.6	33.5	5.9
SR-SE	30.48	27.8	33.8	6.0
SR-SW	30.40	27.7	34.0	6.4
SR-NW	30.40	27.5	34.3	6.7

	PARTIAL SHIELDING OF SIDES ONLY				FULL SHIELDING OF SIDES				BUILDING FULLY SHIELDED			
	mean	min	max	rng	mean	min	max	rng	mean	min	max	rng
SR-NE	28.71	27.8	29.9	2.1	28.25	27.6	29.0	1.4	27.08	26.5	27.7	1.2
SR-SE	29.15	28.1	30.5	2.4	27.98	27.5	28.6	1.1	26.86	26.4	27.4	1.0
SR-SW	29.16	28.1	30.5	2.4	27.98	27.4	28.6	1.1	26.86	26.4	27.4	1.0
SR-NW	29.44	28.2	30.9	2.6	28.04	27.4	28.7	1.3	26.99	26.4	27.6	1.2

TABLE 8.3A: MEAN DAILY INWARDLY TRANSMITTED SOLAR GAIN (MJ)
FOR DIFFERENT SOLAR SHIELDING OPTIONS

(PARTIAL SHIELDING OF SIDES (ONLY))

(RAINY SEASON - (JULY))

	30 DEGREES		45 DEGREES		60 DEGREES		75 DEGREES		87 DEGREES	
	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain
SR-NE	22.0	21.0	21.0	21.0	21.0	20.0	21.0	19.0	21.0	18.0
SR-SE	19.0	25.0	19.0	24.0	19.0	23.0	19.0	22.0	19.0	21.0
SR-SW	19.0	26.0	19.0	25.0	19.0	24.0	19.0	22.0	19.0	21.0
SR-NW	22.0	24.0	22.0	23.0	22.0	21.0	22.0	20.0	22.0	19.0

(HOT SEASON - (APRIL))

	30 DEGREES		45 DEGREES		60 DEGREES		75 DEGREES		87 DEGREES	
	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain
SR-NE	19.0	20.0	19.0	19.0	19.0	18.0	19.0	17.0	19.0	16.0
SR-SE	19.0	26.0	19.0	25.0	19.0	24.0	19.0	22.0	19.0	21.0
SR-SW	19.0	26.0	19.0	25.0	19.0	24.0	19.0	23.0	19.0	21.0
SR-NW	19.0	22.0	19.0	21.0	19.0	19.0	19.0	17.0	19.0	16.0

TABLE 8.3B: MEAN DAILY INWARDLY TRANSMITTED SOLAR ENERGY (MJ) FOR DIFFERENT SOLAR SHIELDING OPTIONS

(FULL SHIELDING OF SIDES (FSS) AND COMPLETE SHIELDING OF BUILDING (CSB))

(RAINY SEASON - (JULY))

	30 DEGREES		45 DEGREES		60 DEGREES		75 DEGREES		87 DEGREES	
	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain
SR-NE	7.0	6.0	5.0	5.0	4.0	4.0	2.0	2.0	0.4	0.3
SR-SE	6.0	5.0	5.0	4.0	3.0	3.0	2.0	2.0	0.4	0.3
SR-SW	6.0	6.0	5.0	5.0	4.0	3.0	2.0	2.0	0.4	0.3
SR-NW	6.0	6.0	5.0	5.0	4.0	3.0	2.0	2.0	0.4	0.3

(HOT SEASON - (APRIL))

	30 DEGREES		45 DEGREES		60 DEGREES		75 DEGREES		87 DEGREES	
	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain
SR-NE	7.0	6.0	5.0	5.0	4.0	4.0	2.0	2.0	0.5	0.3
SR-SE	6.0	6.0	5.0	5.0	3.0	3.0	2.0	2.0	0.4	0.3
SR-SW	6.0	6.0	5.0	5.0	4.0	4.0	2.0	2.0	0.4	0.3
SR-NW	7.0	7.0	5.0	5.0	4.0	4.0	2.0	2.0	0.5	0.4

TABLE 8.4A: MEAN DAILY INDOOR AIR TEMPERATURE VALUES (^{o}C) FOR DIFFERENT SHIELDING LOUVRE ANGLES

(PARTIAL SHIELDING OF SIDES ONLY)

(RAINY SEASON - (JULY))

	45 DEGREES				60 DEGREES			
	mean	min	max	rng	mean	min	max	rng
SS-NE	23.89	22.5	25.7	3.2	22.67	21.7	24.0	2.2
SR-NE	24.77	23.7	26.0	2.3	24.19	23.4	25.2	1.8
SS-SE	23.85	22.6	25.5	2.9	22.66	21.8	23.8	2.0
SR-SE	25.27	24.1	26.6	2.5	24.72	23.8	25.9	2.1
SS-SW	24.01	22.7	26.3	3.6	22.79	21.9	24.4	2.5
SR-SW	25.31	24.2	26.7	2.5	24.75	23.8	25.9	2.1
SS-NW	24.07	22.6	26.9	4.3	22.75	21.7	24.8	3.1
SR-NW	25.61	24.3	27.1	2.8	25.04	24.0	26.3	2.4

	30 DEGREES			
	mean	min	max	rng
SS-NE	24.57	22.9	26.7	3.9
SR-NE	25.04	23.9	26.4	2.6
SS-SE	24.52	22.9	26.5	3.6
SR-SE	25.54	24.3	27.0	2.7
SS-SW	24.70	23.0	27.4	4.4
SR-SW	25.57	24.3	27.1	2.7
SS-NW	24.82	23.0	28.2	5.2
SR-NW	25.86	24.5	27.5	3.0

	75 DEGREES				87 DEGREES			
	mean	min	max	rng	mean	min	max	rng
SS-NE	21.09	20.4	21.9	1.5	19.24	18.6	19.9	1.2
SR-NE	23.61	22.9	24.5	1.6	22.90	22.3	23.7	1.4
SS-SE	21.12	20.5	21.8	1.3	19.32	18.8	19.9	1.1
SR-SE	24.07	23.2	25.1	1.9	23.28	22.5	24.2	1.7
SS-SW	21.20	20.6	22.0	1.4	19.35	18.8	19.9	1.2
SR-SW	24.10	23.3	25.2	1.9	23.28	22.5	24.2	1.7
SS-NW	20.97	20.2	22.1	1.9	19.35	18.8	19.9	1.2
SR-NW	24.35	23.4	25.5	2.2	23.29	22.5	24.3	1.7

TABLE 8.4B: MEAN DAILY INDOOR AIR TEMPERATURE VALUES (^{o}C) FOR DIFFERENT SHIELDING LOUVRE ANGLES

(PARTIAL SHIELDING OF SIDES ONLY)

(DRY SEASON - (APRIL))

45 DEGREES

	mean	min	max	rng
SS-NE	29.14	27.2	31.6	4.4
SR-NE	30.02	28.5	31.8	3.3
SS-SE	29.10	27.3	31.5	4.2
SR-SE	30.51	28.9	32.4	3.4
SS-SW	29.21	27.3	32.3	5.0
SR-SW	30.55	29.0	32.4	3.4
SS-NW	29.31	27.2	33.2	6.0
SR-NW	30.88	29.2	32.9	3.7

60 DEGREES

	mean	min	max	rng
SS-NE	27.85	26.6	29.6	3.0
SR-NE	29.36	28.2	30.7	2.5
SS-SE	27.82	26.6	29.5	2.8
SR-SE	29.87	28.6	31.4	2.8
SS-SW	27.88	26.6	30.1	3.4
SR-SW	29.90	28.6	31.4	2.8
SS-NW	27.85	26.4	30.7	4.3
SR-NW	30.23	28.8	31.8	3.0

30 DEGREES

	mean	min	max	rng
SS-NE	29.87	27.5	32.8	5.3
SR-NE	30.32	28.6	32.4	3.8
SS-SE	29.83	27.5	32.7	5.1
SR-SE	30.81	29.0	32.9	3.9
SS-SW	29.96	27.6	33.7	6.0
SR-SW	30.85	29.1	32.9	3.8
SS-NW	30.14	27.6	34.8	7.2
SR-NW	31.18	29.3	33.4	4.2

75 DEGREES

	mean	min	max	rng
SS-NE	26.18	25.5	27.2	1.8
SR-NE	28.71	27.8	29.9	2.1
SS-SE	26.16	25.5	27.1	1.6
SR-SE	29.15	28.1	30.5	2.4
SS-SW	26.15	25.4	27.3	1.9
SR-SW	29.16	28.1	30.5	2.4
SS-NW	25.89	24.9	27.6	2.6
SR-NW	29.44	28.2	30.9	2.6

87 DEGREES

	mean	min	max	rng
SS-NE	24.20	23.6	24.7	1.1
SR-NE	27.91	27.1	28.9	1.7
SS-SE	24.20	23.7	24.7	1.0
SR-SE	28.25	27.3	29.4	2.1
SS-SW	24.11	23.5	24.6	1.1
SR-SW	28.24	27.3	29.4	2.1
SS-NW	23.56	22.8	24.3	1.4
SR-NW	28.42	27.4	29.7	2.3

