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Expectation and Experience of Thermal Comfort in Transitional Spaces

A field study of thermal environments
in hot-humid climate of Bangkok

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(Kitchai Jitkhajornwanich)

This thesis is concerned with tropical architecture, in particular in regions of hot and humid climates, considering climatic influences as well as trends of design. The focus is on transitional spaces which have distinctive and significant characteristics that are different from those of other climatic zones. The investigation of the spaces was made in terms of the thermal perception of building occupants of their environments. The methodology used for establishing the thermal comfort criteria was the "Field-Studies" technique.

A paradigm study was carried out by field surveys of transitional spaces of selected buildings (two N/V and three A/C) in Bangkok, Thailand. There were 1143 subjects in total in both cool and hot seasons. The findings revealed that the human subjects could achieve comfort at relatively higher air temperatures, compared with the recommendations from international standards. The subjects' thermal expectations and sensations reflected the prevailing temperatures and their preferences were for cooler environments. The adaptive actions they suggested for cooling were by both active and passive means, depending upon the acclimatisation and available methods, such as using A/C or increasing air movement. For cool discomfort, the adaptations were to increase either clothing insulation or metabolic activity level.

This comfort study produces an Adaptive Model and the neutral temperature (T_n) can be estimated using a knowledge of the mean air temperature (T_a) of a group of subjects. The equation is:

$$T_n = 19.1 + 0.30\,T_a \qquad \text{(eq. 9.3)}$$

Some techniques to improve thermal comfort (i.e., adaptive errors) and applications of the results from research to use in practice are suggested. It shows that transitional spaces can be used as a mitigation feature in tropical architecture. Recommendations for design criteria to improve thermal performance of transitional spaces in buildings are also made. These include: east orientation, less exposure, increasing spaces, light materials, and practical ventilation.

Author

Kitchai Jitkhajornwanich

This thesis is dedicated to

Ar Nea and *Ar Ee*

who give me all comfort.

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Contents

List of symbols and definitions

ach (Air Change per Hour) (ach): a unit that denotes the number of times a house exchanges its entire volume of air with outside air in an hour. This is generally used in two ways: (1) under natural conditions and (2) under a 50 Pascal pressure difference.

clo (Icl) (clothing insulation) (clo): the resistance to sensible heat transfer provided by a clothing ensemble (i.e., more than one garment). It is described as the intrinsic insulation from the skin to the clothing surface, not including the resistance provided by the air layer around the clothed body; it is usually expressed in clo units, where 1 clo = 0.155 $m^2 \cdot °C/W$ (0.88 $ft^2 \cdot h \cdot °F/Btu$).

C_m (mean subjective comfort vote) (-3 to +3): an average of the subjective responses given by a large group of subjects on a thermal sensation scale such as the ASHRAE or Bedford scales.

DBT (dry-bulb temperature) (°C): the temperature of a gas or mixture or gases indicated by an accurate thermometer after correction for radiation.

ET (effective temperature) (°C): the arbitrary index which combines into a single number the effect of dry-bulb temperature, humidity and air motion on the sensation of warmth or cold felt by the human body. The numerical value is that of the temperature of still saturated air which would induce an identical sensation.

ET* (new effective temperature) (°C): the operative temperature (T_o) of an enclosure at 50% relative humidity that would cause the same sensible plus latent heat exchange from a person as would the actual environment.

h (heat transmission coefficient) ($W/m^2 °C$): any one of a number of coefficients used in calculating heat transmission by conduction, convection and radiation, through various materials and structures.

HVAC (Heating Ventilating and Air-Conditioning): a term generally applied to the hardware or the industry concerned with the supply of environmental control in buildings.

met (M) (metabolic rate) (met): the rate of energy production of the body. Metabolism, which varies with activity, is expressed in met units, where 1 met = 58.2 W/m^2 (18.4 $Btu/h \cdot ft^2$). It is equal to the energy produced per unit surface area of a seated person at rest. The surface area of an average person in about 1.8 m^2 (19 ft^2).

MT (modified temperature) (°C): the temperature that would be felt equally warm at 50% relative humidity, 0.1 m/s air velocity, 1.0 met, 0.6 clo, and with a mean radiant temperature equal to the air temperature as in the actual environment.

MV (actual mean vote) (-3 to +3): see C_m (mean subjective comfort vote).

P_a (water vapour pressure) (millibar): the pressure exerted by the molecules of vapour contained in air. Enables the rate of diffusion of vapour through materials of construction to be estimated.

PMV (Predicted Mean Vote) (-3 to +3): an index that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale. It is based on heat balance of the human body; it can be determined when the activity (metabolic rate) and the clothing (thermal resistance) are estimated, and the following environmental parameters are measured: air temperature, mean radiant temperature, relative air velocity and partial water vapour pressure.

PPD (Predicted Percentage of Dissatisfied) (%): an index that establishes a quantitative prediction of the number of thermally dissatisfied people. It predicts the percentage of a large group of people likely to feel too warm or cool, i.e., voting hot (+3), warm (+2), cool (-2) or cold (-3) on the seven-point thermal sensation scale.

rh (relative humidity) (%): the ratio of the mole fraction of water vapour present in the air to the mole fraction of water vapour present in saturated air at the same temperature and barometric pressure; alternatively, it equals the ratio of the partial pressure (or density) of the water vapour in the air to the saturation pressure (or density) of water vapour at the same temperature.

SBS (sick building syndrome): symptoms such as headache, eyeache, sore throat, breathing difficulty, cold-like symptoms and lassitude, which are real and can be clinically confirmed. These are from increasing complaints of acute discomfort in office buildings and particularly those equipped with air-conditioning.

SET (standard effective temperature) (°C): the temperature of an isothermal environment which has air and mean radiant temperature equal to each other, a relative humidity of 50% and still air, in which a person with a standard level of clothing insulation would have the same heat loss at the same mean skin temperature and the same skin wettedness as he does in the actual environment and clothing insulation under consideration. The activity level is the same in both actual and standard environment and the standard clothing insulation is a function of activity level.

T_a (air temperature) (°C): the dry-bulb temperature of the air surrounding the occupant. In this thesis, it refers to mean air temperature when used in equations.

T_{eq} (equivalent temperature) (°C): the temperature of a uniform enclosure in which a black cylinder of height 550 mm and diameter 190 mm would lose heat at the same rate as in the actual environment, the surface of the cylinder being maintained at a temperature which is a precise function of the heat loss from the cylinder, and which in any uniform enclosure is lower than 37.8°C by two-thirds of the difference between 37.8°C and the temperature of that enclosure. (Based on Eupathescope. Cooled in the same balance as the human body in relation to air temperature, air movement and mean radiant temperature. Did not take humidity into account.)

T_g (globe temperature) (°C): the temperature read from a globe thermometer, which consists of a thin-walled copper sphere painted black, containing a thermometer with its bulb at the centre of the sphere. In use the globe thermometer is suspended at the test point and allowed to come to thermal equilibrium with its surroundings. The equilibrium temperature depends on both convection and radiation transfer. In equilibrium the net heat exchange of the globe is zero. The standard globe takes up to 20 minutes to reach equilibrium and may produce additional errors if the air speed or temperature changes over that time.

T_i (mean indoor air temperature) (°C): the average air temperature of indoor environments, experienced by the population during the field survey, for providing an empirical method for the prediction of human warmth.

T_m (monthly mean outdoor temperature) (°C): the average air temperature of outdoor environments obtained from meteorological stations or from the measurement taken during the time "up and about" over a period of a month.

T_n (neutral temperature or comfort temperature) (°C): the temperature (or environment) judged by a population to be neutral on the seven-point thermal sensation scale, assumed by most workers in the field to be the desired temperature.

T_o (operative temperature) (°C): the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. Operative temperature is numerically the average of the air temperature (T_a) and mean radiant temperature (T_r), weighted by their respective heat transfer coefficients (h_c and h_r).

${}^nT_{od}$ (daily mean outdoor temperature on day n) (°C): the average outdoor temperature calculated from the data obtained from the meteorological station. The value is not known until the end of the day n.

T_r (MRT) (mean radiant temperature) (°C): the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space.

${}^nT_{rm}$ (running-mean temperature calculated for day n) (°C): The exponentially-weighted running mean time series used to represented the thermal experience of the subjects. It weights recent experience more heavily than that further back in time, in a way which accords with common sense, and it is easily calculated from the daily mean outdoor temperature available in weather records. This running mean is intended as a predictive tool.

T_w (wet-bulb temperature) (°C): the temperature at which liquid or solid water, by evaporating into air, can bring the air to saturation adiabatically at the same temperature. Wet-bulb temperature (without qualification) is the temperature indicted by a wet-bulb psychrometer constructed and used according to specification.

v (air velocity) (m/s): air velocity has an effect on convection heat loss from the body. Some degree of air velocity (or air movement) is essential for feelings of freshness and comfort. Desirable speeds vary with temperature and conditions. In domestic buildings and other similar situations a velocity of 0.10-0.33 m/s is considered reasonable.

Chapter 1

INTRODUCTION

1.1 Background

It is generally accepted that buildings have great effects on the environments of both humans who are living in them, and on those who are surrounded by them. The design strategies or trends of architectural design now include environmental and energy consciousness. This can be seen in many conferences and meetings in recent years, with much concern for "Global Warming". It is therefore an important reason for research to help establish findings to alleviate this circumstance.

Much energy is consumed by building climate control systems (heating, ventilating, air conditioning, etc.). These systems attempt to provide comfort for building occupants, however there is evidence to suggest occupants are more tolerant of variations in conditions and this may be aided by suitable building design. If energy use for HVAC systems can be reduced, this will have both financial and environmental benefits.

For this thesis, it is initially necessary to comprehend all elements and special features which are integrated into tropical architecture. Considering traditional forms, one can see that the previous generations had understood the significant influence on their built-environments of *climate*. It has also affected *culture* and *comfort*. One example of an elemental space, which reflects both categories, is the transitional space. It is the space that is inserted rationally between outdoor and functional indoor environments. The characteristics and significance of this space are different from western architecture, which had been influenced by the Modern Movement. As a consequence, the design criteria of each region has been affected by a balance of climate, culture and comfort requirements.

The study of thermal comfort has aimed to provide a satisfactory thermal condition for building occupants, and especially in recent decades, it has introduced a theory of adaptation, in which it is believed that physiological and psychological parameters are the main causes of comfort/discomfort. The earlier stages of the research showed that the indoor comfort is significantly related to the outdoor environments. By using a field-studies methodology, much recent research has complemented this theory and has suggested that adaptations play importance roles in thermal comfort.

By combining the two subjects of tropical architecture and thermal comfort, this thesis aims to enlarge the pool of knowledge of building science subjects in tropical climates.

1.2 Objectives

The objectives of this thesis are:

1. To investigate tropical architecture in both traditional and contemporary fashion, its significance, the trends of its design, and the special feature of transitional spaces.

2. To review the subject of thermal comfort studies, which have developed from the classical theory of heat balance between human body and environments to a recent theory of adaptive principles.

3. To observe thermal responses in terms of expectation and experience of human subjects in Bangkok as a paradigm of a programme to a field study of thermal comfort in hot and humid tropical regions, which applies the adaptive theory.

4. To establish thermal comfort criteria for a particular region of hot and humid climates, in which various environmental parameters have effects on satisfaction of the subjects.

5. To create design recommendations to be applied to tropical architecture, in particular to transitional spaces.

1.3 Structure of work

This thesis consists of three main parts: firstly, literature on tropical architecture and the particular feature of transitional spaces; secondly, literature reviews of thermal comfort, its theory and practical research including field-studies methodology, adaptive models and some case studies; finally, the main part — a field study of thermal comfort in Bangkok and its applications in practice. There are eleven chapters in total, which are organised in this thesis as a structural diagram, shown in Figure 1.1.

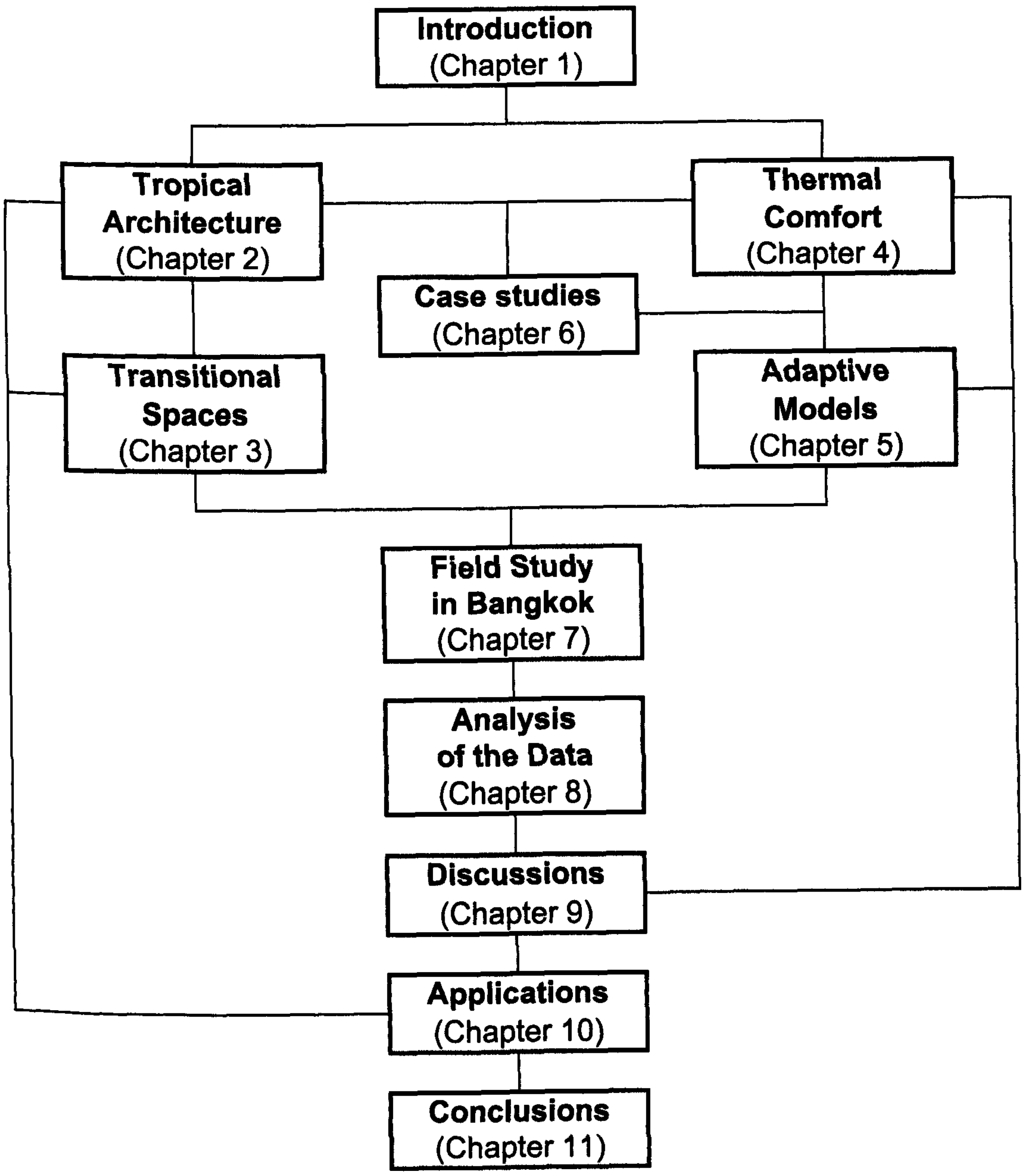

Figure 1.1 *Organisation of the eleven chapters in this thesis.*

The organisation shows a relatively linear relation between chapters, and provides some feedback loops between three main parts. Chapter One functions as an *Introduction*, giving the brief background and the objectives of the study, and leading to two main parts: tropical architecture and thermal comfort. Chapters Two and Three explain the significance and characteristics of architecture and transitional spaces in hot and humid tropical climates. In Chapters Four and Five, the theories of thermal comfort and field studies applying adaptive models are introduced. These two parts are considered and summarised referring to case studies of thermal comfort, especially in tropical regions, presented in Chapter Six.

Chapter Seven, which is inspired by the literature of earlier chapters, presents the methodology and results of a field study of thermal comfort in transitional spaces in buildings in Bangkok. In Chapter Eight, these results are analysed for the comfort conditions. Various factors affecting comfort are tested, based on the adaptive theory. Chapter Nine discusses and refers the reported findings to the literature of thermal comfort in Chapters Four to Six. They are linked by a feedback loop in a comparative description. Chapter Ten uses the comfort findings from research to illustrate how to apply in practice. It also shows thermal simulation modelling of thermal preference, giving design recommendations for transitional spaces in tropical architecture, which is linked by a feedback loop to Chapters Two and Three. Finally, chapter Eleven summarises the study of this thesis and gives some suggestions for future research.

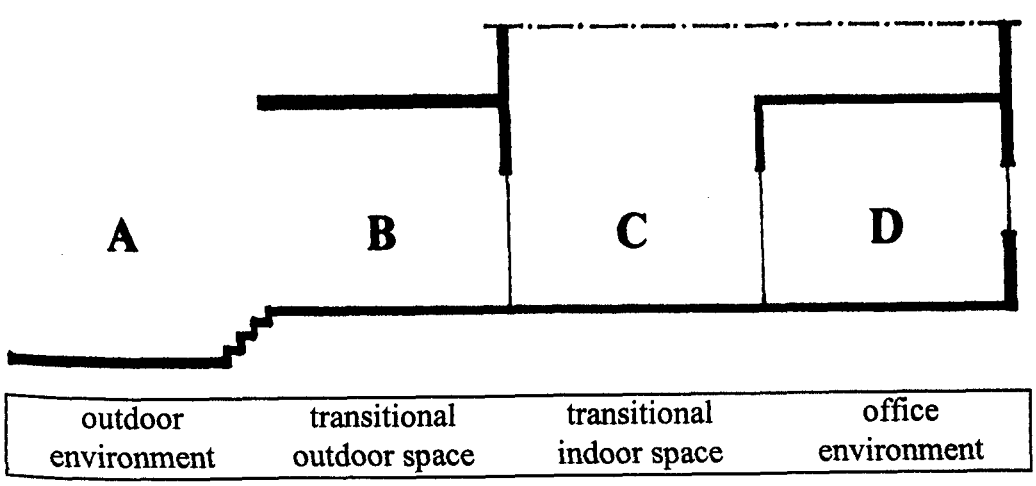

Figure 1.2 *Transitional spaces surveyed in this thesis.*

It should be noted that the spatial conditions of field studies in this thesis is at *transitional spaces*. As shown in Figure 1.2, the subjects concerned therefore will be those who are entering from outdoors to transitional indoor spaces of the buildings (from A to C) and those who are leaving indoor environments to transitional outdoor spaces (from D to B). These subjects will experience both outdoor and indoor environments, thus influencing their thermal responses in terms of comparison. The spaces where people pass through will be considered as transitional in time for this thesis.

1.4 Problems and limitations

Whilst carrying out the work described in this thesis, there were difficulties which arose from some problems and limitations in analysis to establish results. These should be mentioned at this stage to clarify the basis of this study. The problems and limitations were:

1. There are too few subjects in the field surveys for some analyses, which are not able to give significant findings; this could not have easily been predicted before.

2. Many field survey data are considered as naturally-ventilated environments, and in turn, this dominates the findings of comfort criteria.

3. Due to the few days available for data collection, the measurement of the environmental factors may slightly deviate from a typical climate of Bangkok.

4. The data are collected from two climatic conditions — the hot and cool seasons, which cannot represent for year-round analysis.

5. There are limited and concise simulation analyses in this thesis, which can be used in practice only for the transitional spaces. Had time permitted, more detailed analysis might have been performed.

Chapter 2

TROPICAL ARCHITECTURE

"Mankind in the same environments encounters the same stresses as other fauna. From Aristotle to Montesquieu, many scholars believed that climate had pronounced effects on human physiology and temperament. More recently interest has centred on human energy in relation to environment."

V. Olgyay [1963]

2.1 Introduction

This chapter looks at tropical climate and its effects on tropical architecture. It is particularly hot and humid tropical climatic conditions. The study investigates characteristics of the humid tropics' climate; the significance of the living conditions in a warm environment; factors which influence architectural designs; application for and criteria of tropical architecture; a comparison between traditional and contemporary architecture; and finally, trends of tropical architectural design.

The functions of buildings are basically the same everywhere: to provide shelter for a comfortable living and working environment and to avoid extreme weather; but the designs and processes for buildings in different climates (i.e., hot and temperate climates) are significantly different. According to BRE Digest no. 302 [1985], they should be modified to suit the following matters:

1. building services systems (HVAC) to provide heating as well as cooling against heat and cold, the need for ventilation, conditions of natural lighting, and the solutions for noise control;

2. the availability and appropriateness of building materials and equipment;

3. economics and technology, concerned with the consumption of energy and building standards; and

4. local organisations such as management, labour skills, regulations and cultural influences.

In tropical developing countries, Khan [1995] stated that since 1950s, there have been two major phrases of architectural production: firstly, the introduction of *Modern Movement* and the *International Style*, and secondly, the versions of regionalism, searching for identity. While the former was declining and virtually defunct in the 1980s, the latter gained momentum in that decade. It seems that architecture which once showed its own characteristic response to the traditional ways of local lifestyle, i.e., traditional architecture, was designed and developed following from the path of modernism and contemporary needs, but now has experienced a renewal of interest to show its individualistic expression. This expression has been rooted in the influences of the past namely indigenous traditions, local materials and practices.

Naturally, as Ayoade [1983] argued, such structures (in the name of modernisation) could not be as comfortable as the traditional ones and they could only be habitable because of the use of electric fans and air-conditioners which are not only costly, but also very uncomfortable when there are power cuts. If any typical regionalism architecture is profoundly scrutinised, it is clear that our ancestor had found the basis, aware of and responsive to the local climate and environment: *Design with Climate* [Olgyay 1963].

2.2 Tropical climates

2.2.1 Definition and areas of tropical climates

Tropical climates (referred to as the "tropics") have no exact definition, but the best way to define the tropics is to describe their common climatic feature [Nieuwolt 1977]. The most important characteristic is the absence of a cold season, as illustrated by the old phrase: *"where winter never comes"*, in which for instance the mean temperature is 18°C for the coldest month of the year [Koppen 1936]. In turn, this measure would exclude the tropical highlands, where temperatures frequently remain well below this limit; yet the areas are truly tropical because they experience no winter. Another indicator, by the well-know saying, originating from Alexander von Humboldt: *"the nights are the winter of the tropics"* [Nieuwolt 1977].

The areas of the tropics are largely found between the Tropic of Cancer and Tropic of Capricorn (of north and south, respectively), the parallels at a latitude of 23½ degrees, in other words, the regions of *low* latitudes. However, these two lines are too rigid to determine the boundaries, because some regions with tropical characteristics are found at latitudes of more than 23½ degrees, while some non-tropical areas are situated much closer to the equator.

The zones of tropical regions are roughly divided into two areas : humid and dry tropics. This is shown in Figure 2.1.

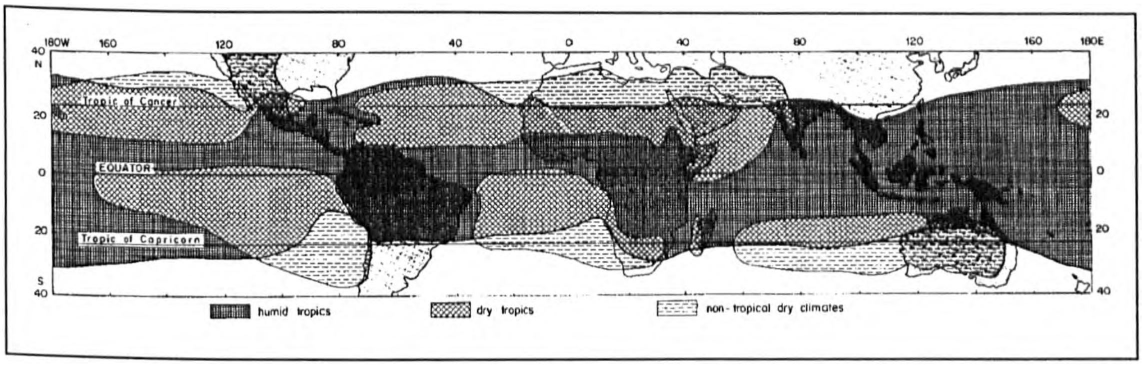

Figure 2.1 *Tropical regions: humid and dry tropics. (After Nieuwolt 1977)*

2.2.2 Hot and humid tropical regions

Besides a comparatively high air temperature, the amount of rainfall is a significant feature in the tropics. Sometimes the term "tropics" is assumed to the regions where sufficient rain is received to carry out agriculture without irrigation [Gourou 1953]. In this sense, the areas with as amount of seasonal rainfall between about 450 mm and 600 mm per year are referred to "humid tropics" [Koppen 1936] or even higher figures of 750-800 mm per year [Tricart 1972]. Proposed by Tricart [1972], the classification schemes to distinguish different types of humid tropical areas, correspond to three zoning categories:

1. constantly humid;
2. constantly humid with a short dry season; and
3. seasonally humid with a long dry season.

In terms of the characteristics of the hot and humid tropical climates that affect building design [Konya 1980; Lippsmeier 1980; BRE Digest no. 302 1985] can be subdivided into three groups:

1. Equatorial lowland: found in tropical belt within 5-10° of the equator; little seasonal difference throughout the year and relatively small variation in air temperature: diurnal 5.5-8.8 K and annual 3.0-5.5 K; annual mean maximum

day temperature in shade around 30°C and night temperature at 24°C; high relative humidity of 55-100%, usually over 75%; precipitation on more than one-third of days throughout the year; wind speed usually low; cloudy and hazy skies (cloud cover 60-90%); and low reflected radiation from ground.

2. Tropical marine (trade-wind coast): mainly found at parts of tropical coasts; little seasonal difference; annual mean maximum day temperature in shade of 28°C and night temperature at 21°C; fairly high constant relative humidity between 55 and almost 100%; strong winds at times (cooling breezes: trade wind and on/off shore winds) and in some areas risk of cyclones or hurricanes; high annual rainfall; clear skies and bright sun more frequent than the equatorial zone; and strong solar radiation and mainly direct with little diffusion.

3. Composite/monsoon: found at tropical inland away from the equator; normally two seasons: two-thirds of year hot dry and one-third warm humid; mean maximum day temperatures in shade approximately 35-28°C and night temperatures 15-24°C, dependent upon different seasons; annual mean temperature fluctuation about 6-11 K; comparatively high relative humidity during wet season of 55-95% and moderate during dry season of 20-55%; different total rainfall from year to year, mostly falls in monsoon period; strong and steady winds during monsoon but hot dusty and variable in dry period; blue sky during dry season and rain clouds during rainy season.

In summary, the typical character of the hot and humid climate is that there is little variations between seasons. The average range of the temperatures between times of days and seasons is around 10 K and the average relative humidity is always between 70 and 90%. Some samples of the hot and humid climatic data from five main continents: Asia, Australia, America, South America and Africa [Pearce and Smith 1984], are shown in Appendix N.

2.2.3 Living in hot and humid tropical regions

According to Ooi Jin Bee [1983], some of the earlier civilisations were located in the humid tropical environments. Their indigenous people were known to have operated sophisticated irrigation systems for their living, and to have adapted to an appreciation of the nature and dynamics of physical systems. Many perceptions, nowadays, of the humid tropics were described by Reading et al [1995]. Firstly, the humid tropics is an area of lush, fertile forest with diversity of flora and fauna. Secondly, the perception of its weather is that days and nights are similarly hot and humid and that rainfall occurs in heavy downpours. Finally, it is of an environment where disease and unhealthiness is commonplace; the constant high temperatures and humidity and abundance of water surfaces are favourable for the persistence of pathogenic complexes.

To live in the hot and humid tropical area, Olgyay [1963] stated two major problems the habitants have to be prepared for: the avoidance of excessive solar radiation and the evaporation of moisture by breezes. Some of the regional solutions are, for example, to allow free air movement, to scatter individual units mixed with the shade of surrounding flora, to raise large gable roofs covered with grass to insulate against the sun and throw large areas of shadow over the dwellings. Koenigsberger et al [1973] supported that, for physiological objectives, heat dissipation from the body to its environments is necessary, in association with the removal of a saturated air envelope due to high humidity, by air movement. Therefore, some degree of comfort can be achieved by encouraging out-door breezes to pass across the body surface of the occupants. Radiant heat gain from the sun and sky also should be prevented.

Besides the comfort quality, Konya [1980] recommended consideration of solutions for further problems such as insects and regional tropical storms. The nuisances caused by flies, mosquitoes and other insects can be prevented, although there is no perfect protection against this problem, by fixing fly-screens on outside openings or ensuring that there is no standing water near the buildings and by using a few external lights to divert the insects away from windows and doors. The latter problem, damaging tropical storms, has to be solved in terms of the structures and materials used to resist the forces of winds. Generally, the requirements are either rigidity or bracing, but one primitive builders' solution is flexibility.

In brief, it is the nature of the relationship between climate and man to live in harmony [Ayoade 1983]. The influence of weather and climate on humans can be harnessed for beneficial effects utilising rain, sunshine, cloud, and wind in the proper proportions of time, place, and intensity or amount. On the other hand, the malevolent effects such as floods, droughts and storms should be controlled and managed.

2.3 Factors affecting building designs in the tropics

2.3.1 People and their needs

People as individuals are different from one to another and between social groups. Each has one's own view in his/her existing circumstances, depending on various factors, i.e., age and income [Fry and Drew 1964]. For example, in government housing at Chandigarh in India, the younger and the poorer inhabitants would like to have a change in their environments and would expect to have better living conditions, while the older and the richer would prefer their existing ones and would be afraid of seriously lowered circumstances if they change. Another instance in a fishing village in Ghana, people who previously lived in single-roomed huts, would be happy if they moved into single-roomed dwellings, because they need both an increased size of dwellings, and to retain the qualities of growth as well as the relationship of close family ties.

In investigation of human needs, it is necessary to take a deep understanding of the individual and his/her relationships with the building, and even further complex, his/her relationships with other people and the effects will have on the design of the building. These human needs are categorised into two types: basic need and social need [Broadbent 1973].

In the tropical countries, it is admitted that the life styles of their people have been changed since the advent of industrialisation and modernism. The society in the past which was agricultural-based is not of interest. Crafts and skills of the old ways are replaced by industrialism, and machines are used for all purposes of manufacture. Ultimately, the dominant phenomena of tropical life may have disappeared. Fry and Drew [1964] therefore suggested that the building designs in the tropics should be conceived with conscious imagination to combine the tropical life-style and the mechanism of modern life, without sacrificing human freedom and dignity in the process.

2.3.2 Climate

Fry and Drew [1964] described that the main characteristic of the humid tropics is the heat from the burning sun alternating with torrential rains. The uncomfortable conditions can easily occur when the environments are at high temperatures and the saturated air prevents the perspiration evaporating from the surface of the skin, causing the body to overheat. Unlike the cool or temperate climates whose environments are at low temperatures and the body can be warmed by metabolism (from food), movement (of activity) and shelter (of building), an essential way to make relief in the humid tropics is to be cooled by providing breezes, naturally or artificially induced [Fry and Drew 1964; Koenigsberger et al 1973]. Therefore, a room where the sun and rain can be shut out, as well as provide ventilation without raising the temperature is required.

Other factors in the local climatic conditions which are essential to be taken into consideration to ensure appropriate building designs [Lippsmeier 1980]. These factors which have negative effects, are:

1. factors which can impair the mental and physical capacities, including the comfort of the occupants such as solar radiation and glare, temperature change, humidity and precipitation, air movement, and air pollution;

2. factors which can impair the safety of buildings such as biological agents and natural calamity, i.e., earthquakes, windstorms, cloudbursts and flooding, and tidal waves; and

3. factors which can lead to building damage and the premature fatigue of building materials such as all natural disasters, intense solar radiation, high humidity and condensation, and salt content of the air.

2.3.3 Materials and the means of buildings

Konya [1980] stated two basic things to be considered when materials are selected for buildings in hot climates: availability and performance. This implies to use local materials, and to conceive along with the extent and rate of deterioration which is caused by design and use. Also, the environmental factors are a major influence and have a profound effect on the durability and behaviour of materials and structure. BRE Digest no. 382 [1993] summarised the effects of weather in hot climates on materials as follows:

1. high temperatures cause more rapid deterioration of both surface and bulk properties such as breakdown or distortion;

2. high humidity and rainfall cause moisture-associated breakdown, weakening of interfacial bonds, mould growth and erosion;

3. maritime conditions enhance the rates of degradation, corrosion of metals and deterioration of substrates;

4. high (dusty) winds have physical effects such as sand erosion; and

5. atmospheric pollution has somewhat effect on organic materials.

In addition, Fry and Drew [1964] suggested that the selection of materials should regard to resist the ravages by insects or to promote conditions of health and well being. Other considerations should be suitable and economical factors, and the methods of construction should be adapted to local skills and traditions, or establish new skills and future traditions. This is because both aspects — skills and traditions — have evolved into our modern civilised societies, emphasising inevitably on craftsmanship and at the same time, industrialisation.

For contemporary and complex buildings especially in towns and cities in tropical countries, some of the newer organic materials are proposed by Building Research Establishment to be used to respond the demand which has grown in recent years for more comfortable and sophisticated lifestyles. These materials, for example, are plastics, roofing membranes, sealant, thermal insulating materials and surface coatings. The guidance for builders and designers is detailed in BRE Digest no. 382 [1993].

Finally, Fry and Drew [1964] mentioned that, structure, which is the putting together of materials by human labour or its substitute the machine, is able to affect the manner of building. The structure can represent the civilisation of a society and also it can express the needs and economics, as its ability and circumstance as a service to man.

2.3.4 Other factors

Lippsmeier [1980] gave information on factors affecting architectural design. These additional factors can be grouped into four categories:

1. Comfort requirements: both human physiology and psychological experiences are main theoretical bases for current thermal comfort research. Some parameters (environmental — temperature, humidity, radiation and wind; and personal — metabolic heat and clothing insulation) are the important variables for comfort considerations. Others are, for instance, acclimatisation and adaptation, expectation and preference, also cultural and social respects.

2. Building site: it emphasises the study on micro-climate of the selected site to suit its planned use. Factors investigated are location and size (topography and peripheral buildings, neighbourhood); ground conditions (types of soil); development and services (accessibility for construction and for the occupied building); and vegetation.

3. Building operations: the factors concerned are labour skills and building techniques, choices of building materials, equipment in construction work, and duration of building.

4. Economic factors: general aspects can be development costs, building costs and maintenance costs.

2.4 Tropical architecture

2.4.1 Applications for hot and humid tropical architecture

Under hot conditions, the concept of the application of thermal control in buildings consists of three objectives [Koenigsberger et al 1973]:

1. preventing heat gain;
2. maximising heat loss; and
3. removing any excess heat by cooling, which can be passive means or some form of energy supply.

Olgyay [1963]; Koenigsberger et al [1973] suggested a structure which can achieve the above objectives and create better living conditions, by reducing undesirable stresses. Its aim is to utilise all passive and active controls, in order to provide favourable conditions for human comfort; it is called "climate balanced". The diagram of the potential of climatic controls is shown in Figure 2.2.

The first two thermal controls: micro-climatic and structural or constructional controls, are passive methods in which varying climatic factors can be influenced by a settlement and a building design. The last one is by mechanical or energy-based controls, which are an alternative and inevitable method when passive approaches cannot be used to achieve comfort. It is able to make level the prevailing thermal conditions, or to produce a constant/static environment. However, the aids of cooling with the mechanical methods should be considered in collaboration with those passive means, aiming to minimise the energy consumption.

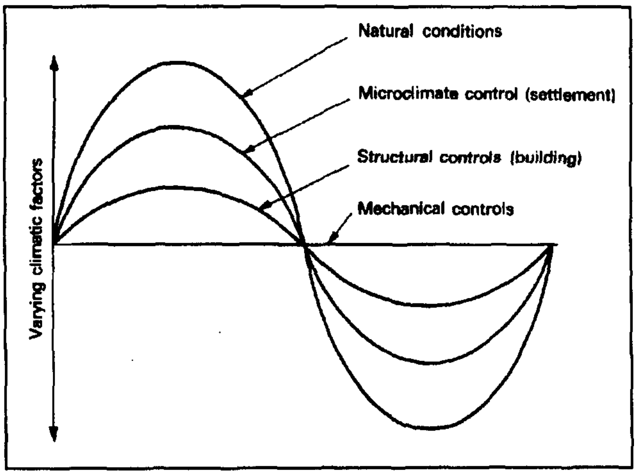

Figure 2.2 *Potential of climatic controls to flatten the temperature curve from natural conditions. (After Koenigsberger et al 1973)*

The extreme climatic control is an arguable subject. Lee [1958] expressed that the degree of sophistication in environmental controls is largely a socio-economic question, which concentrates on the achievement of comfort through the social status and financial support. Heschong [1979] emphasised that thermal qualities should not be produced only by the use of mechanical systems. Fanger [1993] argued that it is important to provide a comfort temperature without trading off the passive means, but the considerations on the side effects such as draught risk, saturation causing discomfort, or pollution from environments, are also significantly important.

2.4.2 Criteria of architectural design

The suggestions on architectural design in this section aim to achieve comfort by means of passive approaches, as a priority. Therefore, the only two thermal controls, micro-climatic and structural controls (see Figure 2.2), will be discussed.

Firstly, microclimate or settlement controls are used to respond to the man-made environments by creating a large scale *urban climate* [Koenigsberger et al 1973]. This includes exteriors and in-between spaces of buildings, which are influenced by the design of the settlement, grouping of buildings, controlling and planning air movement, external wall and space orientation, and so on. The factors affecting microclimate controls are:

1. surface qualities of both pavements and envelopes of buildings can increase or reduce the absorbance and transmittance of solar radiation;

2. the grouping of nearby buildings can cast shadow, act as barriers to wind or channel wind to increase air speed, store heat in their mass and release it at night;

3. planting the surrounding land affords protection against glare from the ground by bushes and grass, and from the sky by tall plants;

4. energy use factors such as heat loss through walls and ventilation, heat output of refrigeration plants and air-conditioning, internal energy used; and

5. atmospheric pollution, waste products, exhaust from motor-cars, fumes and vapours tend to reduce direct solar radiation but increase the diffuse radiation and provide a barrier to outgoing radiation.

Secondly, structural controls are used to ensure the best possible indoor environments and to aim for initial concept of building designs. A summary of the design criteria for buildings in hot and humid tropical regions from previous research [Jitkhajornwanich 1995] is given in seven areas:

1. Orientation: arrangement of a building can maximise cooling breezes and minimise solar radiation. A building should be elongated on east-west axis and this long side should have openings to receive prevailing wind, while the short side on east and west should be designed as opaque walls to avoid direct solar radiation. Staggered form can be used for the orientation on north-south axis.

2. Building form: form can be planned with regard to thermal capacity, and heat transfer to its surroundings. A building in a hot and humid climate should be shallow with single-banked rooms and have openings on two facades. Ceiling height of 2.5 to 2.7 metres is enough, but nevertheless, a higher ceiling on the top floor will be advantage to limit warm air above human height and ventilate it out of the vent at the top. Forming a courtyard, building mass can shield direct solar radiation falling on other walls; cross ventilation must be maintained. Spacing between mass to allow wind to return to ground level should be six times the height. Shaded outdoor spaces can be used as diurnal living areas. The optimum plan shape is suggested at 1:1.7 to 1:3.0, the short side to the long side.

3. Passive ventilation: cross ventilation and stack effect are considered as the main features to achieve comfort, giving fresh air across the body to reduce perspiration. The size and the arrangement of the inlet and outlet openings is the main factor for air movement conditions. A room raised off the ground can receive better air movement and less dust. Using fly-screens may reduce air flow 25-60%.

4. Solar control and shading devices: control of heat absorbance and transmittance ought to be applied to decrease solar radiation by using such shading devices. These devices are suggested to be used on north and south walls to protect from direct sunlight (whereas the east and west walls should be opaque). There is a calculation method to find both vertical and horizontal shadow angles (VSA and HSA, respectively), using the sun-path diagrams [Koenigsberger et al 1973]. Some special glasses can be used to exclude solar radiation, including internal blinds and curtains, but the latter also prevent air movement.

5. Using of vegetation: trees can help reducing glare, solar radiation, and pollution around the building site. However, it should not be grown too close to buildings because it can obstruct and deviate wind from the openings or its roots can damage the structure of the buildings. Properly arranged planting

can direct wind into a room. Porous paving blocks are useful to provide hard pavement surface with grass inside; and climbing plants on the building skin, to act as shading devices for walls (but there should be some protection from snakes).

6. Roof treatment: the choice of materials for roofs should be very light and the upper surface should be of reflecting quality or painted white. Insulation materials and a gap between ceiling and roof are recommended, in order to reduce heat gain. In cases of using concrete roof, it may be cooled down by spraying with water but not used for storing water in the roof. Roof gardens and false roofs can reduce the temperature, too.

7. Wall treatment: the choice of materials for walls should be light, low absorptivity, high reflectivity and high emissivity. Insulation and cavity walls can be used to cool interior. Pierced screen walls or permeable fences can be used for outdoor spaces both to provide air movement and to shade direct sunlight.

The simulation analysis in Chapter Ten will consider certain criteria of these tropical architectural design suggested here. It will be useful in the comparison matter between the literature and the simulation results.

2.4.3 Traditional architecture: delight and disappearance

The term *"tradition"* is adapted from Latin *traditio, -onem* in fifteenth century, meaning *"delivery, surrender, handing down, a say handed down, instruction or doctrine delivered"* [The Oxford English Dictionary 1989]. At the present, the word is used in the meaning of the action of handing down of a culture or approach from one generation to the next.

Traditional architecture herein is in agreement with the concept of the art of building which Rudofsky [1964] referred to some other names for want of a generic label such as *vernacular*, *anonymous*, *spontaneous*, *indigenous* and *rural*, or which Guidoni [1975] called *primitive architecture*. Generally, the traditional architecture does not go through fashion cycles, but is nearly immutable or unimprovable, and its origin of the building forms and construction methods is lost in the distant past. Such architecture demonstrates its humanness that brings forth some response in delight. It admirably fits into the natural surroundings, welcoming the vagaries of climate and the challenge of topography [Rudofsky 1964].

Another characteristic of vernacular is its additive quality, unspecialised and open-ended nature. These qualities enable its architecture to accept changes and additions which would visually and conceptually be opposite to the modern one [Rapoport 1969]. Upton [1993] saw the vernacular side as a different category of experience with a negative aspect: turning away from a search for the authentic, the characteristic, the enduring and the pure, and immersing in the active, the evanescent and the impure. Implicitly, the vernacular is the notion of building as an organic process and involves society as a whole, working through its history [Correa 1997].

Lim and Beng [1998] stated that vernacular structures such as indigenous shelters/dwellings are well adapted to the extremes of climate and their particular environmental settings. They reflect their society's accumulated wisdom and collective images, as well as cosmological and religious values, social and political structures, sensibility and attitude towards time and space. Their forms and proportions, craftsmanship and decorations are symbolic and meaningful, and also their aesthetic values are not pretentious, but generating principles after originality.

In short, two major aspects of traditional forms are: firstly, regional values formed from their socio-economic and cultural background, and secondly, visual and aesthetic values [Lippsmeier 1980]. It is also an expression of the way of life of that society which is its culture. This can be seen in some different societies in the same climate or micro-climate using different materials and construction methods [Rapoport 1969]. Some samples of the traditional architecture in hot and humid climates are shown in Figures 2.3 to 2.6: the first two from Southeast Asia, and the second two, Central Africa.

Figure 2.3 *Jolong, community house, Kontum region, south Vietnam. (After Guidoni 1975)*

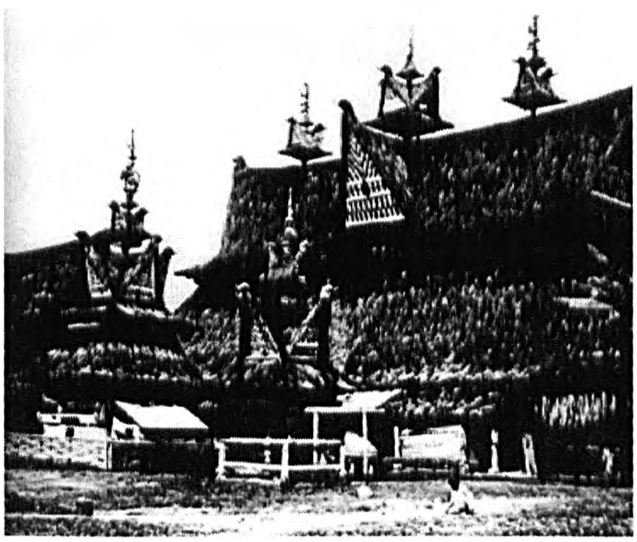

Figure 2.4 *Batak, large house and storehouses for rice, Sumatra, Indonesia. (After Guidoni 1975)*

Figure 2.5 *Unidentified village, Forcados River, southern Nigeria. (After Denyer 1978)*

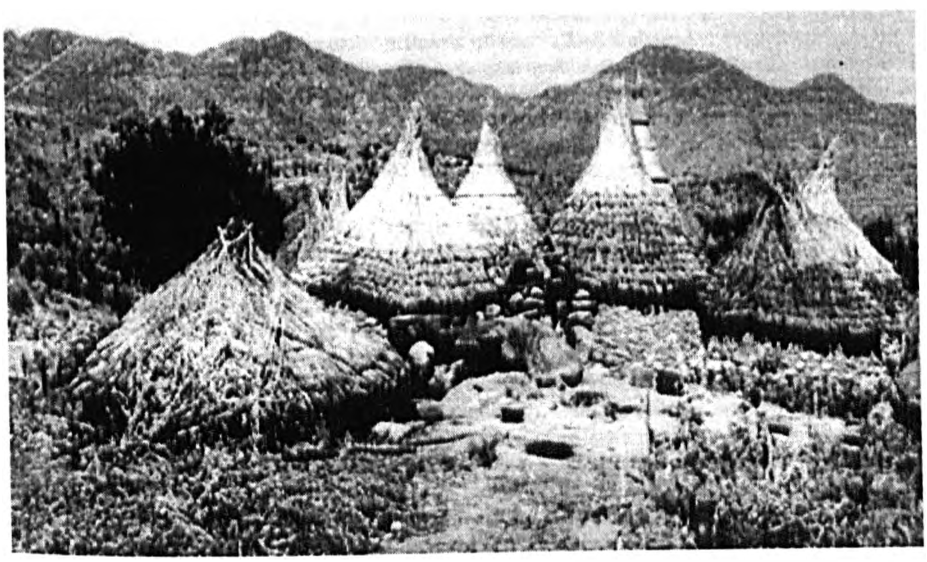

Figure 2.6 *Baya-Kaka homestead, near Batouri, Cameroon. (After Denyer 1978)*

It is clear that the same understanding to traditional architecture considers some common characteristics such as being indigenous to a region, using local materials, low level of technology, and designed and developed by a community, not an individual or experts [Malama 1997]. The model itself is the result of the collaboration of many people over many generations as well as the collaboration between makers and users of buildings and artefacts [Rapoport 1969].

Unfortunately, in many societies and cultures, the traditional architecture has disappeared. Rapoport [1969] gave a number of reasons:

1. many types of contemporary functions and buildings are too complex to create in traditional fashion and this introduces the rise of specialisation and differentiation which involve various trades and professions;

2. loss of common accepted and shared value system and image, is of great significance — such as the lack of the spirit of co-operation between designers and the public, and in turn, it leads to the advent of such controls as building regulations, codes and zoning rules; and

3. a premium on *originality*, striving for its own sake, is pushed as a dominant feature in the modern society, while the traditional cultures ignore the novelty and regard it as undesirable.

Nevertheless, this should conclude with the statement by Correa [1987] that: *"old architecture especially the vernacular has much to teach us as it always develops a typology of fundamental common sense."*

2.4.4 Contemporary architecture: pitfalls and problems

The distinction between traditional and modern societies is understood in terms of the contrast between informal controls, affective and consensus in the former, and impersonality and interdependent specialisation in the latter [Breese 1966]. Therefore, a contemporary paradigm, or a sort of modern tradition is a piece of architecture which is clearly the outcome of an individual's idiosyncratic effort [Correa 1997].

Curtis [1987] depicted the scene of the *Modern Architecture* impinging on many other parts of the world, especially in Africa, the Far and Middle East during 1960s and 1970s that:

> *"...the arrival of modern architecture was usually linked to foreign business, and while the multi-storey, air-conditioned offices and the expensively clad airports may have served as instant status symbols for those intent on attracting international capital, the results were usually crude and lacking in sensitivity to local traditions, values, and climate."*

Lim and Beng [1998] augmented that the vision of architecture and urbanism, which have resulted in the simplification and deculturalisation of Modernism, known as the "International Style": a post-war aesthetic tool of American Capitalism, ignores the environmental context namely disinterested in climatic conditions and non-cultural references.

As modern architecture is claimed to have originated in industrialised countries where an authentic modern style was appropriate to rapidly changing social conditions, when its pattern was repeated elsewhere and was often misapplied, its results were the added problems of a split between Western models and native values [Curtis 1987]. Lim and Beng [1998] argued that the conflict between different cultures should not be pondered about the past, but rather the perception of today's contemporary world culture. Furthermore, it is often incorrectly identified that contemporary culture as *western culture* (associated with Coca-Cola, McDonald's and blue jeans) with new and changing lifestyles, but nonetheless, it must at least have belonged to all who live in today's world.

In the contemporary African context, Arkoun [1982] emphasised upon pitfalls of various disciplines that should avoid falling into. There are four pitfalls mentioned as follows:

1. A number of foreign concepts, ideological forms and aesthetic values, have influenced the local knowledge and expectations of the population groups. For example, large buildings and housing complexes which form the western model, although strongly criticised, are often reproduced with unsuitable means. Therefore, it is suggested that the understanding of the traditional practices to apply into contemporary architecture should be included in the learning process.

2. Ideological discourse about identity has formed a factor of alienation/mystification and destruction to the existing morals and culture, associated with a style of economic development. The idea should be adopting the material development in a role of compromise between practical function and ideological personality.

3. The attitude of elite themselves — political, economic, religious and intellectual elite — should be collaborated in order to reach the *objective* needs of the different ethnic groups and layers of the population. Thus it is necessary to close the gap between the westernised elite and the traditional elite, and to invent a trans-social discourse in which includes the marginalised working classes.

4. The themes of recrimination against the monetary and economic powers, the misdeeds of technology, unequal trade relationships and so on, are the pitfalls which many tropical countries have frequently encountered. Arkoun [1982] stated that: *"... the evaluation of architectural activity and of the process of urban change cannot wind up with usable results if the denunciation of external pressures is only a screen for hiding local responsibilities."*

For contemporary Asia, many architects, i.e., Richard Ho, Tan Hock Beng, Jaya Ibrahim, and so on, have criticised the development of badly designed houses and the bad taste of clients and architects. These proliferate and are aided by forces of the mass media which enslaves itself to anything that come from the West [Powell 1998]. Yeang [1986] advocated the fact the modern architecture from the West has not worked in Asia for most instances, neither physically nor socially. It is because each Asian country has its own priority and problems, e.g., economic development, housing the population, or political problems.

Taylor [1987]; Powell [1993] proposed that there is a possibility to establish the cultural fusion between western and Asian architecture: *Fusing Modernity with the Vernacular* [Powell 1993]. It is the search for an architectural identity, for example, the use of indigenous materials and local craftsmanship, collaborated with the spatial organisation of entirely contemporary/modern styles. Lim and Beng [1998] also espoused the idea of examining how the significant indigenous archetypes can be reinterpreted and applied to modern living.

The synthesis can be seen in some of the finest architects' work, which have expressed an *authentic regionalism.* It is rooted to the socio-cultural, physical and other realities of the region, and not simply only an aesthetic solution. Yeang [1986] expressed that it would be ludicrous to design a western building on the inside but superficially Asian appearance on the outside (or vice versa). However, Curtis [1987] warned for the sake of a fake regionalism that it is a constant danger. A sounder modern architecture should be fundamentally approached to the translation of basic features expressing regional adaptation and meanings of the past (*not* nostalgic regionalism) into a form appropriate to changing social conditions (*not* superficial appearance). Architects such as Murcutt [1995] also strongly rejected any suggestion that is nostalgically reviving old rural images. Instead, it would be suitable to apply the traditional logic into the reappearance of particular contemporary forms: *analogous inspiration* [Fromonot 1995].

2.4.5 Trends in tropical architectural design

One area of the new approach in research in architectural school is to establish the means of providing acceptable environments, without air-conditioning in building. By applying controls of micro-climate or climate within the space, a specific situation has been created using rational and simple design methods and design tools for assessment of energy. Various computer programmes can be used to simulate, according to the relevance in design, ease of operation, accuracy in predicting thermal performance and energy consumption, and then the results are compared with those monitoring of actual buildings [Saini 1982].

Another area takes the influence of factors such as culture into account, which is often more important than the purely physical factors. It is claimed that building forms are a means to a cultural end: *"active element in the cultural process rather than a passive receptacle of cultural meaning"* [J. Hockings, referenced by Saini 1982]. Ando [1998] emphasised the role of culture that if the differences between cultures are blended together into a homogenous uniformity, this trend will destroy the characteristics and traditions that each nation or people has inherited, and it will kill the sense of association to a specific region, the moral and spiritual character in its roots.

It is admitted that, most often, the two worlds — the contemporary and the traditional — appear in direct opposition to each other. Correa [1997] hinted that architects should not learn to be individualistic, but to find the freedom to synthesise the opposing sets of the two totally different cultures. In other words, the considerations should be simultaneous in both contemporary and timeless, both *"ethnic"* and *"modern"*.

Powell [1998] suggested the *purist model* for architecture in the humid tropics by setting up criteria concerning the built-environment and its respect to the nature. Environment-friendly is a theme of the design to minimise the use of energy. Murcutt's minimalism has been applied into his architecture to consume as little energy as possible; knowledge of materials, mastery of manufacturing, and construction processes can draw up a descriptive estimate of the ecological cost of each decision in a building project, taking into account even labour and non-renewable resources [Fromonot 1995]. Finnish architect Juhani Pallasmaa gave a lecture (quoted from Fromonot [1995]) that:

> *"...Architecture will again take root in its cultural and regional soil. This architecture could be called Ecological Functionalism ... It must be more primitive and more refined at the same time: more primitive in terms of meeting the most fundamental human needs with an economy of expression and mediating man's relation to the world ... and more sophisticated in the sense of adapting to the cyclic systems of nature in terms of both matter and energy. Ecological architecture also implies a view of building more as process than a product ..."*

However, the environmental-friendly issue itself is confronting the philosophical challenges of the notion of a global culture (globalisation), especially in the urban context. Some considerations have to be realised namely the spaces for technical innovation and information technology; the necessity of air-conditioning to exclude dust, pollution and noise; urbanised function such as home office; and the desire to express individual personality [Powell 1998; Grover 1990].

Lim and Beng [1998] proposed that another trend is the notion of a *contemporary vernacular*. It is defined as a self-conscious commitment to uncover a particular tradition's unique response to place and climate; and to exteriorise the formal and symbolic identities to creative new forms, which are in touch with contemporary realities and lasting human values. Its issues concern the growing ecological consciousness; the ideological quest for national roots; the extensive use of local materials and craftsmanship; the application of appropriate technology; and the introduction of contemporary approaches to plan arrangement, spatial relationships and visual complexity.

Certainly, the current trends of tropical architectural design are partly with respect to climates, environments and energy consciousness, including contemporary cultural lifestyle. Implicitly, the built-environments of neither entirely enclosed nor open will be able to respond to the above aspects. It will be an architecture containing the spaces that welcome local climate, and that are able to adapt to everyday living, minimising the energy use, and are not harmful to environments. It may be impossible to use the language of modern architecture in this situation. Rather, the profound root of its own tradition in living and working environments will be the answer to the future of tropical architecture.

2.5 Summary

This chapter discusses tropical architecture and its influences upon design, particularly the effect of tropical climates. The fundamental functions of buildings are explained and their development since the modern period is briefly described. It is clearly seen that there are two distinct separations of architectural movement: the contemporary and the traditional. While the former has hardly proved successfully, the latter seems to gain a renewal of interest. It is mentioned in particularly terms of comfort and in relation to design with climate.

Much studies of tropical climates have given details about their definition and areas, the dominant characteristics of a particular hot and humid climate (humid tropics), and the perception of the living conditions in these regions such as the difficulties/problems and solutions, including comfort quality. For building designs, the factors which have been affected, are considered and they are mainly three categories: people and their needs; climate; and materials and the means of buildings. Other factors are also briefly given such as comfort requirements, building site, building operations and economic factors.

The concept of the application for hot and humid tropical architecture, or thermal control strategies is explained. Basically, there are two types of controls: passive means (microclimate or settlement controls, and structural or building controls) and active method by mechanical controls. Only the passive criteria of architectural design are mentioned in details, which include: the considerations on exteriors and in-between spaces of buildings (settlement); orientation; building form; passive ventilation; solar control and shading devices; using of vegetation; and roof and wall treatments.

Further reviews concentrate on a comparison between traditional architecture and contemporary. It seems that the features of traditional forms reflect the delight of regional and visual/aesthetic values, mainly related to culture. However, with the contemporary societies, the traditional architecture has disappeared. On the other hand, the contemporary or modern architecture, originated in industrialised countries of western culture, has been able to cope with the new and changing lifestyles, but shows some pitfalls and problems for many tropical countries. The solutions have nevertheless been suggested, which lead to the trends in tropical architectural design.

The next chapter will discuss a particular feature of tropical architecture, which has a distinct significance and characteristic different from western architecture, and that is the transitional space. It will be these spaces that are discussed in the main research of this thesis.

Chapter 3

TRANSITIONAL SPACES

"I'm interested in an architecture that continually acknowledges the physical and climatic character of its sites; that recognizes the sorts of changes in scale we experience when we move from the inside to the outside ..."

G. Murcutt [1995]

3.1 Introduction

In the previous chapter it was established that the trends in tropical architecture should consist of climate responsive, environment and energy conscious design, and relate to contemporary-cultural issues. The quest has to be scrutinised in the whole process of architectural design, in which the fulfilment is essentially the collaboration of multi-disciplinary professions. In this chapter an attempt will be made to discuss a space type much related to the current research interest often mentioned in relation to tropical architecture. Such spaces, neither indoors nor outdoors (or — ambiguously both indoors and outdoors), is the *transitional spaces*. The study of their significance and characteristics will be carried out in this chapter.

Before anything else, it needs to be understood that the very loose territory between the indoor spaces and outdoors in a tropical region is different from that in western architecture [Kurokawa 1997]. An ambiguity between enclosed and open spaces has been developed for years through cultural expectation, based on traditional built-form and function.

Generally speaking, domestic life in hot and humid tropical climate takes place out of doors during the day and evening (if it is not raining), but at night it is indoors [Fry and Drew 1964]. However, these out of door spaces do not mean exposed to the sun (or on the sun deck), but rather in a shaded area (the avoidance of excessive solar radiation) allowing breezes to pass across the body surface (the evaporation of moisture by breezes) [Olgyay 1963; Koenigsberger et al 1973]. Accordingly, these areas will be referred to as *transitional spaces*.

Transitional spaces can be seen in many examples of Asian architecture. In India, Correa [1987] stated that *"disaggregating architectural form into a series of separate but interdependent volumes"* is linked by such spaces as pergola-covered courtyards, verandas, terraces and balconies. In Malaysia, Yeang [1994] described that transitional spaces are the "in-between" zones of exterior and interior such as *air spaces* and atrium.

Kurokawa [1997] explained that in Japan, *engawa* — a space inserted between nature and building or the intermediary space, is one of the important features in the philosophy of symbiosis between interior and exterior. It is a sort of veranda running around the house as a projecting platform on stilts and protected by the eaves, serving as an exterior space of the garden or interior space for entertaining guests. An illustration of *engawa* is shown in Figure 3.1.

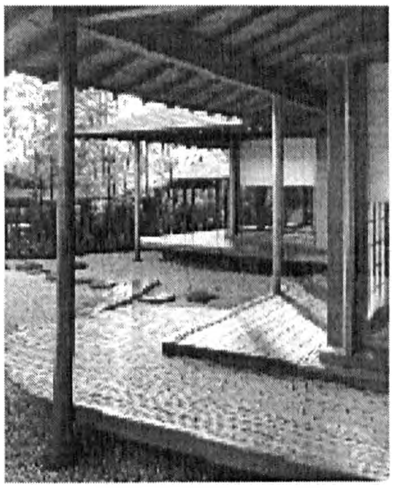

Figure 3.1 *The Japanese* engawa *— an intermediary space between indoors and outdoors. (After Kurokawa 1997)*

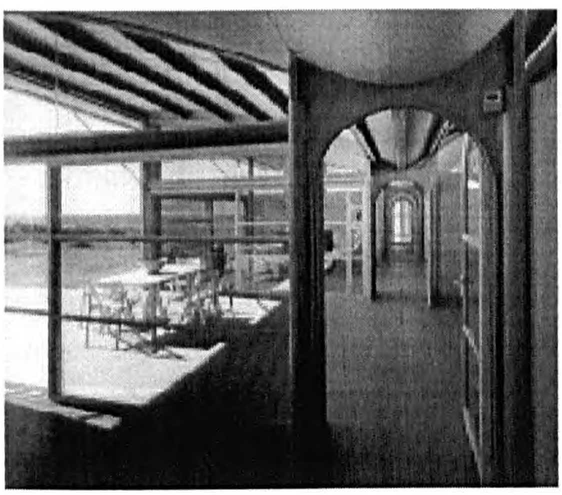

Figure 3.2 *View of the interior through the outdoor living.*
The Magney House, Bingi Point, New South Wales (1982-84).
Architect: Glenn Murcutt. (After Fromonot 1995)

Designing for contemporary Australian architecture, Murcutt [1995] applied the principle but not the traditional form of the veranda. As an open area protected from the sun and rain, this transitional social space is inserted between an often inhospitable outside and the intimacy of the interior. As a result, this space becomes not only the passage and the entrance, but the everyday living or sitting area for the daytime as well, shown in Figure 3.2.

3.2 Significance of transitional spaces

In tropical Australia, over thousands of years, Aboriginal people have come to terms with nature and have learnt to live in harmony with it. Their cultural heritage is partly known in terms of their basic shelters (in Figure 3.3) and the adaptation of their life and work style to ensure a balanced ecology, with least harm to the surroundings. Like many other cultures, Aboriginal people live around, and not in, houses [Saini 1982].

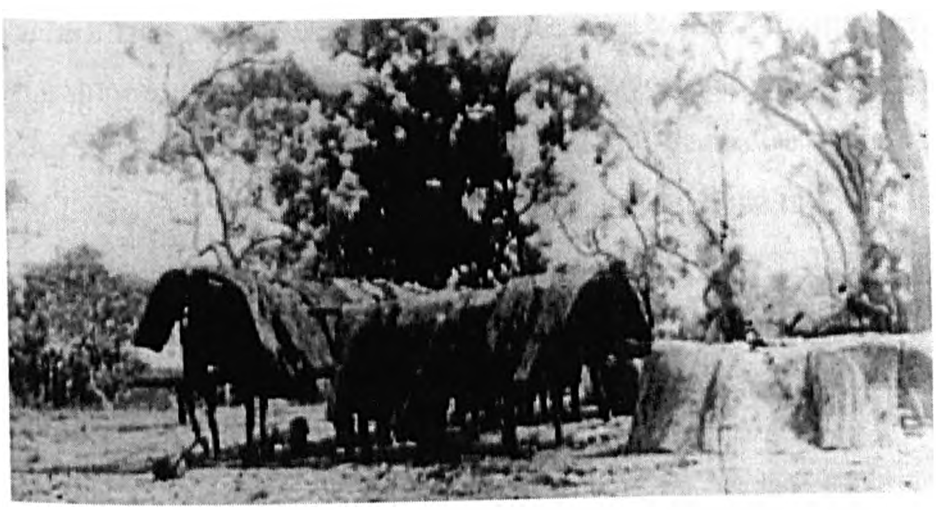

Figure 3.3 Traditional Aboriginal dwellings — bark huts in tropical Australia, photographed by Walter Roth c. 1905, Australian Museum. (After Fromonot 1995)

In Asian houses, Taylor [1987] showed that the hierarchy of spaces (or spatial hierarchies) tend to be organised more rigidly, for example, reception areas for strangers are clearly separated from areas for family activities. This is a function of the transitional spaces used in the Asian context. Another is implying in terms of the living conditions. There are many architectural features which signify the use of transitional spaces, such as open-to-sky courtyards, pool courtyards, pergolas, verandas, pavilions, patios and loggias [Powell 1998].

Correa [1987] categorised the use of the spaces between warm and cold climates. While the people in warm climates need only minimum protection such as a *chhatri* (a small umbrella) during the day, or stay outdoors under the open sky only in the early morning and at night; those in the cold climate have to live in a protected sealable weather-resistant box. In terms of *transition* from one condition to the other, therefore, it obviously means that the movement through a hard and clearly defined boundary — the "front door" occurs in cold climates. On the other hand, the architecture in the warm climate is considered as the processional unfolding of spaces: some enclosed and some open-to-sky.

The architectural reinterpretations by Murcutt [1995] of an intermediate area punctuating the journey between outside and inside, are as a sequence of living areas. They are: a porch opened on three sides to the horizon; a terrace or outside platform attached to the house by a light and removable screen; courtyards as rooms left open to the sky, paved and planted; atriums as focal points of living rooms; and the veranda extended and modified into a large open area. An example is shown in a sketch of the Muston House in Sydney, in Figure 3.4.

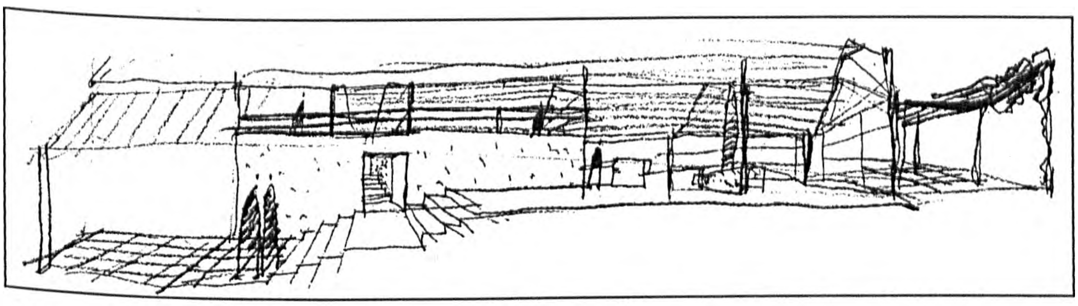

Figure 3.4 *A sketch of the longitudinal section from the front of the house to backyard with canvas awnings.*
The Muston House, Seaforth, Sydney.
Architect: Glenn Murcutt. (After Fromonot 1995)

In our contemporary urban society, another type of buildings — the skyscraper, is widely built for double benefits of land used and economic investment. Designing the skyscraper by bioclimatic approach, Yeang [1996] suggested that one of the design primers is to avoid a hermetically-sealed character by adding layers of transitional spaces between the inside area and the outside. These transitional spaces as air spaces, are named *"skycourts"*, which are large terraced areas located in the upper parts of tall buildings, shown in Figure 3.5.

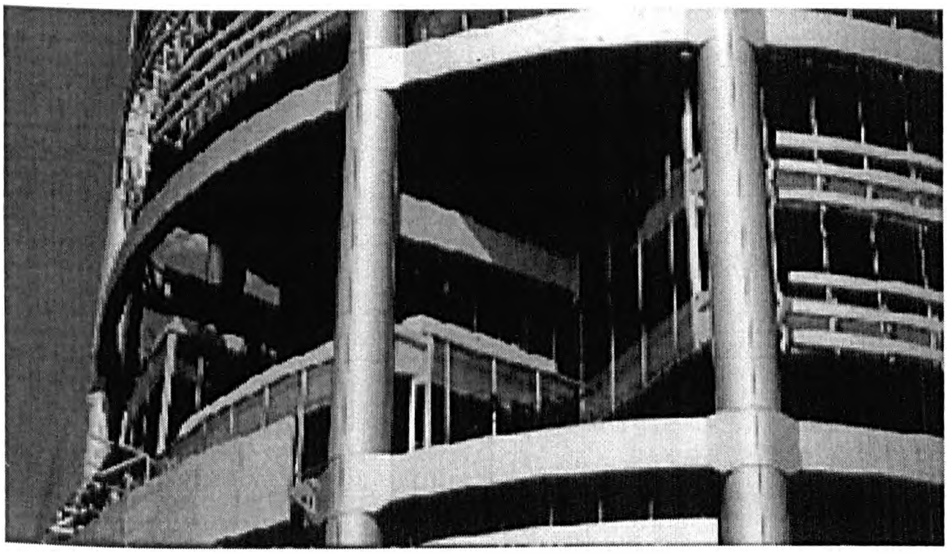

Figure 3.5 *The skycourt.*
Menara Mesiniaga, Subang Jaya, Selangor, Malaysia.
Architect: Ken Yeang. (After Yeang 1994)

The skycourts can be used as areas for communal-interactions or serve as evacuation and refuge-zones in the event of emergencies. To enhance low-energy benefits, the spaces can be wind-controlled zones (natural ventilation ports) and sun-receiving areas. Exit to the skycourts gives the individual access to fresh air, experience of the climate of the place, and views of the outside. There are opportunities for greening the city and vertical landscaping. A further way to improve the interior life of the skyscraper is to connect these skycourts by external stairs or ramps so that occupants can have an alternative access to other floors. Ultimately, at the skyscraper's ground floor access to the street outside should deserve special consideration; preferably, it should be entirely open to the outside as a naturally-ventilating space, serving effectively as a transitional space between the exterior and the enclosed interior of the building.

Kurokawa's idea [1997] of *architecture of the street* or *street architecture* in contemporary Japanese architecture (in Figure 3.6) is the interpenetrating of interior and exterior spaces within a single building, creating an overlapping, multivalent intermediary zone. It is an application of the third space in-between inside and outside. By this means, it is achieved by interpolating a spatial distance (neutral zone) or a temporal space (cooling-off period) between them. This space therefore creates a dynamic relationship between contradictory elements (interior and exterior) while allowing them to remain opposed: *the Philosophy of Symbiosis* [Kurokawa 1997].

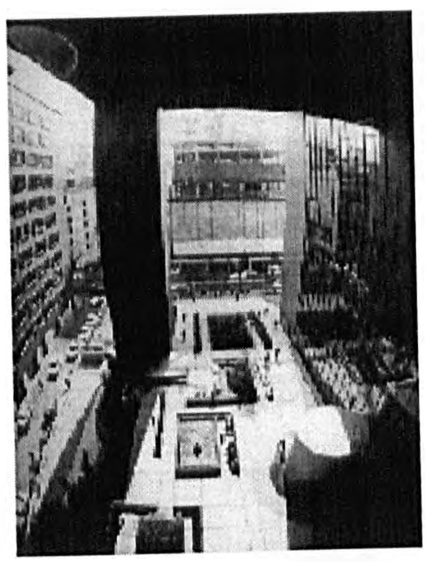

Figure 3.6 *Architecture of the street —the intermediary space.*
The Fukuoka Bank Head Office (1975).
(After Kurokawa 1997)

3.3 Characteristics of transitional spaces

As mentioned above, the conditions of the living in the transitional spaces are widely appreciated. Some illustrations by Powell [1998] given here will explain the characteristics. The living area, where it extends into the landscape is a convivial space which is in harmony with nature (in Figures 3.7 and 3.8).

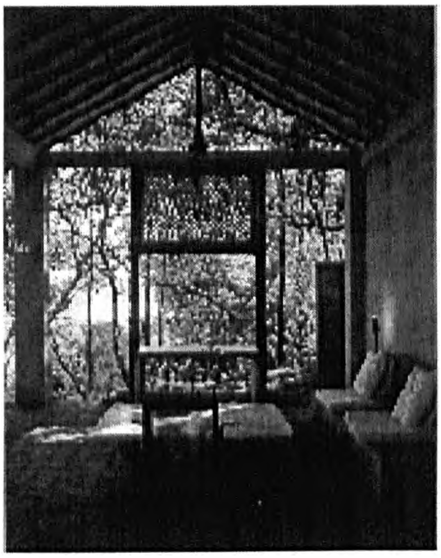

Figure 3.7 *The open living area which extends into the landscape.*
The Cinnamon Hill House, Lunuganga, Bentota, Sri Lanka.
Architect: Geoffrey Bawa. (After Powell 1998)

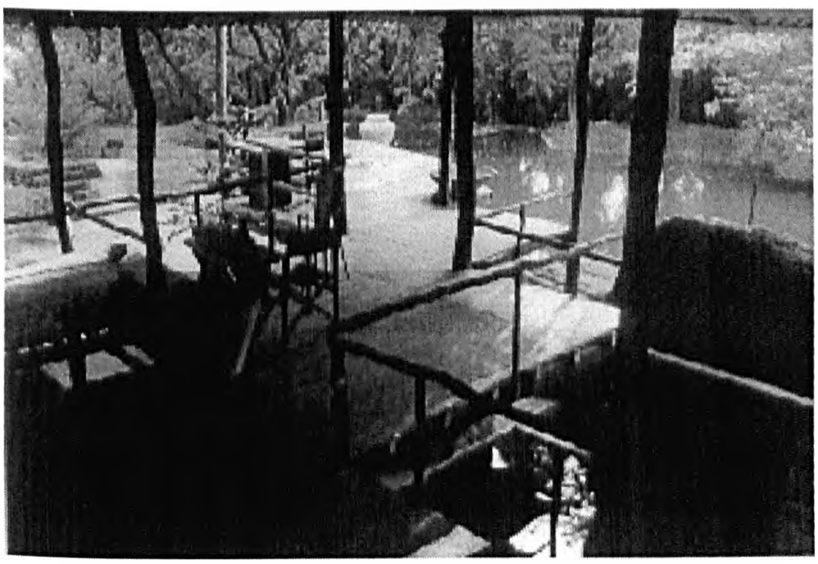

Figure 3.8 *The spartan living and sleeping area on the edge of a dam.*
The Laki Senanayake House, Diyabubula, Dambulla, Sri Lanka.
Architect: Laki Senanayake. (After Powell 1998)

The entrance loggia (in Figure 3.9) and the veranda (in Figure 3.10) are open spaces which link the outdoors and the living areas. These areas provide a covered route with the long eaves, protected from the sun and rain.