TABLE 8.5A: MEAN DAILY INDOOR AIR TEMPERATURE VALUES (°C) FOR DIFFERENT SHIELDING LOUVRE ANGLES

(FULL SHIELDING OF SIDES ONLY)

(RAINY SEASON - (JULY))

	45 DEGREES				60 DEGREES			
	mean	min	max	rng	mean	min	max	rng
SS-NE	24.24	23.1	25.8	2.7	23.05	22.3	24.1	1.8
SR-NE	25.06	24.2	26.0	1.8	24.23	23.7	24.8	1.2
SS-SE	24.06	22.9	25.6	2.7	22.85	22.1	23.9	1.9
SR-SE	24.90	24.2	25.7	1.5	24.02	23.5	24.5	1.0
SS-SW	24.19	23.0	26.2	3.2	22.96	22.1	24.4	2.3
SR-SW	24.94	24.2	25.8	1.6	24.06	23.6	24.6	1.0
SS-NW	24.16	22.8	26.7	3.9	22.82	21.9	24.7	2.8
SR-NW	25.15	24.3	26.1	1.8	24.24	23.7	24.9	1.3

	30 DEGREES			
	mean	min	max	rng
SS-NE	24.91	23.5	26.8	3.3
SR-NE	25.43	24.4	26.5	2.1
SS-SE	24.74	23.3	26.6	3.3
SR-SE	25.31	24.4	26.2	1.8
SS-SW	24.88	23.4	27.3	3.9
SR-SW	25.36	24.5	26.3	1.9
SS-NW	24.91	23.3	27.9	4.7
SR-NW	25.58	24.6	26.8	2.2

	75 DEGREES				87 DEGREES			
	mean	min	max	rng	mean	min	max	rng
SS-NE	21.43	20.9	22.1	1.2	19.49	19.0	20.0	1.0
SR-NE	23.22	22.8	23.7	0.9	21.93	21.7	22.2	0.5
SS-SE	21.24	20.7	21.9	1.2	19.29	18.8	19.8	1.0
SR-SE	22.96	22.6	23.3	0.7	21.64	21.4	21.9	0.4
SS-SW	21.30	20.7	22.1	1.4	19.31	18.8	19.8	1.1
SR-SW	22.99	22.6	23.4	0.7	21.65	21.4	21.9	0.4
SS-NW	21.01	20.3	22.1	1.9	18.82	18.2	19.4	1.2
SR-NW	23.08	22.7	23.6	0.9	21.59	21.3	21.9	0.5

TABLE 8.5B: MEAN DAILY INDOOR AIR TEMPERATURE VALUES (^{o}C)
FOR DIFFERENT SHIELDING LOUVRE ANGLES

(FULL SHIELDING OF SIDES ONLY)

(HOT SEASON - (APRIL))

	45 DEGREES				**60 DEGREES**			
	mean	min	max	rng	mean	min	max	rng
SS-NE	29.55	27.9	31.6	3.6	28.29	27.2	29.7	2.5
SR-NE	30.30	29.0	31.8	2.8	29.37	28.5	30.3	1.8
SS-SE	29.45	27.8	31.5	3.7	28.16	27.1	29.6	2.5
SR-SE	30.14	29.0	31.4	2.3	29.15	28.4	30.0	1.6
SS-SW	29.49	27.8	32.1	4.3	28.16	27.0	30.1	3.1
SR-SW	30.17	29.1	31.4	2.3	29.17	28.4	30.0	1.5
SS-NW	29.38	27.5	32.8	5.3	27.90	26.6	30.4	3.8
SR-NW	30.41	29.1	31.9	2.7	29.35	28.5	30.3	1.9

	30 DEGREES			
	mean	min	max	rng
SS-NE	30.28	28.3	32.7	4.5
SR-NE	30.73	29.2	32.5	3.3
SS-SE	30.19	28.2	32.7	4.5
SR-SE	30.61	29.3	32.1	2.8
SS-SW	30.25	28.1	33.4	5.3
SR-SW	30.65	29.3	32.1	2.8
SS-NW	30.26	28.0	34.4	6.4
SR-NW	30.91	29.4	32.7	3.3

	75 DEGREES				**87 DEGREES**			
	mean	min	max	rng	mean	min	max	rng
SS-NE	26.57	26.0	27.4	1.4	24.49	24.1	24.9	0.9
SR-NE	28.25	27.6	29.0	1.4	26.80	26.4	27.3	0.9
SS-SE	26.42	25.8	27.3	1.4	24.32	23.9	24.8	0.9
SR-SE	27.98	27.5	28.6	1.1	26.49	26.1	26.9	0.7
SS-SW	26.37	25.7	27.5	1.8	24.21	23.7	24.7	1.0
SR-SW	27.98	27.4	28.6	1.1	26.47	26.1	26.9	0.7
SS-NW	25.88	25.0	27.4	2.4	23.44	22.8	24.1	1.3
SR-NW	28.04	27.4	28.7	1.3	26.33	25.9	26.8	0.9

TABLE 8.6A: MEAN DAILY INDOOR AIR TEMPERATURE VALUES (°C) FOR DIFFERENT SHIELDING LOUVRE ANGLES

(COMPLETE SHIELDING OF BUILDING)

(RAINY SEASON - (JULY))

45 DEGREES

	mean	min	max	rng
SS-NE	23.03	22.3	24.0	1.7
SR-NE	23.97	23.3	24.8	1.5
SS-SE	22.90	22.2	23.9	1.7
SR-SE	23.79	23.2	24.5	1.3
SS-SW	22.98	22.2	24.3	2.1
SR-SW	23.81	23.2	24.5	1.3
SS-NW	22.90	22.0	24.6	2.5
SR-NW	24.04	23.3	24.9	1.5

60 DEGREES

	mean	min	max	rng
SS-NE	22.60	22.0	23.5	1.5
SR-NE	23.36	22.9	23.9	1.1
SS-SE	22.45	21.8	23.3	1.5
SR-SE	23.18	22.7	23.7	0.9
SS-SW	22.53	21.8	23.7	1.9
SR-SW	23.21	22.8	23.7	0.9
SS-NW	22.42	21.7	24.0	2.4
SR-NW	23.42	22.9	24.0	1.1

30 DEGREES

	mean	min	max	rng
SS-NE	23.25	22.5	24.3	1.8
SR-NE	24.27	23.4	25.2	1.8
SS-SE	23.14	22.4	24.2	1.9
SR-SE	24.08	23.4	24.9	1.5
SS-SW	23.21	22.4	24.6	2.2
SR-SW	24.11	23.4	24.9	1.5
SS-NW	23.16	22.2	24.9	2.7
SR-NW	24.34	23.5	25.3	1.8

75 DEGREES

	mean	min	max	rng
SS-NE	20.96	20.5	21.5	1.0
SR-NE	22.16	21.8	22.6	0.8
SS-SE	20.81	20.4	21.4	1.0
SR-SE	21.95	21.6	22.3	0.7
SS-SW	20.86	20.4	21.6	1.2
SR-SW	21.97	21.6	22.3	0.7
SS-NW	20.63	20.1	21.6	1.5
SR-NW	22.11	21.7	22.6	0.8

87 DEGREES

	mean	min	max	rng
SS-NE	22.10	21.5	22.9	1.4
SR-NE	22.56	22.3	22.9	0.6
SS-SE	21.92	21.4	22.7	1.4
SR-SE	22.42	22.1	22.7	0.6
SS-SW	22.01	21.4	23.1	1.7
SR-SW	22.45	22.2	22.8	0.6
SS-NW	21.85	21.1	23.3	2.2
SR-NW	22.59	22.3	23.0	0.7

TABLE 8.6B: MEAN DAILY INDOOR AIR TEMPERATURE VALUES (°C) FOR DIFFERENT SHIELDING LOUVRE ANGLES

(COMPLETE SHIELDING OF BUILDING)

(HOT SEASON - (APRIL))

	45 DEGREES				60 DEGREES			
	mean	min	max	rng	mean	min	max	rng
SS-NE	28.25	27.2	29.6	2.4	27.77	26.9	29.0	2.1
SR-NE	29.12	28.0	30.4	2.3	28.41	27.7	29.3	1.6
SS-SE	28.18	27.1	29.6	2.5	27.67	26.8	28.9	2.1
SR-SE	28.92	28.0	30.0	2.0	28.23	27.6	28.9	1.4
SS-SW	28.17	27.0	29.9	2.9	27.67	26.7	29.3	2.5
SR-SW	28.94	28.0	30.0	2.0	28.24	27.6	28.9	1.4
SS-NW	28.00	26.8	30.3	3.5	27.45	26.4	29.6	3.2
SR-NW	29.18	28.1	30.4	2.3	28.46	27.7	29.3	1.6