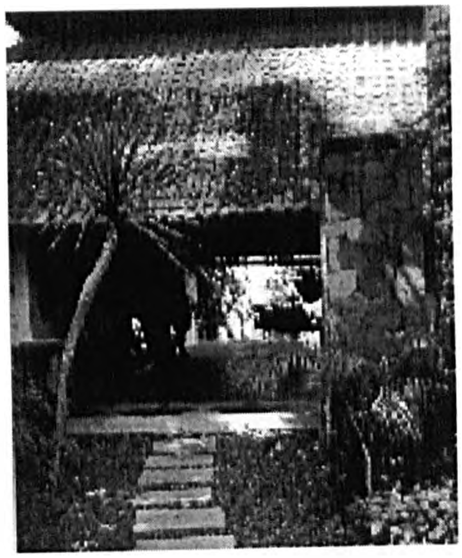

Figure 3.9 *The entrance loggia linking entrance court and living-dining area.*
Taman Bebek, Sayan, Bali, Indonesia.
Architect: Michael White (Made Wijiya). (After Powell 1998)

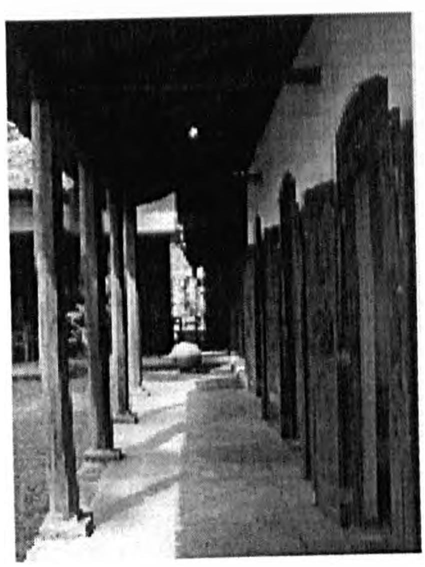

Figure 3.10 *The veranda providing a covered route to dinning room.*
The Fell-Smith House, Galle, Sri Lanka.
Architects: Bruce Fell-Smith and Wong Mun Summ.
(After Powell 1998)

Some expressions in terms of traditional domestic features hinted at the use of the in-between spaces for living, sitting or sleeping during daytime and night-time. For instance, the Thai *sala* (in Figure 3.11) has the meaning of open-sided pavilion, which can be compared with the Indian *bungalow* or the Indonesian *bale*, which is a hipped-roof pavilion with a thatch covering.

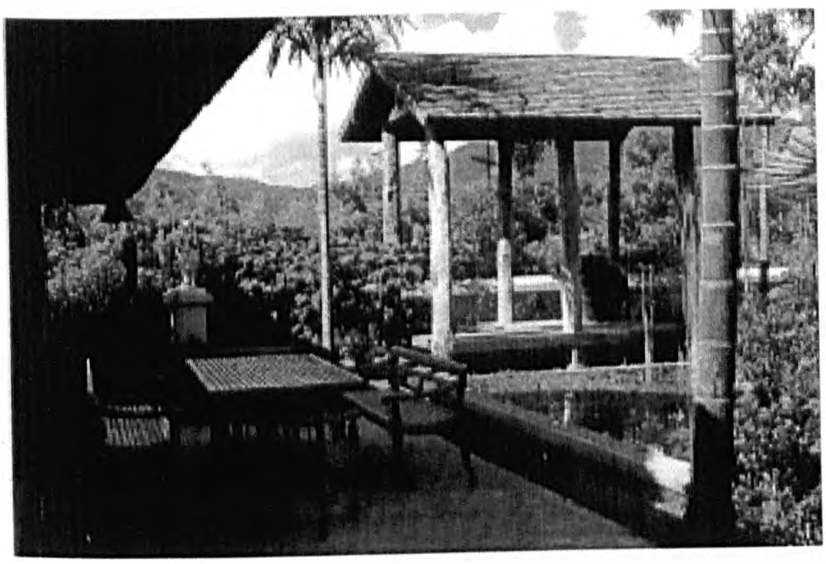

Figure 3.11 *The Thai* sala *—an open-sided outdoor pavilion.*
Baan Chang Nag, Changmai, Thailand.
Architect: Nithi Sthapitanonda. (After Powell 1998)

In Thailand and the Philippines, a type of outdoor living space is *lanai*, which is a large day-space on ground level as an essence of a house in the tropics, shown in Figure 3.12.

Figure 3.12 *The Filipino* lanai *—a large in-between living space.*
The Apacible House, Forbes Park, Manila, Philippines.
Architect: Susan Castillo. (After Powell 1998)

The Javanese audience hall *pendopo* which is used for formal reception has openings on three or four sides and its structure supported by columns, shown in Figure 3.13.

Figure 3.13 *The Javanese audience hall* pendopo *—openings on three sides.*
The Jaya Ibrahim House, Cipicung, Bogor, Java, Indonesia.
Architect: Jaya Ibrahim. (After Powell 1998)

The Malay *anjung* (in Figure 3.14) is a timber veranda raised on tall, slender timber columns and its space is used as an outdoor extension of the living area at the front of a house. The traditional Malay *serambi* or open veranda, is also used as living area but at a lower level in the front of the house and effectively bars access to visitors to the private area.

Figure 3.14 *The Malay* anjung *— a timber veranda raised on tall, slender columns and used as an outdoor extension of living area.*
The Salinger House, Bangi, Selangor, Malaysia.
Architect: Jimmy C S Lim. (After Powell 1998)

Conceptually, the Indonesian *serambi* (in Figure 3.15) which has the meaning of the station platform (a linear space), is an outdoor sitting area. In contemporary design, it is used as a feature of the principal living space.

Figure 3.15 *The Indonesian* serambi *— a linear outdoor sitting area enclosed by the sliding glazed windows.*
The Tan Tjiang Ay House, Bandung, Java, Indonesia.
Architect: Tan Tjiang Ay. (After Powell 1998)

In the Indian open-to-sky courtyard, there is a tree, or *tulsi* planted in the middle of the space (in Figure 3.16), and the *kund* or a traditional stepped well (in Figure 3.17) can be designed as an outdoor garden for extension of the living area.

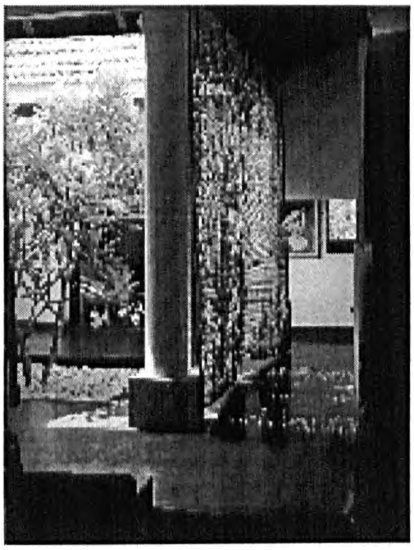

Figure 3.16 *The Indian open-to-sky courtyard with a tree or* tulsi *plant in the middle and the shaded veranda.*
The Correa House, Koramangala, Bangalore, India.
Architect: Charles Correa. (After Powell 1998)

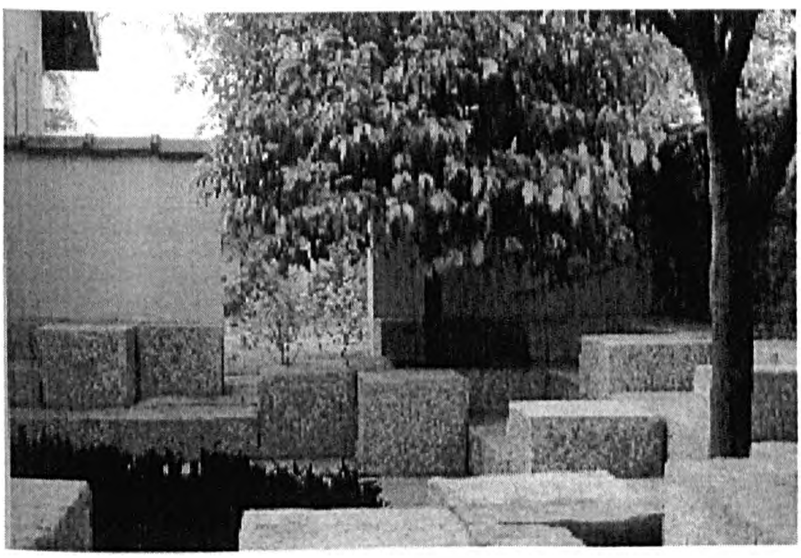

Figure 3.17 *An enclosed outdoor garden* kund *—a traditional stepped well.*
The Correa House, Koramangala, Bangalore, India.
Architect: Charles Correa. (After Powell 1998)

In contemporary architecture, transitional spaces retain the same meaning and application in practice as the vernacular. Correa [1984] gave three strategies using a veranda to achieve the residential building design. First of all, designing a veranda to warp around the main living areas, creating a protective zone (in Figure 3.18); then, turning the veranda into a garden and providing adequate height as a garden zone (in Figures 3.19 and 3.20); finally, combining the garden zone with the east-west orientation using an interlocking form (in Figure 3.21).

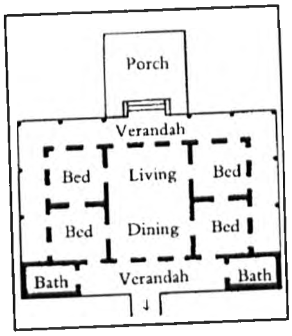

Figure 3.18 *Designing a veranda to wrap around the main living areas. (After Correa 1984)*

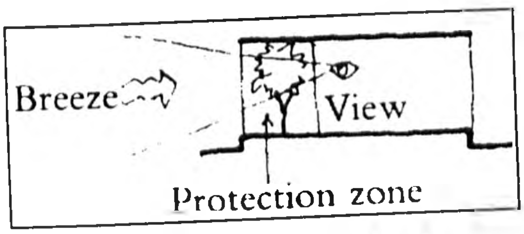

Figure 3.19 *Creating protective zone and turning into a garden. (After Correa 1984)*

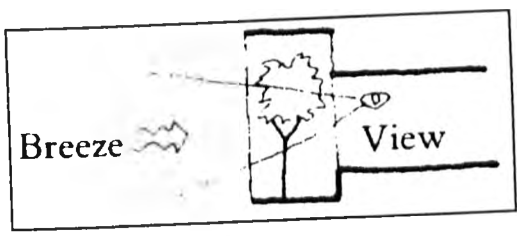

Figure 3.20 *Providing an adequate height for the garden zone. (After Correa 1984)*

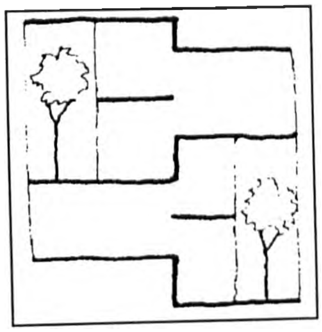

Figure 3.21 *Combining the garden zone by using interlocking form.*
(After Correa 1984)

Designing for high-rise/skyscraper, Yeang [1991] gave the idea of the use of multi-storey recessed transitional spaces that would represent another way of shading the hot sides of a tall building (in Figure 3.22). Such huge transitional air-spaces or atria could be designed to function as wind scoops to control ventilation to the inner part, comparing to the verandahways of vernacular architecture. This may take the form of totally recessed windows, balconies or small-scale courtyards in the upper floors or skycourts, as mentioned above.

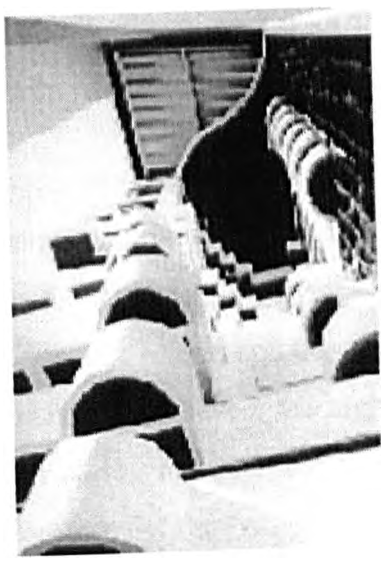

Figure 3.22 *The recessed transitional space in a skyscraper.*
The Plaza Atrium, Jalan P Ramlee, Kuala Lumpur, Malaysia.
Architect: Ken Yeang. (After Yeang 1994)

3.4 Summary

Transitional spaces are obviously a significant feature in hot and humid tropical architecture. Their spatial quality is fitted into the context of climate and culture of the region. The mixture of the "in-between" spaces in buildings enables the smoothness of a series of parts of a journey which is taken from exterior to interior, or vice versa. A diagram of the transitional space in an office building, which will be mentioned later in the main part of this thesis, is shown in Figure 3.23 (repeated Figure 1.2).

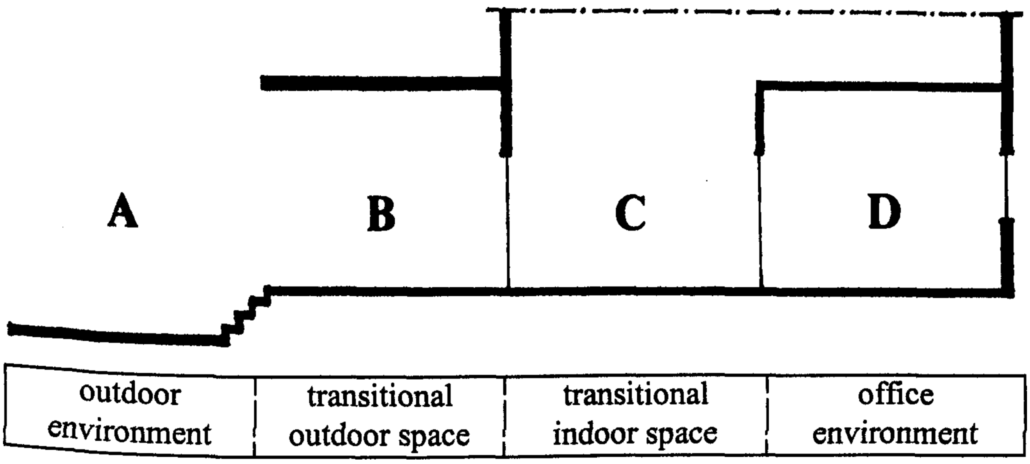

Figure 3.23 *A diagram of a series of spaces in tropical architecture — an office buildings. (Repeated Figure 1.2)*

Thus transitional spaces have an environmental significance which can be examined in relation to thermal comfort. To examine the benefits, a scientific methodology should be used. Although the typical climatic characteristics of transitional spaces involve dynamic effects and transient conditions, they must be investigated in relation to making less severe the high air temperatures and high solar radiation from the sun during the day, and their performance as a buffer zone. Satisfaction in comfort is the major aim in physiological terms. Simultaneously, the research will focus on the application of passive means, especially in naturally-ventilated buildings to create a preferable environment for both living and working.

In terms of the cultural and psychological aspects, such transitional spaces have already been developing for many years, i.e., architecturally transitional —

somewhere between an indoor space and an outdoor space such as a loggia or a veranda. In the evolution from traditional context to contemporary fashion, they have always been a feature of tropical architecture, except in the ignorance of modernism.

This research will focus on the observation and analysis of occupants of transitional spaces in time (i.e., spaces which people pass through) in order to determine their experience of comfort or discomfort. This will add to the body of knowledge concerning the scientific and environmental analysis of such spaces which in turn complements the cultural background to their use.

Chapter 4

THEORY OF THERMAL COMFORT

"The study of thermal comfort touches on many disciplines, including heat and mass transfer, thermal physiology, psycho-physics, ergonomics, biometeorology, architecture, textile engineering. The present work attempts to bridge the gap between artificial professional boundaries and to integrate these various disciplines."

P. O. Fanger [1970]

4.1 Introduction

This chapter looks at the theory of thermal comfort. By and large, it is known that there are heat transfers between human body and its environment, and a thermal balance between the two, which is simplified as the condition of thermal comfort. However, it should be noted that this criterion is expressed in terms of physiological measurements, where recent research has yet to investigate profoundly into any other aspects namely psychological and cultural concerns. The theory of thermal comfort nowadays, is therefore a dynamic and debatable discourse. This chapter will try to trace the theory of thermal comfort based on many research investigations, aiming at clarifying the significance of the issue itself and the application which later can be employed in the design of built environments.

In brief, this chapter will discuss the significance of thermal comfort studies and the problems of the definition of *"thermal comfort"*. The classic theory will be mainly concerned with the physiology of thermal heat exchange and thermoregulatory systems in man, and factors effecting comfort which lead to comfort equations and the comfort zone. The standards of thermal comfort (i.e., ISO Standard 7730-1994 and ASHRAE Standard 55-1992) will be considered in terms of practical application. Finally, this chapter will be concluded by the debate between two methodologies of research: climatic chamber experiments or field studies; and between two thermal conditions: steady state or transient condition.

4.2 The need to study thermal comfort

Macpherson [1962] described that the assessment of the thermal environment as one of the oldest judgements made by man, commenting on the prevailing weather by comparatively evaluating in everyday conversation. The ability to evaluate such assessment with numerical values was of relative modernity, being introduced by Galileo at the beginning of the seventeenth century. It was then that the first type of air thermometer was invented.

By the end of the nineteenth century, all four environmental parameters (the temperature and humidity of the air, the speed of air movement and the intensity of radiation) were not only able to be measured, but also able to be controlled in a quantitative fashion, and this relative importance was to contribute in the research to determine the total thermal stress. Other factors such as the rate of working and the clothing worn or individual parameters have now been recognised to be part of the assessment [Macpherson 1962]. With a thorough quantitative knowledge of both environmental and individual parameters, investigations have been made possible in establishing thermal comfort [Fanger 1970].

As mentioned in the previous two chapters (Chapters Two and Three), all elements of buildings and any building types should be designed whenever possible to respond to the climate as priority and to provide delightful living conditions for occupants. This is a part of the relationship between humans and their environments whose physical elements, in a complex composition, consist of light, sound, climate and space [Fitch 1948].

The influences of such composition, especially climate, have determined human productivity, health, as well as physical and mental energy. Huntington [1951] suggested that all human conditions/capacities will be generally at their peak when they are in the most comfortable periods and they will decrease in the unfavourable seasons. This is one of the reasons for creating thermal comfort in built environments. Other reasons stated by Fanger [1970] are to satisfy man's desire to feel thermally comfortable and to improve human performance (intellectual, manual and perceptual performance).

Macpherson [1962] gave the advantages of the assessment of environmental stress in the direction towards some practical ends — diagnostic, therapeutic, or prognostic. It represents an attempt to determine:

1. the intensity of the stress in a given situation;
2. the means to remedy a situation known as uncomfortable; and
3. the environmental conditions to be acceptable to expose to.

According to Raw and Oseland [1994], there are five advantages from a knowledge of thermal comfort research:

1. guiding the design of buildings and enclosed environments;
2. controlling over environments which are too extreme for people;
3. improving internal air quality, reducing the risk of sick building syndrome and promoting good health;
4. achieving energy savings and reducing the potential harm on the environments by reducing the production of CO_2; and
5. affecting the work efficiency of the building occupants.

4.3 Definitions of thermal comfort

The etymological origin of the word comfort comes from the Middle Latin *"confortare"*, denoting the possession of God given spiritual and physical strength. During the 19th century its meaning changed into two respects: firstly, denoting worldly good which could enhance mental and physical well being; and secondly, for the physiological and psychological well being of the dwelling occupants [Heijs 1994].

The definition of *thermal comfort* for a person, in agreement with ASHRAE standard 55 [1966; 1981; 1992] is *"that condition of mind which expresses satisfaction with the thermal environment"* [Fanger 1970]. When it is applied to a group of people, who are subject to the same room climate, the aim is to create optimal thermal comfort for the highest possible percentage of the group. For example, Goulding et al [1992] aimed to create a range of optimal thermal comfort for 75% of a group of the people at the same location, whereas Hensen [1990] stated that the standards specify environmental parameter ranges (i.e., comfort zones) in which generally at least 80% will regard the environment as acceptable.

However, this definition of thermal comfort appears to have controversial precision. Heijs [1994] referred to a psychological point of view that *"condition of mind"* could be the result of either a perceptual process, or a state of knowledge or cognition, or a general feeling or attitude, and could take many different forms such as a feeling of well being, or in a pattern of behaviour or clothing. In addition, the term *"thermal environment"* is vague with respect to the variables involved. Mayer [1993] also questioned the meaning of *"satisfaction with the thermal environment"* whether it is objective criteria.

Heijs [1994] argued that if comfort is regarded as a subjective mental state, it will be elusive because it cannot be measured objectively and it is continuously changing depending on various factors. Consequently, it is suggested that thermal comfort should be considered as *"an environmental property, determining the satisfaction of thermal needs both physiologically and psychologically."* This environmental property is probably composed of three components: thermal climate, thermal environment and thermal control.

On the other hand, Hensel [1981] implied thermal comfort as an emotional experience which can be characterised in terms of *"pleasant"* and *"unpleasant"*. McIntyre [1980] pointed out that the meaning of the words like *"pleasant"* and *"comfortable"* do not have an absolute value, but will be relative to experience and expectation. The idea of positive comfort or *"thermal pleasure"* is associated with the partial relief of thermal discomfort, and therefore the idea of comfort as a lack of discomfort. Benzinger [1979] defined the condition of thermal comfort as *"a state where there are no driving impulses to correct the environment by behaviour,"* and this is a more objective definition than the standard [Hensen 1990].

Another term, *"thermal neutrality"*, is treated synonymous as thermal comfort (in this thesis), and it is defined as *"the condition in which the subject would prefer neither warmer nor cooler surroundings"* [Fanger 1970]. This definition is very much similar to that of thermal comfort defined by Markus and Morris [1980] as *"that state in which a person will judge the environment to be neither too cold nor too warm —a kind of neutral point defined by the absence of any feeling of discomfort"*. It is automatically rebounded that *"dissatisfaction may be caused by the body being too warm or cold as a whole, or by unwanted heating or cooling of a particular part of the body (local discomfort)"* [Hensen 1990].

Regarding application to building design, Limb [1992] defined thermal comfort as *"a condition of satisfaction expressed by occupants within a building to their thermal environment."* Another expression of thermal comfort at the Building Science Unit [1994-95], School of Architectural Studies at the University of Sheffield, is that *"an important property of the internal environment which architects or environmental engineers attempt to incorporate into buildings by suitable design of structure and services."*

Comfort is considered as a subjective issue. It is possible that somebody at the same time and at the same place may not be satisfied his or her own environmental conditions because of biological, emotional and physical variances [Evans 1980]. Therefore, comfort may not be measured objectively; the problem is that human physiology can indeed be expressed in numbers but the psyche cannot [Lippsmeier 1980].

4.4 Classic theory of thermal comfort

4.4.1 Human comfort and thermoregulatory system

Chadderton [1991] claimed that building services engineering is involved in the basic needs for human comfort: visual comfort by rendering natural and artificial illumination; acoustic environment by quiet services equipment; and thermal comfort by the consideration of thermal control systems.

In several previous research investigations [Fanger 1970; McIntyre 1980; Gagge et al 1971; 1986], thermal comfort is strongly related to thermal balance between the body's heat and its surroundings. The body temperature must remain balanced and constant around 37°C. In order to maintain this steady level, there are many physiological mechanisms of the body which can occur [McMullan 1992].

Koenigsberger et al [1973] explained that there is some form of heat exchange between the body and the environment, and this mechanism is shown in Figure 4.1.

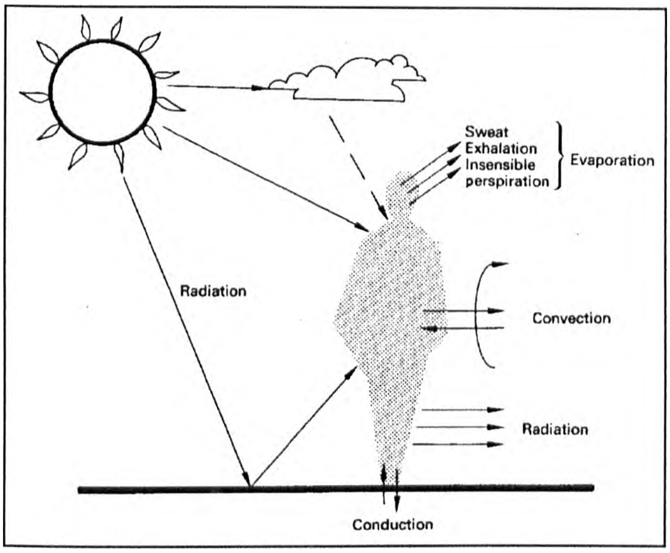

Figure 4.1 *Body heat exchange. (After Koenigsberger et al 1973)*

There are four different heat transfers between the human body and its environment [Koenigsberger et al 1973; Egan 1975; Chadderton 1991]:

1. Radiation: heat gain from the environment is by solar radiation or warm surfaces, while radiant heat loss between skin and clothing surfaces and the room depends on the absolute surface temperature, the emissivity, the surface area and the geometric configuration of the emitting and receiving areas. Thus a moving person will experience changes in comfort level depending on the location of the hot and cold surfaces in the room. The heat exchange by radiation is about 40%.

2. Convection: heat transmission from the body to the air in contact with the skin or clothing by natural convection currents or ventilation is a major source of cooling. The rate of convection heat loss is influenced by two factors: speeds of air movement and temperatures of air. The body's response to a cool environment is by restrict blood circulation to the skin, involuntary reflex action such as shivering, or in extreme cases, lower the body temperature. Body heat loss is primarily by convection (about 40%).

3. Evaporation: heat loss takes place on the skin as insensible perspiration and sweat, and in the lungs through respiration or exhalation. Basically, man loses about one litre of water a day by perspiration. The rate of evaporation depends on the amount of moisture transfer and on the air humidity. Other variables such as temperature, speed of air, clothing and activity also affect the evaporation. Heat transfer by evaporation is about 20%.

4. Conduction: heat exchange depends on thermal conductivity of materials contacting directly with the skin, or in other words, the temperature difference between the body surface and the object that is in direct contact with the body. Usually, there is very little heat transfer by conduction.

Koenigsberger et al [1973] stated that the body constantly produces heat from the consumption and digestion of food and the processes are known as *metabolism* of the energy produced in the body. Only about 20% is utilised in useful work, while the remaining 80% must be dissipated to the environments. The body's heat balance [Auliciems and Szokolay 1997] can be expressed as:

$$M \pm R \pm Cv \pm Cd - E = \Delta S \qquad \text{(eq. 4.1)}$$

where	M	=	metabolic rate
	R	=	net radiation
	Cv	=	convection
	Cd	=	conduction
	E	=	evaporation heat loss
and	ΔS	=	change in heat stored.

If ΔS is zero, it is the state of thermal balance between the body and its environments; if positive, the body temperature increases; and if negative, it decreases [Auliciems and Szokolay 1997].

Hensen [1990] included the heat transfers into the theory of thermoregulatory system, explaining thermal interaction between man and his environment. The diagram of basic features of the thermoregulatory system in man is shown in Figure 4.2.

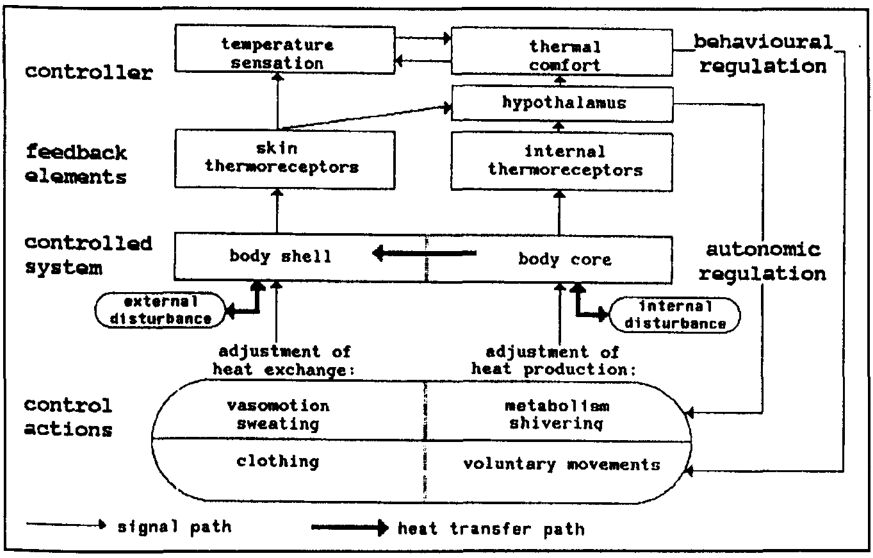

Figure 4.2 *Schematic diagram of the thermoregulatory system in man. (After Hensen 1990)*

According to Hensel [1981], man's thermoregulatory system is more complicated than any actual technical engineering control system. It is highly non-linear in the mathematical sense and contains multiple sensors, multiple feedback loops, and multiple outputs. Hensen [1990] described that the controlled system is influenced by both internal (e.g. internal heat generation by exercise) and external (e.g. originating from environmental heat or cold) disturbances. These thermal disturbances are detected by thermoreceptors in the skin and the body core. The thermoreceptors in the skin respond to the temperature sensation and those in the brain or hypothalamus, thermal comfort.

Mayer [1993] explained a difference between these two thermoreceptors that the cold-receptors in the skin react, when skin temperature falls below a certain threshold-temperature, combined with freezing, or locally, e.g. by draught, whilst the warm-receptors react combined with sweating, when a certain threshold-temperature in the brain is surpassed. Warm-sensors in the skin and cold-sensors in the brain exist too, but do not contribute to the discomfort sensation.

Hensen [1990] further stated that there are two types of regulations in the system which control heat balance in the human body: autonomic and behavioural temperature regulations. Autonomic thermoregulation, by hypothalamus, controls actions such as adjustment of heat production, internal and external thermal resistance, water secretion and evaporation; and behavioural thermoregulation controls active movements and adjustment of clothing, which is associated with conscious temperature sensation and with thermal comfort/discomfort. Hensel [1981] found that the temperature sensation depends mainly on the activity of thermoreceptors in the skin whereas the thermal comfort reflects a general state of the thermoregulatory system.

4.4.2 Factors affecting comfort

Conventionally, there are two groups of factors which influence the condition of thermal comfort in man, and these are environmental and individual factors. The environmental factors are air temperature (T_a); mean radiant temperature (T_r)[1], relative humidity (rh) (usually, converted into units of water vapour pressure in ambient air — P_a)[2]; and relative air velocity (v). The individual factors[3] are activity level or metabolic rate (M) and clothing thermal resistance (I_{cl}) [Fanger 1970].

These variables have been used in various extensive investigations and experiments involving numerous subjects; and have resulted in methods to establish the prediction of the degree thermal comfort of people in a still thermal environment [Hensen 1990]. It is cited by Fanger [1970] that thermal comfort is

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[1] $T_r = T_g + 2.35\ (\sqrt{v})\ (T_g - T_a)$: where T_r = mean radiant temperature; T_g = globe temperature; T_a = air temperature; and v = relative air velocity [Building Science Unit 1994-95].

[2] $P_a = rh * \exp\ (18.956 - 4030.18\ /\ (T_a + 235))$ (millibar): where P_a = water vapour pressure; rh = relative humidity (units in fraction); and T_a = air temperature [McIntyre 1980].

[3] 1 met = 58.2 Wm^{-2} and 1 clo = 0.155 m^2KW^{-1}. See Appendices B (Metabolic rates) and C (Clothing insulation values) for the standard values.

the "product" which can be achieved by many different combinations of the above variables and therefore by the use of many different techniques. The effect of any of the physical parameters should not be considered independently because each of them and the necessary requirements depend on the level and conditions of the other factors; the combined thermal effect of all variables on the human body. Furthermore, detailed measurements of all parameters are required to make proper control, measure and report, particularly the impact of individual factors [Fanger 1992; 1993].

Besides the above-mentioned six variables, there are a number of subjective parameters which have influences on thermal preference [Oseland 1992]. These are: individual or group (ethnic and cultural); social classification (gender and age); somatic factors (body build or menstrual phase); psychology (attitude and expectation); economics (income or cost of heating or cooling); and external circumstances (time of the year or climate). However, Fanger [1970] argued that most of these factors have little or no effect upon the comfort conditions.

Heijs [1994] reviewed many thermal comfort research and reported that human comfort can be influenced by:

1. consequences of classificatory and physiological variables such as gender, age and physical conditions [Rohles and Nevins 1973; Hawkins 1976];

2. perceptual filtering and integration of information in laboratory experiments [Howell and Kennedy 1979; Rohles 1980];

3. process of affective evaluation between thermal sensation and comfort votes [Howell and Kennedy 1979];

4. manipulation of the knowledge of subjects concerning environmental temperatures [Rohles 1980; Stramler, Kleiss and Howell 1984]; and

5. attitudes and habits, usually assumed to be based on affective evaluations and cognition in field studies, in choices of clothing or behaviour [Humphreys 1976; Fishman and Pimbert 1982; McIntyre 1982].

In recent research [Humphreys and Nicol 1998; de Dear and Brager 1998], many other parameters concerning the adaptation or the Adaptive Model, which have influenced thermal comfort, are considered. This issue will be discussed in more details in Chapter Five.

4.4.3 Comfort equations

Fanger's comfort equations [Fanger 1970; ISO 7730 1994] is one of the most well known and widely accepted methods in establishing thermal comfort conditions and later standards [Hensen 1990]. It considers the heat balance as the first requirement for thermal comfort and the expressions for skin temperature and sweat secretion at a given activity level as the second. These conditions are claimed to be valid only for steady state, with the combined clothing and environmental variables [Fanger 1970].

It should be noted that the comfort equations are based on experiments with Danish and American college-age persons exposed to a uniform environment under steady state conditions. Therefore, the reliability of the equations applied for extreme climates is questionable and needs further experimental verification [Fanger 1970].

Chadderton [1991] expressed the Fanger's comfort equations in the form of mathematical statement:

$$f(\text{met, clo}, T_a, T_r, P_a, v) = 0 \qquad \text{(eq. 4.2)}$$

where f represents a mathematical function connecting all the variables contained in the bracket.

Fanger [1970] applied his equations by using the following variables:

1. a function of clothing:
   - I_{cl} = thermal resistance of clothing (m^2 °C/W);
   - f_{cl} = ratio of man's surface area while clothed to while nude;
   - t_{cl} = surface temperature of clothing (°C);

2. a function of activity:
    - M = metabolic rate (W/m^2);
    - W = external work (W/m^2);
    - A_{du} = DuBois area: body surface area of the human body (m^2);
    - η = external mechanical efficiency of the body;

3. environmental variables:
    - T_a = air temperature (°C);
    - T_r = mean radiant temperature (°C);
    - P_a = water vapour pressure in ambient air (millibar);
    - v = relative air velocity (m/s); and

4. others:
    - h_c = convective heat transfer coefficient ($W/m^2{}^\circ C$).

The practical assessment of any given thermal environment is evaluated in quality in terms of "Predicted Mean Vote" (PMV) and "Predicted Percentage of Dissatisfied" (PPD) [Fanger 1970]. The PMV is a rather complicated mathematical expression (and therefore hardly suitable for calculations by hand) that predicts the mean value of the votes of a large group of persons. It uses thermal sensation as assessment. The thermal sensation applies a seven-point scale as the subjective rating responses for the thermal environment by subjects in thermal comfort research.

There are two widely used scales: the Bedford scale and the ASHRAE scale. The Bedford scale [Bedford 1936] was first used by Thomas Bedford in his pioneering survey of the comfort of factory workers in England and it is a combined estimate of warmth and comfort; the ASHRAE scale is the one normally used in American work and it refers strictly to thermal sensation [McIntyre 1980]. The Bedford scale was criticised on the ground that it consists of semantic relationship between warmth and comfort which may not be necessarily constant, whereas the ASHRAE scale contains no explicit reference either to comfort or pleasantness [Humphreys 1976]. However, it was later reported that the two scales in practice behave in a very similar way, and the results obtained by them may be compared directly with each other (see also 5.4.2) [Humphreys 1976; McIntyre 1980; Brager et al 1994].

These thermal scales are shown in Table 4.1.

Table 4.1 *The ASHRAE and Bedford Scales of thermal sensation.*

ASHRAE Scale	numbering of votes	Bedford Scale
Hot	3	Much too warm
Warm	2	Too warm
Slightly warm	1	Comfortably warm
Neutral	0	Comfortable
Slightly cool	-1	Comfortably cool
Cool	-2	Too cool
Cold	-3	Much too cool

Note: +1, 0, -1 are considered to constitute the comfort zone.

The PMV index can be precisely determined if both environmental and individual parameters are correctly measured and only for steady-state conditions or minor fluctuations of variables. It must be remembered that the index is derived on the basis of experimental conditions which are near thermal neutrality (slight discomfort). Therefore, it is recommended to use only if the PMV values are between -2 and +2 [Fanger 1970; ISO 7730 1994].

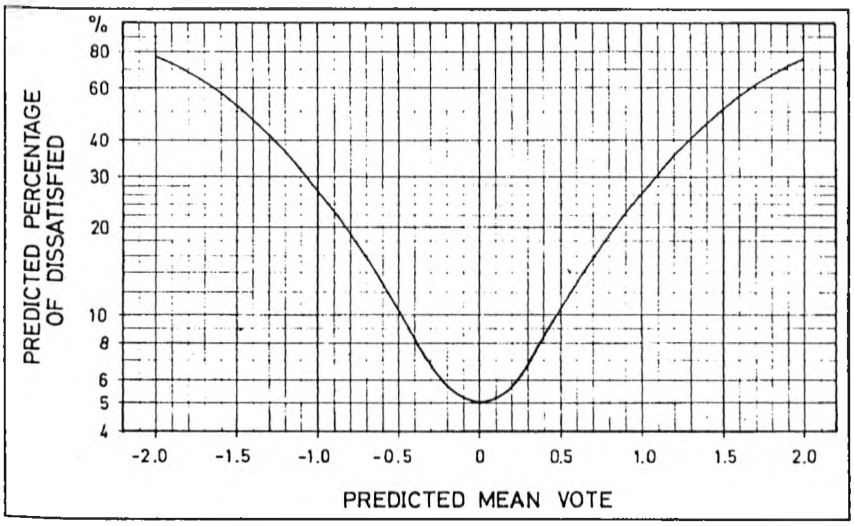

Figure 4.3 *Predicted Percentage of Dissatisfied (PPD) as a function of Predicted Mean Vote (PMV). (After Fanger 1970)*

The PPD is another index that establishes a qualitative prediction in percentage of the number of persons who are expected to feel uncomfortable in a given environment and these dissatisfied persons who in practice incline to complain about their environments. It is defined as those who vote "hot (+3), warm (+2), cool (-2) or cold (-3)" on the ASHRAE Scale [Fanger 1970; ISO 7730 1994]. It was reported by Gagge et al [1967] as evidence that real discomfort is first expressed by those voting higher than +2 or lower than -2.

From Figure 4.3, the PPD can be written as function of the PMV, in the following equation:

$$PPD = 100 - 95 * e^{-(0.03353 * PMV^4 + 0.2179 * PMV^2)} \qquad \text{(eq. 4.3)}$$

The curve is symmetric and its minimum value is at five per cent dissatisfied for the mean PMV equal to zero. This point corresponds to the optimal comfort condition, where the least percentage of the subjects would complain their environment. This curve signifies that complaints cannot be avoided, but they should be kept to a minimum.

The maximum/minimum values of the PMV are at ±2.0, since it excludes the extreme cases as mentioned above. The more the PMV deviates from zero, the more the PPD increases, in a semi-logarithmic manner. When the PMV is at ±0.5, there are ten per cent of dissatisfied persons. After this, the PPD increases quite rapidly: for PMV = ±1.0, there are over five times as great as the minimum value.

In recent years, a thermal comfort prediction tool had been developed as a part of ASHRAE research projects [Fountain and Huizenga 1996a; 1996b; 1997]. It is a predictive task software which provides a user-friendly front-end, a comparative analysis and information. Briefly, it incorporates models such as heat balance models to simulate the heat transfer process; empirical models to fit thermal sensation data; and adaptive models that account for outdoor climate. Using this tool, users have to input six-parameter values (i.e., four environmental and two individual) and the programme will be run. The results determine whether the environment is within the ISO and the ASHRAE comfort zones, including thermal indices such as ET*, PMV and PPD, and so on. The neutral temperatures calculated from the Adaptive Models by Humphreys [1978] and Auliciems [1982] (see Chapter Five), are also given.

4.4.4 Comfort zones

Many researchers attempt to define a range of the conditions within which at least 80% of the people would feel comfortable, or the *"comfort zone"*. The conditions can be represented as a person sitting in the a shaded area with negligible air movement and feeling comfortable [Olgyay 1963]. An example of the comfort zone is estimated at temperatures between 21°C and 28°C (in tropics, 24-30°C), with relative humidity 30% to 70% [Brooks 1950].

This estimation can only be thought as an approximate idea. Olgyay [1963] mentioned that, regarding the range from observations, there is no precise criterion by which comfort can be evaluated. Such a zone can vary from individual to individual, depending on types of clothing worn, activities performed, acclimatisation and so on. As a result, the exact boundary of the comfort zone does not exist. Any definite comfort perimeter outline merely is based on arbitrary assumptions selected at a particular condition.

There have been attempts to devise methods to establish the comfort zone by drawing all the environmental parameters (T_a, T_r, rh and v) into one single chart to represent thermal-comfort threshold. This chart will enable building designers or architects to make a quicker and easier assessment to building design. Here will present two types of charts: the Bioclimatic Chart by Olgyay [1963] and the Building Bioclimatic Chart by Givoni [1969].

The first chart, the Bioclimatic Chart [Olgyay 1963] shown in Figure 4.4, represents the combination of dry bulb temperatures on a vertical axis and relative humidities on a horizontal axis, composing the comfort zone in the centre. Outside the comfort zone, the curves and lines indicate the recommendations used to achieve comfort by means of radiation or air movement. These corrective measurements are necessarily to restore thermal comfort. The chart is applicable to inhabitants wearing a typical business suit (1.0 clo) and performing sedentary or light work (1.2 met) in a warm climate.

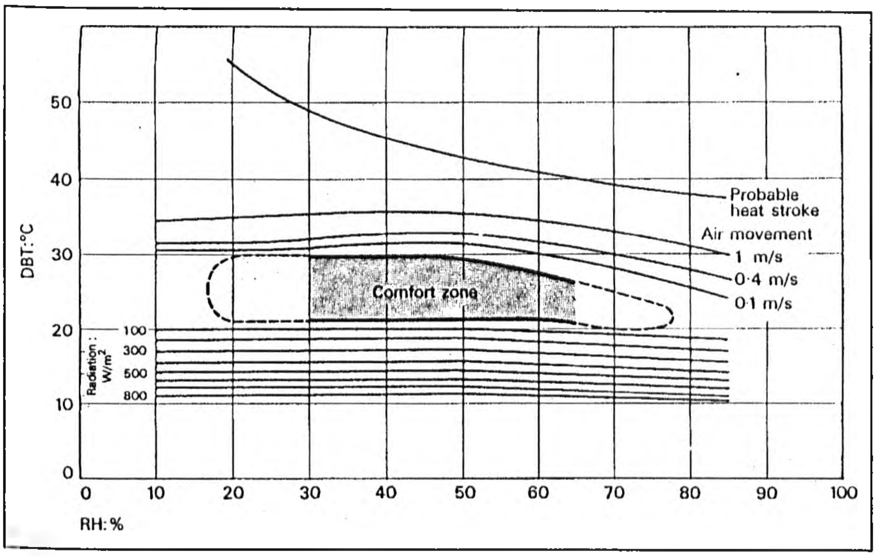

Figure 4.4 *The Bioclimatic Chart by Olgyay (1963), with activity level of 1.2 met and clothing insulation of 1.0 clo in warm climates. (After Koenigsberger et al 1973)*

This seems to be the first attempt to encourage architects to consider climate seriously in their design. However, Olgyay's chart has some limitations when applied: firstly, the chart is based on outdoor climatic conditions and does not predict or expect inside buildings, and secondly, it does not relate any strategies to building design. [Givoni 1976].

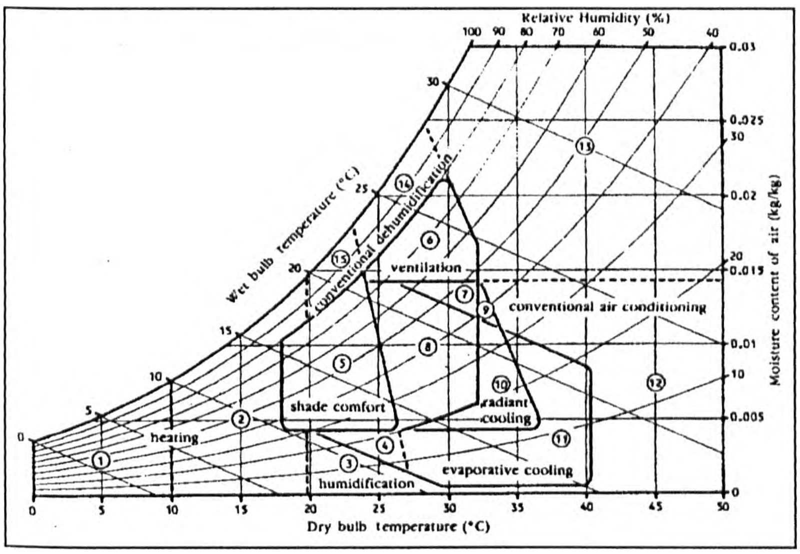

Figure 4.5 *The Psychometric Chart marked up as the Building Bioclimatic Chart by Givoni (1969). (After E.C. 1986)*

The second chart, the Building Bioclimatic Chart [Givoni 1969] shown in Figure 4.5, has been developed to address the weakness identified in Olgyay's Bioclimatic Chart. It evaluates the comfort requirements and suggests the applications used for building design. The chart consists of 15 areas, each of which indicates necessary controls and design strategies applied to the environmental conditions for the comfort zones. It uses the psychometric chart, which asks for dry bulb and wet bulb temperatures, and relative humidity, as a plotted sheet.

The Building Bioclimatic Chart is later revised by taking account of the effects of acclimatisation, various design strategies and passive cooling systems [Givoni 1992]. The comfort zone herein is differentiated between persons living in developed, and in hot-developing countries. The temperature ranges of acceptable conditions in still air for people living in developed countries, are 18-25°C in winter and 20-27°C in summer. The upper temperature limits are applicable at low humidity levels. For people living in hot-developing countries, the upper temperature limit can be increased 2°C. More details can be found in Givoni [1992].

Apart from both Bioclimatic and Building Bioclimatic Charts, several researchers mentioned the comfort zone in their findings. Fanger [1970] defined comfort zones corresponding to wide temperature intervals and recommended for the optimal comfort that the number of dissatisfied persons must not be more than half as large as the minimum value, i.e., the PPD = 7.5%; and therefore, the PMV must lie between -0.35 and +0.35. Such a limit will be linked with a design meteorological condition and be determined the capacity of the environmental system.

ISO 7730 [1994], which is based on Fanger's work, recommended thermal comfort requirements that the PPD should be lower than 10%; and this thus corresponds to the criteria for the PMV between -0.5 and +0.5. When applying to a particular interest in practice where light, mainly sedentary activity[4] is characteristic of many occupied spaces such as offices and homes, the comfort

[4] Sedentary activity = 70 W/m^2 = 1.2 met [ISO Standard 7730-1994].

limits for summer (where clothing of 0.5 clo) are between 23°C and 26°C[5], and for winter (1.0 clo), 20°C to 24°C[6], with the relative humidity 30% to 70%. This is estimated that more than 80% of the occupants will find the thermal conditions acceptable. However, this International Standard does not differentiate between different climatic regions.

Auliciems and Szokolay [1997] accounted for the historical development of the ASHRAE comfort zones since 1966 and drew a comparison in Figure 4.6.

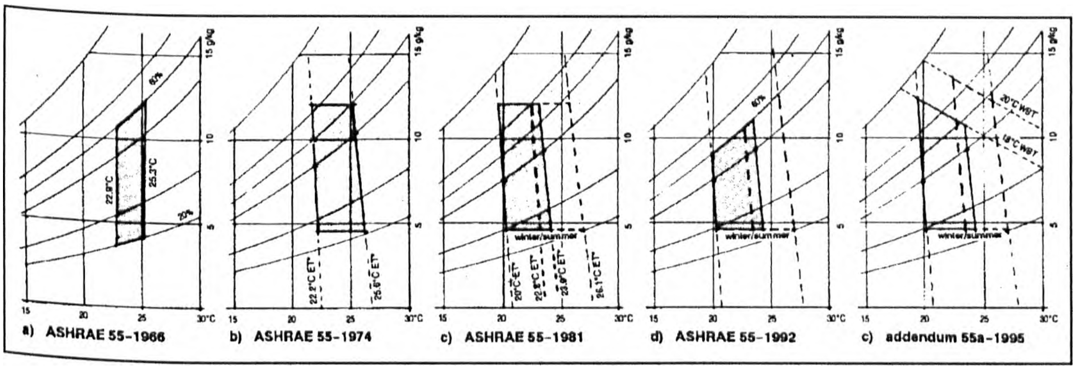

Figure 4.6 *Historical development of the ASHRAE comfort zone. (After Auliciems and Szokolay 1997)*

ASHRAE has used the psychometric chart for the definition of the comfort zone. In 1966, the comfort zone was defined by dry bulb temperature (DBT) lines and humidity (rh) lines. The 1974 version changed DBT to ET*[7] lines, and rh to vapour pressure (P_a), because the vapour pressure at the skin hardly changes within comfort limits. The standard in 1988 was the first to distinguish the comfort zones in summer and in winter. In the 1992 revision, the temperature boundaries and the lower humidity limit remained the same, but the upper humidity limit reverted to the 60% rh curve. The argument was that higher humidity, even at low temperatures, may have non-thermal ill-effects. In addendum of 1995, the upper humidity limit was changed to two wet bulb

[5] The unit is "operative temperature (T_o)" which is the average of the air temperature (T_a) and mean radiant temperature (T_r), weighted by their respective heat transfer coefficients (h_c and h_r). The equation is $T_o = (h_c * T_a + h_r * T_r) / (h_c + h_r)$ [ASHRAE Standard 55-1992].

[6] Operative temperature.

[7] ET* (the new effective temperature) is the operative temperature (T_o) of an enclosure at 50% rh that would cause the same sensible plus latent heat exchange from a person as would the actual environment (compare with ET) [ASHRAE Standard 55-1992].

temperature (WBT) lines. The reason was that this is a thermal standard, therefore non-thermal effects should not be included (but it is also less restrictive on evaporative coolers.) The upper humidity limit is still a contentious issue and several research projects are currently aimed at this question.

ASHRAE Standard 55 [1992] defined the *acceptable thermal environment* as *"an environment that at least 80% of the occupants would find thermally acceptable"* and stated the acceptable ranges in terms of operative temperature for people during light, primarily sedentary activity (≤ 1.2 met) at 50% relative humidity and mean air speed ≤ 0.15 m/s. The comfort zone[8] for winter (0.9 clo) is 20-23°C, and for summer (0.5 clo), 23-26°C.

Generally, it is believed that the comfort zone has no precise limits and varies with individuals, different clothing levels and activities, and different climates. Koenigsberger et al [1973] compared the findings from some very early research which show considerable discrepancy between the comfort limits, in Table 4.2. All values are given in ET (effective temperature).[9]

Table 4.2 *Comparison of the comfort temperatures (°C). (After Koenigsberger et al 1973)*

location	source	comfort temperature (°C)		
		minimum	optimum	maximum
UK - winter	Bedford [1936]	14	17	20
- summer	Hickish [1955]	-	18	22
US - winter	Yaglou [1927]	15	20	23
- summer	Yaglou [1927]	18	22	26
Sydney summer	Weiss [1959]	-	22	25
Singapore	Webb [1960]	24	-	27
Limits probably valid for most tropical regions		22	25	27

From Table 4.2, the comfort temperatures for most tropical regions are adopted on the basis of Australian and Singapore data. Koenigsberger et al [1973] further stated that the comfort zone must be limited in terms of air velocity

[8] Operative temperative range (10% dissatisfaction criterion) [ASHRAE Standard 55-1992].

[9] ET (the old effective temperature) is the temperature of a still, saturated atmosphere, which would, in the absence of radiation, produce the same effect as the atmosphere in question (compare with ET*) [Koenigsberger et al 1973].

between 0.15 and 1.50 m/s in most tropical climates. Many recent research investigations in warm climates have shown different comfort temperatures, and increased comfort zones (i.e., by Busch [1992]; Nicol et al [1994]; Karyono [1996]; Malama [1997]; Kwok [1998]). The findings of these research will be discussed and compared with the results of this thesis in Chapter Nine.

4.5 The Standards

4.5.1 Introduction

According to Parsons [1994], there have been many international standards concerned with thermal comfort. These standards are used to define conditions of thermal comfort, to indicate the likely degree of discomfort, and to provide guidance on environmental design and control. Present standards often concentrate on defining methodology and not limits (which they are generally provide techniques and methods such as subjective assessment methods). Future standards are suggested to take account of user requirements.

In this research, two thermal comfort standards are concerned: International Standard ISO 7730 [1994] and ANSI/ASHRAE Standard 55 [1992]. These standards are largely based on research conducted by Fanger [1970]. The aim of these current standards is to present the *right* temperature for a given built-environment. They give the predictions of thermal sensation and the degree of discomfort (thermal dissatisfaction) and the specifications of the acceptable thermal environmental conditions.

4.5.2 International Standard ISO 7730-1994

ISO (the International Organization for Standardization) is a world-wide federation of national standards bodies; and *International Standard ISO 7730:1994 (E)* was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Subcommittee SC 5, *Ergonomics of the physical environment.*

This standard specifies methods of measuring and evaluating thermal environments to which man is exposed. It is based on the theory of the heat balance of human body and environments, and its comfort conditions are determined by calculating the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) indices. It considers discomfort caused by draught, which is defined as an unwanted local cooling of the body caused by air movement. It also gives the recommended thermal comfort requirements during winter and summer conditions in the annex, which is information but not part of the standard.

Parsons [1995] explained that this International Standard is expected to apply to healthy people in most parts of the world, although it was originally based on studies of North American and European subjects. Therefore, the ethnic and national-geographic deviations may be required further studies. It applies to people exposed to indoor environments where moderate deviations from comfort occur, and thus extreme thermal environments may need other standards. This standard may be used in both designing new environments and assessing existing ones. It was previously prepared for workspaces, but can be applied to any kind of environment. Finally, it is important to remember that this standard, standardises the method, not the limits.

4.5.3 ANSI/ASHRAE Standard 55-1992

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) is a member of the American National Standards Institute (ANSI), and *ANSI/ASHRAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy*, was prepared by Project Committee TC 2.1, *Physiology and Human Environment*.

The standard specifies conditions in which 80% or more of the occupants will find their environments thermally acceptable. It incorporates the relevant research and experiences gained since the 1981 version, including the two-node model [Gagge et al 1986]. This standard is in good agreement with ISO Standard

7730 [1984]. In 1995, there was an addendum which revised the standard regarding the rationale for the upper humidity limit [ANSI/ASHRAE 55a-1995]. This is mentioned above by Auliciems and Szokolay [1997] (see Figure 4.6).

Nevins and McNall [1973] claimed that ASHRAE has accepted the responsibility to provide the standard for use by designers, and the specifications have been based on current states of knowledge of environmental physiology, comfort research, and commercial practice. The standard applies to the occupants with sedentary, healthy, and normal clothing in an *"occupied zone"* where is defined as two feet (0.61m) from walls, and three inches (0.076m) from the floor to the 72 inches (1.83m) level. The standard also specifies the points at which various environmental parameters have to be measured and emphasises that the criteria must *not* be applied separately.

4.5.4 Comments on the Standards

Oseland [1992] noted that these standards which are based on algorithms derived from thermal exchange physics theory, do not regard the comfort definition which has a psychological element (i.e., condition of mind). Nevins and McNall [1973] reported that psychological responses to an environment would be determined by stimuli which affect all body senses, and physiological response would be determined by thermal exchange, which is *"the condition of the body."* Macpherson [1962] stated a similar idea that these static models have denied the role of *acclimatisation.*

It has been a moot point whether thermal comfort standards which were developed based on knowledge gained from laboratory experiments can be applied to the field or practical work to create acceptable thermal environments [Oseland 1992; Fanger 1992; Bunn 1995a; 1995b; Fanger 1995].

Brager et al [1994] questioned which methodology is appropriate to determine the criteria of the standards to be met in practice. In general, it is to compare the extent of the interior environment with the physical specifications of the standards' comfort zone. Alternatively, it may be either to directly measure thermal acceptability of the subjects or to analyse and assess many different thermal scales such as sensation, comfort and preference as indirect measurements. Moreover, the suggestion is to relate thermal comfort research to other issues namely *adaptation* and *expectation*.

Nicol [1993] expressed that the standards give the *right* temperature but a constant value, due to the empirical approach in climatic chambers basis. The notion of a single temperature is derived from the heating, ventilating and air-conditioning (HVAC) systems, which control over both temperature and humidity. Rather comfort temperatures should be variable and be modified corresponding to different seasons, cultures and climatic regions. In fact, the thermal relationship between man and environment is active and complex, bringing in time, climates, building forms, social conditions, economic and other factors. This complexity implies that a variable standard is needed, and therefore, a standard should allow the built-environments to change and to respond to occupants.

Fanger [1994] argued that the temperatures maintained are to satisfy the actual group of occupants in space, but individual control may be provided for one preferring a warmer or cooler environment than average. In addition, the argument puts the PMV/PPD as a flexible model because it can be altered both met and clo values, and therefore, a wider range of acceptable temperatures. The importance is to correct the two individual variables (for example, 0-0.4 clo for a chair should be added in thermal insulation of the clothing).

Oseland [1994] noted that the effect of the individual parameters namely metabolic rates and clothing insulation levels on comfort temperatures is not emphasised in the current standards and their importance should be made clearer. It is also criticised that these two values are difficult to measure in the field and difficult to predict at the design stage. In addition, the consideration of thermal comfort standards should not be isolated from health, economics, productivity, and energy consumption. In particular, the higher design temperatures (in the UK) may cause increased sick building syndrome (SBS) symptoms, thereby leading to absenteeism and lower productivity.

Wyon [1994] paid the attention to the need for the individual control, rather than the group average comfort conditions. It is reported that even under standard conditions, the range of individual neutral temperatures could be varied and exceed 10 K. The importance is to provide the practical means for occupants to control their environment, which can lead to the cost-effective benefit and increasing productivity.

Parsons [1994] suggested that future developments should integrate thermal comfort standards into the overall environmental design, and the evaluation of individual performance. It is also suggested the use of standards in computer-aided environmental design.

Humphreys and Nicol [1998] compared both standards and reported that the ISO Standard 7730 [1994] offers greater flexibility than the ASHRAE Standard 55 [1992] because the former is a standard method while the latter is a standard environment. However, both standards can be improved: the ASHRAE Standard is recommended to be drafted according to climate rather than the season, and the ISO Standard whose resulting comfort temperatures depends on the correctness of the comfort equations, should include the adaptive approach for practical adjustments (see Chapter Five).

De Dear and Brager [1998] further studied on the Adaptive Models and proposed the Adaptive Comfort Standard: a standard for buildings with centrally controlled HVAC, and a standard for naturally ventilated buildings (see Chapter Five).

4.6 Research in thermal comfort

4.6.1 Climate chamber experiments or field studies

There are two main methods of research in thermal comfort: climate chamber experiments and field studies. McIntyre [1982] recounted that climate chamber studies have been central to thermal comfort research and the very first chamber was set up in Pittsburg in 1919 by the American Society of Heating and Ventilating Engineers (ASHVE). This is the direct ancestor of the modern chamber at Kansas State University (KSU), sponsored by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE).

In recent thermal comfort research, the climate chamber studies referenced to the experiments by Nevins et al [1966] and Fanger [1970], provided the knowledge for the comfort equations (see 4.4.3) and the comfort standards (see 4.5.1).

Many environments tested in the chambers are controlled and steady-state conditions. McIntyre [1982] claimed the advantage of using a chamber as the ability to produce the desired thermal conditions at will.

The methodology of the experiments is basically conducted in environmental test chambers which can be altered a range of climatic conditions, including all relevant combinations of air temperature, air humidity, mean radiant temperature and air velocity. The test subjects are clothed in uniform clothing, and are seated and asked to perform quiet activities such as to read or study. These subjects report their feelings in their environmental conditions at the time scheduled, using a thermal sensation voting scale (see Table 4.1).

An example of the experiments in a climatic chamber in the KSU-ASHRAE environmental facilities is shown in Figure 4.7.

Figure 4.7 *Typical arrangement of five subjects seated at a table in the KSU-ASHRAE environmental facilities. (After Nevins et al 1966)*

On the other hand, field studies [Humphreys 1976; Nicol 1993] are a method of field surveys of subjective thermal responses from human subjects, and at the same time, the climatic environmental measurements are taken. The aim of this methodology is to study thermal comfort in the real world where all subjects are left to suit themselves in their choices of clothing, their uses of environmental controls, their postures, activities and so on. Therefore, field studies will give the results that are very specific to the conditions measured, including the basic six-parameters and other features such as culture, climate and season, or psychological effects (i.e., attitude and expectation) [Oseland 1992]. Because of this, the process of analysis must be treated with extreme caution, and the use of any formula should be judged on physical and statistical grounds.

Nicol [1993] and Humphreys [1994a] stated that the research in thermal comfort is in crisis. It is because there is a discrepancy between the empirical findings from field studies and the comfort predictions based on heat balance models, shown in Figure 4.8.

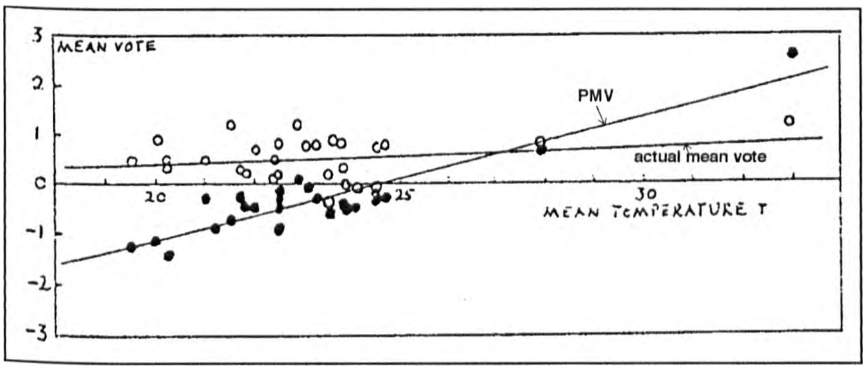

Figure 4.8 *The difference of comfort predictions between the actual mean vote and the PMV in some field surveys. (After Humphreys 1992)*
Note: (o) = *actual mean vote (MV) and* (●) = *PMV.*

Humphreys [1992] calculated the PMV by using data from five field studies [de Dear and Auliciems 1985; Baillie et al 1987; Busch 1990; Griffiths 1990; Shiller 1990] to compare with the actual mean vote. It is clear that there is a different prediction between the two results, and the PMV almost always overestimates the actual mean vote (MV). This means that people could feel warmer than the theory says they ought to do. The difference between the actual and the predicted mean vote can be estimated by the following equation:

$$D = (0.226 * T_a) - 6.05 \qquad \text{(eq. 4.4)}$$

where D = difference between the actual mean vote and the PMV

and T_a = mean air temperature (°C).

Previously, Humphreys [1976] compared the results predicted from the theoretical models based on climate chamber experiments with those from the empirical models of field studies and reported that the former seem to make too little allowance for people's adaptability to thermal variations, while the latter prove especially useful if the clothing insulation or the physical activity levels can be adjusted. The results from Figure 4.8, thus confirm that in practice, people are comfortable in a much wider range of indoor climates than would have been expected from the heat exchange models.

Nicol [1993] indicated that the reasons for the mismatch between both methods need to be explored to provide more information for standards, and to evaluate the needs and the cost of thermal control in buildings. Some possible sources of errors in assumptions underlying the analytical method (experimental approach) should be noted:

1. uniform clothing are assumed to be independent of climate and culture;
2. activity and posture (metabolic rate) can be affected by climate in systematic and economic ways;
3. according to the order in time, variations of environments in the real world are not a steady-state;
4. expectations and experiences reflect the way people react to an actual environment whereas the same environment in climate chambers are assumed with some *"absolute"* scale; and

5. individual controls can be used to modify the environments to respond to people's liking and then the desired temperature would be more suitable than some imposed standard.

Fanger [1994] argued that, to make a fair comparison, all environmental parameters in the field surveys must be properly measured, and the activity and clothing must be carefully estimated. Otherwise, *"poor input data will provide a poor prediction."* It is also mentioned that some cases of the field studies found an excellent agreement with the PMV model. Moreover, the PMV/PPD model is claimed to be a useful and flexible application for predicting optimal temperature (i.e., the standards) and has the following advantages in use:

1. to study the relative importance of four environmental factors such as in designing radiant heating or cooling systems;

2. to analyse the comfort consequences when applying mechanical controls in spaces; and

3. to use extensively in cfd (computerised fluid dynamics) to predict the ventilated occupied zone.

McIntyre [1982] noted that chamber studies provide a sound understanding of the quantitative relation between the variables and the average thermal sensation of a group of people, but their approach using a basic reductionism position, disregards some important but ill-understood factors affecting comfort. In the contrary, the field comfort studies realise that people have been remarkably successful in adjusting to their surrounding conditions, and have automatically included culture and climate in their description of sensation. For comfort assessment, it is certain that the comfort criteria derived from the central three categories of the seven-point thermal sensation scale in the chamber studies, cannot tackle the wider findings of the field work. There are much problematic evidences that need to be addressed. These include the need of an independent measure to identify the cause of discomfort; the reliability of analysis of thermal comfort/preference due to subjective responses; the subject of complaints whether come from the physical causes or anything else; and the time and expense involved in comfort experiments which may restrict or manipulate variables.

Humphreys [1994a] stated that there is no definite conclusion can be made about which method is most appropriate for predicting thermal comfort conditions. The doubt is cast upon both studies of that neither the sophisticated combination of environmental variables in laboratory experiments, nor the common analytical method in the field can produce credible comfort temperatures.

> "*... the field study results were suspect, being incomplete in their measurements, or biased in some way ... the heat exchange equations were suspect, being inaccurate or inapplicable, for reasons not apparent ...*" [Humphreys 1994a].

Baker and Standeven [1996] believed that both laboratory and field survey theories are correct, but the discrepancy between them is the result of a series of *adaptive errors* such as the subjects' behaviour and actions. These errors are always bias a comfort calculation to a pessimistic value. The explanation of this discrepancy is shown in Figure 4.9.

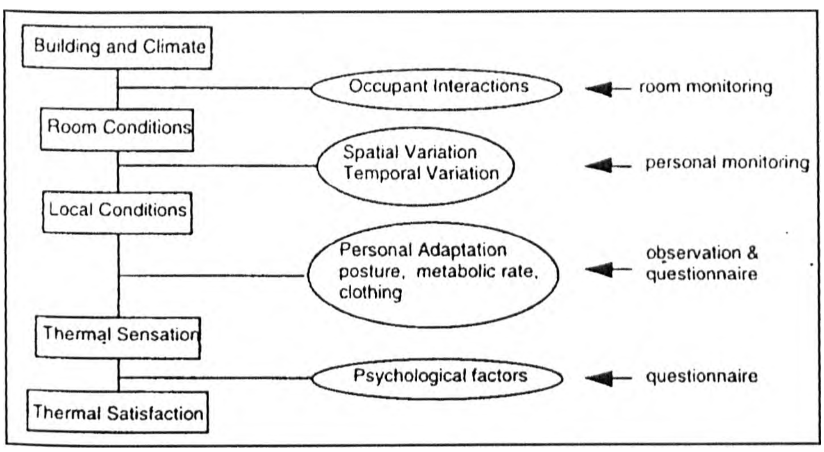

Figure 4.9 *Diagram explaining the discrepancy between predicted thermal satisfaction and observations, resulted from adaptive errors (shown in ellipses). (After Baker and Standeven 1996)*

From Figure 4.9, the rectangular boxes show the sequence of the inputs such as building and climatic conditions sliding down to the outputs of thermal sensation and thermal satisfaction. This sequence is influenced by the sources of errors (in ellipses) which may result in the cumulative error and add up to a very significant effect. The right hand column lists the procedures in monitoring surveys and questionnaire. The effect of adaptive errors is suggested to improve comfort in this thesis too (see 9.3.4 and 9.5.3).

Brager et al [1994] commented that laboratory studies provide fundamental insight of human and thermophysiology, while field studies are equally important to complement the information about thermal comfort in real buildings where the dynamics of both people and indoor climate are complex. It is believed that a conflict between these two methodologies in research comes from the different conception behind, thereby providing different thermal comfort findings. Therefore, the suggestion is that instead of considering the conflict, it should be used collaboratively to contribute to the new findings of how and what to create acceptable thermal environments in which will be involved interesting issues for building professionals such as architects, engineers and facility managers.

4.6.2 Steady state or transient conditions

The basis of the heat exchange theory is the *assumption of steady state* conditions where the environments are constant or do not vary very much, for instance, the fluctuations do not exceed 3 K at a given temperature [Koenigsberger et al 1973]. This steady state assumption is useful in building services engineering to determine the rate of heat loss or heat gain in buildings and to calculate the capacity of the mechanical controls. This is considered as a preliminary study, which will lead to the understanding of non-steady-state heat transfer problems.

In the ASHRAE Handbook [1993], two commonly used models are described. Both models assume that skin temperature and skin surface heat transfer are uniform across the body, and the unit used in these thermal models (see eq. 4.5-4.7) is energy per unit area (W/m^2), referred to the surface area of the nude body.

Firstly, the steady-state model developed by Fanger [1970;1982] assumes that the whole body is in a state of thermal equilibrium with negligible heat storage. The rate of heat generation is equal to the rate of heat loss, and thus energy balance. The model is:

$$\begin{aligned} M - W &= Q_{sk} + Q_{res} \\ &= (C + R + E_{sk}) + (C_{res} + E_{res}) \qquad \text{(eq. 4.5)} \end{aligned}$$

where M = rate of metabolic heat production

W = rate of mechanical work accomplished

Q_{res} = total rate of heat loss through respiration

Q_{sk} = total rate of heat loss from skin

C_{res} = rate of convective heat loss from respiration

E_{res} = rate of evaporative heat loss from respiration

$C + R$ = sensible heat loss from skin

and E_{sk} = rate of total evaporative heat loss from skin.

Secondly, the two-node transient model, developed by Gagge et al [1971; 1986] represents the body as two compartments or two concentric cylinders: the inner cylinder represents the body core (skeleton, muscle, internal organs), and the outer, the skin layer. The rate of heat storage is equal to the net rate of heat gain minus the heat loss, and the thermal models are applied to each compartment:

$$S_{cr} = M - W - (C_{res} + E_{res}) - Q_{cr,sk} \qquad \text{(eq. 4.6)}$$

$$S_{sk} = Q_{cr,sk} - (C + R + E_{sk}) \qquad \text{(eq. 4.7)}$$

where S_{cr} = rate of heat storage in core compartment

S_{sk} = rate of heat storage in skin compartment

and $Q_{cr,sk}$ = rate of heat transport from core to skin.

Wang and Peterson [1992] criticised the two-node model that although it is developed from the transient theory, it is only applicable to a steady state. Jones and Ogawa [1992] argued that it is transient in nature and simpler than other dynamic models. Therefore, the two-node model is usually chosen for simulating the human physiological response.

As the fact stated by Koenigsberger et al [1973]: "*... perfectly static conditions do not occur in nature ...*", and by Wang and Peterson [1992]: "*people's daily routines constantly place them in thermal transients.*" De Dear et al [1989]; Hensen [1990]; Jones and Ogawa [1992] also noted that in the real situations people interact with various thermal effects such as between buildings, climate and other control systems, and therefore pure steady-state conditions are rarely encountered in practice. This can be seen in many field studies where all environmental factors always fluctuate [Humphreys 1976].

Wang and Peterson [1992] identified three examples of transient conditions:

1. metabolic transients: the metabolic rate changes with the type of activity;
2. clothing transients: people change their clothing to maintain their comfort; and
3. environmental transients: these include changes in temperature, humidity, dust concentration, the presence of drafts, and so on.

The main concern in thermal transient research is the temperature changes, which can be mainly categorised into three modes [Hensen 1990; Wang and Peterson 1992]:

1. cyclical change: temperature fluctuations caused by the mechanical controls, and characterised by mean value, peak to peak amplitude and fluctuation period or frequency;

2. ramp or drift change: gradual temperature changes with time, characterised by starting value, amplitude and rate of change (ramp refers to active controlled change and drift, passive change); and

3. discrete or step change: abrupt temperature changes from one thermal environment to another, characterised by starting value, direction and amplitude.

Hensen [1990] reviewed a number of transient experiments and summarised as following findings:

1. The cyclical temperature changes [Sprague and McNall 1970; Wyon et al 1971; Wyon et al 1973; Nevins et al 1975; Rohles et al 1980]: the maximum range of acceptability is similar to that under the steady-state conditions. The fluctuation frequency has influences on the acceptable temperatures; the increasing frequency will decrease the comfort zone and vice versa. ASHRAE Standard 55 [1992], regarding cycling temperatures, stated that "... *if the peak cyclic variation in operative temperature exceeds 1.1 K, the rate of temperature change shall not exceed 2.2 K/h ...*"

2. The temperature ramp or drift experiments [McIntyre and Griffiths 1974; Berglund and Gonzalez 1978a; 1978b]: if the temperature changes at the rate below 0.5 K/h, the environment will be similar to steady-state conditions. If the change rate is between 0.5 and 1.5 K/h, there is no clear evidence of increased or decreased comfort zone due to the uncommon acceptability assessment. ASHRAE Standard 55 [1992], stated that "... *maximum allowable drift or ramp condition from a steady-state starting temperature of between 21 °C and 23.3 °C is a rate of 0.5 K/h ... change should not extend beyond the upper operative temperature limits of the comfort zone guidelines ...*"

3. Other transient experiments in 1950s [Hensel 1981]: when human skin is exposed to changing temperatures, thermal sensations occur inversely with the rate at which the temperature is changed. The thermal sensations depend on the changing temperatures, the direction of change, the exposed part of the body and the area being exposed. These factors have influences on the

intensity of temperature sensations, which is partly the causes of the contradictory results of the experiments.

4. Clothing, activity and season: McIntyre and Gonzalez [1976], using college-age subjects exposed to a 6 K step temperature change, reported that the skin temperature is greater when unclothed than when clothed and thermal sensitivity is greater when resting than when exercising. As well as subjects have acclimatisation, regarding seasons (subjects feel cooler in August than in June). Wyon et al [1971] also reported that thermal sensitivity is greater when resting than when performing mental work in the cyclical temperature change experiments.

Many research investigations have been based upon steady-state experiments, aiming at finding practical methods for predicting a particular thermal environment in terms of comfort or discomfort. Later, the developments have involved establishing the standards. Fanger [1970] accepted that his comfort equations can be employed only when minor fluctuations of the variables are found, but the mean value should be reasonably constant or quasi-steady-state. For a sudden large change, for example, a person moves from hot outdoor environments into an air-conditioned space (or vice versa), it is believed that there is an unhealthy "shock" effect. Other studies [Glickman et al 1947; Hick et al 1952; Inouye et al 1954] showed that the necessary adjustments in the temperature regulatory mechanisms should be prompt, unstressful and not unhealthy.

The evidence from the steady-state references shows that cold discomfort is strongly related to mean skin temperature and warmth discomfort to skin wettedness caused by sweat secretion. However, these factors are unlikely to be adequate indices to be applied in transient conditions and no experimental proof has been yet found [Hensen 1990].

According to McIntyre [1980] in conventional studies, an objective quantity of thermal sensation has been used to achieve the result for thermal comfort/discomfort, which is a subjective condition. This may be accepted in the cases of steady-state conditions, but probably not in the transient environments.

For example, the experiments by Gagge et al [1967] using step changes of temperature transient, are reported that when subjects experience a change of neutral condition to a much colder or warmer and then return to neutral, they fail to reach neutral sensation although discomfort disappears.

Hardy et al [1971] also reported that comfort and discomfort is independent from the skin temperature. Wang and Peterson [1992] added if a person undergoes a climate change, the thermal sensation will be experienced as nonstationary. Within a wide range of skin temperatures from 28°C to 34°C, a person can be either comfortable or uncomfortable. The argument suggests that the sensation of comfort in transient conditions depends largely on heat storage within the body, not on skin temperature.