	30 DEGREES			
	mean	min	max	rng
SS-NE	28.50	27.4	30.0	2.6
SR-NE	29.46	28.2	30.9	2.7
SS-SE	28.44	27.3	30.0	2.7
SR-SE	29.26	28.2	30.5	2.3
SS-SW	28.44	27.2	30.3	3.1
SR-SW	29.27	28.2	30.5	2.3
SS-NW	28.29	26.9	30.7	3.7
SR-NW	29.53	28.3	30.9	2.7

	75 DEGREES				87 DEGREES			
	mean	min	max	rng	mean	min	max	rng
SS-NE	26.01	25.6	26.7	1.1	27.19	26.4	28.2	1.8
SR-NE	27.08	26.5	27.7	1.2	27.46	27.0	27.9	0.9
SS-SE	25.91	25.4	26.6	1.2	27.07	26.3	28.1	1.8
SR-SE	26.86	26.4	27.4	1.0	27.34	27.0	27.8	0.8
SS-SW	25.86	25.3	26.8	1.5	27.07	26.3	28.5	2.3
SR-SW	26.86	26.4	27.4	1.0	27.34	27.0	27.8	0.8
SS-NW	25.47	24.8	26.8	2.0	26.78	25.9	28.8	2.9
SR-NW	26.99	26.4	27.6	1.2	27.47	27.0	28.0	1.0

TABLE 8.7: MEAN HOURLY INDOOR AIR TEMPERATURE (IN SR-NE) (^{o}C)
FOR DIFFERENT SOLAR RADIATION CONTROL OPTIONS
(RAINY SEASON - (JULY))

	NO SHADING	OVERHANG/ SIDEFIN	BALC.	PSS	FSS	CSB
HR	C	C	C	C	C	C
1	23.81	24.08	24.12	23.21	23.07	22.00
2	23.63	23.90	23.95	23.15	23.02	21.95
3	23.43	23.71	23.76	23.08	22.97	21.90
4	23.26	23.53	23.60	23.03	22.92	21.86
5	23.11	23.39	23.46	22.98	22.88	21.82
6	23.07	23.34	23.41	22.96	22.85	21.81
7	22.98	23.25	23.33	22.93	22.82	21.78
8	23.20	23.46	23.53	23.03	22.85	21.81
9	23.82	24.05	24.06	23.28	22.95	21.91
10	24.44	24.63	24.55	23.53	23.06	22.01
11	25.37	25.47	25.30	23.82	23.24	22.18
12	25.79	25.81	25.69	23.98	23.35	22.27
13	26.11	26.13	26.03	24.12	23.45	22.36
14	26.27	26.29	26.20	24.20	23.50	22.42
15	26.49	26.51	26.42	24.29	23.56	22.48
16	26.84	26.89	26.74	24.45	23.65	22.56
17	26.63	26.75	26.59	24.45	23.62	22.54
18	26.33	26.49	26.37	24.34	23.59	22.50
19	25.91	26.10	26.01	24.11	23.53	22.45
20	25.45	25.65	25.59	23.86	23.46	22.38
21	25.07	25.29	25.25	23.68	23.39	22.31
22	24.62	24.85	24.84	23.51	23.29	22.22
23	24.35	24.60	24.60	23.40	23.23	22.15
24	24.03	24.29	24.31	23.29	23.16	22.08

(HOT SEASON - (APRIL))

	NO SHADING	OVERHANG/ SIDEFIN	BALC.	PSS	FSS	CSB
1	28.93	29.07	29.07	28.21	27.99	26.82
2	28.71	28.86	28.87	28.14	27.93	26.77
3	28.53	28.68	28.70	28.08	27.88	26.72
4	28.21	28.37	28.41	27.98	27.80	26.65
5	28.09	28.25	28.29	27.93	27.76	26.62
6	27.96	28.12	28.17	27.88	27.72	26.59
7	27.68	27.86	27.92	27.79	27.64	26.53
8	27.75	27.93	27.99	27.84	27.63	26.52
9	28.29	28.45	28.50	28.04	27.70	26.61
10	29.88	29.95	29.84	28.53	28.02	26.91
11	30.83	30.85	30.59	28.85	28.22	27.07
12	31.42	31.35	31.14	29.08	28.38	27.21
13	32.17	32.09	31.87	29.35	28.59	27.39
14	33.02	32.91	32.67	29.64	28.81	27.59
15	33.44	33.33	33.09	29.82	28.93	27.69
16	33.21	33.12	32.91	29.80	28.91	27.66
17	32.94	32.88	32.70	29.74	28.86	27.63
18	32.71	32.67	32.48	29.64	28.83	27.60
19	32.16	32.15	31.99	29.41	28.75	27.52
20	31.24	31.27	31.15	29.05	28.57	27.36
21	30.49	30.56	30.48	28.78	28.41	27.22
22	30.06	30.14	30.08	28.61	28.32	27.13
23	29.76	29.85	29.81	28.50	28.25	27.06
24	29.41	29.52	29.49	28.39	28.16	26.98

TABLE 8.8: MEAN HOURLY INDOOR AIR TEMPERATURE (IN SR-SE) (^{o}C) FOR DIFFERENT SOLAR RADIATION CONTROL OPTIONS

(RAINY SEASON - (JULY))

HR	NO SHADING C	OVH/ FINS C	BALCONY C	PSS C	FSS C	CSB C
1	24.24	24.33	24.32	23.58	22.83	21.81
2	24.06	24.16	24.16	23.51	22.79	21.77
3	23.86	23.96	23.98	23.44	22.75	21.73
4	23.68	23.79	23.82	23.37	22.71	21.69
5	23.54	23.65	23.68	23.32	22.67	21.66
6	23.48	23.60	23.63	23.29	22.65	21.65
7	23.39	23.51	23.55	23.25	22.63	21.63
8	23.65	23.75	23.77	23.38	22.65	21.66
9	24.31	24.38	24.37	23.67	22.74	21.75
10	24.99	25.02	24.94	23.97	22.84	21.84
11	25.91	25.89	25.73	24.33	22.99	21.98
12	26.33	26.26	26.15	24.55	23.08	22.06
13	26.63	26.60	26.50	24.72	23.15	22.13
14	26.79	26.78	26.69	24.83	23.20	22.18
15	27.02	27.01	26.93	24.95	23.25	22.23
16	27.36	27.35	27.26	25.10	23.32	22.31
17	27.18	27.19	27.11	25.06	23.30	22.29
18	26.88	26.90	26.83	24.91	23.26	22.25
19	26.43	26.46	26.39	24.66	23.21	22.21
20	25.89	25.93	25.86	24.34	23.15	22.15
21	25.49	25.53	25.48	24.13	23.09	22.09
22	25.03	25.10	25.06	23.93	23.02	22.00
23	24.76	24.83	24.80	23.81	22.97	21.95
24	24.45	24.53	24.51	23.69	22.91	21.89

(HOT SEASON - (APRIL))

HR	NO SHADING C	OVH/ FINS C	BALCONY C	PSS C	FSS C	CSB C
1	29.03	29.24	29.28	28.54	27.75	26.63
2	28.82	29.03	29.08	28.46	27.70	26.59
3	28.65	28.86	28.92	28.39	27.66	26.55
4	28.35	28.57	28.65	28.28	27.59	26.49
5	28.22	28.45	28.53	28.23	27.56	26.47
6	28.10	28.32	28.41	28.17	27.53	26.44
7	27.84	28.07	28.17	28.08	27.47	26.39
8	27.98	28.21	28.30	28.17	27.46	26.39
9	28.62	28.83	28.90	28.45	27.53	26.47
10	30.23	30.36	30.27	29.01	27.80	26.72
11	31.19	31.29	31.03	29.38	27.96	26.86
12	31.77	31.75	31.58	29.63	28.09	26.97
13	32.45	32.43	32.28	29.91	28.26	27.13
14	33.25	33.21	33.05	30.21	28.44	27.29
15	33.66	33.62	33.47	30.41	28.54	27.38
16	33.46	33.47	33.34	30.43	28.52	27.36
17	33.21	33.26	33.15	30.40	28.48	27.33
18	32.93	32.99	32.90	30.27	28.46	27.31
19	32.31	32.39	32.31	29.95	28.38	27.24
20	31.33	31.44	31.40	29.52	28.24	27.10
21	30.57	30.72	30.70	29.20	28.11	26.98
22	30.13	30.29	30.29	29.00	28.03	26.91
23	29.83	29.99	30.00	28.87	27.98	26.85
24	29.49	29.67	29.69	28.74	27.91	26.78

TABLE 8.9: MEAN HOURLY INDOOR AIR TEMPERATURE (IN SR-SW) (^{o}C) FOR DIFFERENT SOLAR RADIATION CONTROL OPTIONS (RAINY SEASON - (JULY))

HR	NO SHADING	OVH/ FINS	BALCONY	PSS	FSS	CSB
	C	C	C	C	C	C
1	24.13	24.26	24.30	23.61	22.86	21.83
2	23.95	24.08	24.13	23.54	22.82	21.79
3	23.75	23.89	23.95	23.46	22.78	21.75
4	23.57	23.72	23.79	23.40	22.74	21.71
5	23.43	23.58	23.66	23.34	22.70	21.68
6	23.38	23.53	23.61	23.31	22.68	21.67
7	23.29	23.45	23.52	23.27	22.66	21.65
8	23.52	23.67	23.74	23.40	22.67	21.67
9	24.12	24.25	24.30	23.69	22.76	21.76
10	24.74	24.84	24.88	23.99	22.85	21.84
11	25.63	25.70	25.69	24.35	23.00	21.99
12	26.11	26.16	26.13	24.57	23.09	22.07
13	26.50	26.53	26.49	24.74	23.17	22.14
14	26.78	26.74	26.69	24.85	23.22	22.19
15	27.16	27.15	26.93	24.97	23.27	22.25
16	27.60	27.61	27.32	25.12	23.36	22.33
17	27.44	27.48	27.30	25.09	23.34	22.32
18	27.07	27.13	27.02	24.94	23.31	22.28
19	26.49	26.56	26.49	24.69	23.25	22.23
20	25.88	25.95	25.91	24.37	23.19	22.17
21	25.43	25.51	25.49	24.15	23.13	22.11
22	24.95	25.05	25.05	23.95	23.05	22.02
23	24.66	24.77	24.79	23.83	23.00	21.97
24	24.34	24.46	24.49	23.71	22.94	21.91

(HOT SEASON - (APRIL))

HR	NO SHADING	OVH/ FINS	BALCONY	PSS	FSS	CSB
1	28.89	29.11	29.21	28.56	27.76	26.64
2	28.68	28.90	29.01	28.47	27.71	26.59
3	28.51	28.73	28.85	28.40	27.67	26.55
4	28.21	28.44	28.57	28.29	27.60	26.49
5	28.09	28.32	28.46	28.24	27.56	26.47
6	27.97	28.20	28.34	28.18	27.53	26.44
7	27.71	27.95	28.10	28.09	27.47	26.39
8	27.81	28.05	28.20	28.18	27.45	26.39
9	28.36	28.58	28.72	28.46	27.52	26.45
10	29.87	30.01	30.07	29.01	27.77	26.70
11	30.79	30.89	30.91	29.38	27.94	26.85
12	31.45	31.52	31.50	29.63	28.08	26.96
13	32.28	32.29	32.22	29.92	28.24	27.12
14	33.25	33.13	33.01	30.22	28.43	27.29
15	33.87	33.80	33.44	30.42	28.53	27.38
16	33.82	33.82	33.45	30.45	28.53	27.37
17	33.58	33.63	33.42	30.42	28.51	27.35
18	33.21	33.28	33.15	30.29	28.48	27.33
19	32.41	32.50	32.42	29.97	28.40	27.25
20	31.32	31.45	31.43	29.53	28.25	27.11
21	30.50	30.66	30.68	29.21	28.12	26.99
22	30.03	30.19	30.24	29.01	28.04	26.91
23	29.71	29.88	29.94	28.88	27.98	26.85
24	29.36	29.55	29.63	28.75	27.91	26.78

TABLE 8.10: MEAN HOURLY INDOOR AIR TEMPERATURE (IN SR-NW) (^{o}C)
FOR DIFFERENT SOLAR RADIATION CONTROL OPTIONS
(RAINY SEASON - (JULY))

HR	NO SHADING	OVH/ FINS	BALC	PSS	FSS	CSB
	C	C	C	C	C	C
1	23.84	23.92	23.92	23.83	22.93	21.96
2	23.65	23.75	23.76	23.74	22.88	21.91
3	23.45	23.55	23.57	23.65	22.83	21.86
4	23.27	23.38	23.41	23.56	22.78	21.82
5	23.12	23.24	23.27	23.49	22.73	21.78
6	23.08	23.20	23.23	23.45	22.71	21.77
7	22.99	23.11	23.15	23.40	22.68	21.74
8	23.25	23.34	23.37	23.52	22.70	21.77
9	23.91	23.95	23.96	23.82	22.79	21.86
10	24.57	24.55	24.55	24.14	22.89	21.95
11	25.55	25.46	25.41	24.58	23.08	22.12
12	26.05	25.93	25.86	24.87	23.18	22.22
13	26.47	26.40	26.32	25.10	23.27	22.30
14	26.77	26.65	26.57	25.26	23.33	22.35
15	27.19	27.03	26.94	25.39	23.39	22.42
16	27.68	27.49	27.39	25.50	23.52	22.54
17	27.47	27.31	27.22	25.43	23.51	22.53
18	27.04	26.91	26.84	25.27	23.47	22.49
19	26.35	26.30	26.23	24.99	23.40	22.41
20	25.69	25.68	25.62	24.66	23.31	22.34
21	25.21	25.23	25.17	24.44	23.24	22.27
22	24.70	24.75	24.71	24.22	23.15	22.18
23	24.41	24.47	24.44	24.09	23.09	22.11
24	24.06	24.14	24.13	23.94	23.01	22.04

(HOT SEASON - (APRIL))

HR	NO SHADING	OVH/ FINS	BALC	PSS	FSS	CSB
1	28.81	28.91	28.83	28.83	27.78	26.74
2	28.59	28.70	28.63	28.73	27.72	26.69
3	28.41	28.53	28.47	28.64	27.67	26.64
4	28.09	28.22	28.18	28.50	27.59	26.57
5	27.97	28.10	28.07	28.43	27.55	26.54
6	27.85	27.98	27.95	28.36	27.51	26.51
7	27.57	27.71	27.70	28.25	27.43	26.45
8	27.66	27.81	27.80	28.32	27.41	26.44
9	28.23	28.35	28.33	28.59	27.48	26.51
10	29.85	29.89	29.78	29.20	27.79	26.80
11	30.81	30.81	30.66	29.60	27.98	26.97
12	31.48	31.46	31.29	29.88	28.14	27.10
13	32.36	32.29	32.07	30.21	28.33	27.28
14	33.42	33.30	33.02	30.56	28.55	27.48
15	34.09	33.97	33.68	30.79	28.67	27.58
16	34.02	33.94	33.68	30.80	28.70	27.61
17	33.77	33.70	33.47	30.76	28.69	27.58
18	33.37	33.31	33.08	30.64	28.66	27.55
19	32.50	32.47	32.25	30.34	28.55	27.45
20	31.36	31.36	31.18	29.89	28.36	27.28
21	30.49	30.53	30.38	29.56	28.20	27.14
22	30.00	30.06	29.92	29.35	28.11	27.05
23	29.67	29.73	29.61	29.20	28.03	26.98
24	29.30	29.38	29.28	29.05	27.95	26.90

TABLE 8.11: MEAN DAILY INDOOR AIR TEMPERATURE VALUES (C)
FOR INNER ROOF TYPES FOR THE CSB OPTION
(RAINY SEASON - (JULY))
(COMPLETE SHIELDING OF BUILDING)

	ORIGINAL ROOF				**150mm CONCRETE + FELT**			
	75 DEGREES				75 DEGREES			
	mean	min	max	rng	mean	min	max	rng
SS-NE	22.03	21.5	22.6	1.1	20.96	20.5	21.5	1.0
SR-NE	23.98	23.5	24.4	0.9	22.16	21.8	22.6	0.8
SS-SE	21.82	21.3	22.5	1.1	20.81	20.4	21.4	1.0
SR-SE	23.74	23.4	24.1	0.8	21.95	21.6	22.3	0.7
SS-SW	21.88	21.3	22.7	1.4	20.86	20.4	21.6	1.2
SR-SW	23.77	23.4	24.2	0.8	21.97	21.6	22.3	0.7
SS-NW	21.55	20.9	22.7	1.8	20.63	20.1	21.6	1.5
SR-NW	23.79	23.3	24.3	0.9	22.11	21.7	22.6	0.8

(HOT SEASON - (APRIL))

	ORIGINAL ROOF				**150mm CONCRETE + FELT**			
	75 DEGREES				75 DEGREES			
	mean	min	max	rng	mean	min	max	rng
SS-NE	27.25	26.7	28.0	1.3	26.01	25.6	26.7	1.1
SR-NE	29.08	28.4	29.8	1.4	27.08	26.5	27.7	1.2
SS-SE	27.08	26.5	27.9	1.4	25.91	25.4	26.6	1.2
SR-SE	28.83	28.2	29.4	1.2	26.86	26.4	27.4	1.0
SS-SW	27.02	26.4	28.1	1.8	25.86	25.3	26.8	1.5
SR-SW	28.83	28.2	29.4	1.2	26.86	26.4	27.4	1.0
SS-NW	26.49	25.7	28.0	2.3	25.47	24.8	26.8	2.0
SR-NW	28.82	28.1	29.5	1.4	26.99	26.4	27.6	1.2

TABLE 8.12: MEAN HOURLY INWARDLY TRANSMITTED SOLAR GAIN (MJ) FOR DIFFERENT SOLAR RADIATION CONTROL OPTIONS

(HOT SEASON - (APRIL)) (SR-NE)