However, Fanger [1970] claimed that the changing thermal sensation from neutral to cold or warm environments, is correlated with the skin temperature and sweat rate in the same way as under steady-state conditions, but it fails in the transient reversed proceeding. Gagge et al [1967] explained this phenomenon that the rate of change of skin temperature compensates for and predominates over the sensation of discomfort, which is caused by the skin temperature itself. The thermal sensation leads the body temperature changes and thus is anticipatory. This effect is an aid to man's reaction to fluctuating temperatures.

Wang and Peterson [1992] proposed a model for thermal transient sensation, which is based on the thermoreception concept (the dynamic and static responses) by Hensel [1981]. It is assumed:

$$U = U_0 + \Delta U \qquad \text{(eq. 4.8)}$$

where U = thermal transient sensation

U_0 = thermal sensation at a steady-state, or static term

and ΔU = a dynamic term.

The seven-point thermal sensation scale is used for both U and U_0; and the dynamic term (ΔU) is assumed to be a function of the rate of heat storage. The model is claimed to give quite reasonable results. It can be used to predict the thermal transient comfort for different conditions such as metabolic, clothing, and environmental transients. However, more physiological data and more experiments are needed to improve its application.

For sudden changes in humidity, the classic experiments are investigated by Houghten and Yaglou [1923]; Yaglou and Miller [1924; 1925]. These led to the development of the old effective temperature (ET). The effect of humidity was previously mistaken as a steady-state, but later Yoglou [1947] realised that this significant moisture influence was transient experiments. Fanger [1970] stated that in practice, the thermal effect of humidity changes can cause thermal discomfort, regarding the types and textile materials of clothing for indoor/outdoor environments. It is also suggested that a low indoor air humidity will be advantageous and will decrease thermal discomfort.

Hensen [1990] concluded that the effect of humidity on thermal comfort and thermal sensation is probably considered as a minor influence. There are only few experiments investigating the effect of changing humidity. Four studies [Gonzalez and Gagge 1973; Nevins et al 1975; Gonzalez and Berglund 1979; Stolwijk 1979] indicated that when temperatures are inside or near comfort zone, fluctuations of relative humidity from 20% to 60% do not have any effect. It will be of significant effect when the environments become warmer.

De Dear et al [1989] argued that there is a large impact of air humidity on thermal comfort. Their study on humidity step-changes using twin climate chambers of 20% and 80% relative humidity, reported that the standards underestimate the thermal impact of humidity transients on man. People feel cooler instantly for down-steps of relative humidity and they feel warmer instantly for up-steps. The increased thermal impact of humidity transients also depends on textile materials due to the absorption and desorption of moisture in the clothing.

Regarding changing air velocity, Hensen [1990] reported that no references are found, except the experiments with the effect of air turbulence on sensation (or draught). Velocity fluctuations in terms of turbulence are generally much faster than ambient temperature fluctuations. Fanger et al [1988] concluded that an air flow with high turbulence (draught) causes more complaints than air flow with low turbulence at the same mean velocity. However, Fountain [1995] found no effect of turbulence on preferred velocity in his experiment of predicting air movement in warm office environments.

Theoretical knowledge concerning thermal comfort in transient conditions is still limited. Many results from experiments appear to be only information on thermal acceptability in changing conditions [Hensen 1990]. It should be mentioned that thermal performance in reality is always in transient conditions. To provide thermally comfortable conditions to occupants in buildings, transient studies are significantly necessary. It may be conducted by using field study methodology, but care must be taken when experimenting and applying the results because various parameters will have influences on thermal comfort and thermal sensation.

4.7 Summary

The theory of thermal comfort study has been described. It is believed that thermal environments have significant effects on humans, especially, on their productivity, health, physical and mental energy, and in the most comfortable periods, on improving intellectual, manual and perceptual performance.

However, with the definition of thermal comfort at the moment, there are many arguments in evaluating this property. Objectively, it is concerned with satisfactory states in thermal environments, involving both physiology and psychology. Further arguments put forward to use other keywords namely "pleasant", "thermal pleasure", "thermal neutrality" and "discomfort" (the latter one is the negative meaning of comfort), which are considered as subjective terms.

Physiologically, thermal comfort has been studied through classic theory of the heat transfers between human body and its surroundings; and thermoregulatory system. It leads to the implication of both environmental and individual factors affecting comfort, in the prediction of thermal comfort of a group of people in a steady-state environment. Mainly, the contribution is to the establishment of the comfort equations, determining the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) by Fanger [1970].

The comfort zones and the comfort charts have been given in order to demonstrate the attempts to put climatic considerations into architectural design in practice. In recent decades, the comfort zones have been inscribed in the thermal standards of both the International Standard ISO 7730-1994, and the ANSI/ASHRAE Standard 55-1992. These two standards are widely-used for the specifications of thermal comfort conditions. Nevertheless, there have been many arguments whether they are appropriate to be applied to the field work or in the real buildings. The considerations of the adaptive theory in relation to the proposal of the Adaptive Models are therefore an alternative. This topic will be discussed in more details in the next chapter.

Finally, methodologies (climate chamber or field studies) and environmental conditions (steady-state or transients) in thermal comfort research are compared. Firstly, the arguments between climatic chambers and field studies are given. It is clear that the findings from both laboratory experiments and empirical models contribute to a pool of knowledge of the study of thermal comfort. They make understanding of both the objective quantitative relation between the variables and the subjective thermal responses in expectation and experience. The correlation between the two will lead to a new finding that can help architectural design.

Secondly, the environmental conditions of either steady-state or transient are considered. Although the current theory in thermal comfort is based mainly on the assumption of steady-state conditions, the need to research in transients is equally significant. In real situations, people always interact with various thermal effects which are non-stationary. It is therefore encouraged to conduct a field study which will be able to investigate this transient effects as in reality.

Chapter 5

FIELD STUDIES AND THE ADAPTIVE MODEL

"During the last forty years more than thirty field-studies of thermal comfort have been made. The total number of observations exceeds 200,000. They come from a wide variety of climates and countries, ranging from winter in Sweden to summer in Iraq."

M. A. Humphreys [1976]

"It seems clear that human thermal needs, and behavioural thermoregulatory responses, must involve mental integrations beyond those so far thought to have been defined by laboratory studies, and loosely termed "thermal comfort". ... It must now incorporate several psychological control processes which link the mechanisms of physiological and behavioural thermoregulation."

A. Auliciems [1982]

5.1 Introduction

In the previous chapter, a comprehensive study of the classical theory of thermal comfort was made. It seems that clear understanding of thermal comfort issues is still being found. There are many moot points that should be considered, particular the thermal criteria for designers to be applied in practice. One of the methodologies which is encouraged to be used for this thesis is *field studies* in the environmental transient conditions. It is believed that this method will bring to the explanation of the thermal comfort studies in the dynamic environments towards the *Adaptive Model.*

There are some useful sources of information to be mentioned here relevant to the research of field studies towards the adaptive model. Among these are: a literature review of field studies by Humphreys [1976]; a handbook for field studies by Nicol [1993]; a report of thermal comfort in Pakistan by Nicol et al [1994], another literature review by Brager and de Dear [1998] and the ASHRAE Technical Data Bulletin from the ASHRAE Winter Meeting edited by Geshwiler [1998].

This chapter consists of two main parts: field studies and the Adaptive Model. The first part will explain the fundamental methodology of the field studies in details, including process of the field surveys, analysis of the data and its information, thermal indices and the findings of the study. Neutral temperature is one of the main results, which will be discussed in relation to the Adaptive Models such as the earlier models by Humphreys [1976; 1987a] and by Auliciems [1982; 1986], and the recent models of the ASHRAE RP-884 [de Dear and Brager 1998].

The second part of this chapter will explain the concept of the Adaptive Model. It is introduced to the thermal comfort study with the adaptive principle that human subjects are able to adapt/adjust their environmental and personal factors to secure their comfort. Other factors namely adaptive constraints, time sequence and adaptive opportunity will also be discussed. The chapter will conclude with the establishing the thermal comfort of a new trend: the Adaptive Model and its advantages for the practical application.

5.2 Field studies of thermal comfort

5.2.1 Field-study methodology

Field studies are one approach to thermal comfort study which involves conducting surveys to find what conditions are comfortable [Nicol 1993]. Humphreys [1976] stated two purposes: firstly, to find a way of describing thermal environment which correlates well with human response, thus enabling reliable predictions to be made, and secondly, to define the range of conditions found to be pleasant or tolerable by the population concerned.

These objectives are very similar to the experimental studies in climate chambers, where the traditional thermal comfort standards, based on the heat exchange theory, have been established. The field-study methodology, on the other hand, is based on observations in the actual world, and as a consequence, it is expected that their empirical results would compare with the theoretical models (the important parameters of which are controlled in laboratory experiments). The findings, a range of pleasant or tolerable conditions of human, will be considered as "the acceptability" or "thermal comfort zone" used as a factor for building designs.

According to Humphreys [1976], the methodology of field studies are explained as: firstly, all respondents continue their normal activity and wear their normal clothing, while there is a slight intrusion of climatic measurements and subjective questionnaires giving out. (The questionnaires used for this research are given in Appendix D.) Most previous studies are of office workers in light activity and their everyday clothing.

Secondly, there is no attempt to control environmental conditions due to the realism required. The survey is accompanied by measurements of the environment. Several different thermal environments are selected to study to create a variety of conditions for the findings. For example, the results from different seasons, or from air-conditioned/naturally-ventilated environments are examined and compared, or the condition of extreme heat environment is individually investigated. It should be noted that if typical environmental conditions cannot be found to provide analysis of thermal comfort, atypical situations will be studied and analysed by means of statistical processes to give the appropriate findings. Importantly, due to the fact that there is no control, the influencing parameters such as air movement or solar radiation, which have a significant effect on the results of the field studies, must be very careful observed.

Thirdly, all environmental parameters should be completely measured and recorded. According to Bedford's classic study [1936], equipment such as a wet and dry bulb thermometer, a six-inch (150 mm) globe thermometer and a kata thermometer can give the environmental data of air temperature, relative humidity, air velocity and mean radiant temperature. However, with the current technology, modern equipment can be used for the optimum results and convenience. The equipment used for this research are described in Chapter Seven.

The personal parameters such as clothing and metabolic values should be given in general descriptions. The observations on clothing ensembles allow the understanding of the way people respond to their prevailing environments. The observations on activities made at a given time provide assumed metabolic rates of the subjects.

The questionnaires used in comfort surveys consist of enquiries on subjective thermal responses. The seven-category scales namely the Bedford scale and the ASHRAE scale (see Table 4.1) is used for *thermal sensation*. Concerning thermal comfort, Brager et al [1994] suggested to use a direct question such as the ASHRAE comfort scale which would be more appropriate. It is shown below:

The ASHRAE comfort scale:

Very comfortable
Moderately comfortable
Slightly comfortable
Slightly uncomfortable
Moderately uncomfortable
Very uncomfortable.

In addition, McIntyre [1980] proposed another thermal scale which is used to find *thermal preference* and it is shown below:

The preference scale: I would like to be:

warmer

no change

cooler.

Finally, the survey designs are categorised into two types: the "longitudinal" and the "transverse". The former is to collect the survey data from comparatively few respondents and repeat the surveys over a period of weeks or months. This will investigate the consistency of the individual respondent and observe the progress of adjustment to changing environments. However, its result should not be used as a representative for a wider population because of too small number of respondents involved.

The latter is to use a large number of respondents and make only one assessment at a particular time and space. This will indicate the extent of variation among individuals' responses and its result can be estimated as the representative for a population group. However, this type cannot be used for the consistency of the adaptability of individual. In fact, both survey designs will be useful if they could be used in collaboration and therefore supplementary [Humphreys 1976].

Each field study of thermal comfort is usually individual and often mainly relates to a particular region. Such surveys have often been set up by a local person, or someone who is interested in that particular climate. The findings from each study can regard the comfort characteristic for that locality and can be compared with other studies, but cannot be fully applied to others. Two studies of thermal comfort in the same town may give different results [Nicol 1993][1].

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[1] Two different findings from the same town (Roorkee in India): one by Nicol [1974]; and the other by Sharma and Ali [1986].

5.2.2 Analysis of field study data

Two common statistical methods to analyse the field study data are: simple linear regression and probit analysis. Humphreys [1976] explained that the analysis using simple linear regression technique, examines the trend of the mean responses over the range of temperatures encountered. Usually, this method is accompanied with a correlation technique, measuring the degree of strength of linear relationship between two variables such as temperature and subjective thermal responses. An example of the simple linear regression analysis of mean responses of a seven-category scale is shown in Figure 5.1.

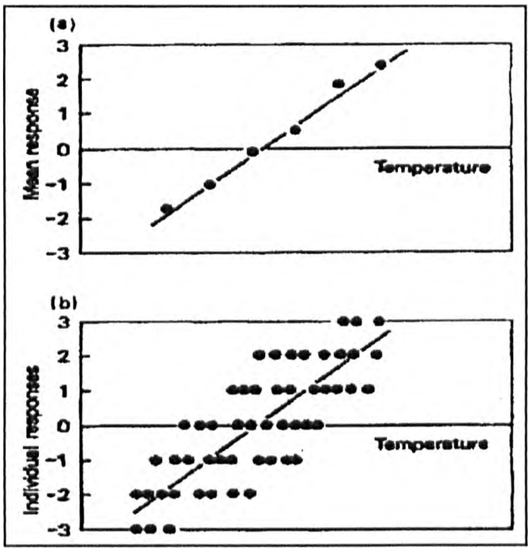

Figure 5.1 *Simple linear regression analysis of mean responses. (After Humphreys 1976)*

In Figure 5.1(a), the regression line drawn through the mean responses of a grouped population, indicates the temperature at which any particular mean response would be expected to occur, and in Figure 5.1(b), the scatter diagram indicates the extent of the variation of the individual responses. The simple linear regression of thermal responses upon temperatures gives the information of the regression coefficient (slope), intercept (constant) and goodness of fit (R^2). These information can be used to form an equation to calculate the *neutral* temperature.

The general form of the linear equation [Kinnear and Gray 1997] is:

$$y = a\,x + b \qquad \text{(eq. 5.1)}$$

where y = subjective thermal response (dependent variable)

x = temperature (independent variable)

a = regression coefficient (slope)

and b = regression constant (intercept).

Humphreys [1976] suggested that the simple regression analysis may be extended to include more than one environmental variable by using multiple correlation and regression technique.

The second statistical method is the analysis into proportions, or probit analysis. This technique was initially developed for use in finding the effectiveness of pesticides by Finney [1971]. Busch [1990] described the probit analysis technique as: "... *a technique whereby data are sorted into two categories: those that possess some quality and those that do not ... these binary sets are transformed into percentages ... thought of as relative frequencies within each bin ... these relative frequencies done over the range of bins are, in effect, a cumulative frequency distribution.*"

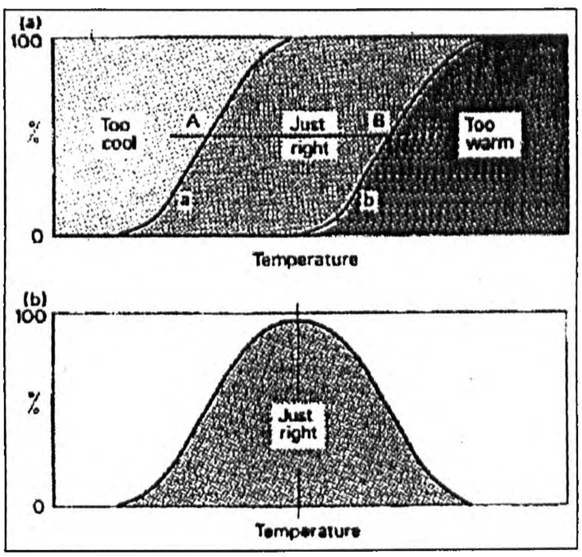

Figure 5.2 *Probit analysis or analysis into proportions.*

(After Humphreys 1976)

An example of a three-category comfort scale: "too cool", "just right" and "too warm" is used as a simple illustration [Humphreys 1976], shown in Figure 5.2. The curves in Figure 5.2(a) show the cumulative relative frequency distributions of the category "too cool" to "just right" (curve a) and the category "just right" to "too warm" (curve b). As the temperature rises the proportion of "too cool" votes diminishes while the proportion feeling "too warm" increases. The line A to B at 50% level or the median respondent, gives the temperature interval corresponding to the verbal description "just right" [Humphreys 1976]. Ballantyne et al [1977] defined each distribution curve representing the transition from one thermal response to the next and temperatures at the points A and B called "transition temperature". Nicol [1997] suggested to calculate the parameter estimations by using *logit* model of the probit analysis according to the following equation:

$$y = \exp(a\,x + b) \,/\, [1 + \exp(a\,x + b)] \qquad \text{(eq. 5.2)}$$

where
y = transition of binary sets of thermal responses
x = temperature (independent variable)
a = regression coefficient (slope)
and b = regression constant of binary sets (intercept).

The subtraction of curves a from curve b is the proportion feeling "just right" and it is drawn in Figure 5.2(b). Humphreys [1976] explained that the temperature at the peak of the curve is called the "optimum" or "neutral" temperature for the population and the standard deviation is used to estimate the response boundaries among the population in the case of a transverse survey, or the individual consistency in the case of a longitudinal survey. The advantages of this method are that confidence limits can be placed upon the positions of the curves and that it can be used to inspect the interval property of a warmth scale.

5.2.3 Thermal indices

The assessment of environmental stress has received increased awareness and has shown that attention must be given to the effects of all six parameters. It therefore attempts to combine the effect of two or more, or even all six, into one single index, in order to make a ready comparison of various thermal situations.

Fanger [1970] gave some samples of the earlier thermal indices, categorised into several groups. For instance, a group of indices with an evaluation of extreme heat stress such as P4SR [McArdle et al 1947] or Index of Thermal Stress [Givoni 1962; 1963], another group with attempts to combine two or more variables into a single index such as the effective temperature (ET, ET*) or the operative temperature (T_o) (see footnotes in Chapter Four).

In a comprehensive field study, Bedford [1936] set up an index which is found from a correlation analysis, giving the subjective mean vote as a function of the four environmental variables. Likewise, Webb [1959] set up an Equatorial Comfort Index based on a field study in Singapore, which incorporated the environmental variables such as dry bulb temperature, humidity and air velocity. However, Fanger [1970] claimed that these earlier thermal indices included neither activity level nor clothing value, and therefore he has developed thermal indices such as the PMV and the PPD (see 4.4.3).

From various field studies, Humphreys [1976] noted two practical issues of importance. Firstly, the variation of responses to changing temperatures is greater than changes of either humidity or air velocity. The temperatures of air and of surrounding surfaces (represented by globe temperature) are always considered as a significant variable to set up thermal comfort. Air temperature can be used as a suitable index if there is no or little difference between air temperature and mean radiant temperature.

Secondly, the composite index (i.e., ET* or SET*) which includes air temperature and other parameters such as mean radiant temperature, humidity and air movement, or with clothing value and activity level, theoretically should be a decisively superior index, especially for comparison among many environmental conditions. However, the evaluation of a composite index may require a knowledge of many variables, which are in practice difficult to measure accurately under field conditions. Therefore, it may bring to an error to estimation.

Doherty and Arens [1988] proved that comprehensive indices of comfort often fail to predict the comfortable temperatures in both laboratory and field studies. For example, Gagge's SET* (the new standard effective temperature) does not agree well with the experimental data in the laboratory when clothing insulation values and activity levels increase. As a consequence, a simple thermal index such as air temperature or globe temperature is perhaps best assessment to explain the subjective responses.

Humphreys [1976] proposed four sets of the measurements, depending on restrictions upon their use, shown in Table 5.1. These sets of environmental parameters are likely to provide an adequate record of various circumstances in order to predict human comfort.

Table 5.1 *Sets of measurement of thermal environment.*
(After Humphreys 1976)

Set of measurements	Restrictions upon their use
1. Air temperature	Difference between air temperature and mean radiant temperature is small (<2°C). Air velocity is very slight (<0.2 m/s). Sweat is freely evaporated from the skin.
2. Globe temperature	Air velocity is very slight (<0.2 m/s). Sweat is freely evaporated from the skin.
3. Globe temperature* Air velocity	Sweat is freely evaporated from the skin.
4. Globe temperature* Air velocity Wet-bulb temperature	None.

Note: * Air temperature can be used instead of globe temperature, if the difference between air temperature and mean radiant temperature is small.

5.3 Neutral temperatures

5.3.1 Introduction

Neutral temperature (T_n), derived from the process of statistical analysis of the field survey data, is the temperature at which the average subjective thermal sensation response is "neutral" (0). From various studies, it varies from 17°C in references in England [Auliciems 1969; Fox et al 1973] to 33°C in hot dry weather in Iraq and India [Nicol 1974]. The influences upon this comparatively large temperature range are claimed to be the various environmental conditions encountered and other factors such as level of activity, insulation of clothing and physiological state Humphreys [1976].

It should be noted that if the neutral temperature was calculated by the heat balance theory and the comfort equation [Fanger 1970], its range could be found only 5-6 K. Therefore, the range of more than 10 K must be affected by another parameters and Humphreys [1976] concluded that it was *acclimatisation*.

Many researchers of thermal comfort have proposed their analysis to predict the neutral temperature or comfort temperature and some important findings namely Humphreys' models; Auliciems' models; the ASHRAE RP-884 and Griffiths' value, will now be introduced.

5.3.2 Humphreys' models

When neutral temperatures (T_n) and mean indoor air temperatures (T_i) from many field studies are tested in terms of their linear relationship by using simple regression analysis and correlation techniques, it is found that there is a very high and positive relationship. The correlation coefficient between them is 0.96 [Humphreys 1976]. This is shown in Figure 5.3.

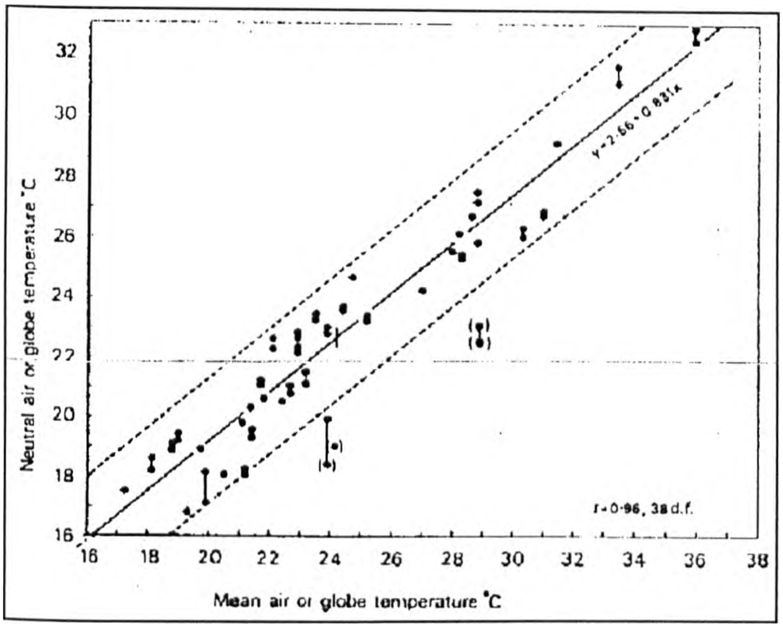

Figure 5.3 *Relationship between mean indoor air temperatures and neutral temperatures. (After Humphreys 1976)*

The regression line, which is used to predict the neutral temperature (T_n) from the mean indoor air or globe temperature (T_i), gives the following equation:

$$T_n = 2.56 + 0.831\,T_i \qquad \text{(eq. 5.3)}$$

This equation shows that the neutral temperature will be low when in the moderate climates and it will be high in the hot climates. The finding goes against the traditional thermal comfort theory that the neutral temperature is a constant value. Humpherys [1976] stated that the standard error of prediction is only 1.1 K and such an accurate prediction can be made simply from a knowledge of the mean temperatures.

Poulton [1973; 1975] and Wilkinson [1974] cited that the tendency of subjective ratings depends upon the range of recent experience of the observer and this "range effect" may introduce bias to the results of an investigation. However, when the subjective effect is the prime interest, then the range of recent experience should be regarded as one of the factors for the acceptability of the environment. It is therefore unhelpful to regard it as a source of bias because it would be impossible to specify an "unbiased" condition which could be used as a reference standard.

Later, Humphreys [1978a] indicated a strong relationship between the outdoor temperatures and the comfort indoors. The models for "free-running" buildings (which are neither heated or cooled) and other buildings (i.e., both heated or cooled buildings and climate-controlled) are studied separately. It shows that there is a strong linear relationship between the monthly mean outdoor temperatures (T_m) and the indoor comfort temperatures (T_n) for the "free-running" buildings, but a fairly strong curvilinear line for other buildings. It is shown in Figure 5.4.

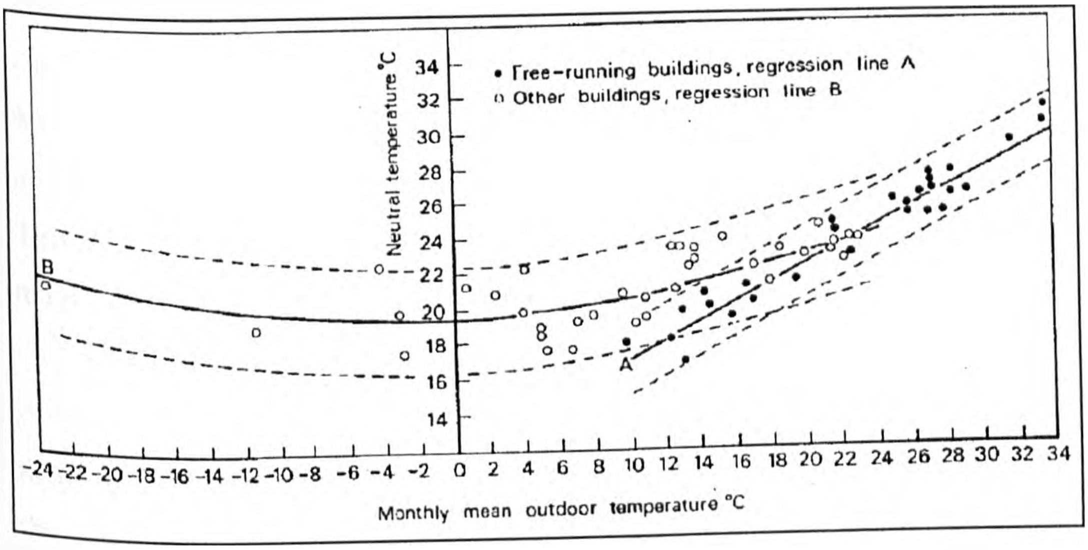

Figure 5.4 *Relationship between monthly mean outdoor temperatures and neutral temperatures. (After Humphreys 1978a)*

From Figure 5.4, the monthly mean outdoor temperatures are obtained from the published meteorological data [HMSO 1958-72]. The regression line A of the "free-running" buildings suggests that for every degree change in the monthly mean outdoor temperatures (T_m), the neutral temperatures (T_n) will approximately change over half a degree. The surveys are found that 94 per cent of the variations of the neutral temperatures are associated with the variations of the mean outdoor temperatures and their correlation coefficient is 0.97. The standard deviation of the prediction is 1.0 K and the range of application is between 10°C and 33°C. The regression equation is:

(free-running buildings)

$$T_n = 11.9 + 0.534\, T_m \qquad \text{(eq. 5.4)}$$

For the heated or cooled buildings — the regression line B, there is no data from hot environments. The curvature shows over the range between -24°C and +24°C outdoor temperatures. The best fit is found to suit the following equation:

(climate-controlled buildings)

$$T_n = 23.9 + 0.295\,(T_m - 22)\exp\{-[(T_m - 22)/(24\sqrt{2})]^2\} \quad \text{(eq. 5.5)}$$

This equation explains only 52 per cent of the variation relationship between neutral temperatures and mean outdoor temperatures, and the correlation coefficient is 0.72. The standard deviation of the prediction is 1.5 K However, when the average daily maximum temperature of the hottest month of the year is added, the explained variation of the neutral temperatures is slightly increased. This implies an influence of summertime temperatures on the comfortable temperatures at other times of the year.

Humphreys [1978a] advised that the intersection area of line A and line B indicates the joint optimum indoor temperatures for both types of buildings. This zone implies that the buildings with heating or cooling plant should use energy by the "free-running" conditions, which can then achieve comfort and saving energy.

Another application is suggested that, at every outdoor temperature below 26°C, the neutral temperatures are slightly higher, and therefore it is unnecessary to use the cooling plant for the desired indoor comfort. In climates where the mean outdoor temperatures exceed 26°C, it may be necessary to consider a factor such as the large diurnal temperature variation to keep mean indoor temperatures close to the values suggested by the regression line A. Use of appropriate material and construction techniques can help provide this. In other buildings where it proves necessary to use heating or cooling systems, the regression line B indicates the temperatures likely to be satisfactory for the occupants. Nevertheless, further study in hot environments is needed to improve the fitted regression line B.

5.3.3 Auliciems' models

Auliciems [1982] developed a model for predicting neutral temperatures by using some field studies from Humphreys [1976] and adding more data from Australia. The total data includes that from both heated or cooled buildings and from passively controlled buildings. The multiple regression is applied to calculate the neutral temperatures (T_n) as a function of both mean indoor air temperatures (T_i) and mean outdoor temperatures (T_m). The regression equation is:

$$T_n = 0.48\,T_i + 0.14\,T_m + 9.22 \qquad \text{(eq. 5.6)}$$

However, Auliciems [1982] stated that there may be a difficulty to apply the above equation for practical purposes for the design of new buildings because the indoor air temperatures are yet to be measured. The problem is also associated with whether such a relationship is maintained under indoor environments greatly different from prevailing conditions as determined by climate and custom. In addition, the adaptations required under enforced circumstances to the inhabitants are still in question. As a result, an alternative model is proposed by considering the relationship between indoor comfort (neutral temperatures — T_n) and outdoor warmth (mean outdoor temperatures — T_m). It is shown in Figure 5.5.

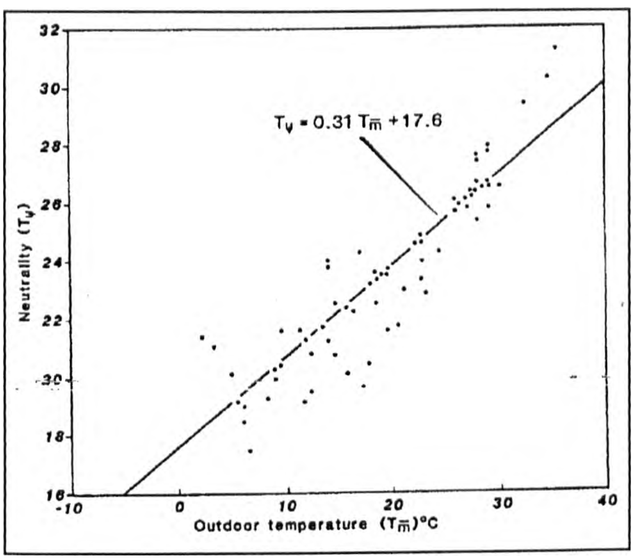

Figure 5.5 Relationship between mean outdoor temperatures and neutral temperatures. (After Auliciems 1982)

The range of the neutral temperatures under real life situation is approximately 14 K (17-31°C), considering all parts of the world. Roughly, the regression line shows that the increase in neutral temperatures is at the rate 0.3 K per 1.0 K change in mean outdoor temperature, with the origin being at 25.5°C. The prediction of neutral temperature from the combined data can be written as the equation:

$$T_n = 0.31\, T_m + 17.6 \qquad \text{(eq. 5.7)}$$

Auliciems and de Dear [1986] developed another prediction model based on available samples from the field survey data from Auliciems [1982]. The temperatures at minimum group discomfort (neutral temperatures — T_n) are used as a function of mean indoor air temperatures (T_i) by simple linear regression analysis, shown in Figure 5.6. The regression equation is:

$$T_n = 0.73\, T_i + 5.41 \qquad \text{(eq. 5.8)}$$

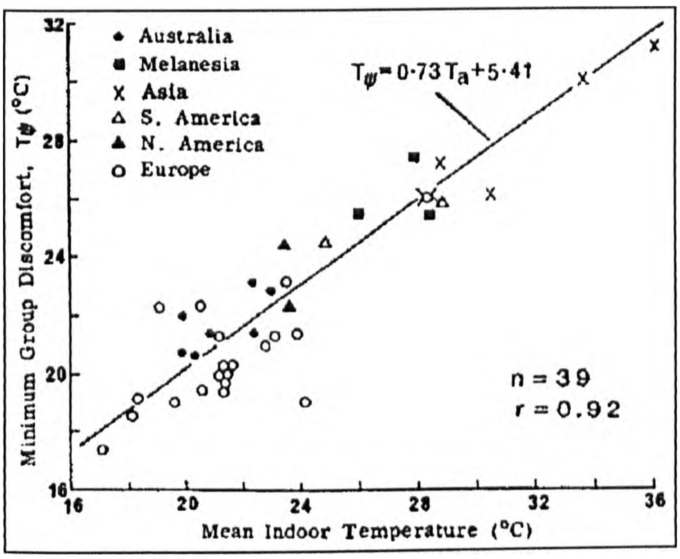

Figure 5.6 *Relationship between mean indoor temperatures and neutral temperatures. (After Auliciems and de Dear 1986)*

5.3.4 The ASHRAE RP-884

The ASHRAE RP-884 project assembled a quality-controlled database from field studies world-wide, which includes about 21,000 observations from 160 buildings [de Dear and Brager 1998]. The statistical analysis has been used to investigate the relationship between subjective thermal sensations and thermal environments. The analysis is categorised into two groups: buildings with centralised HVAC and buildings with natural ventilation.

Weighted linear regression models are fitted to the relationship between mean indoor temperature (T_i) and neutral temperatures (T_n) (operative temperature) for each category and are shown in Figure 5.7.

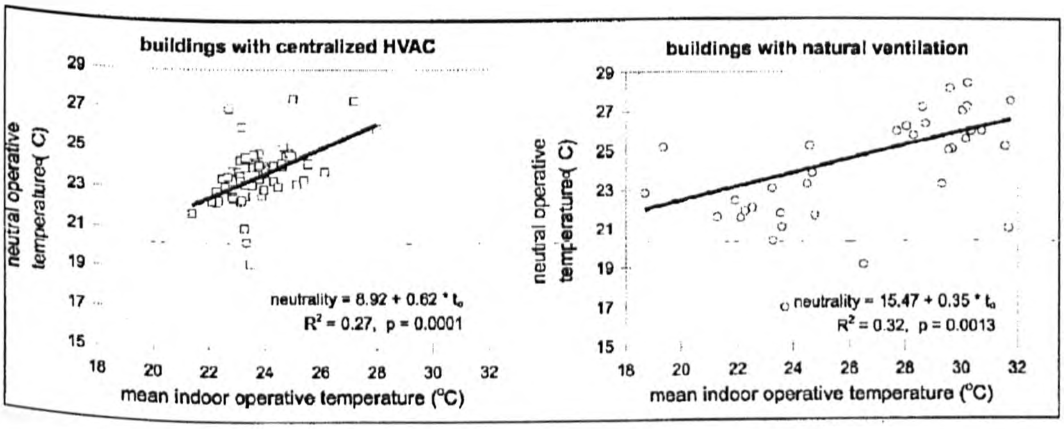

Figure 5.7 *Mean indoor operative temperatures and neutral operative temperatures. (After de Dear and Brager 1998)*

The regression coefficient or slope suggests that the occupants of the centralised HVAC buildings are twice as sensitive to indoor operative temperature deviations away from optimum to those of the naturally ventilated buildings. The regression equations of each graph are:

$$T_{n\,(HVAC)} = 8.92 + 0.62\,T_i \qquad \text{(eq. 5.9)}$$

$$T_{n\,(N/V)} = 15.47 + 0.35\,T_i \qquad \text{(eq. 5.10)}$$

The same method is applied to examine the relationship between the neutral operative temperatures (T_n) and the mean outdoor effective temperature (T_m). This is shown in Figure 5.8.

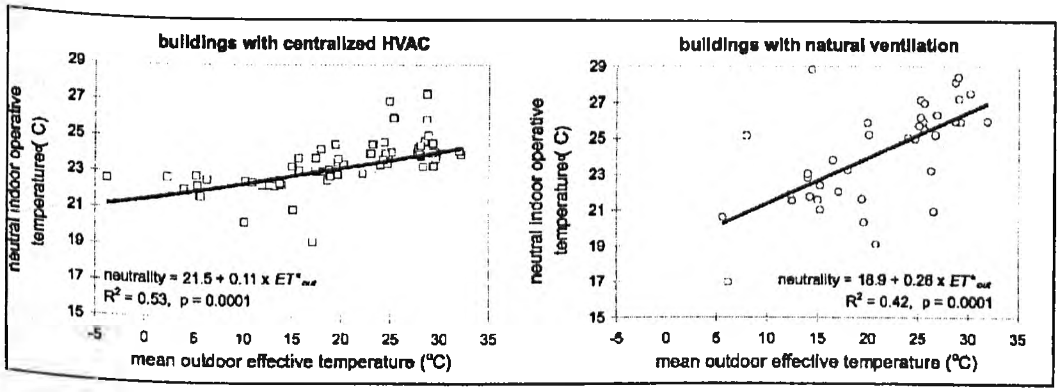

Figure 5.8 *Mean outdoor effective temperatures and neutral operative temperatures. (After de Dear and Brager 1998)*

The regression equations are:

$$T_{n\,(HVAC)} = 21.5 + 0.11\,T_m \qquad \text{(eq. 5.11)}$$

$$T_{n\,(N/V)} = 18.9 + 0.26\,T_m \qquad \text{(eq. 5.12)}$$

The regression line in the HVAC buildings is confined to between 21°C and 25°C of neutral temperatures, compared to a wider range (20-27°C) in the naturally ventilated buildings. The regression coefficient or slope of the centralised HVAC buildings, is very low and less than half of that in the naturally ventilated buildings. This implies that the comfort conditions of the occupants in climatic-controlled environments are nearly constant with a comparatively narrow range of neutral temperatures, regardless of the variations of outdoor conditions. On the other hand, the tendency of comfort conditions in environments with natural ventilation depends upon the variations of outdoor temperatures.