	NO SHADING		**OVERHANG/ SIDEFIN**		**BALCONY**		**PARTIAL SHIELDING****		**FULL SHIELDING****	
HR	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	1.38	1.14	1.38	1.14	1.35	1.12	0.63	0.53	0.09	0.08
9	3.10	2.58	3.06	2.54	3.06	2.54	1.35	1.12	0.20	0.19
10	4.18	3.48	4.16	3.46	3.35	2.79	1.74	1.44	0.27	0.26
11	4.24	3.53	4.24	3.53	2.78	2.31	1.81	1.50	0.17	0.17
12	3.42	2.85	2.70	2.25	2.70	2.25	1.76	1.46	0.17	0.16
13	2.68	2.23	2.68	2.23	2.68	2.23	1.75	1.45	0.17	0.16
14	2.79	2.32	2.79	2.32	2.79	2.32	1.81	1.51	0.18	0.17
15	3.01	2.51	3.01	2.51	3.01	2.51	1.96	1.63	0.19	0.18
16	3.25	2.70	3.22	2.68	3.22	2.68	2.09	1.74	0.20	0.19
17	3.12	2.60	3.04	2.53	3.04	2.53	1.98	1.64	0.19	0.18
18	2.30	1.92	2.30	1.91	2.21	1.84	1.44	1.20	0.14	0.13
19	0.88	0.73	0.88	0.73	0.88	0.73	0.57	0.48	0.06	0.05
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(RAINY SEASON - (JULY)) (SR-NE)

7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	1.29	1.07	1.29	1.07	1.25	1.04	0.71	0.59	0.08	0.08
9	2.80	2.33	2.80	2.33	2.52	2.09	1.49	1.24	0.16	0.15
10	3.90	3.25	3.74	3.11	2.79	2.32	1.87	1.56	0.22	0.21
11	4.22	3.52	3.76	3.13	2.76	2.29	1.82	1.51	0.17	0.16
12	3.82	3.19	2.81	2.34	2.81	2.34	1.83	1.52	0.18	0.17
13	3.40	2.84	2.85	2.37	2.85	2.37	1.85	1.54	0.18	0.17
14	3.54	2.96	2.95	2.45	2.95	2.45	1.91	1.59	0.19	0.18
15	3.75	3.13	3.13	2.61	3.10	2.58	2.05	1.70	0.19	0.18
16	3.82	3.19	3.56	2.97	3.16	2.63	2.46	2.05	0.20	0.19
17	3.47	2.89	3.47	2.89	2.89	2.41	2.46	2.05	0.18	0.17
18	2.55	2.12	2.55	2.12	2.44	2.03	1.79	1.49	0.16	0.15
19	1.04	0.87	1.04	0.87	1.04	0.87	0.68	0.56	0.07	0.06
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

** shielding at 75 deg louvre angle

TABLE 8.13: MEAN HOURLY INWARDLY TRANSMITTED SOLAR GAIN (MJ)
FOR DIFFERENT SOLAR RAD. CONTROL OPTIONS
(HOT SEASON - (APRIL)) (SR-SE)

	NO SHADING		**OVERHANG/ SIDEFIN**		**BALCONY**		**PARTIAL SHIELDING****		**FULL SHIELDING****	
HR	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans mitted	total gain
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	1.69	1.40	1.65	1.37	1.55	1.29	0.63	0.71	0.08	0.07
9	3.79	3.15	3.73	3.10	3.67	3.05	1.35	1.51	0.18	0.17
10	5.10	4.24	5.06	4.21	4.25	3.54	1.74	1.94	0.25	0.23
11	5.23	4.36	5.21	4.34	3.75	3.12	1.81	2.00	0.15	0.14
12	4.44	3.71	3.65	3.04	3.65	3.04	1.76	1.89	0.15	0.14
13	3.74	3.12	3.62	3.02	3.62	3.02	1.75	1.91	0.15	0.14
14	3.85	3.22	3.77	3.13	3.77	3.13	1.81	2.00	0.16	0.15
15	4.10	3.41	4.07	3.39	4.07	3.39	1.96	2.17	0.17	0.16
16	4.35	3.62	4.35	3.62	4.35	3.62	2.09	2.32	0.18	0.17
17	4.11	3.42	4.11	3.42	4.11	3.42	1.98	2.19	0.17	0.16
18	2.98	2.48	2.98	2.48	2.98	2.48	1.44	1.59	0.12	0.11
19	1.19	0.99	1.19	0.99	1.19	0.99	0.57	0.63	0.05	0.05
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(RAINY SEASON - (JULY)) (SR-SE)

7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	1.47	1.22	1.39	1.22	1.23	1.02	0.58	0.65	0.06	0.06
9	3.16	2.63	2.98	2.63	2.82	2.35	1.20	1.34	0.15	0.14
10	4.35	3.62	4.06	3.62	3.50	2.92	1.62	1.80	0.20	0.19
11	4.69	3.91	4.35	3.91	3.72	3.10	1.79	1.98	0.15	0.14
12	4.28	3.57	3.80	3.57	3.80	3.16	1.83	1.99	0.15	0.15
13	3.84	3.20	3.84	3.20	3.84	3.20	1.85	2.05	0.16	0.15
14	3.98	3.31	3.98	3.31	3.98	3.31	1.91	2.12	0.16	0.15
15	4.18	3.48	4.18	3.48	4.18	3.48	2.01	2.23	0.17	0.16
16	4.27	3.55	4.27	3.55	4.27	3.55	2.05	2.28	0.17	0.16
17	3.91	3.25	3.91	3.25	3.91	3.25	1.88	2.09	0.16	0.15
18	2.91	2.42	2.91	2.42	2.91	2.42	1.40	1.55	0.12	0.11
19	1.41	1.17	1.41	1.17	1.41	1.17	0.68	0.75	0.06	0.05
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

** shielding at 75 deg louvre angle

TABLE 8.14: MEAN HOURLY INWARDLY TRANSMITTED SOLAR GAIN (MJ) FOR DIFFERENT SOLAR RAD. CONTROL OPTIONS

(HOT SEASON - (APRIL)) (SR-SW)

	NO SHADING		**OVERHANG/ SIDEFIN**		**BALCONY**		**PARTIAL SHIELDING****		**FULL SHIELDING****	
HR	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain	trans-mitted	total gain
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	1.32	1.10	1.32	1.10	1.32	1.10	0.63	0.70	0.05	0.05
9	2.80	2.33	2.80	2.33	2.80	2.33	1.35	1.49	0.11	0.10
10	3.60	3.00	3.60	3.00	3.60	3.00	1.74	1.92	0.15	0.14
11	3.77	3.14	3.75	3.12	3.75	3.12	1.81	2.00	0.15	0.16
12	3.73	3.11	3.65	3.04	3.65	3.04	1.76	1.95	0.15	0.14
13	3.74	3.12	3.62	3.02	3.62	3.02	1.75	1.93	0.15	0.14
14	4.64	3.88	3.77	3.13	3.77	3.13	1.81	1.96	0.15	0.14
15	5.93	4.94	5.90	4.91	4.07	3.39	1.96	2.17	0.17	0.16
16	6.53	5.43	6.53	5.43	5.34	4.44	2.09	2.34	0.32	0.30
17	5.89	4.89	5.89	4.89	5.89	4.89	1.98	2.21	0.29	0.27
18	3.99	3.31	3.99	3.31	3.99	3.31	1.44	1.61	0.19	0.18
19	1.19	0.99	1.19	0.99	1.19	0.99	0.57	0.63	0.05	0.05
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(RAINY SEASON - (JULY)) (SR-SW)

7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	1.20	1.00	1.20	1.00	1.20	1.00	0.58	0.64	0.05	0.05
9	2.50	2.08	2.50	2.08	2.50	2.08	1.20	1.33	0.10	0.10
10	3.36	2.79	3.36	2.79	3.36	2.79	1.62	1.79	0.14	0.13
11	3.72	3.10	3.72	3.10	3.72	3.10	1.79	1.99	0.15	0.14
12	3.80	3.16	3.80	3.16	3.80	3.16	1.83	2.03	0.15	0.15
13	3.84	3.20	3.84	3.20	3.84	3.20	1.85	2.05	0.16	0.15
14	4.52	3.77	3.98	3.31	3.98	3.31	1.91	2.08	0.16	0.15
15	5.46	4.54	5.46	4.54	4.18	3.48	2.01	2.23	0.17	0.16
16	5.82	4.84	5.82	4.84	4.73	3.94	2.05	2.29	0.28	0.26
17	5.22	4.34	5.22	4.34	5.22	4.34	1.88	2.10	0.25	0.24
18	3.71	3.08	3.71	3.08	3.71	3.08	1.40	1.57	0.17	0.16
19	1.41	1.17	1.41	1.17	1.41	1.17	0.68	0.75	0.06	0.05
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