5.3.5 Griffiths' value

Griffiths [1990] introduced a method for predicting neutral temperature (T_n) from a small sample group of comfort votes in the case that there is insufficient data to analyse by regression techniques. The assumption is that the increase in temperature of each scale point on the subjective comfort scale is 3.0 K for a seven-point scale. (Nicol [1993] stated that, originally, Griffiths used a nine-point scale and allowed 2.33 K per scale point.) This scale category width is used to refer to regression line of simple regression analysis, with the slope of 0.33/°C, which is identical to that from climate chamber experiments [Fanger 1970].

When each sensation vote is plotted on a chart against temperatures, it will be projected onto the temperature axis by using the slope line of 0.33/°C, shown in Figure 5.9. The projected temperature of each vote will therefore represent individual neutral temperature, and the mean of every individual neutral temperature will represent group neutral temperature (T_n), or mean comfort temperature.

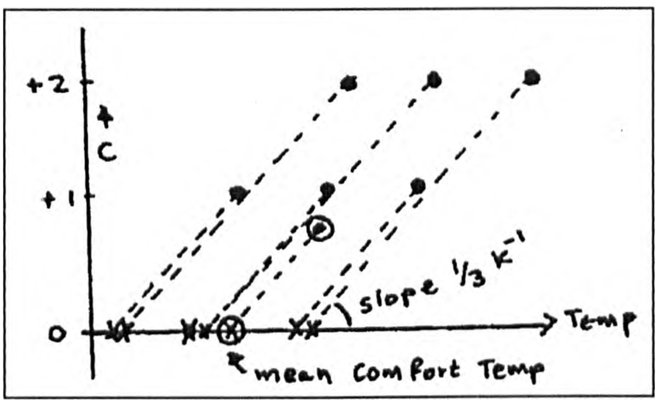

Figure 5.9 *Griffiths' method for finding mean comfort temperature from a small sample or group neutral temperature. (After Nicol 1993)*

In practice, Nicol et al [1994] modified the method by applying it not to the individual votes but to the centroid of the data, where is the position of mean comfort vote (C_m) at mean indoor temperature (T_i). By taking an assumed value of the regression coefficient of 0.33/°C, the equation is:

$$T_n = T_i + (0 - C_m) / a^* \qquad \text{(eq. 5.13)}$$

where	T_n	=	neutral temperature (or comfort temperature)
	T_i	=	mean indoor temperature
	0	=	"neutral" category in seven-point sensation scale
	C_m	=	mean subjective comfort vote
and	a^*	=	regression coefficient of 0.33/°C.

This equation needs a knowledge of both mean subjective comfort vote (C_m) and mean indoor temperature (T_i) from the field survey data. Nicol [1993] suggested that the Griffiths' value is useful method to assess neutral temperature for a group of subjects that there is little variation in temperatures and subjective sensation votes, as might occur in many transverse surveys. It is also applicable to the case whose climate is a narrow range of diurnal deviation of temperatures (in longitudinal surveys).

5.4 Information from field study analysis

5.4.1 Thermal responses

The thermal responses are the subjective rating scales used in field surveys. Usually, there are two thermal responses: sensation (Bedford scale or ASHRAE scale — see Table 4.1) and preference (McIntyre scale — see 5.2.1). Firstly, thermal sensation is to investigate the enquiries of warmth/coldness of subjects, corresponding to their environments. The mean responses are analysed as a function of air or globe temperatures to predict the neutral temperature by means of regression procedures, as mentioned above.

Secondly, thermal preference is to examine the subjects' preferred temperature which the neutral temperature cannot represent. Fisk [1981] defined the idea of preference that relates to a choice for alternatives. Humphreys [1976] gave evidence that during winter survey in England, the respondents give their preference state between "comfortable" and "comfortably warm", whereas in hot climates, the respondents prefer to be cooler than neutral, which expresses in the wording used in a field survey by Moorkerjee and Sharma [1953].

For purpose of comparison, the responses have to be standardised by the number zero represented for the neutral category, and the positive step to the category +1, while the negative to category -1. Here the comparison of the standardised mean thermal sensation responses from many field studies are made [Humphreys 1976]. They are regressed against mean air or globe temperatures, shown in Figure 5.10.

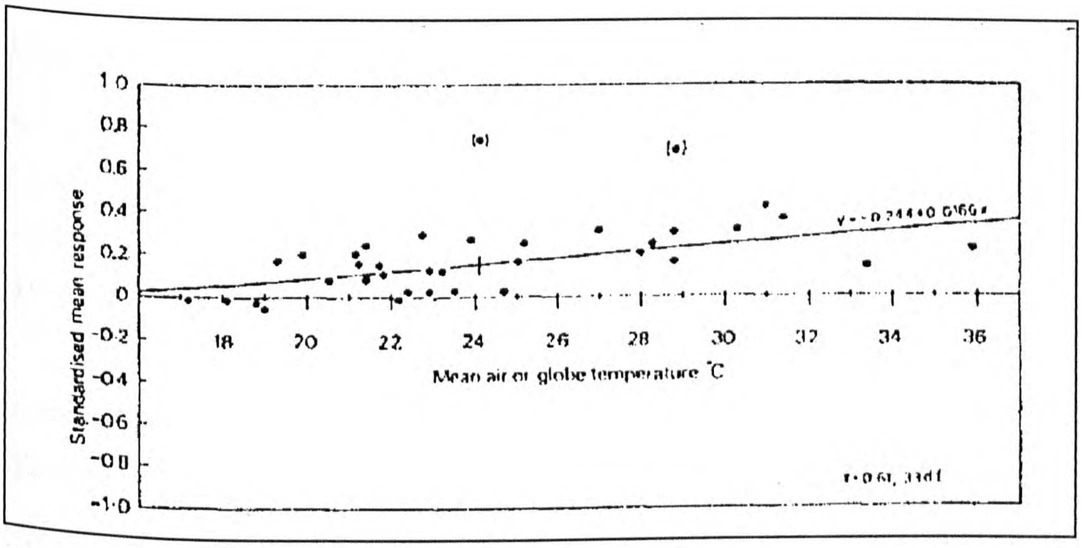

Figure 5.10 *Standardised mean thermal responses against mean temperatures. (After Humphreys 1976)*

From Figure 5.10, it should be noted that there are two points which are not included in the analysis. They are field studies in Sweden [S.I.B. 1967] and in Southern Russia [Goromosov 1963] where there exists high solar radiation. The regression equation is:

$$y = -0.244 + 0.0166\,x \qquad \text{(eq. 5.14)}$$

where y = standardised mean thermal sensation response

and x = mean temperature.

The regression is positive but very low at only 0.02/°C. This regression coefficient is statistically highly significant. The values of standardised mean sensation responses in Figure 5.10, are generally positive and its neutral temperature is approximately 14.7°C.

5.4.2 Category intervals

The category interval is the temperature range associated with a particular scale category. It may be obtained from analysis into proportions or probit analysis (see Figure 5.2a) [Humphreys 1976]. On the numbering system of a seven-category scale, the width of the neutral (zero) category is considered first and followed up with category -1 and +1. The average category width is approximately 4 K. The scale category -1 or +1 may have category width slightly narrower than the category 0, but the effect of the difference does not reach significance if one selects the central three categories as the thermal comfort zone [Hickish 1955; Humphreys 1976].

Griffiths and Boyce [1970]; Wyon [1994b] raised the question of investigating the seven-category semantic differential thermal scales namely Bedford and ASHRAE scales. Humphreys [1976; 1994b] argued that the number of scale categories has more influence on the behaviour of a scale than does the labelling; and stated that: *"a scale is not subject to irregular widths which sometimes result from the use of individual category labels, and would be easy to translate."* Fox et al [1973] used a preference scale as a supplement, being advantageous to *"... enable a check for bias to be made, although this kind of bias is not a severe problem in scales of warmth"* [Humphreys 1976].

5.4.3 Regression coefficients

The regression coefficient (or slope of the regression line) indicates the respondents' sensitivity to temperature change or the respondents' adjustment to thermal environment. Humphreys [1976] analysed many field studies using symmetrical seven-category scale, and obtained a mean value of the regression coefficient of 0.22/°C, being equivalent to a change of one scale interval in 4.5 K. It is interesting to compared with the regression coefficient from climatic chamber studies, which is 0.33/°C [Fanger 1970]. The difference between these two regression coefficients is perhaps because of the different nature of each study. In climate chambers, respondents have no opportunity to adjust their clothing, activity or environments, whereas those in field studies are free to personal and environmental adjustment and therefore a wider range of comfortable conditions. This will be given in the section on the Adaptive Model of thermal comfort (see 5.5.1).

If the observations in the field surveys have made several times a day for a period of a few weeks (i.e., longitudinal surveys), the findings will explain how people respond to variations of their thermal environments and how they adjust/adapt themselves and their environmental conditions in order to achieve their comfort over a time-span. In much longer duration, the effect of seasonal adjustment to temperature variations will be included.

The lowest regression coefficients are found in field studies done over a year by Hindmarsh and Macpherson [1962] and Davies [1972], reporting the slope of 0.16/°C and 0.10/°C, respectively. Other two field studies by Humphreys and Nicol [1970] and Humphreys [1978b] reported the regression coefficient can be as low as 0.05/°C.

5.4.4 Standard deviations

As mentioned above, the standard deviation in a longitudinal design gives the deviation of the consistency of individual respondents; and in a transverse design, the expression of uniformity between respondents [Humphreys 1976; Nicol 1993]. From many field studies, the standard deviations of the longitudinal tend to be slightly greater than those of the transverse but the difference does not reach statistical significance. This implies a somewhat greater of the inconsistency of an individual than the difference between people [Humphreys 1976]. People at the same place would sense their thermal environment as similar as others do, and when they moved to another place, their thermal sensation would be altered regarding the environmental conditions. However, the standard deviation does not appear to be related to the neutral temperature.

In addition, Humphreys [1976] reported that the standard deviations of respondents in air-conditioned environments are relatively small, and the discrepancy to those in "free-running" environments, is statistically significant. This shows that personal inconsistency and the differences between people are considerably greater in the less controlled environments. The constant temperature maintained in the air-conditioned rooms will result in people becoming accustomed to a single temperature and would be less tolerant of temperature change. As a consequence, it would be concluded that there is a perceived need or desire for, or addiction to air-conditioning [Prins 1992]. Further discussion is given in the section on the adaptive opportunity [Baker and Standeven 1996] (see 5.5.6).

5.5 The Adaptive Model[2]

5.5.1 Introduction

The proposal for the *Adaptive Model* was previously conceived as *"thermal comfort as part of a self-regulating system"* [Nicol and Humphreys 1973] and subsequently, this concept has been developed to the *"adaptive approach to thermal comfort"* [Humphreys and Nicol 1998]. With the adaptive principle, it is suggested that field studies are an appropriate methodology toward an adaptive model [Nicol 1993].

[2] The Adaptive Model (with the capital letter A and M) refers to the mathematical expression which will be able to estimate/predict the comfort conditions, whereas the adaptive model (ordinary text) implies general term for theoretical discussion.

Humphreys and Nicol [1970] investigated many field studies that show the relationship between the comfort votes and the climate of office workers and compared the results, shown in Figure 5.11.

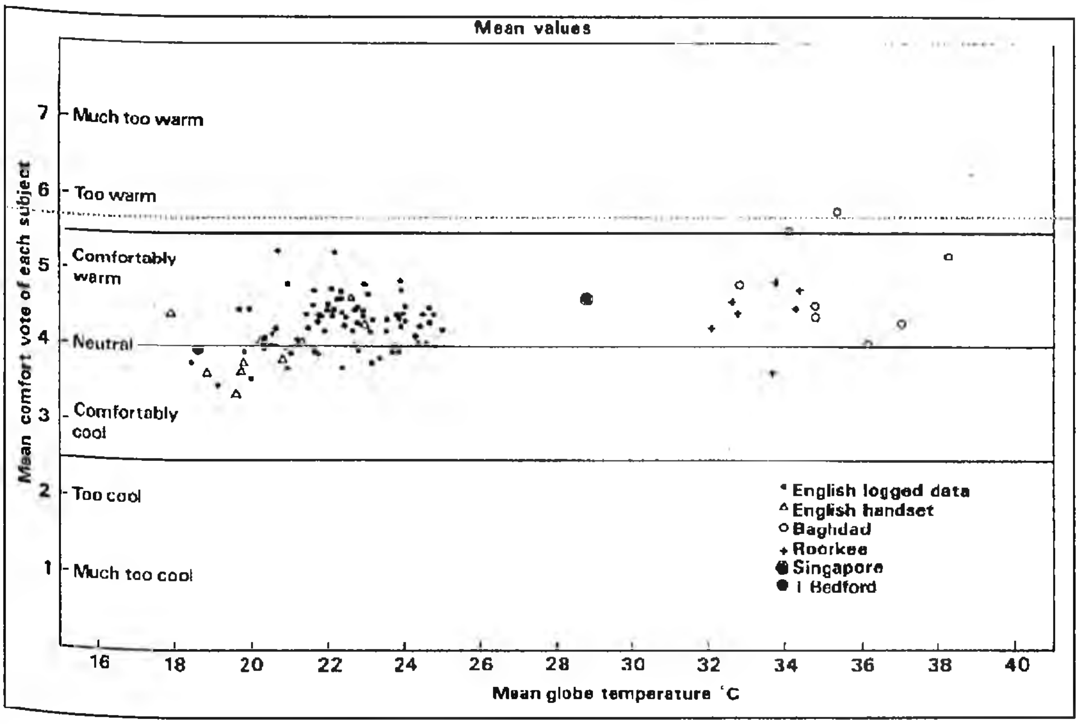

Figure 5.11 *Relationship between mean comfort votes and mean globe temperatures. (After Humphreys and Nicol 1970)*

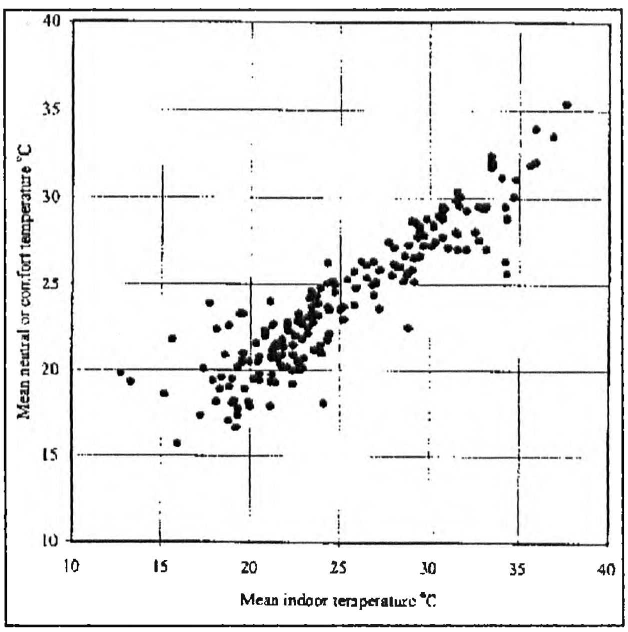

Figure 5.12 *Correlation between mean comfort temperatures and mean indoor temperatures. (After Nicol et al 1995)*

It is clear that the acclimatisation has influences on the comfort votes of the subjects who have experienced their actual environments. As seen in Figure 5.11, the English subjects respond their comfortable conditions at a range of comparatively low temperatures, whereas the subjects from the tropics can be tolerate higher temperatures. Many researchers have cited the effects of acclimatisation and among these are: Macpherson [1962]; McIntyre [1980]; Auliciems [1981].

Nicol et al [1995] included the field-study data from Humphreys' data [1975] together with other data collected since that time, and statistically analysed them by using correlation technique to investigate the linear relationship between mean comfort temperatures and mean indoor temperatures, shown in Figure 5.12. It shows that the strength of the correlation ($r = 0.92$) is a measure of the power of the adaptive principle.

5.5.2 The concept of the adaptive model

Humphreys [1994a] stated that people seek to be comfortable and take actions to secure their thermal comfort. They are likely to adjust their environments or to change their activity, posture or clothing if they feel uncomfortable. For the longer term, they may move to a different thermal environment in order to obtain a better climate. Alternatively, they may stay but devise thermal control systems, such as heating or air-conditioning. Perception of the adjustment or adaptation between the actual state and the desired state is the feedback in a person's thermal comfort control system.

The desire to achieve thermal satisfaction in a person are viewed as a set of continuous modifications in the real world. There are many modifications to suit at different times but some for comfort may conflict with others (i.e., adaptive constraints — see 5.5.4). In this way, a person will be in dynamic motion like the environment [Humphreys 1994a].

Brager and de Dear [1998] supported that a person is no longer a passive recipient of a given thermal environment. Instead, one plays an active role, interacting with the person-environment system via multiple feedback loops for their preferences.

Fountain et al [1996] examined how people's sensation and preference are influenced by culture and climate, and are associated with issues of thermal expectations and adaptation. Further discussion is on how incorporating these factors into future comfort standards that might yield more effective indoor climate control.

Humphreys [1994a] suggested to use the adaptive feedback model to discover how people modify their environments so that they are, on average, comfortable. This operates by the use of predicting neutral temperatures (i.e., Humphreys' models — see 5.3.2). The models provide an explanation of the crises and many difficulties in thermal comfort studies, such as human heat exchange and thermal design for buildings. These early findings revealed that ambient temperatures are highly related to comfort temperatures.

The concentration on establishing the optimum indoor climates or the precise fixing of optima, suggests a switch into the design of how to allow the building occupants to react positively to their thermal environments, i.e., effective controls used by the subjects [Humphreys 1992]. Wilson and Hedge [1987] stated that low control is associated with higher annoyance and stress, increased sick building syndrome symptoms and low productivity.

Auliciems [1981] argued that recognition plays an important role in the adaptive principle, acting as high levels of mental integration of information flow of human thermal environments; and proposed a holistic approach to thermal comfort research of which the model must include parameters of past cultural and climatic experiences and expectations. A diagram of a psycho-physiological model is shown in Figure 5.13.

This diagram, developed from Hensel's thermoregulatory model [1973], considers many levels of integration and suggests the general doctrines of "*cognitive behaviourism*" which hypothesise that an individual responds to perceived environments according to prior experience [Sprout and Sprout 1965; Saarinen 1973]. It also allows consideration of *"thermopreferendum"* or thermal preference. Auliciems [1981] stated that: "*... thermal preferences either* *researched by verbal questioning of hypothetical situations, or involving subjects in active decision-making with immediately perceivable effects, must involve responses clearly with both affective and cognitive components not inherent ...*"

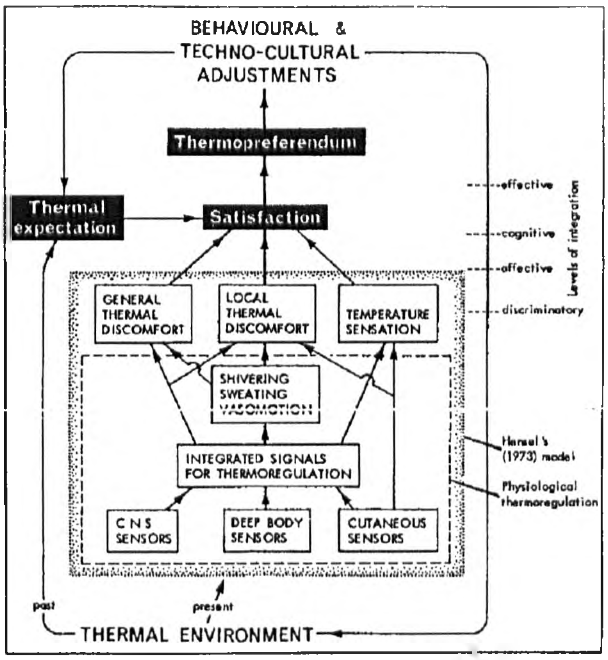

Figure 5.13 *Hypothetical model of psycho-physiological warmth perception. (After Auliciems 1981)*

Humphreys and Nicol [1998] summarised the adaptive principle as: "*if change occurs such as to produce discomfort, people react in ways that tend to restore their comfort.*" These reactions are referred to as "*adaptation*".

5.5.3 Factors in the adaptive model

De Dear and Brager [1998] explained that the adaptive model of thermal comfort is a variable temperature standard which would be based on an alternative to traditional comfort theory, where fundamental factors — physics and physiological, interact with thermal perception.

According to Humphreys and Nicol [1998], the adaptive principle includes physiological, psychological, social, technological, cultural and behavioural strategies. Some conceivable adaptive actions in response to warmth or coolness are:

1. regulating the rate of internal heat generation (e.g. increasing the level of activity, adding clothing, curling up or cuddling up, sipping a hot drink);
2. regulating the rate of body heat loss (e.g. taking off some clothing, adopting an open posture, reducing the rate of activity or adopting the siesta routine, having a beer or a cold drink or ice-cream, taking a bath or washing a face or going for a swim);
3. regulating the thermal environment (e.g. turning on air-conditioning or electric fan, lighting a fire, opening or closing windows, insulating the wall and roof, building a better building);
4. selecting a different thermal environment (finding a warm or cool spot in/out the house to suit one's satisfaction, emigrating); and
5. modifying the body's physiological comfort conditions (e.g. vaso-constriction, increasing muscle tension and shivering, vaso-dilation, sweating, acclimatising).

Brager and de Dear [1998] reviewed much literature on thermal adaptation and concluded that there are three modes of adaptation as follows:

1. behavioural feedback — adjustment: sub-categories are personal adjustment (changing personal variables), technological or environmental adjustment (modifying the surroundings) and cultural adjustment (adopting dress codes, siesta, scheduling activities, etc.);
2. physiological feedback — acclimatisation: sub-categories are genetic adaptation or alterations (heritage of an individual or group of people) and acclimation or acclimatisation (changes in the settings over a period of days or weeks); and

3. psychological feedback — habituation and expectation: sometimes referred to as perceptual adaptation is defined as *"repeated or chronic exposure to an environmental stressor leading to a diminution of the evoked sensation's intensity"* (cognitive and cultural variables).

Davies and Davies [1995] presented their findings in terms of the correlation coefficients (r) between thermal comfort and associated quantities, based on the field data recorded in 1968-69 at St. George's School, Wallasey. Figure 5.14 shows the relationships between environmental conditions, moderator and subjective variables.

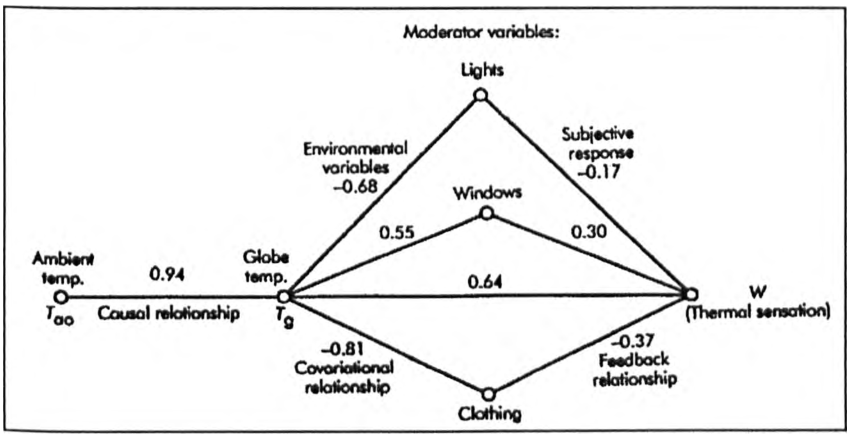

Figure 5.14 *Patterns of correlation coefficients in the study at St. George's School. (After Davies and Davies 1995)*

It is found that the ambient temperature is highly correlated with the globe temperature, and subsequently with thermal comfort. The pattern of correlation between thermal environment and the moderator variables (namely the number of windows open, the lights being off or on, and the clothing worn) and thermal comfort, are significant and logical. These moderator variables (or adjustments) prove important factors to achieve comfort and describe the feedback mechanisms supporting the adaptive model.

Other factors such as adaptive constraints, time sequence, and adaptive opportunity are discussed in more details in 5.5.4, 5.5.5 and 5.5.6, respectively.

5.5.4 Adaptive constraints

Humphreys [1994a]; Humphreys and Nicol [1998] stated that there is a set of complex adaptive functions of various constraints (c_1, c_2, c_3 ... c_n), which affect thermal comfort in the adaptive model. These constraints are circumstantial restrictions[3], viewed together as an entire set of conceivable adaptive actions. It considers an appeal for non-intervention field studies, where the tasks explain the concurrent and correlated time-sequences [Humphreys 1994a].

Thus, the constraints or circumstances lead to the restrictions that determine a range of temperatures, at which comfort could be obtained (with adaptive actions such as operating individual controls, changing activities or clothing) or perhaps prevent comfort being achieved (such as a limited window-opening in summer, or the requirement to be in uniform) [Humphreys and Nicol 1998]. In general, the effect of social factors or constraints which are to restrict the options available for control, will prevent an individual to modify his/her response to thermal satisfaction [Nicol and Humphreys 1973].

The Adaptive Model [Humphreys 1994a; Humphreys and Nicol 1998] can be written in mathematical terms of comfort temperature (T_n) as a function of various constraints on the indefinite set of conceivable adaptive actions as:

$$T_n = f(c_1, c_2, c_3 \dots c_n) \qquad \text{(eq. 5.15)}$$

Then thermal discomfort (D) [Humphreys 1994a; Humphreys and Nicol 1998] can be explained by the difference between the comfort temperature (T_n) and the actual temperature (T_a) as:

$$D = f(T_n - T_a) \qquad \text{(eq. 5.16)}$$

Adaptive constraints tend towards a self-regulating system, explaining the way people react positively to their thermal environments [Nicol and Humphreys 1973]. In the adaptive feedback system, such constraints can be categorised into

[3] The term *constraint* has been generally applied to the circumstances and to the restrictions they impose. Distinguishing between them helps to clarify the working of the adaptive model [Humphreys and Nicol 1998].

two groups [Humphreys and Nicol 1998]. The primary constraints or circumstances, which are not independent of one another and thus may overlap their restrictions on the adaptive actions, are:

1. Climate: many aspects of life are influenced by climate. It is considered as the chief constraint [Humphreys 1994a]. Considering the buildings in "free-running" mode [Humphreys 1978a], is an initial step in unravelling the effect of climate.

2. Affluence: the wealth of the region leads to the influence on building design, building services systems, and building energy consumption. Brooks [1950] showed that the comfort zone in North America lies between 20.6°C and 26.7°C, while in Europe, between 15.0°C and 21.1°C, for the same outdoor temperatures [Humphreys 1994a].

3. Culture: the culture of a nation or a people has a general effect on perceptions and actions, affecting the styles of buildings and the ways people use them. It also affects typical styles of dress, leading to the adaptation to achieve comfort, for instance, the thermal comfort standard in Pakistan [Nicol et al 1994].

The secondary constraints/circumstances are:

1. Working conditions and social contexts: these constraints act as subjective factors, influencing thermal preferences [Oseland 1992]. In some tropical countries, people feel that important politicians and businessmen are necessarily required to wear suits and ties, although there is more sensible adjustment in the dress to the local climate. Hence there is a need for air-conditioning to achieve comfort. Cowan [1993] quoted that the more important the person, the more clothes he wears, and the lower the temperature in his office.

2. Thermal control operated by another: a restriction on the adjustment of the environment can occur if the control is given to someone other than the

person whose comfort is considered. Bauman et al [1998] carried out a field study to assess the impact of a desktop task/ambient conditioning (TAC) and reported that overall occupant satisfaction for thermal quality, acoustical quality and air quality increases if there is an individual control.

3. Conflicting requirements: there will be restrictions on the adaptive actions if the control of a requirement is in conflict with another. For example, a window opens onto a noisy street. A trade-off between the different elements of environmental comfort is necessary [Wilson and Nicol 1994; Dubiel et al 1996].

4. Personality, fashion and gender: the restrictions to the adaptive actions in a person with a rigid personality is stronger than a person with a flexible and ingenious approach to living [Robinson 1956]. In some societies, fashion may amount to a uniform and people may trade thermal comfort for *social comfort*. In many cultures, the clothing of men differs from that of women, and the social constraints imposed on different genders are in different ways, leading perhaps to different comfort temperatures. However, there is only one study that shows the significant difference [Black 1954].

5. Health: illness or disability can be circumstances that impose restrictions on the adaptive actions, and so thermal requirements would be likely to differ from a healthy or able-bodied person. Thermal comfort research on people with physical disabilities can be seen in Webb and Parsons [1997; 1998].

Within these categories, there are virtually endless sub-factors and it is impossible to consider all of them. The necessity is to consider what is the relevant constraint for an adaptive model and which constraint should be regarded to what people have and what they prefer. The answer to these questions will enhance the prediction for comfort. On the contrary, if the constraints used are irrelevant, the prediction for thermal comfort will be in doubt [Humphreys 1994a].

5.5.5 Time sequence in the adaptive model

Nicol and Humphreys [1973] stated that time element has effects on the process of behavioural thermo-regulation to restore thermal comfort. Time has a dimension and it plays a crucial part in people's thermal experience [Nicol 1992]. Correlated variables with time, for example, are clothing and posture, varying from different time of the day, different social circumstances, and different thermal conditions. Nicol [1994] suggested that the essence of the time-sequence is, in fact, what the way people experience their environments is not only over the last hour or the last day, but the last week and the last month.

In the Middle East, such as in Iran, the occupants in traditional houses move between various rooms to ensure their comfort throughout the day [Roaf 1992; Roaf and Nicol 1993].

According to Nicol [1992], time in the adaptive model can be identified into four principal relations:

1. instantaneous: changes occur suddenly such as a transition between warm outdoor and cool indoor, or vice versa;
2. within day: changes depend on thermal conditions during the day;
3. day to day: changes are in pattern of "normal" or transient conditions; and
4. longer term: changes are derived from seasons, over months or years.

In the longer term, people tend to adapt to the average conditions they experience, as seen in field studies where neutral temperatures are highly correlated to the mean air temperatures [Humphreys 1976; 1978a]. However, the question is raised as to whether there is adaptation in a shorter term and the speed of the adaptation.

Humphreys [1972] found that, in "within-day" adaptation, the clothing of the subjects does not respond to the temperature they are experiencing at the time, but to a moving average of the temperature they experienced in the immediate past, exponentially weighted with a half-life of some two hours. For "day-to-day" adaptation, Humphreys [1978c] showed that people change their clothing in response to a moving-average of the temperatures they experienced with a half-life of twenty hours. In other words, people take account of the yesterday's temperature in deciding the clothing to wear today.

When there is an "instantaneous" or sudden change in temperature, Nicol [1992] suggested utilising the building design as strategy to achieve comfort. By using the building mass to damp temperature variation and smooth large jumps in temperature, it is possible to lessen the thermal differences. If the internal temperature changes slowly, the occupants will adapt and discomfort will be avoided. Humphreys and Nicol [1998] concluded that, in general, adaptive actions will respond in the long term and thus, for a sudden change in the environment or in any circumstances, there is a limited range of available adaptive paths.

Nicol and Raja [1996; 1997a; 1997b] used an exponentially weighted running mean time series to characterise the subjects' past experience of daily mean outdoor temperature (T_{od}). Values of the running-mean temperature (T_{rm}) can be calculated by assuming the different values of the time constant (α) in the series:

$$^{n}T_{rm} = (1-\alpha)\ \{^{(n-1)}T_{od} + \alpha.^{(n-2)}T_{od} + \alpha^{2}.^{(n-3)}T_{od} + ...\} \qquad \text{(eq. 5.17)}$$

where $^{n}T_{rm}$ = running mean temperature on day n

α = time constant ($0 \leq \alpha \leq 1$)

and $^{n}T_{od}$ = mean outdoor temperature on day n.

In each day, the value of the running-mean temperature (T_{rm}) can be calculated from the previous day data using the formula:

$$^{n}T_{rm} = (1-\alpha)\ ^{(n-1)}T_{od} + \alpha.^{(n-1)}T_{rm} \qquad \text{(eq. 5.18)}$$

To calculate a time-constant for the adaptive process, the concept of the half-life for radioactive decay is used. A large value of α implies a greater weighting for values of T_{od} in the past. The theory approximates that a step change of T_{od} will give a value of T_{rm}, given by $0.69/(1-\alpha)$ [Humphreys 1972].

Considering this model, Nicol and Raja [1997b] claimed that the daily outdoor temperatures are more appropriate to measure for the comfort temperatures over a period of time. It is because the weighted recent temperatures are more heavily experienced than those further back in time in a way which accords with common sense. Full details of the study can be found in Nicol and Raja [1996].

5.5.6 Adaptive opportunity

Humphreys and Nicol [1998] suggested that an alternative consideration in the thermal adaptive model is the *adaptive opportunity* [Baker and Standeven 1996; Baker 1996]. It is a theory to extend the band of the comfort zone by partly an adjustment of built-environments and partly a social context. Baker and Standeven [1996] claimed that psychological adaptation gives a person the ability to tolerate thermal sensation other than neutrality due to extenuating circumstances. The best explanation is given following the Figures 5.15 to 5.18, on a hypothetical temperature/time graph.

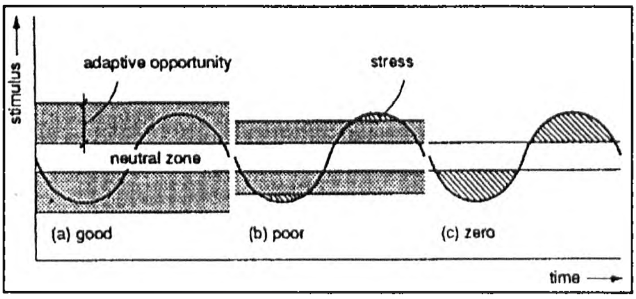

Figure 5.15 *Comfort zone is extended beyond the neutral zone by adaptive opportunity. (After Baker and Standeven 1996)*

From Figure 5.15, the ambient temperature fluctuations (solid line) can be extended beyond the neutral zone without sacrificing comfort if the adaptive opportunity is *good.* When adaptive opportunity is *poor* or *zero*, any departure from the neutral and adaptive zones will cause thermal stress or dissatisfaction. Both excessive stimulus amplitude and insufficient adaptive opportunity are potential causes of discomfort.

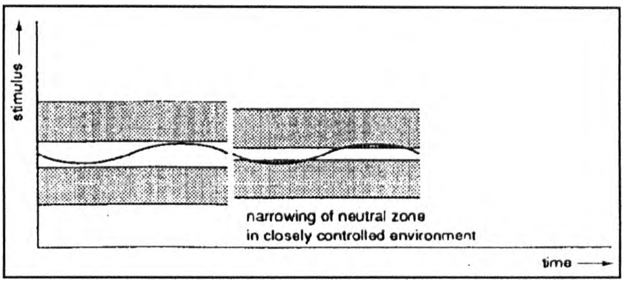

Figure 5.16 *Neutral zone is narrowed in closely controlled environment. (After Baker and Standeven 1996)*

In Figure 5.16, the ambient temperatures and neutral zone are narrowed by mechanical means and the need for adaptive processes is eliminated. As a result, the perceived need to provide closely controlled environments is self-fulfilling.

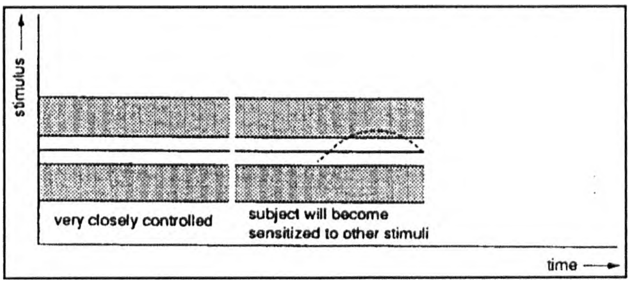

Figure 5.17 *Sensitising to secondary stimulus when variation in thermal stimulus is eliminated. (After Baker and Standeven 1996)*

Figure 5.17 shows a circumstance that all variation is eliminated and a subject develops sensitivity to other stimuli (dotted) such as lighting, acoustics, odour and so on. This is consistent with numerous findings in studies of sick building syndrome (SBS).

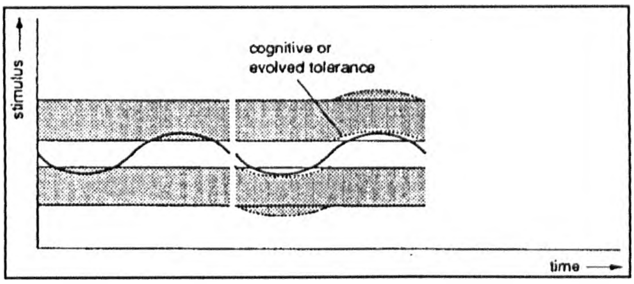

Figure 5.18 *Knowledge of the cause of the stimulus may increase tolerance. (After Baker and Standeven 1996)*

Finally, in Figure 5.18, it is suggested that if the cause of a stimulus is known and understood, a subject could be more tolerant and the adaptive zone can be extended. This is referred to a *"cognitive tolerance"*. There may also exist evolved physiological changes which are applied unconsciously. For example, the core body temperatures go through a temperature swing which roughly coincides with a diurnal swing in ambient temperatures. This is referred as an *"evolved tolerance"*.

Humphreys and Nicol [1998] stated that: *"the possible adjustments would not be uncorrelated actions cancelling each other out but would be purposive and cumulative."* Then thermal comfort can be restored if there are sufficient effects of adaptive opportunity to compensate for the comfort temperature in a spatial variation of temperatures across a room.

Baker [1996] concluded these recent developments in thermal comfort theory by considering that all living organisms exhibit the characteristic of *"irritability"* which is defined as: *"responsiveness to change in the environment by complex adaptive activity — a universal property of living things"* [Abercrombie et al 1966].

5.5.7 Establishing the Adaptive Model

If considering the adaptive model of thermal comfort is an example of a *"complex adaptive system"* [Casti 1996], it is unfortunate that no formal mathematical framework can be used to probe the properties of the basic insight of this theory. There has been only a proposal to apply several interacting time-series and actions of intelligent agents, making decisions on limited information to establish comfort temperature [Nicol and Humphreys 1973; Humphreys and Nicol 1998].

An example of the application based on the Adaptive Model for control engineering and design for office buildings, is the comfort control algorithm [Willis and Perera 1995].

The structure of its initial prototype is:

$$T_{control} = (a\,T_{outside} + b) + [c + d / (e + f\sqrt{v})] \quad \text{(eq. 5.19)}$$

where $T_{control}$ = target control temperature

$T_{outside}$ = measure of external temperature

$\sqrt{v}$ = square root air velocity in building

and a, b, c, d, e, f = constants (to be determined in the future).

The anticipated advantages from the above model include:

1. energy savings: by the relaxation of the target control temperature and the extended band of thermal acceptability, referred to a linkage between the internal and external environments;

2. comfort improvement: due to the provision of thermal environmental responses from the direct perception of comfort by the occupants;

3. reduction of the plant sizing requirements: in retrofit applications; and

4. opportunity to use alternative sources of building services system to maximise energy efficiency and to minimise capacity of servicing in new building design.

The aim of the model in a longer term is to affect the design of controls, i.e., the shift from passive means towards active systems with comfortable environment and cost effectiveness. This model is still in the test process.

Humphreys and Nicol [1998] recommended that future developments will be based upon the adaptive principle by applying modern technology in workplaces (i.e., those equipped with their own computer terminal) to measure the comfort votes continually and using fuzzy logic systems to fine tune the room temperatures. The proposal of this sophisticated environmental control in workstations and probably, localised control devices, will make it possible for individual comfort.

Fountain et al [1996] suggested that it is the researchers' challenge to understand various adaptive mechanisms, and to develop mathematical predictive models where eventually incorporate relevant adaptive factors into "responsive" standards that acknowledge the relationship between humans and their environmental interactions. The "responsive" standards may include heat balance models which account for a short-term physiological adaptation, and empirical equations for describing a long-term shift or contextual effect on thermal expectation.

At the initial stage, de Dear and Brager [1998] proposed a variable temperature thermal comfort standard that considers the Adaptive Model. The statistical analysis is conducted separately for buildings with centralised HVAC systems and for those with natural ventilation shown in Figures 5.19 and 5.20, respectively.

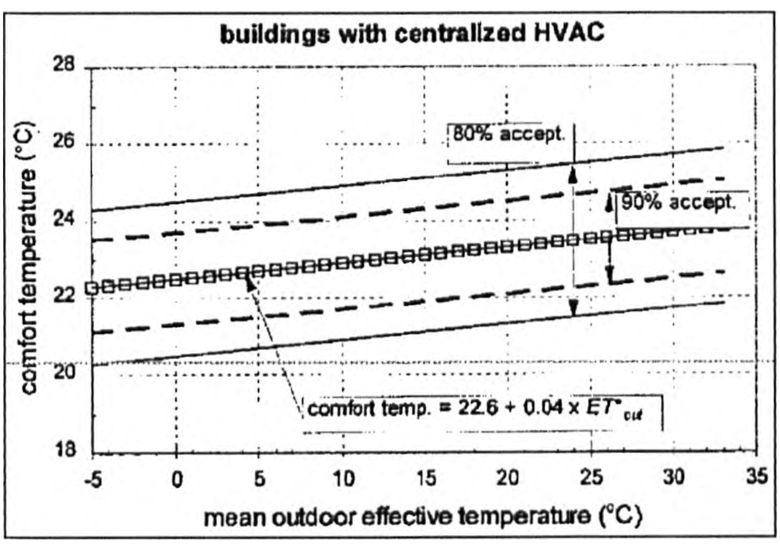

Figure 5.19 *The Adaptive Model — standard for buildings with centralised HVAC. (After de Dear and Brager 1998)*

From Figure 5.19, the range of 80% thermal acceptability is 4.1 K, and that of 90% acceptability is 2.4 K. Comfort temperatures (T_n) for buildings with centralised HVAC systems can be calculated from the knowledge of mean monthly outdoor effective temperatures (ET^*_{out}) and the regression equation is:

$$T_n = 22.6 + 0.04\, ET^*_{out} \qquad \text{(eq. 5.20)}$$

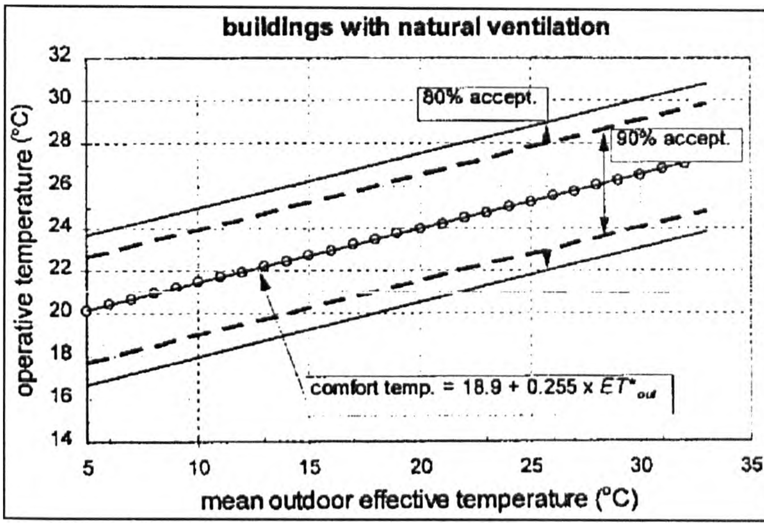

Figure 5.20 *The Adaptive Model — standard for building with natural ventilation. (After de Dear and Brager 1998)*

From Figure 5.20, thermal acceptable ranges for buildings with natural ventilation are significantly wider than those for centrally HVAC buildings. The 80% acceptability range is 6.9 K, and the 90% acceptability is 4.9 K. Comfort temperatures (T_n) for naturally ventilated buildings assume the regression equation of eq. 5.12, which accounts from many recent field studies (see 5.3.4). The equation is:

$$T_n = 18.9 + 0.255\ ET^*_{out} \qquad \text{(eq. 5.21)}$$

5.6 Advantages of the Adaptive Model

5.6.1 PMV and actual mean vote (MV)

The differences between the PMV and the actual mean vote (MV) are often found in field studies [Busch 1990; Schiller 1990; Karyono 1996b; Oseland 1994b; 1995; 1998; Chan 1998]. These discrepancies sometimes can be reduced by rectifying the metabolic and clothing values [Fanger 1994; 1995; de Dear and Fountain 1994; Brager et al 1994; Donnini et al 1997].

Humphreys [1994a] stated that the discrepancy between the predicted and the observed is related to the prevailing mean indoor temperatures (T_i); and proposed to use the Adaptive Model to explain the PMV by an empirical adjustment. This will calculate the PMV by applying the actual mean vote (MV) and T_i into the equation:

$$MV = a\,PMV + b\,T_i + c \qquad \text{(eq. 5.22)}$$

where MV = mean vote found in a field study

PMV = predicted mean vote from Fanger's equation

T_i = mean indoor temperature

and a, b, c = constants.

5.6.2 Heat exchange equations

The concept of the adaptive feedback model at the present cannot explain the adjustments of physiological temperature control system in the body, considering for the heat exchange equations. Humphreys [1994a] suggested that more work is needed to improve thermal comfort mathematical models. These include the following criteria:

1. steady-state and transient conditions;
2. acclimatisation from different populations; and
3. freedom from bias for higher levels of activity and clothing values.

The feedback system therefore should be applicable not only to field studies, but also to climate chamber experiments which take account the adjustments of environments in consequences.

5.6.3 Comprehensive indices

Humphreys [1994a] stated that the failure of the comprehensive indices such as PMV and SET* in field study conditions occurs because they assume standardised values of metabolic rate and clothing insulation. In statistics, if adding in a "correction" for individual difference, the effects will increase the scatter and the feedback system which secures human comfort will undermine the effectiveness of the comprehensive indices.

Adaptation has influences on individual comfort votes which are correlated to room temperatures. If a group of people experiences a single uniform environment, they will adjust their clothes and their levels of activities over a period of time and then they will have their own comfort for that environment, compensating for every individual difference. People's votes will rise and fall in sympathy with the changes of room temperatures.

5.6.4 Regression coefficients

In field studies, the regression coefficient or slope of the regression analysis is considered as a measure of the effectiveness of the Adaptive Model. Usually, it is a slightly positive value (see 5.2.2). If a perfectly adaptive feedback system is applied, all respondents from various environments will be expected to have well adapted to their conditions and then the comfort responses will be attributed to a regression line with a slope of zero. This means that people from different environments have different comfortable conditions at different temperatures, and the comfort temperatures would be no longer a constant value. Complete success in adaptation would entirely invalidate the use of regression analysis as a means of ascertaining the comfort temperature. [Humphreys 1994a].

5.6.5 Energy efficiency

The setting of a desired temperature in heated or cooled buildings using the Adaptive Model, would result in energy savings and greater comfort due to less chance of overheating in winter or cold discomfort in air-conditioned buildings in hot climates [Nicol and Humphreys 1973]. The prospect will be for local or individual control, tending to reduce the demand for large plant and centralised control systems. However, increasing demand for small high-quality individual units should be considered with effective local control systems [Humphreys 1998].

5.6.6 Building designs

Nicol and Humphreys [1973] suggested an approach to building designs by using the adaptive principle that if a self-regulating control system is working to secure thermal comfort, the whole system will tend toward its own optimum. It focuses interest on the control of thermal environments, rather than on a single fixing of optima. The HVAC engineers will need to be involved in the design team from the initiation of a building project to ensure good thermal design principles. The incorporation of building design, structure, and the appropriate types of heating and cooling will specify the building services systems [Humphreys and Nicol 1998].

5.7 Summary

The methodology of "Field Studies" in thermal comfort research has been explained, including the procedure of the field surveys, the realism required of environmental conditions, the measurement of both environmental and personal parameters, the questionnaires, and the categories of the survey designs. Analysis of the field-study data has been described. Basically, there are two types of statistical methods: simple linear regression and probit analysis. Both analyses give fairly similar information which can be used to calculate neutral temperatures (T_n).

To establish neutral or comfort temperatures, several researchers have proposed their models, which have been introduced in this chapter. Humphreys' [1976; 1978a] and Auliciems' [1982; 1986] models use prevailing climate of either indoor or outdoor temperatures as the main variables. It should be noted that the relationship between the mean values of prevailing temperatures and the neutral temperatures is very strong and positive, especially in the "free-running" buildings.

The ASHRAE RP-884 [de Dear and Brager 1998], whose data are derived from a quality-controlled database from field studies world-wide, gives recent predictive models. Its analysis is categorised into two groups of buildings: with centralised HVAC and with natural ventilation. It should be mentioned that the Humphreys' and the Auliciems' models are considered as earlier Adaptive Models and the models from the ASHRAE RP-884 are recent Adaptive Models. These models will be used later in the comparative studies in this thesis.

Finally, Griffiths' value [1990] is a technique to predict neutral temperature when there are a small number of data or a little variation of temperatures and subjective thermal responses (variation in comfort votes). Its method is to assume the regression coefficient from climatic chamber experiments to each comfort vote and to average the comfort temperature.

The information from field-study analysis gives an understanding of the correspondence of subjects to their thermal environments. Comparison between thermal responses from various field studies shows the relationship between climate and comfort. The category width gives a range of comfortable conditions; the regression coefficient or slope indicates respondents' sensitivity to temperature change or respondents' adjustment to thermal environment; and the standard deviation refers to the consistency of individual respondents or the uniformity of between group respondents.

The *Adaptive Model* — its concept and the theory behind it has been introduced. It is believed that the research of thermal comfort through the adaptive principle will provide appropriate findings, which will be basis of application for building services systems and architectural designs.

The adaptation or adjustment by subjects themselves is the desire to achieve thermal satisfaction, considered as a set of continuous modifications in the real world. It relates to parameters of past cultural and climatic experiences and expectations, as well as thermal preference. Factors in the adaptive model include some conceivable adaptive actions and involve in three different modes of feedback: behavioural (adjustment), physiological (acclimatisation), and psychological (expectation). Other factors, which are discussed in details, are adaptive constraints, time-sequence, and adaptive opportunity.

A knowledge of all factors will give the ability to establish the algorithm of the Adaptive Model. It is expected that, with this model, many problems and difficulties in thermal comfort research can be solved, and recommendations for building energy consciousness and its design criteria can be beneficially achieved. The following chapter will discuss on many case studies, giving more views and understandings on thermal comfort findings and their application in practice.

Chapter 6

CASE STUDIES OF THERMAL COMFORT RESEARCH

"The three methods[1] produce some contradictory results. The method of direct determination finds that individuals are very reliable, and that the preferred temperature of different groups of people is the same, whatever the general thermal experience of the group. Chamber studies, however, find people apparently much less reliable, and the results of field studies, which also employ rating scales, show that the neutral temperature of a group varies over a wide range, and can be predicted from a knowledge of the local climatic conditions."

D. A. McIntyre [1978a]

[1] The first two methods are carried out in climate chambers and the last one, by field surveys.

6.1 Introduction

Studies of thermal comfort have been carried out throughout the twentieth century. The examination of comfortable conditions have considered from purely physiological knowledge in the relationship between the human body and its thermal environments, to the recent theory of the adaptive model namely behavioural, physiological and psychological adaptations. Two main methods of studies — climatic chamber experiments and field surveys — have been used. Although the published results from both methodologies are contradictory, they help understand the thermoregulatory system in man and the irritability (namely thermal expectations and experiences, the acclimatisation and the adaptation) of our species.

This chapter will introduce various case studies of thermal comfort research from nearly every part of the world. The areas of the study concern geographical, ethnic and cultural, and climatic criteria, which affect human comfort. Two types of research (climate chamber and field studies) will be described separately. Each of which will be given: its brief methodology and procedure; the reason and advantages; and some case studies.

Case studies of thermal comfort in climatic chambers consist of earlier experiments in America and Denmark, experiments in England and in Asia (i.e., Japan, Hong Kong, Singapore, and Malaysia). More case studies of field work are reviewed. They consist of earlier field studies, recent studies of the ASHRAE projects, studies in Australia and in England, studies of field work in South Asia (i.e., Pakistan, India, and Bangladesh), and in Southeast Asia (i.e., Thailand, Singapore, and Indonesia), and finally, other field studies (such as in Hong Kong, Athens, Zambia, and Hawaii).

In summary, this chapter will concentrate on the findings of research in tropical regions (in many Asian countries), which will lead to the subsequent chapters of this thesis, thermal comfort in Thailand.

6.2 Thermal comfort by climate chambers

6.2.1 Experimental facilities and experimental conditions

One example of a climatic chamber is at the Technical University of Denmark. Figure 6.1 shows the plan view of the chamber and adjoining facilities such as the control panel, laboratory, dressing room and pre-test room.

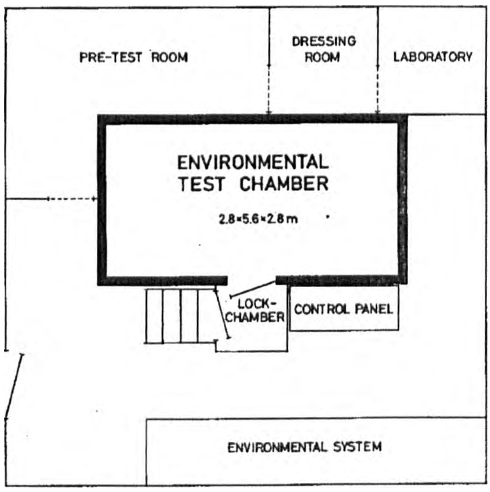

Figure 6.1 *Floor plan of the environmental test chamber at the Technical University of Denmark. (After Fanger 1970)*

Fanger [1970] stated that in the chamber, the combinations of air temperature, air humidity, mean radiant temperature and air velocity can be produced and accurately controlled. Especially, the mean radiant temperature can be controlled independently of the air temperature. It should be noted that, however, in various chambers, the environmental variables are kept at a suitable neutral level for experiments.

McIntyre [1978a] identified two different approaches in climatic chamber studies: the direct determination of preferred temperature and the use of rating scales for subjective thermal responses. The former method is to adjust the chamber temperature to subjects' preferences, which is normally assessed during the average temperature over the last two hours of a three-hour experiment. The latter is to expose subjects to a given temperature or a range of temperatures in an environment chamber for a set exposure time, and at the end of the period, the subjects will indicate their sensation on a rating scale.

6.2.2 Reasons to use climatic chambers

The beneficial features of using climatic chambers in the thermal comfort studies are [Fanger 1970]:

1. All physical variables (T_a, T_g, rh, v) can be precisely controlled and maintained throughout the studies. Individual parameters (met and clo) can also be controlled by restricting the participants' activity and their clothing.

2. Investigation on a particular parameter is possible. The control can effectively hold some other independent variables to be constant, while the studied parameter is altered.

3. The studies carried out in thermal chambers assume the optimum comfort because there is minimal thermoregulatory strain on the body of the participants, and this is the basis of the thermal comfort equation.

6.3 Case studies of thermal comfort in climate chambers

6.3.1 Earlier experiments in America and Denmark

In America

During the early twentieth century, there were several thermal experiments carried out in an attempt to establish or specify conditions, which provide a comfortable environment. Initial carefully conducted and well-documented research was by Nevins et al [1966], who reported the comfort conditions, based on American college-age subjects. There were 360 males and 360 females, wearing 0.52 clo who were seated (reading, studying, and playing cards) in an environmental chamber in Kansas State University (KSU) (see Figure 4.7). The test conditions were set up at temperatures between 18.9°C and 27.8°C with 15-85% relative humidity, and the subjective rating thermal sensation used the seven-point ASHRAE scale. The results showed that there was a strong and linear effect of temperature upon subjective warmth responses and a smaller, yet substantial, linear effect of relative humidity with thermal votes. The comfort condition was established in terms of effective temperature (ET) at 25.6°C with 50%rh and there was no different between males and females.

Rohles and Nevins [1971] repeated the above experiments but extended the range of temperatures upward and downward until none of subjects were feeling "comfortable". Therefore, the test conditions were between 16.7°C and 36.7°C. The test subjects were 800 males and 800 females college students, wearing clothing of 0.6 clo. The results showed that in the short time (i.e., one hour) men felt significantly warmer than women did, but in the longer time, men were able to adapt downward so as to attain the same thermal sensation as women. In contrast, if the men were in comfortable temperatures, the women would be cooler rather than comfortable. A regression analysis gave coefficient value which demonstrates that women were more sensitive to temperatures than men. The temperature is a more important index in determining thermal sensation than other environmental factors. The neutral temperature for the combined subjects was approximately at 25-26°C, which was not significantly different from the previous study.

<u>In Denmark</u>

Fanger [1970] investigated the effect of different temperatures upon 128 Danish college-age persons and 128 Danish elderly persons. All subjects were clothed in a uniform of 0.6 clo and were seated in the climate chamber (see Figure 6.1) where eight different thermal conditions[2] were maintained. The findings reported that in steady-state conditions, the comfort temperature was approximately at 25.7°C with 50%rh, but that between genders was sometimes found to be different. There was no significant difference in preferred temperatures between Danish and American subjects, as well as between ages.

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[2] Four different temperature levels (21.1°C, 23.3°C, 25.6°C, and 27.8°C) at either 30% or 70% relative humidity; mean radiant temperature = air temperature; air velocity ≈ 0.1 m/s.

Other climate chamber studies at the Technical University were to investigate whether humans were able to adapt to prefer lower ambient temperatures. There were three experimental groups: firstly, sixteen winter swimmers who had been exposed to cold shock daily by bathing in the sea (0-6°C) for at least two winter seasons [Fanger et al 1977]; secondly, sixteen persons who had been working in a modern meat packing industry at an ambient temperature of approximately 8°C for eight hours a day during at least half a year [Olesen and Fanger 1971]; and thirdly a group of sixty-four college-age students [Fanger and Langkild 1975].

The experimental procedure was to set the start of air temperature and mean radiant temperature at approximately 25.6°C, considered as the comfort temperature, and to allow the subjects to adjust to their wishes[3]. The results showed that there was no significant difference of the preferred ambient temperatures among the three investigated groups. The mean preferred ambient temperature of the winter swimmers and the college-age group was 25.0°C, and that of the meat packing personnel was 24.7°C. It was concluded that there was no adaptation in cold-preference.

6.3.2 Environmental chamber experiments in England

During 1970s, there were extensive thermal comfort studies in the human environment chamber at the Electricity Council Research Centre, in Capenhurst, Chester, England. In many experiments, subjects were male, research officers from the centre. Some of their studies are reviewed as follows:

Griffiths and Boyce [1971] hypothesised that an optimal level of performance (i.e., an auditory inspection task and a visual tracking test) would coincide with comfortable conditions. The temperatures estimated at values between 18.3°C and 21.3°C had significant effects upon the performance, but

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[3] This method was first suggested by Gagge et al [1964].

when temperatures were outside the comfort range[4], the performances appeared to decline. However, there is a possibility that performance would increase if there is arousal with increasing temperature due to an interpretation of electrophysiological work [Okuma et al 1965; Wyon 1970]

Griffiths and McIntyre [1975] investigated the effect of mental effort on subjective assessments of warmth. It is believed from anecdotal evidence [Langkilde et al 1973] to support the notion, that people performing difficult intellectual tasks require lower temperatures than those in recreational activity, if optimal comfort is to be achieved. Twenty-four students of both genders were employed in the environmental chamber where air and mean radiant temperature were equal at 23°C. The intellectual task was *Raven's Advanced Progressive Matrices* [Raven 1965]. The results showed that there was no statistically significant difference for subjects with either intellectual or recreational activities. It was argued that the possibility of subjects' preferences for lower temperatures was due to a relatively high metabolic rate in some other experiments.

McIntyre and Griffiths [1972] reported an experiment in investigating the subjective responses to radiant and convective environments. The experiment was set in various combinations of air temperature (T_a) and mean radiant temperatures (T_r) (applied by wall and ceiling temperatures). It was found that the relative contribution of T_a and T_r was 0.59:0.41, meaning that a drop in T_a of 1°C would be compensated for by a rise in T_r of 1.5°C. If assumed T_a to be equal to T_r, the comfort temperature was found at approximately 23°C. There was no evidence of subjective difference between radiant and convective environments. Only air velocity was an important factor in the balance between radiant and convective heat loss.

Griffiths and McIntyre [1974] investigated subjective responses to overhead thermal radiation. The experiments were applied by conditions in which ceiling temperatures varied between 26.5°C and 45.0°C, and wall temperatures were reduced from 26.5°C to 15.0°C to maintain the perceived

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[4] The comfort assessment (using 4-point comfort scale — comfortable, slightly uncomfortable, uncomfortable, very uncomfortable) yields its best values between 18.3°C and 21.1°C; and Bedford scale gives optimal values between 20.5°C and 21.3°C.

mean radiant temperature constant. Thus, the experimental variable was radiation asymmetry. Other variables namely air temperature, air velocity and humidity, were held constant. The results indicated that overhead thermal radiation had significant effects on thermal assessment, and surprisingly, increasing ceiling temperatures (reducing wall temperatures) were perceived as cooler reports of warmth. It was therefore suggested that there was a greater sensitivity to radiant exchange with walls than with ceiling, and the findings may be applied to the ceiling heating or light fittings.

McIntyre [1977] further investigated subjective responses associated with overhead radiation. The degree of radiant asymmetry was characterised by *vector radiant temperature* (v.r.t.), which is a temperature difference between two opposed hemispheres that would produce the same radiation vector as exists in the actual environment [McIntyre 1970]. An experiment was conducted in four different levels of the v.r.t. of 0, 5, 9 and 14 K, by controlling ceiling temperatures at 23, 30, 38 and 45°C. Air and wall temperatures were held equal to each other, and were reduced to compensate for the raised ceiling temperatures, so that warmth condition would be constant. The results showed that there was no significant difference between thermal responses in each condition, but clearly, the subjects had noticeability to the raised overhead temperatures. In the direct inquiry in relation to discomfort from ceiling temperatures, there was a steady increase of discomfort with increasing radiant asymmetry. It was concluded that a design recommendation of a maximum asymmetry of the v.r.t. should not be more than 10 K. In practice, if the mean radiant temperature — m.r.t. (T_r) is 23°C (comfortable condition), the maximum permitted ceiling temperature will be about 38°C, that would expect unlikely to produce complaints.

McIntyre and Griffiths [1975] examined the effect of atmospheric humidity upon subjective thermal responses. Three levels of relative humidity of 20, 50 and 75% at either 23°C (comfortable) or 28°C (elevated) were set up in the environmental chamber. The findings showed pronounced increase in the warmth vote with increasing humidity at the higher temperature. The subjects found high humidities to be more oppressive, more moist and to cause more discomfort. At the comfort temperature, only an increase in rating of moistness of the skin was found. A level of 50%rh was more comfortable and less oppressive than either 20 or 75%rh.

Recent studies of thermal comfort in climatic chambers in England have been done by Oseland [1995]; Webb and Parsons [1997; 1998]. Oseland [1995] carried out a comparative study of thermal comfort conditions in climate chamber, and the actual environments of offices and homes. This study also compared the reported results with the predicted calculation using the PMV model. It will be discussed later in the section — Field studies in England (see 6.5.4).

At Loughborough University, Webb and Parsons [1997; 1998] compared thermal comfort requirements of people with physical disabilities to those without physical disabilities, based on the comfort standard [ISO 7730 1994]. A laboratory study was conducted by using thirty-two subjects (each eight-subject group of with/without physical disabilities and of male/female) exposed to three different thermal environments of 18.5°C (PMV = -1.5, slightly cool to cool); 23.0°C (PMV = 0, neutral); and 29.0°C (PMV = +1.5, slightly warm to warm).

The results indicated that there was no different thermal comfort requirement for the people with physical disabilities from the normal people. However, the range of mean thermal sensation for people with physical disabilities was comparatively wide at the PMV = -1.5 and the PMV = 0, showing a consensus in greater variation in their needs at 18.5°C and 23.0°C. These results were well matched with the predict from the Standard ISO 7730 [1994], but the total percentage dissatisfied was somewhat higher than Fanger's PPD (predicted percentage dissatisfied). It implied that the standard underestimated the thermal acceptability of the sample group of subjects.

6.3.3 Thermal comfort experiments in Asia

In Japan

Tanabe et al [1987]; Kimura et al [1994]; Tanabe and Kimura [1994] carried out several experiments to investigate thermal comfort under hot and humid conditions in Japan. The study on air temperature and humidity used 172 subjects wearing 0.60 clo under sedentary activity during the summer season and used 78 subjects during the winter season. It was concluded that the comfortable conditions for Japanese college-age subjects were not significantly different from previous studies of those in temperate climates. The neutral temperature[5] in summer was 26.3°C and that in winter was slightly lower at 25.3°C. A possible explanation for the difference might be metabolic rate due to diet between seasons [Tanaka 1981]. Female subjects preferred slightly higher temperatures and were more sensitive to cold than male subjects. In the summer season, high humidities (i.e., higher than 70%rh) and skin wettedness were associated with a high percentage of uncomfortable subjects, as explained by Brundrett [1990].

On subjective experiments of ventilative cooling, 64 subjects were exposed to higher air movement from a wind box in the chamber. The findings revealed that the higher the air temperatures, the higher the preferred air velocity[6]. The subjects also preferred to have their thermal sensation at "slightly cool" condition, and thus the PMV cannot predict thermal sensation correctly at high levels of air movement (namely above 0.5 m/s).

Recommended air velocities to relieve discomfort were presented for the summer season, where reductions in clothing insulation and skin wettedness with increased air movement were taken into account. For seated occupants under relatively high temperatures and high humidities, the recommended air velocities are shown in Figure 6.2.

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[5] This neutral temperature was established in terms of modified temperature (MT), which is defined as the air temperature that would be felt equally warm at 50%rh, 0.1 m/s air velocity, 1.0 met, 0.6 clo, and with a mean radiant temperature equal to the air temperature as in the actual environment.

[6] From 27.8°C 50%rh, preferred air velocity at 1.0 m/s, to 31.1°C 80%rh, at 1.6 m/s.

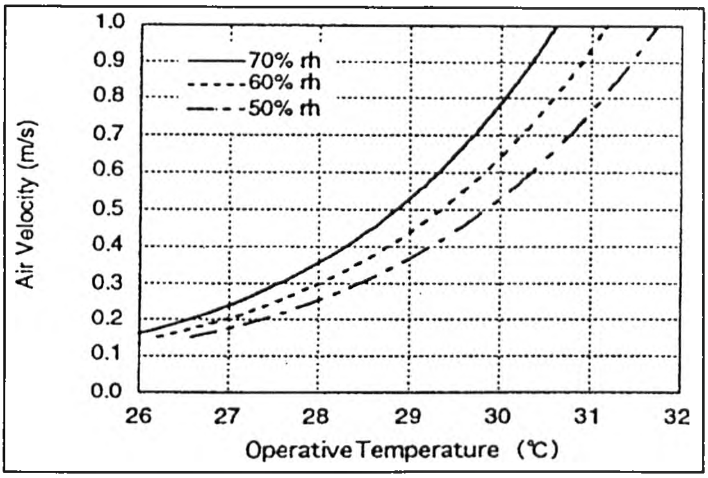

Figure 6.2 *Recommended air velocities. (After Tanabe and Kimura 1994)*

In addition, it is recommended to use fluctuating air movement to increase the cooling effect for energy-efficiency reasons. This is because even at the same mean air velocities, the subjects felt cooler under fluctuating sine wave air movement patterns than under constant air movement.

In Hong Kong

Chung and Tong [1990] investigated thermal comfort of young Chinese in Hong Kong by using 134 subjects wearing standard 0.6 clo under sedentary activity. The neutral temperature[7] of this study was 24.9°C, which is slightly lower but is not significant different from the above studies. The neutral zone, analysed by probit technique, was found at 22.2-25.2°C. Female subjects preferred a slightly higher air temperature (by 1°C) and were more sensitive to temperature changes than males subjects. It was also found that an insufficient air supply was a cause of increased uncomfortable conditions in the warm zone.

Another climatic chamber study in Hong Kong in relation to the effects of air movement was carried out by Chow and Fung [1994]. Twenty subjects were used in the experiments and exposed their backs of their necks to the horizontal fluctuating airflow of mean speed of 0.1-0.5 m/s with turbulence intensity of 0.6-0.9. The findings showed that, at high air temperatures (namely 28°C or above),

[7] Modified temperature.

subjects preferred to have a sense of air movement. High air turbulence intensity would induce a higher convective heat transfer rate and would provide a better means of relieving heat stress. Therefore, the air draught will give a comfortable feeling. Alternatively, in practice it is suggested that fans can be installed in spaces, rather than use mechanical ventilation by air-conditioning, in an attempt to achieve comfort and to cut down the cost of using energy in buildings.

In Singapore

De Dear et al [1991a; 1991b] performed two climate chamber experiments (part 1: temperature preference; and part 2: thermal acceptability) on Singaporean subjects. At first, it should be noted that although the conditions in Singapore year-round is a hot and humid equatorial climate, their experimental college-age subjects' daily routine included several hours in temperatures below 25°C and 60%rh, since the university campus is fully air conditioned. Nevertheless, these subjects could be regarded as naturally acclimatised.

In part 1 [de Dear et al 1991a] thirty-two subjects participated in a chamber which was initially set to an operative temperature of 25.7°C[8] and later was adjusted according to the subjects' wishes. It was found that the mean preferred ambient temperature was 25.4°C with the comfortable range of 23.1-29.9°C at 50%rh. There was no statistically significant difference between temperatures preferred by male and female subjects. The findings revealed that the "neutral" thermal sensation was not, in fact, the preferred state, but rather thermal sensations tending toward "slightly cool". The argument is supported by the preference theory by McIntyre [1978b].

In part 2 [de Dear et al 1991b] ninety-eight subjects were exposed to ten experimental conditions (a range of temperatures between 25-30°C at either 35 or 70%rh). Three subjective scales were used — the ASHRAE seven-point scale of thermal sensation, a four-point asymmetric thermal comfort scale (ranging from

[8] According to Fanger's comfort equation to produce a predicted mean vote (PMV) of zero for the given clothing, activity level, humidity, and relative air velocity conditions.

0 = "comfortable" to 3 = "very uncomfortable"), and a simple "yes/no" question on thermal acceptability of the environments. It was found that humidity had a negligible effect on thermal sensation and thermal comfort if ambient temperatures are lower than approximately 28°C. The acceptability[9] was assumed by using a simple average of the three scales. The upper limit of thermal acceptability at 35%rh was 27.9°C, and at 70%rh was 27.6°C. These findings are not different from those of a temperate climate, and therefore, it may suggest that humans cannot be naturally adapted to prefer or to accept warmer ambient temperatures in the use of Singaporean subjects.

<u>In Malaysia and with Malaysian in London</u>

Abdulshukor [1993] conducted two climate chamber experiments to investigate and to compare thermal comfort of Malaysian subjects who live in Malaysia and in London, UK. Some interesting knowledge in terms of ethnic background and acclimatisation to prevailing thermal environments was revealed.

The college-age subjects who participated in London's thermal chamber had to live in the UK for at least six months, and those in Malaysia were acclimatised to the local equatorial climate. For the longitudinal study, there were twenty-seven Malay ethnic origin in the UK chamber and twelve subjects of both Malay and Chinese ethnic in Malaysia. For the transverse study, one hundred and thirty subjects of both ethnic background participated only in the Malaysian chamber. The studies had approximately equal number of males and females.

Using simple regression analysis, the neutral temperature of all subjects combined was found at 25.7°C in London, which is identical to that of American and Danish. However, the neutral temperature in Malaysia was significantly higher at 28.3°C. It is clear that although anthropometric factors of the two groups of Malaysians are similar, the acclimatisation has an effect on the

[9] Using a 20% dissatisfaction criterion.

comfortable conditions. The findings also revealed that gender did not have much influence on the temperatures, but ethnicity did. Malay's tolerance to heat was higher than that of Chinese.

6.4 Thermal comfort by field studies

6.4.1 General procedure

Field Studies are an approach to thermal comfort by conducting surveys in homes, offices, factories or other buildings. McIntyre [1978a] described that field surveys are conducted by asking human subjects to indicate their state of thermal sensation on a descriptive scale (two commonly used scales are the ASHRAE scale and the Bedford scale). The subjective responses are indicated concurrently with the measurement of immediate thermal environments. At least, air temperature and preferably other parameters (namely relative humidity, air speed, and mean radiant temperature) are taken. Although it is difficult to control the effect of unwanted variables, the field studies consider the thermal responses in the subjects' normal surroundings. Details of the field-study methodology can be found in Chapter Five.

6.4.2 Classifications of field studies

Brager and de Dear [1998] classified thermal comfort investigations in the field into three groups, based on the standard of instrumentation and procedures used for indoor climatic measurements.

1. Class one: field surveys in which all equipment used and procedures are in 100% compliance with the specifications contained in ASHRAE Standard 55-1992 and ISO 7730-1994. All measurements done with laboratory-grade instrumentation (see Figure 6.3) at three heights above floor level (0.1, 0.6 and 1.2 m). Examples of the class one field studies are the three ASHRAE projects in the San Francisco Bay Area [Schiller et al 1988; Brager et al

1994], Townsville [de Dear and Fountain 1994], and Montreal [Donnini et al 1997] (see 6.5.2). Another sample is a large-scale survey in Hong Kong [Chan et al 1998]. Data from this class are more carefully investigated for the effects of non-uniformity in the environments, and give results with the same high quality across different buildings. Thermal enquiries usually include thermal sensation, preference, and the acceptability.

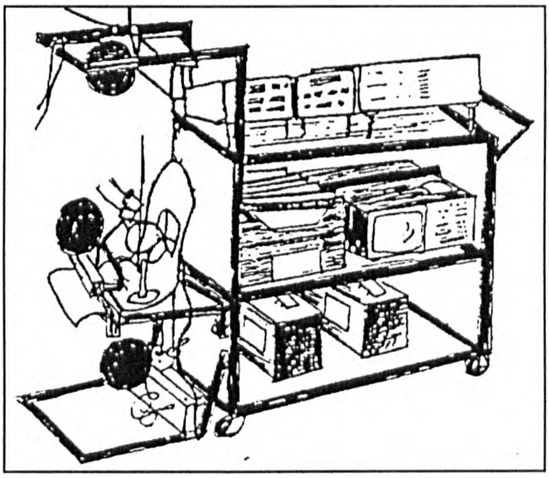

Figure 6.3 *Mobile measurement system. (After Donnini et al 1997)*

2. Class two: field experiments in which all physical environmental variables (T_a, T_g, rh and v) and individual parameters (met and clo) are collected simultaneously as the thermal questionnaires are administered. Usually, the measurement is taken at only one height. Data field studies of class two can be used for the calculation of heat-balance equations and for the PMV/PPD indices. They allow an assessment of the impact of behavioural adjustment and control on warmth subjective responses. Thermal comfort field studies in this class have been common in research in recent decades.

3. Class three: field studies which are based on simply measurements of indoor temperature and possibly humidity at one height above the floor. Possibly asynchronous and non-contiguous physical (temperature) and subjective (warmth responses) measurements. Many field studies of this class were reviewed and proposed as the earlier Adaptive Models by Humphreys [1976; 1978] and Auliciems [1982; 1986]. Although the quality of this data class

does not necessarily allow explanatory analysis, it can be used for simplified statistical techniques if the research questions being asked are relevant. This class offers the widest range of published data.