** shielding at 75 deg louvre angle

TABLE 8.15: MEAN HOURLY INWARDLY TRANSMITTED SOLAR GAIN (MJ)
FOR DIFFERENT SOLAR RAD. CONTROL OPTIONS
(HOT SEASON - (APRIL)) (SR-NW)

HR	NO SHADING trans-mitted	NO SHADING total gain	OVERHANG/SIDEFIN trans-mitted	OVERHANG/SIDEFIN total gain	BALCONY trans-mitted	BALCONY total gain	PARTIAL SHIELDING** trans-mitted	PARTIAL SHIELDING** total gain	FULL SHIELDING** trans-mitted	FULL SHIELDING** total gain
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	1.01	0.84	0.98	0.81	0.98	0.81	0.63	0.53	0.05	0.04
9	2.11	1.76	2.07	1.73	2.07	1.73	1.35	1.12	0.10	0.09
10	2.68	2.24	2.67	2.22	2.67	2.22	1.74	1.44	0.13	0.12
11	2.78	2.31	2.78	2.31	2.78	2.31	1.81	1.50	0.13	0.12
12	2.70	2.25	2.70	2.25	2.70	2.25	1.76	1.46	0.13	0.12
13	2.68	2.23	2.68	2.23	2.68	2.23	1.75	1.45	0.13	0.12
14	3.58	2.99	3.49	2.91	3.43	2.86	1.81	1.51	0.13	0.13
15	4.85	4.03	4.81	4.00	4.78	3.98	1.96	1.63	0.14	0.14
16	5.43	4.52	5.40	4.49	5.40	4.49	2.09	1.74	0.45	0.42
17	4.91	4.08	4.83	4.01	4.83	4.01	1.98	1.64	0.38	0.37
18	3.31	2.75	3.21	2.67	3.21	2.67	1.44	1.20	0.24	0.23
19	0.88	0.73	0.88	0.73	0.88	0.73	0.57	0.48	0.04	0.04
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(RAINY SEASON - (JULY)) (SR-NW)

HR	NO SHADING trans-mitted	NO SHADING total gain	OVERHANG/SIDEFIN trans-mitted	OVERHANG/SIDEFIN total gain	BALCONY trans-mitted	BALCONY total gain	PARTIAL SHIELDING** trans-mitted	PARTIAL SHIELDING** total gain	FULL SHIELDING** trans-mitted	FULL SHIELDING** total gain
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	1.02	0.85	0.89	0.74	0.89	0.74	0.62	0.52	0.04	0.40
9	2.13	1.78	1.85	1.54	1.85	1.54	1.26	1.05	0.09	0.08
10	2.90	2.42	2.49	2.07	2.49	2.07	1.73	1.44	0.12	0.11
11	3.25	2.71	2.76	2.29	2.76	2.29	2.12	1.77	0.13	0.12
12	3.34	2.79	2.81	2.34	2.81	2.34	2.35	1.97	0.13	0.13
13	3.40	2.84	3.37	2.82	3.37	2.82	2.40	2.01	0.13	0.13
14	4.09	3.42	3.49	2.91	3.49	2.91	2.51	2.10	0.14	0.13
15	5.03	4.19	4.38	3.64	4.38	3.64	2.45	2.05	0.15	0.14
16	5.37	4.48	4.71	3.92	4.71	3.92	2.24	1.87	0.36	1.34
17	4.79	3.98	4.21	3.50	4.21	3.50	2.00	1.66	0.31	0.30
18	3.34	2.78	2.95	2.45	2.95	2.45	1.52	1.27	0.21	0.20
19	1.04	0.87	1.04	0.87	1.04	0.87	0.68	0.56	0.05	0.05
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

** shielding at 75 deg louvre angle

Table 8.16 Measured and computed temperature values (^{o}C) in July

	SS-NE		SR-NE		SS-SE		SR-SE		SS-SW		SR-SW	
	comp	meas	comp	meas	comp	meas	comp	meas	comp	meas	comp	meas
8	25.43	29.7	25.66	29.4	25.38	28.8	26.18	28.9	25.51	28.5	26.21	28.7
9	25.48	28.2	25.73	28.1	25.44	27.7	26.26	28.3	25.56	27.3	26.28	27.4
10	25.49	28.7	25.75	28.6	25.46	28.0	26.29	27.9	25.58	27.6	26.32	27.9
11	25.49	25.8	25.77	27.3	25.46	25.7	26.32	26.5	25.59	25.6	26.35	26.4
12	25.49	28.6	25.78	26.4	25.46	25.6	26.33	25.6	25.59	25.6	26.35	25.9
13	25.50	28.2	25.80	27.3	25.48	27.1	26.35	26.7	25.60	27.2	26.37	27.3
14	25.49	29.4	25.79	27.6	25.48	27.3	26.35	27.4	25.60	26.9	26.37	27.2
15	25.44	28.0	25.75	28.0	25.42	27.7	26.31	27.5	25.54	25.5	26.33	27.7
16	25.40	26.1	25.73	27.7	25.39	26.5	26.28	26.6	25.51	25.4	26.31	26.7
17	25.39	29.3	25.71	28.9	25.38	28.9	26.27	28.4	25.50	29.1	26.29	28.7
18	25.42	28.0	25.73	28.3	25.41	27.5	26.28	27.4	25.52	26.9	26.30	27.3
19	25.39	28.5	25.71	26.3	25.38	24.8	26.26	25.6	25.49	25.1	26.28	25.6
20	25.46	26.7	25.76	26.4	25.45	25.5	26.30	25.6	25.56	25.7	26.33	25.6
21	25.43	27.9	25.75	27.8	25.43	27.0	26.29	26.9	25.53	27.1	26.31	27.1
22	25.43	27.6	25.75	28.0	25.43	27.4	26.29	26.9	25.53	27.1	26.31	27.2
23	25.46	27.4	25.78	27.8	25.46	26.8	26.31	27.1	25.56	26.6	26.33	26.9
24	25.47	28.5	25.78	28.3	25.47	27.5	26.32	27.6	25.58	27.3	26.34	27.5
25	25.47	26.8	25.80	25.3	25.48	22.9	26.34	24.2	25.58	23.0	26.36	23.5
26	25.42	25.5	25.77	24.9	25.44	24.0	26.31	24.5	25.53	24.4	26.33	24.3
27	25.46	25.4	25.79	25.5	25.47	25.0	26.32	25.0	25.57	25.2	26.34	25.0

comp = computed
meas = measured

Table 8.17: Percentage errors between computed and measured temperatures in July

Day	SS-NE	SR-NE	SS-SE	SR-SE	SS-SW	SR-SW
8	14.377	12.721	11.875	9.412	10.491	8.676
9	9.645	8.434	8.159	7.208	6.374	4.088
10	11.185	9.965	9.071	5.771	7.319	5.663
11	1.202	5.604	0.934	0.679	0.039	0.189
12	10.874	2.348	0.547	2.852	0.039	1.737
13	9.574	5.495	5.978	1.311	5.882	3.407
14	13.299	6.558	6.667	3.832	4.833	3.051
15	9.143	8.036	8.231	4.327	0.157	4.946
16	2.682	7.112	4.189	1.203	0.433	1.461
17	13.345	11.038	12.180	7.500	12.371	8.397
18	9.214	9.081	7.600	4.088	5.130	3.663
19	10.912	2.243	2.339	2.578	1.554	2.656
20	4.644	2.424	0.196	2.734	0.545	2.852
21	8.853	7.374	5.815	2.268	5.793	2.915
22	7.862	8.036	7.190	2.268	5.793	3.272
23	7.080	7.266	5.000	2.915	3.910	2.119
24	10.632	8.905	7.382	4.638	6.300	4.218
25	4.963	1.976	11.266	8.843	11.217	12.170
26	0.314	3.494	6.000	7.388	4.631	8.354
27	0.236	1.137	1.880	5.280	1.468	5.360

Chapter 9

Conclusions and Recommendations

9.1 Introduction

The technique of modulated solar shielding of buildings has been conceptualised and presented and a methodology was developed to thermally simulate its performance as a solar radiation control strategy for buildings, using an existing thermal model (SERI-RES Version 1.2). The results of the thermal simulation studies indicate that solar shielding is a potentially more effective solar radiation control technique than formal methods of shading with overhangs, sidefins and balconies. The simulated and measured results also portrayed a significant agreement, and thereby, not only validating the thermal model but also the methodology with which the concept was modelled. In this chapter conclusions drawn from the entire study are used not only as the basis for putting forward the use of modulated solar shielding for solar radiation control in buildings but also as a framework upon which some practical application of shielding to solar thermal control can be based. This framework is by no means exhaustive as there is still a lot of work to be done to evaluate an all-round environmental performance of shielding as a bioclimatic design technique.

9.2 Main conclusions from the study

Modulated solar shielding is a potentially more efficient solar radiation control technique for buildings in hot semi-arid/hot-dry climates where the outdoor temperature is so high that passive ventilation cooling is not only ineffective during the day-time but actually contributes to the indoor thermal gain. Even for a building such as this case study for which the materials have been used purely on aesthetic and "prestige" grounds rather than for thermal control, shielding has demonstrated that indoor thermal conditions can be brought very close to the comfort temperature range.

Whilst shielding has been shown to be relatively more effective in reducing indoor thermal gain, its efficiency is a function of not only the area of the building's external surface that is shielded, but also of the angle of inclination of the louvre slats of the shielding system. When the external surfaces of the rooms are partially shielded, there is a substantial reduction in solar thermal gain which is even higher when the whole sides are shielded. Shielding is fully optimised when the external surfaces exposed to the sun, including the roof, is shielded.

Whilst huge reductions (over 90%) of the inwardly transmitted solar radiation can be obtained from solar shielding technique, it does not give a relatively corresponding high reduction of indoor temperatures. This is *partly* because the shielding system's solar thermal gain is partially re-radiated as longwave radiation, coupled by convective transfer, inwards into the living spaces. This effect must be minimised by appropriate choice of materials, colour, and adequate ventilation of the shielded buffer spaces.

The decrease by a louvre shielding system to airflow is dependent upon the angle of inclination of the louvre slats from the horizontal. At very low angles, between 0^o and 30^o there is very little decrease to airflow. Between 45^o and 60^o, the decrease begins to get substantial and is quite high from 75^o onwards up to nearly 90^o (the louvre angle is never exactly 90^o as explained earlier in chapter 6). However, unless the louvre system is used permanently at nearly 90^o inclination for a long period, the system would not impair the airflow in so much as to decrease ventilation below the recommended standard for health and hygiene. Even at nearly 90^o, (vertical position) there are always tiny gaps between the louvre slats for a measure of infiltration to take place.

The thermal efficiency of the shielding system is as dependent on its design and material specifications as on the need to limit its impairment of convective/radiative longwave heat loss, which is especially vital at night except during the cold seasons. The shielding system must be so modulated after sunset as to keep this impairment to the minimum possible for all seasons except the cold season.

Furthermore, the need to reduce the impairment of daylighting by the shielding system requires wider apertures between the slats, and consequently, greater porosity to shortwave radiation. This, coupled with inter-reflected radiation between the slats, reduces the shielding efficiency. Therefore, this paradox of maximising both shading and daylighting must be resolved, within limits, by the user to suit his particular needs by modulating the shield accordingly. This would be a function of such factors as the season, weather conditions, time of day, occupancy schedules, desired indoor tasks, personal preference, intrinsic socio-cultural/personal values and so on. For the shielding design option therefore, it is the duty of the designer to provide not only a high level of flexibility and the opportunity for choice but also the implications of the choice so made by the final user. For example, solar shielding at louvre slat angle of 75^{o} may give an effective solar thermal control but may also be at the expense of little outward view, and perhaps (depending on the physical parameters of the louvres), relatively poor indoor illuminance levels.

Actual measurements of the impairment of indoor illuminance by a shielding system has not been undertaken in this work as it was considered to be outside the scope of the present study. But full-scale and simulated indoor air temperatures, and transmitted solar gain values, for a shielded building have been presented for different angles of louvre slat inclination and for different shielding options. Until full-scale measurements of the interior illuminance levels for different slat inclinations in a shielded building are made it would be difficult to determine the exact limit at which natural lighting is *unacceptably* impaired by the shielding system. It would be simplistic, in this respect, to lay all the emphasis upon the angle of the slat inclination. As has been pointed out earlier, the interior illuminance is also dependent upon many other slat parameters such as its width, thickness, surface reflectance, the number of slats, and also upon the size of the "window", the solar altitude and the ambient weather conditions.

From the experience of the users in four other *identical* shielded houses on the site in the private housing estate in which full-scale measurements were made for this study (see Plate 4.5 in Chapter 4), and the experience of the author when carrying out the measurements in one of the two unoccupied ones, daylight was not so impaired by the shielding system as to be either detrimental to normal domestic tasks, or to constitute such a problem as to require artificial lighting during the daytime. Taking a look at Plate 4.1 in Chapter 4, it would be observed that a relatively dark colour was chosen for the shielding elements to minimise reflection of light into the shielded rooms.

Where a *fixed* integrated satisfaction of the diametrically opposing parameters of reduction of inwardly transmitted solar radiation, adequate indoor illuminance levels and outward view is desirable ***all through the daytime hours***, then the shielding efficiency *may* be so reduced by the large apertures required in the shielding system that the difference between shielding and conventional shading techniques would be quite subtle (see discussion of results in Chapter 8). Hence solar shielding may not be desirable for such situations.

However, in suggesting the use of modulated solar shielding, one is not advocating the design of monotonous facades. The ability to design an aesthetically appealing facade with the shielding technique would depend upon the ingenuity of the architect. This shouldn't constitute a handicap. There is no infrangible injunction that the shielding system must all be "horizontal slats", or that they must take a particular configuration. If well conceived and designed, modulated solar shielding should give exciting architectural forms. It may be pertinent here to look at some other potential advantages of modulated solar shielding as a passive design technique through a **generalisation** of the experimental results in conjunction with the application of the general principles of bioclimatic design.

9.2.1 Other advantages of solar shielding

1. The shielded space satisfies the need for outdoor sleeping in hot dry and semi-arid climates especially after sunset. Although the roof may still be used, whether or not it is shielded, the shielded spaces on the sides would be handy especially where no provision for roof-sleeping is made. With solar shielding, outdoor sleeping will not be disturbed by sudden rainfall, or the hazard of mosquitoes and flies since these **can** be kept out by the shielding system where necessary.

2. Since it is modulated the shielding system effectively controls ventilation, enabling it to be kept to the barest minimum during the day-time and max-

imised at night. This helps to reduce or prevent convective gain in day-time hours.

3. By shielding the entire building fabric (*both* the opaque and transparent parts) and preventing direct irradiance and to a great extent reducing diffuse sky and intereflected irradiances, the building greatly reduces its solar thermal gain and thus its cooling loads. Also this prevents the hazards of structural damage due to thermal stresses imposed on the building by the very high day-time and low night-time outdoor air temperatures. This would definitely have a bearing on the life-span of the building and the furniture/equipments within it. The principle of solar shielding is that it attempts to address the control of solar radiation while it is still *radiation* rather than allow it to become *heat* in the building structure before taking measures to remove it. Secondly, the creation of a buffer space by the shielding technique directly ameliorates the surrounding microclimate of the building, and hence alters the dynamic of thermal transfer through the fabric. The buffer space also enables further passive cooling measures to be taken. Also the impairment of longwave heat loss by the shielding system is a another important effect that reduces its efficiency. All these allude to a more subtle effect of the shielding option than merely the fact that it protects both the transparent and the opaque parts of the building fabric.

4. In addition, and in line with the above, since the temperature range in a shielded building is much lower than that of a non-shielded one, there is a higher quality indoor environment.

5. The buffer zone created at the building periphery not only gives the occupants a semi-outdoor space that is much thermally 'softer' than the harsh outdoors (no heat wave, no excessive glare etc) but, also gives them the opportunity to further initiate passive cooling measures such as having some flowers, water pots or little water sprays within the buffer zone. In conditions where water is scarce, placing water pots in the buffer zone is an added advantage since they would not dry up as quickly as when they are exposed directly to the ambient. Likewise the flowers would not dehydrate as much as when directly exposed to the outdoor heat. The buffer zone would be with a relatively higher humidity than the dry ambient and would be cooler and

fresher. Such a buffer surrounding the whole building would definitely make some difference to the sense of comfort and well being of the occupants.

6. Shielding not only addresses solar radiation control like the other shading options but is a much more effective climatic control for both the building and their occupants because unlike other shading options it also addresses the problems of the biting winds, and rain. The shielding system may allow further measures to be taken to address the problem of mosquitoes and flies - e.g. by provision of netting.

7. Shielding may not make large windows, which are commonly used in contemporary buildings in hot climates a disadvantage since very little shortwave radiation can be incident on them.

8. A shielded building should be very effective in promoting longwave heat loss of the outer-most external surface (the shielding structure) (which takes place as long as the ambient air temperature is less than the surface temperature) because of its large cooling surfaces. The available cooling surface in a shielding system of louvres at 90^o (vertical position) is twice the amount of the actual shield area since it would be losing heat convectively on both its 2 sides. When the louvre slats are open the available cooling area is further increased. Hence when the slats are opened after sunset, it would further promote structural cooling convectively. This is one of the reasons for the buffer average daily temperature being less than that of the indoors. This facility also enables the buffer to respond to the changes in the ambient conditions much faster than the indoors spaces bounded by a heavy thermal mass. However, the overall longwave heat loss of the entire building structure of a shielded building will be partially impaired by the shielding system for reasons mentioned earlier.

9. In the context of a developing country the application of the solar shielding technique may be found to be relatively simple and easy to integrate with local building practice. The concept may be viewed as being imbibed in the design process either by the professional designers or vernacular builders. By conceiving the building as a solar shielded one, in the genesis of the design process, they will have fundamentally initiated a primary passive solar

thermal control measure for the proposed building.

9.2.2 Disadvantages

1. There would be extra *initial* cost for the additional spaces on the building periphery and of the shielding system.

2. The space taken up by making provision for the peripheral "shielded spaces" implies relatively smaller spaces for the actual indoor living spaces.

3. The shielding system may be considered as an obstruction to the view, and it also impairs daylighting. But in this climate where the ambient is so harsh (high air temperature, dust, low relative humidity etc.) window sizes have always been kept to the minimum. Since it is a *modulated* system these parameters can be addressed and controlled accordingly.

4. Modulating the shield may be considered too much of a burden by people who cannot afford, time-wise, to effect the control (especially if manual) demanded by the system.

9.3 Suggestions For Solar Shielding Applications

1. It is suggested that, to derive maximum advantage from solar shielding, as much of the external surfaces, possibly all, should be shielded. Solar radiation penetration through the shield must be minimised.

2. The immediate periphery of the building beyond the shield must not be concrete-paved but should be *preferably* of grass and/or flowers where possible.

3. The shield must be a modulated system, to enable it to be "closed" during the day-time and opened or possibly moved after sunset.

4. It has been shown that massive reduction of solar transmitted gain does not necessarily imply high reduction of indoor temperatures since the shield re-radiates most of its thermal gain inwards into the living spaces. This is where the choice of a suitable shielding material is crucial. The material definitely

cannot be glass, or metals and their alloys, which have high conductivity. A suitable shielding material should
(a) minimise solar gain (i.e. should have high reflectivity),
(b) minimise heat storing capacity and be capable of losing any heat gain relatively quickly (i.e. should have low thermal inertia),
(c) The inner surfaces of the shielding system (or the outer surface of the main shell) facing the buffer should be of low emmissivity.
A lightweight material such as plywood louvres is recommended, for thermal, structural and economic reasons.

5. The ceiling of the buffer spaces should be of white or near white colour to adequately reflect natural light into the interiors. However since the reflectivity of white paint drops by about 30% in one year and by more than 50% in three years, regular maintenance would be required. In the context of daylighting, a solar shielded building need not be deep-plan, so that adequate natural light can be obtained. Also the use of beam-core daylighting techniques may be very instrumental to the provision of natural light in deep-plan buildings.

6. Whilst the number and configuration parameters of the louvre shielding system is not an important parameter for solar control, it is a significant parameter for daylighting considerations. The work of Fikry (1981) as discussed in Chapter 1, suggested that the optimum no of louvre slats for maximum interior illuminance varies for different parts of the room. Ironically, the various optimum number of louvres also gave the highest levels of internally transmitted shortwave solar radiation. The choice of the number of slats must be made to reflect the design objective.

7. In shielding the roof, the enclosed roof space must be well ventilated and thermal conductivity should be encouraged between the roof space and the living spaces below, especially after sunset. Where the night sky temperature is sufficiently low enough to act as a cooling sink an appropriate design of the roof shield to permit radiative cooling to the night sky would be imperative

8. The shield must be so designed as to reduce monotony, by using multiplicity of shapes, textures, colours and configurations. The poetics of those variables in harmonic repetitions should give a balanced and aesthetically pleasing

architectural forms.

9.4 The long-term significance of the study

The effective control of solar radiation in buildings is a very crucial part of a passive solar and/or low energy building design for hot climates. It will be remembered that the main objective of this study was to investigate the thermal implications of solar shielding as a passive thermal control strategy for buildings in hot semi-arid climates. The technique was simulated on a real building in which actual measurements were made. Comparisons between the simulated and measured data not only validated the thermal model but also the simulation methodology adopted for studying the effect of shielding in contemporary buildings. The study subsequently demonstrated the use of the shielding technique with results indicating that shielding is a potentially more effective solar thermal control technique than formal shading of glazing. It has also been understood that shielding must be optimised to realise its full potential. This must be done in conjunction with other bioclimatic design principles since the generation and flow of thermal energy in buildings is a complex phenomena which no single design parameter can fully address. As suggested by Bryan Lawson, (Lawson, 1980) the one thing that seems certain is that design is a multi-facated and multi-varied phenomenon. Although this study has indicated that solar shielding has promise for the solar thermal control in buildings, its full potential can only be exploited within a well-balanced design strategy aimed principally at not only meeting socio-cultural needs of the user but also particularly to enable the building to face up to its true adversary, the climate. The building must respond to the variability of the climate. Essentially, in the words of Olgay, (1989), the particular problem of the designer "*is to build a shelter which will adjust to the seasonal, daily, and hourly variation in the intensity of the sun's radiation*". It is envisaged that solar shielded buildings would epitomise the true spirit behind that message. In any case, the variability and complexities of different climates (and cultures) primarily calls to question the so called international approach that seemingly extols the application of a universal design vocabulary.

With the ever-increasing interest in research seeking passive solution to the problems of comfort in buildings it is envisaged that different approaches would evolve for architecture truly adapted to its place, climate and countryside. Recently Baker, (1987) re-echoed this theme by making suggestions for a passive and low energy architecture specifically addressing the challenges of the tropical island climates.

Furthermore, in a fairly recent Passive and Low Energy Architecture (PLEA) Conference, in Porto, Portugal, in 1988 (PLEA '88), a common denominator and an ever recurring theme was the emphasis on architectonic regionalism with a focus on a "Mediterranean Regional Approach". It is fervently hoped that such themes would be extended to, and lasting solutions evolved for hot semi-arid and hot-dry climates whose design problems are no less complex than other climatic regions, and that solar shielding would integrate with other design approaches in the field to establish a strong foundation for bioclimatic and cultural regionalism for the above climates. A low energy architecture in which perhaps little, if any, glazing is exposed directly to the ambient.

9.5 Limitations of the Study

1. As mentioned in Chapter 1, this study deals mainly with an unconditioned, unoccupied building which was deliberately selected in order to adequately isolate the significance of shielding in the thermal studies. Hence no latent or internal gains were considered.

2. SERI-RES does not adequately handle diffuse sky radiation so the actual extent to which shielding reduce diffuse radiation may not have been adequately modelled. The understanding is that the shielding effect may have been underestimated by the program.

3. The sum of the separate little gaps between the louvre system has been modelled as a single opening in the simulation. Also the thickness of the louvres was assumed to be negligible. Therefore the assumption has been made that the effect of small strips of openings is collectively equal to one large opening which, in reality, has a different view factor from the small openings.

4. The results are dependent on the shortcomings of the shading concept of SERI-RES, in which the overhang is infinitely long and the sidefins are in-

finitely high, (see limitations of SERI-RES in Chapter 7). If the shading of individual windows was separately modelled, then the efficiency of the overhang/balcony may be slightly higher than predicted by the program.

9.6 Recommendations for Further Work

The number of closely related areas that need to be further investigated to refine and extend the applicability of the present study include

1. The airflow models through a louvre system need to be extended to include a comparative study with other more polished materials e.g.. aluminium slats, plastic slats etc). Also airflow studies need to be extended to include other angles of wind incidence (e.g. 45^o wind incidence). Also a more detailed study need to be carried out to investigate the changes in friction in the direction of flow with respect to the louvre inclination.

2. Further studies is required to enhance the performance of a louvre shielding system by the optimisation of their surface properties.

3. The study and full-scale measurements of the implication of solar shielding for daylighting and of a *possible* integration of beam core daylighting techniques into the design of solar shielded deep-plan buildings. The shielding system is a potential daylight control system that would enable selective admission of daylight from desired orientations.

9.7 The end is only a beginning

It may be said by way of concluding this thesis that whilst this study has indicated that modulated solar shielding could be a more effective solar thermal control technique than formal shading methods, for buildings in hot dry and semi-arid climates, its potential as a full climatic/environmental control system is yet to be adequately explored. Whilst the results seem reassuring, some relevant questions pertaining to its application remain unanswered.

It is nevertheless envisaged that the results from this study may encourage the design and use of solar shielded buildings in this climate in future, and stimulate the consciousness, within the bioclimatic design field, of the need to evolve a regionalist approach to solar radiation control in buildings of hot climates in every part of the tropical and subtropical worlds. Naturally, solar shielding would, in application, have a far-reaching bearing on the way buildings are conceived, designed, built and used, while providing a resort for an effective **passive** climatic, solar thermal and environmental control for both the building and the users.

However it will be remembered that this study is an attempt to address the problems of **hot dry and semi-arid** climates, and that whatever recommendations were made apply *mainly* to these climates. With the unfortunate tendency towards the adoption of an international design vocabulary, design concepts can be easily misapplied. For example, no sooner did Le Corbusier suggest the use of *"brise-soleil"* than it became a fashion and was *plastered* on buildings in different parts of the world irrespective of climate, latitude, orientation and shading principles. Although no one is under any illusion that this piece of work is in any way comparable, in whatever context, to the great work of the *Master*, it is hoped that even a little suggestion such as this would neither be misunderstood nor misapplied. Solar shielding is only a solar radiation/environmental control technique in the *regionalist* context.

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