6.5 Case studies of thermal comfort by field studies

6.5.1 Earlier field studies

Many earlier field studies were conducted in a cross-section of climates to demonstrate the relationship of indoor comfort with not only thermal range of recent experience by subjects, but also local outdoor climates. Thirty-six field studies reviewed by Humphreys [1976] found that the mean indoor temperatures span from 17°C in England [Fox et al 1973] to 33°C in Iraq [Nicol 1974]. The majority of the respondents were office workers but some studies were made of naval ratings, school teachers and children, housewives, hospital staff and workers in light industry. The surveyed environments concerned the advantages of realism with natural conditions — typical of the respondents' experience. There are some studies carried out in atypical environments: a study of teachers in Sweden [S.I.B. 1967] on a spring day of high solar radiation; a study of summertime over-heating in dwellings in the south of the USSR [Goromosov 1963]; and studies on-board ships during voyages in which there were continuous changes of climates [Ellis 1952; Malhotra 1955].

The measurements of environmental and personal parameters were simply taken in a normal manner. Subjective estimates of warmth used various scales with four, five, seven, nine or thirteen categories, as well as the wording of the category describing both symmetrical and asymmetrical in the use of qualifying adjective. Thus these may occur a risk of bias in the analysis.

The analysis of information from many field-studies combined was done by various techniques. Correlation techniques showed the efficiency of different thermal indices. However, in comparison, it has been very difficult to state with confidence that there was significant difference from each field work. Another analysis of the distribution of each category vote of subjective scales gave the characteristic and mean values of thermal responses. Various scales can be standardised for a purpose of comparison, and nearly all of the standardised mean responses in these earlier field studies were positive (or in the warm side), even for the coolest conditions (see Figure 5.10). Finally, simple linear regression and probit analysis were used to predict neutral temperatures and it was reported that both methods gave similar findings.

Further analysis was performed by Auliciems [1982], using the Humphreys' database, and including more recent data from Australian and Asian research [Auliciems 1977; Woolard 1980]. These revisions brought the database up to fifty-three field studies. In summary, the findings from the earlier field studies gave the initial theory of the adaptive principle and established the basic Adaptive Models such as Humphreys' models (see 5.3.2) and Auliciems' models (see 5.3.3).

6.5.2 The ASHRAE projects

The following three research projects were sponsored by ASHRAE TC 2.1 (Physiology and Human Environment). They were conducted by field surveys to investigate indoor climates and occupant comfort in office buildings, in relation to prevailing thermal environments. Here is the summary:

Firstly, Schiller et al [1988] carried out field surveys in the San Francisco Bay region. A total of 304 participants gave 2342 thermal responses in two seasons: winter (a cool coastal climate) and summer (a drier). The results showed that cool sensations were associated with draughty ratings, while warm sensations with stuffy (or still) ratings. The environmental conditions leaning toward cool and draughty were perceived as comfortable. Using linear regression analysis, the neutral temperature was established at 22.0°C ET* in winter and 22.6°C ET* in summer. There was no significant difference between genders. The preferred temperature, defined as a temperature at which subjects' requests of "no change", was approximately 0.4 K cooler than neutral temperature in both seasons. Thermal acceptability was also established, by using the three central categories of the thermal sensation scale. Approximately 80-85% acceptability of the subjects were at a temperature range of 20.5-24.0°C in either season.

Secondly, de Dear and Fountain [1994] investigated comfort characters of occupants in air-conditioned buildings in Townsville, tropical north of Australia. A total of 836 subjects provided 1234 sets of subjective thermal responses in wet (June-July) and dry (January-February) seasons. The results indicated that mean thermal sensations on seven-point ASHRAE scale were -0.3 to -0.4, meaning marginally cooler than neutral for both seasons. Analysed by probit technique, the neutral temperature in terms of operative temperatures was 24.2°C in the dry season and 24.6°C in the wet season. The effect of seasonality on thermal comfort was minor, and there was little difference between genders. Linear regression analysis was performed and yielded the neutral temperature at 24.3°C for the combined seasons. For thermal acceptability, a fit curve from a direct question crossed 80%-line at between 22.5°C and 24.5°C. The direct assessment coincided closely with the indirect assessment by the central three categories of the ASHRAE scale. Thermal preference, assumed at a joint percentage of votes between "cooler" and "warmer", was approximately 23.5°C ET*. Air movement was also an important preference feature of the thermal satisfaction in hot and humid climatic zone, but further research is needed.

Finally, Donnini et al [1997] conducted a field study of occupant comfort and thermal environments in twelve mechanically ventilated office buildings in southern Quebec, Montreal, Canada, where the climate is a combination of a severe dry and cold in winter and a hot summer. There were 887 subjects in the surveys. The clothing insulation of the subjects (plus chair insulation) in the cold season (mean = 1.06 clo) was higher than that in the hot season (mean = 0.73 clo); and mean clothing value of males was 0.11 clo higher than that of females. The results indicated that mean thermal sensation on the seven-point scale was marginally cooler than neutral (-0.3 for both seasons). Probit analysis gave the neutral temperatures in the hot and cold seasons in terms of operative temperature (T_o) at 24.0°C and 23.1°C, respectively, as well as in terms of new effective temperature (ET*) at 24.1°C and 22.6°C, respectively. The differences of the neutral temperatures between seasons could be explained by the prevailing temperatures and clothing. Linear regression analysis of the combined seasons also determined the neutral temperature at around 23.5°C (T_o). For thermal acceptability, a direct question yielded the minimum level in the hot and cold seasons at 23.0°C 23.5°C, respectively. In the combined data, the 90% acceptability was an operative temperature at 23.0°C, and the 80% acceptability at between 21.5°C and 24.5°C. The indirect assessment of thermal acceptability coincided closely with the direct report. Thermal preference, assumed at a point of the intersection between "cooler" and "warmer", was 23.0°C ET* in the hot season, and 22.0°C ET* in the cold season. The effect of air movement was also investigated and the mean air movement acceptability ratings were classified as "slightly acceptable" in both seasons. Like the Townsville study, the warmer the operative temperature, the more people wanted higher air speed.

6.5.3 Field studies in Australia

De Dear and Auliciems [1985] reported six field studies in office environments, which were conducted in three Australian cities: monsoonal Darwin (two seasonal conditions — "the Dry" and "Build-up" or wet season); subtropical Brisbane (both air-conditioned and free-running buildings); and mid-latitude Melbourne (both air-conditioned and free-running buildings). Total number of complete thermal responses were 3290 data sets. For subjective ratings, three seven-point scales were used: the ASHRAE scale, the Bedford scale and the preference scale[10].

The results revealed that this study supported the proximate accuracy of the earlier adaptive models proposed by Humphreys [1976; 1978] and Auliciems [1982; 1986]. The neutral temperatures, analysed by probit analysis, of both the ASHRAE and the Bedford scales were not significantly different. A reasonably uniform indoor temperature for air-conditioned buildings was found at 23.5°C, regardless of outdoor climatic variations. On the other hand in free running

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[10] The preference scale (much cooler = +3, cooler = +2, slightly cooler = +1, no change = 0, slightly warmer = -1, warmer = -2, much warmer = -3).

buildings, the neutral temperatures had a great variability (from 21.3°C to 25.6°C), depending largely on outdoor climates (mean monthly outdoor temperatures of 20.0-28.8°C). In comparison between thermal scales, the preferred temperature of the Preference scale was cooler than the neutral temperatures from the other two sensation scales and the discrepancies are statistically significant.

Melbourne's neutral temperature was cooler than the other two cities and it can be explained by that Melbourne is a city in a temperate climate and the people are accustomed to cooler temperatures. In contrast, the neutral temperature of the free-running buildings in Brisbane was the warmest, due to the higher air temperatures the subjects exposed to. These observations clearly do not take account of heat-balance variables, but air temperatures affecting subjective responses. The neutral temperatures calculated from the comfort equation [Fanger 1970] were warmer than those analysed by probit analysis. Therefore, Fanger's comfort models failed to predict the actual mean votes of the Australian subjects.

6.5.4 Field studies in England

Oseland [1994] carried out field surveys of new homes built during 1988-1990 in winter and summer seasons. There were 808 respondents taking part. The subjective rating scales used were the ASHRAE scale and a seven-point preference scale. The environmental conditions showed that mean indoor air temperature was 19.2°C in winter and 21.7°C in summer (difference of 2.5 K), while mean outdoor air temperature was 12.1°C in winter and 19.2°C in summer (difference of 7.1 K). The amount of clothing worn was approximately 0.2 clo less in summer (0.7 clo) than in winter (0.9 clo). Mean thermal sensation in winter of 0.6 was not significant different from that in summer of 0.3, but surprisingly, the subjects rated somewhat warmer in winter than in summer. This may be explained by the subjective preference to be "slightly warm" in winter and "neutral" in summer.

Using linear regression analysis, the neutral temperature was 17.0°C in winter and 18.9°C in summer; and the preferred temperature was 19.5°C in winter and 21.8°C in summer. The reported findings were compared with those calculated by the PMV model. It was found that the predicted temperatures were higher than the actual regressed results (5°C in winter and 3°C in summer).

Oseland [1995] compared thermal comfort findings between the reported and the predicted from climate chamber, offices and homes. Thirty BRE employees were the subjects in this study which was divided into two phrases. The first phrase was to compare the reported and the predicted results from the three environments. The subjects wore the same clothing and performed sedentary activity, in a range of temperatures of 18-26°C. The second phrase was to study only in offices and homes, in which subjects were allowed to adjust their clothing, activity and environmental controls.

In the first phrase, the actual temperatures in offices were lower than the climate chamber and homes. Linear regression analysis gave the neutral temperatures: 22.8°C in the climate chamber, 22.1°C in offices and 20.6°C in homes. It confirms a general conclusion that a temperature required for comfort in homes is lower than elsewhere. Calculating by the PMV model, the predicted temperatures were 1.1 K and 0.6 K lower than that observed in climate chamber and in offices, respectively, but 1.1 K higher in homes. It should be noted that the predicted temperatures were quite constant everywhere, while among observed neutral temperatures differed by up to 2°C. The discrepancies between the three environments, and between the observed and the predicted results were claimed to be explained by two personal and four environmental parameters affecting thermal comfort, and possibly, the difference of furnishings. The earlier study by Rohles and Wells [1977] showed that the presence of furnishings could make people feel warmer.

In the second phrase, the subjects had to indicate their clo and met and the averages were 0.8 clo and 1.2 met in offices, and 0.7 clo and 1.1 met in homes. These personal factors had similar values to those in the phrase one. The similarity of clothing maybe explained by the same clothing worn at homes as in offices on the working days. The activities in homes were comparatively broad including non-sedentary activities and eating, and they were light activities. Mean air temperature in offices was 21.7°C and was higher than in homes (20.2°C). This re-confirms that lower temperatures were found comfortable in the homes. The average thermal sensations of the subjects in both offices and homes are identical at 0.6, meaning between "neutral" and "slightly warm". In this phrase, the statistical analysis cannot produce the neutral temperature, because there was no relationship between the thermal sensation and operative temperatures in both offices and homes.

Oseland [1998] conducted field surveys of thermal environments in eight naturally ventilated and eight air-conditioned offices located throughout England during winter and summer. In total, 3055 subjects made 20955 thermal subjective responses, using the ASHRAE scale and the seven-point preference scale. Mean clothing insulation (including a chair insulation of 0.13 clo) was 0.91 clo in winter and 0.63 clo in summer, and mean metabolic rate was 1.26-1.27 met in both seasons, or just slightly higher than the normally assumed level of office activity (1.2 met). In summer, mean indoor temperature of air-conditioned buildings was 23.2°C and was approximately 1 K lower than that of naturally ventilated buildings, but both means were fairly similar in winter at 22.3-22.6°C.

The results showed that the subjects voted "neutral" sensation in winter, but close to "slightly warm" in summer. The analysis used weighted regression technique to compute the neutral temperature and the acceptable temperature range[11]. Surprisingly, the neutral temperatures in N/V (22.3°C in winter and 21.1°C in summer) were lower than those in A/C (23.0°C in winter and 22.9°C in summer). The neutral temperatures in A/C were similar in both seasons, whereas unexpectedly 1.2 K lower in N/V summer. This finding is not as prescribed by the adaptive theory. The possible explanations are that the previous use of the thermal sensation scale is affecting subjects to their subsequent votes in the longitudinal surveys, and the coarseness of the seven-point scale forces subjects

[11] The acceptable temperature range is defined as a range of temperatures regressed from the votes between -0.5 and +0.5 of the ASHRAE scale. This assumes 90% satisfaction.

to give a higher/lower than requirement such as only one-quarter or one-half of thermal sensations.

For the acceptable temperature range, the N/V subjects had a considerably wider range (4.9 K) than the A/C subjects (2.6 K) in winter. In summer, the acceptability range was relatively similar (3.9 K in N/V and 3.3 K in A/C). This is advocated by world-wide research which indicates that occupants are more tolerant in naturally ventilated than in air-conditioned offices, and therefore, find their conditions satisfactory. The direct question on thermal acceptability gave the relatively high percentage of the acceptable responses (varied from 69-76%).

Analysis of the preference scale revealed that the preferred temperatures were generally higher than the neutral temperatures, except that in A/C summer. The comparison between the observed findings and the predicted results from the PMV model of the summer data showed a discrepancy of up to 3 K in N/V buildings, and 1.8 K in A/C buildings. This was suggested that the application of the PMV model perhaps was not appropriate for naturally ventilated offices in summer (as suggested by de Dear [1994]); and the discrepancy may be due to the anomaly in weather and the resulting offset in the observed neutrality in this study.

Nicol and Kessler [1998] investigated the perception of comfort on three different floors of the administrative office (the Wilson Building) of the Open University. The number of staff in each floor was approximately 30 subjects, with slightly more females than males. Each floor used different environmental control strategies: the first floor is a single open-plan office and applies night ventilation and thermal mass; the second floor consists of standard cellular offices with 60% glazing; and the third floor of an open-plan office uses mechanical cooling units. The surveys were conducted in August to October, when the season changes from summer to autumn. The study asked the staff's satisfaction with their environment, their opportunities to control their environment, and the self-reported productivity.

The results showed that there were variations of thermal responses between office floors and between the positions of the subjects in the open-plan office. Although an open-plan office type often leads to greater dissatisfaction

[Leaman and Bordass 1993], the first-floor subjects were the most satisfied of the three floors. The feature of the weather changing throughout different months played a significant role in the perception and adaptation of the occupants. The thermal assessments of the subjects in the third floor were better in August and September than in October, while those in the second floor were better in October. The first-floor responses were unchanged in different months but were better for the subjects close to the windows, signifying adaptive opportunities to control environment. Thermal comfort and self-assessed productivity were dependent on the level of control as well. Using linear regression analysis, the limit for comfort was found at a mean temperature of 24.0°C whereas the limit for self-reported productivity was at 26.0°C. This means that the limit for the productivity was maintained despite mild discomfort.

6.5.5 Studies of field work in Asia

In Pakistan

Nicol et al [1994] carried out longitudinal field surveys in five climatic regions of Pakistan[12] in both summer and winter seasons. The aims of the project were to examine the appropriateness of the existing design indoor temperatures recommended by the standards derived from laboratory studies, and to suggest a new standard which related indoor temperatures to local climate and season, with the aim of reducing energy consumption in buildings. There were thirty-six subjects giving 4783 data in total. Mean value of clothing level (traditional Pakistani clothing) of the subjects in summer was 0.67 clo, which was different from that of 1.17 clo in winter.

Based on the models by Humphreys [1978] (eq. 5.4) and by Auliciems [1982] (eq. 5.7) as guides, the neutral temperatures took account of the knowledge of the monthly mean outdoor temperatures (T_m). The analysis (using

[12] These are Karachi (Lower Indus Plain); Quetta (Baluchistan Plateau); Multan (southern Upper Indus Plain); Peshawar (northern Upper Indus Plain); and Saidu Sharif (northern mountains).

Griffiths' value) gave comfortable conditions differentiated by region and season, which can be calculated by the following equation:

$$T_n = 17.0 + 0.38\, T_m \qquad \text{(eq. 6.1)}$$

For Pakistani subjects, the comfort temperatures in summer varied between 26.7°C and 29.9°C, while in winter, 19.8-25.2°C. The difference of comfort temperatures between climatic zones and between seasons averaged about 7 K throughout the country. It was explained by the change in clothing insulation[13] and the change in mean air velocity. In practice, using the above equation (eq. 6.1) for designing indoor temperatures, the energy consumption was expected to show savings of approximately 20-25%. The preferred temperatures were somewhat below the comfort temperatures in hot conditions and above comfort temperatures in cold conditions.

The study also found that, in summer, normal air velocity gave cooling equivalent of a shift of up to 4 K, but high humidity was perceived as increasing hotness in environments by the equivalent of 2 K. In the winter, air movement and humidity showed no significant effect.

Humphreys [1994c] conducted a transverse survey — a small investigation to supplement the main project of Nicol et al [1994]. One hundred office workers gave their subjective warmth responses in Mingora and Peshawar in the north-west of Pakistan. The results from the study showed that mean comfort votes in summer were not different from those in winter, although mean air temperatures of the two seasons were 6-10 K different. The mean votes were clustered around "neutral" sensation. Using Griffiths' value in analysis, the range of neutral temperatures was from 15.6°C to 26.4°C. The success in achieving thermal comfort over a wide range of prevailing temperatures was explained by the flexibility of Pakistani traditional clothing: the number of garments to wear and the material used for different seasons.

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[13] A change in clothing insulation of 0.5 clo implies a change of comfort temperature of 3.5-4.0°C [Humphreys 1970].

In India

Sharma and Ali [1986] studied thermal comfort of Indian subjects and proposed the Tropical Summer Index (TSI), which was expressed by a mathematical equation and was found to be easy in application. The study was carried out by field surveys of eighteen subjects giving their thermal sensation within the prevailing environmental conditions during the summer months at the Central Building Research Institute in Roorkee. The subjects were able to record the environmental data by themselves. The observations were taken over a period of a month and each subject could collect around 270-300 data sets. The subjective rating scale used was the Bedford scale.

Using multiple regression analysis, the Tropical Summer Index takes four environmental variables[14] into account and a simple equation for the rapid determination of TSI is:

$$TSI = 1/3\ T_w + 3/4\ T_g - 2\ V^{1/2} \qquad \text{(eq. 6.2)}$$

where TSI = Tropical Summer Index (numbering in sensation scale of 1 to 7)

T_w = wet-bulb temperature

T_g = globe temperature

and V = air velocity.

In practice, It calculates a dry-bulb temperature as the neutral temperature at 50%rh. Therefore, the Indian subjects were found to be slightly cool, comfortable and slightly warm at approximately 23.5°C, 28.0°C and 32.5°C, respectively.

Analysis by using probit technique was also performed and it found that the maximum percentage of votes for the "comfortable" sensation occurred at 27.5°C, which was in good agreement with the TSI model. The changeover from "comfortable" to "slightly cool" was at 24.7°C, and that to "slightly warm" at

[14] Globe temperature (T_g) takes account of air temperature and radiant heat; wet-bulb temperature (T_w) takes care of humidity; and square root air velocity ($V^{1/2}$) of air movement.

30.0°C. The subjects felt "too warm" when the temperature was at 33.9°C. Thermal acceptability (80% of "comfortable" subjects) was within a range of 25.0-30.0°C with 30-70%rh.

In Bangladesh

Mallick [1996] performed a field study of occupants in urban housing in Bangladesh and found that tropical subjects' comfort could still be measured at high temperatures and very high humidities. The thermal observations were made in homes where the occupants went about their daily lives. Due to the natural ventilation and the use of ceiling fans in many homes surveyed, the significant environmental parameter was air flow and this was measured under different speed settings. The activity in ordinary domestic situations and the lightness of the traditional clothing was approximated at 0.8-1.2 met, and 0.5 clo, respectively. Thermal assessments were made by using the Bedford scale.

The results showed that the tolerance of the subjects was wide with high temperatures of 24-32°C and high relative humidity up to 95%. The comfort temperatures were correlated well with the speed of air movement at certain values. There was no appreciable change in comfort for a lower velocity of 0.15 m/s, but for the air flow of 0.3 m/s, there was a rise in comfort range (around 2 K). However, at a higher air flow of 0.45 m/s, the comfort range was less (around 1 K). Using linear regression analysis, the neutral temperature was at approximately 28.0°C and the range between the central three categories was between 22.8°C and 33.9°C. The study concluded with the recommended design criteria of thermal mass (thickness of walls), exposure to the outside conditions, orientation of rooms, and cross ventilation, as passive means for urban housing in hot-humid climates [Mallick 1994].

In Hong Kong

Chow and Lam [1992] conducted field measurements in commercial buildings in Hong Kong and evaluated actual thermal situations. The measured locations included offices, hotels, convenience stores, a department store and a hospital. The thermal surveys in summer found that most places were over-cooled by 3-4 K. The low temperatures in buildings caused *thermal shock* when the occupants moved between inside and outside of buildings, and at the same time, energy consumption to cool buildings was wasted. The research implied that Hong Kong people have experienced cool environments for most of the year by becoming accustomed to air-conditioned environments (or addicted to air-conditioning). The study suggested that if the temperature settings could be changed from 21.5°C to 25.5°C, energy could be saved up to 29% of the total, and thermal "cool discomfort" could be reduced. With the new settings of thermal control, it was believed that the condition of living would respond to and well correlated with the local micro climate.

Chan et al [1998] carried out a large-scale survey of thermal comfort in office premises in Hong Kong. All thirteen buildings surveyed were air-conditioned. There were a total of 2173 subjects in summer and winter seasons. Mean clothing insulation (including a chair insulation) in winter was 1.01 clo and was higher than that in summer of 0.73 clo. The set temperatures in many buildings were lower than the standard recommendation, and this energy used was compensated for by a comparatively high clothing insulation. Linear regression technique with operative temperature was used to determine neutral temperature. In summer, the regressed neutral temperature was 23.5°C, and in winter, 21.5°C. Probit analysis was used to determine preferred temperature, and it was reported that the preferred temperature in summer was 22.5°C and in winter, 20.8°C. Although the existing environments were *overcooled*, the subjects yet preferred to be "cooler". The findings of cool preferences in this study was possibly explained by the social background and subtle business cultures of Hong Kong whereas the effect of the geographical zones was of secondary significance.

6.5.6 Studies of field work in Southeast Asia

In Thailand

Busch [1990a;1992; 1995] conducted a field study of thermal comfort in air-conditioned and naturally-ventilated offices in hot and wet seasons in Bangkok, Thailand. Mean indoor air temperatures of A/C buildings was 23.7°C, and was much different from that of N/V buildings of 30.8°C. Average air-velocity in A/C was 0.13 m/s, but that in N/V was 0.33 m/s due to the use of local fans (2.25 m/s). High humidity in terms of vapour pressure was found in N/V of 24.3 Torr[15] but in A/C of 13.2 Torr. There were 1146 subjects in total, giving thermal responses. Two subjective ratings scales, the ASHRAE scale and the McIntyre scale[16], were used.

The results showed that there was no significant difference of the findings between seasons, but the pronounced discrepancy of the neutral temperature was found between subjects of A/C and N/V groups. Using linear regression analysis, the neutral temperature of A/C group was 24.7°C ET*, and that of the N/V group was 27.4°C ET*. For the combined data, the neutral temperature was estimated at 25.0°C ET*. Thermal acceptability, defined as 80% of the responses within the three central categories of the ASHARE scale, was between 22.0°C and 28.0° C in A/C buildings, and for N/V buildings, the lower boundary was undefined but the upper boundary was approximately at 31.0°C. Analysed by probit technique, the transition temperature and the width of the thermal sensation scale could be estimated. The transition from "slightly cool" to "neutral" took place at approximately 22.5°C; from "neutral" to "slightly warm" at 27.5°C; and from "slightly warm" to "warm" at 33.5°C. Therefore, the width of the "neutral" and "slightly warm" categories was 5 and 6 K, respectively. The McIntyre scale was cross-tabulated against the ASHRAE scale to examine the relationship between "preference" and "neutrality". For both building types, the subjects' response to preferred conditions was closer to "slightly cooler" than "neutral".

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[15] Pressure: 1 Torr = 1.333 millibar [Yarwood 1967].

[16] The McIntyre scale is a three-point preference scale ("I would like to be ... warmer ... no change ... cooler").

In Singapore

De Dear et al [1991c] carried out field surveys both in naturally ventilated dwellings and in air-conditioned office buildings in Singapore. In N/V apartments, there were 583 subjects, wearing mean clothing insulation of 0.26 clo[17] and performing mean metabolic rate of 70 W/m² (or 1.2 met). Mean environmental variables were: air temperature 29.6°C, relative humidity 74%, and air velocity 0.22 m/s. In A/C office buildings, there were 235 subjects with average clothing insulation of 0.44 clo and mean metabolic rate of 67 W/m² (slightly passive). Mean radiant temperatures measured in A/C buildings were on average 1 K warmer than air temperatures, resulting from high solar radiation combined with low thermal mass and large areas of glazing in the office buildings surveyed. Mean environmental parameters were: air temperature 23.5°C, relative humidity 56%, and air velocity 0.11 m/s. The seven-point sensation scale were used to assess subjective warmth responses.

The results reported that the mean vote in N/V was +0.66, which was between "just right" and "slightly warm", and the neutral temperature is 28.5°C (operative temperature — T_o) while the mean vote in A/C was -0.34, which was on the cool margin of "just right", and the neutral temperature was 24.2°C (T_o). Discrepancy between thermal comfort responses in apartment blocks and office buildings was explained in terms of contemporary perceptual theory. In other words, a difference in thermal comfort in naturally-ventilated and air-conditioned environments could not be accounted for in terms of the basic heat balance variables, but seemed consistent with a psycho-physiological model of thermal perception [Auliciems 1981] in which building occupants' indoor climatic expectations vary from one context to another.

[17] The clothing insulation of 0.26 clo refers to the casual dress with the typical male ensemble consisting of shorts and T-shirt, and the typical female ensemble of a light skirt and blouse.

In Indonesia

Karyono [1995a; 1995b; 1996a; 1996b] conducted a field study in seven multi-storey office buildings in Jakarta, Indonesia. Five of them were air-conditioned, one was naturally-ventilated and one was a hybrid buildings. There were 596 subjects in the surveys, responding on the thermal sensation seven-point scale.

Using linear regression analysis, the neutral temperature for the combined data was 26.5°C (T_a) or 26.8°C (T_o) or 25.6°C (T_{eq})[18]. The neutral temperature from the actual votes was approximately 1 K lower than that calculated from the PMV model. The range of the comfort zone, defined as temperatures within the votes between -1 and +1 of the ASHRAE scale, was found between 23.8°C and 29.3°C (T_a). When compared the subjects' percentage of dissatisfaction, the temperature at the lowest actual value was approximately 1 K higher than that of the PPD model. It was concluded that the comfort standard overestimated the actual findings, and suggested that properly designed buildings would be able to provide indoor comfort without using air-conditioning, because the comfort range of the workers lies closely to the prevailing outdoor temperatures.

6.5.7 Other field studies

In Athens

Baker and Standeven [1996] conducted field monitoring surveys in free-running buildings (mainly in Athens), aiming at developing comfort criteria based on a considerable amount of adaptation. There were more than 1500 longitudinal data collected linking thermal environmental conditions to subjective responses of warmth. The results showed that a large number of subjects were satisfied at a range of operative temperatures between 27.8°C and 30.5°C, which was far higher than expectation from conventional comfort theory. Although clothing was not used to improve comfort on this timescale, subject adaptations such as

[18] Equivalent temperature (T_{eq}) is defined as a temperature measured as a combination effect of air temperature, mean radiant temperature and air velocity.

drinking cold beverage or building adaptations namely opening doors or windows and using fans, made an impact on human comfort. The external conditions also affected the subjects' thermal expectations. The study further suggested that the cumulative effect of adaptive errors (see Figure 4.9; and discussion in 9.3.4 and 9.5.3) and the psychological adaptation (i.e., adaptive opportunity, cognitive or evolved tolerance — see 5.5.6) could be biased towards improving comfort.

In Zambia

Malama [1997]; Sharples and Malama [1997] reported a field study of thermal comfort in traditional and contemporary housing in Zambia, which has a tropical upland climate. Two surveys were carried out in both cool and warm seasons. A total of 43 subjects gave 3800 thermal response data sets in the longitudinal survey. Mean clothing insulation of the subjects in the cool season was 0.70 clo, while that in the warm season was 0.50 clo.

The results revealed that the mean comfort vote using the Bedford scale, in the cool season was -0.6 ("neutral" to "slightly cool") and in the warm season was 0.7 ("neutral" to "slightly warm"). Using linear regression analysis, the neutral temperature was 26.0°C in the cool season, and surprisingly, cooler 25.2°C in the warm season. When the comfort temperature was calculated by using Griffiths' equation (eq. 5.13), it yielded 22.2°C for the cool season and 25.4°C for the warm season. The preferred temperature, using seven-point preference scale, was also regressed on globe temperature and it yielded 29.7°C for the cool season and 23.0°C for the warm season, indicating that the subjects preferred temperatures higher than the comfort temperature in the cool season and a cooler in the warm season.

Malama et al [1998] investigated the above results and concluded that the main forms of adaptation and adjustment in the cool season were clothing and environmental controls, while in the warm season, only environmental controls were used. These controls were such as opening the doors, windows or curtains.

In a comparison between traditional and contemporary housing, in the cool season the contemporary houses performed better than the traditional ones [Malama and Sharples 1997], because there were more subjective responses within the central three categories in the contemporary housing. However, in the warm season the situation is the opposite. The explanation of this could be the characters between two housing types. All traditional houses had openings between the roof and the wall plate where cool air from outside could circulate freely inside the houses. The contemporary houses on the other hand were designed in such a way that the outside environment could easily be shut off.

In Hawaii, USA

Kwok [1998] conducted a field study of tropical classrooms in Hawaii. Subjects of the surveys were 3492 students and 52 teachers in 29 naturally ventilated and air-conditioned classrooms of six schools. They wore average clothing of 0.41 clo, with variations from 0.36 clo in hot season of N/V rooms to 0.51 clo in cool season of A/C rooms. Subjective measurements consisted of the ASHRAE scale, the McIntyre preference scale and the direct question on thermal acceptability.

It was found that thermal conditions ranged in terms of new effective temperature (ET*) from 23.1°C to 30.9°C in N/V environments and from 19.7°C to 27.7°C in A/C. The mean thermal sensation vote for the A/C subjects was -0.9 (slightly cool) but for the N/V subjects was 0.2 (neutral). Probit regression analysis was used to determine neutral temperature, and surprisingly, the neutral temperature of N/V (26.8°C ET*) was lower that that of A/C (27.4°C ET*). The preferred temperature, defined as the intersection of "want warmer" and "want cooler", of N/V was 24.3°C and of A/C was 23.2°C. This supported the hypothesis that there was a climate-based semantic *bias* in people's thermal responses [McIntyre 1978b].

From the direct question on thermal acceptability, it was found that very high percentage of the subjects indicated their environments acceptable. This was coincided with the high measurement by indirect method, which assumed the responses in the central three sensation categories as thermal acceptability. However, if considered thermal preference vote of "no change" as the acceptable condition, there was quite low percentage. The acceptability range of 80% of the subjects was approximately at 22.0-29.5°C (T_o) in the N/V and at 23.0-28.5°C (T_o) in the A/C. The findings from this study were not in good agreement with the comfort criteria specified in the standard.

6.6 Summary

From various case studies of thermal comfort research using both climate chamber experiments and field studies, there is a lack of consensus in the findings concerning comfort criteria. This includes the results from tropical regions. Generally, it seems constant neutral temperatures are found in chamber studies, and in contrast, the neutral temperatures vary in field studies. The former has been developed into the thermal comfort standards, whereas the latter has been proposed as the theory of adaptation.

The classic study by Fanger [1970] prescribing the comfort temperature at 25.7°C, applied to Danish and American subjects, is in good agreement with many research in the climate chambers in tropical regions namely in hot summer Japan [Tanabe et al 1987], in Hong Kong [Chung and Tong 1990], and in Singapore [de Dear et al 1991a], with the discrepancy less than 1 K. Compared with Malaysians in London [Abdulshukor 1993], the comfort standard is still a useful application. However, it cannot be used for Malaysians who acclimatise to the equatorial climate in Malaysia; the discrepancy is up to 3 K [Abdulshukor 1993]. The comfort temperature in England [McIntyre and Griffiths 1972] is also found to be lower than the standard by approximately 3 K.

Regarding the climate chamber studies, thermal acceptability of the subjects in the tropics shows a comparatively wide range. Chinese subjects in Hong Kong have the neutral zone from 22.2°C [Chung and Tong 1990], whereas Singaporeans can tolerate up to 27.9°C [de Dear et al 1991b] and Malaysians, up to 31.4°C [Abdulshukor 1993].

The findings from earlier field studies demonstrate the relationship of comfort temperatures with the environments subjects exposed to or with the outdoor air temperatures, as seen in both Humphreys' and Auliciems' models. They explain the acclimatisation to local climates of the subjects. Recent field works show that the neutral temperatures vary from 17.0°C in homes in England during winter season [Oseland 1994b] to 28.5°C in naturally-ventilated apartment blocks in Singapore [de Dear et al 1991c]. This evidence shows a confident argument for the adaptation of the subjects by various means namely clothing or activity (posture) adjustments, individual controls, and more importantly, psycho-physiological perception such as expectations and adaptability to local climates.

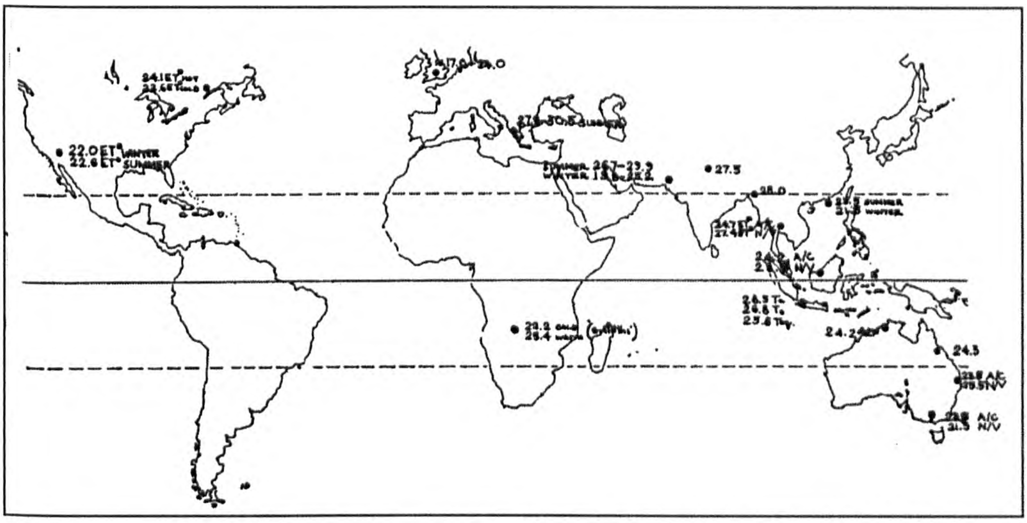


Figure 6.4 *Neutral temperatures established from field studies across the globe. (The map does not include Hawaii of 26.8ET* N/V and 27.4ET* A/C).*

Figure 6.4 summarises the neutral temperatures established from various field studies across the globe from literature reviews in this chapter. In general, the neutral temperatures in winter are lower than those in summer, but in some cases namely housing in Zambia [Malama 1997] and office in UK [Oseland 1998] have the opposite findings. Also, air-conditioned environments have lower neutral temperatures than naturally-ventilated ones, but surprisingly, the findings are opposite in the N/V and A/C classrooms in Hawaii [Kwok 1998]. Theoretically, this is explained by some errors of the regression analysis technique [Humphreys 1998].

Compared with the findings from the standards (ISO 7730-1994 and ASHRAE 55-1992), the neutral temperatures in air-conditioned environments are in good agreement, but those in naturally-ventilated are significantly higher. However, the exceptional case is in Hong Kong [Chan et al 1998], where the comfort finding is much lower than the standards. Thermal acceptability of the tropical subjects is also much higher than the standards, reporting the tolerance up to 30°C or above. The lower limit of the acceptability appears at approximately 22°C. Regarding thermal preference, the subjects in warm climates prefer lower temperatures than the neutral temperature, while those in cold climates are opposite.

The published literature of many case studies helps understand the conditions of thermal comfort on world-wide basis. It clarifies the thermal requirement of man in different places and climatic regions. Recent research indicates not only environmental and personal parameters affecting human comfort, but also some factors of psychological feedback namely habituation, expectation and preference or non-thermal factors such as culture, context of buildings and environmental interactions [Brager and de Dear 1998]. This will be dealt with in the main work of this thesis: investigation of thermal comfort in transitional spaces in Chapters Seven to Ten.

Chapter 7

THERMAL COMFORT SURVEYS IN BANGKOK

"It is important to examine thermal comfort in the context of tropical developing countries because of the concentration of world population and growth there ... the conditions are so different (from the West) in most developing countries in terms of race, age distribution, climatic experience and perhaps expectation ..."

J. F. Busch [1990b]

7.1 Introduction

The following four chapters will investigate, analysis and discuss the field work on thermal comfort in Bangkok, as well as give suggestions of applications to use in practice, which is the main part of this thesis. There are two comfort surveys: the first was in December 1996 and January 1997, which was considered as the cool season and the second one in April 1997, the warm season.

This field study is undertaken as a programme to analyse comfort in air conditioned and naturally ventilated environments. In particular, the expectation and experience of thermal comfort in transitional spaces of buildings will be discussed. The research areas are inspired by the combination of the two previous studies: the dominant characteristics and significance of transitional spaces in tropical architecture, and the new approach to thermal comfort study by the Adaptive Model.

This chapter will report the general background, aims of the research and climatic characteristics of Bangkok. The methodology of the field study will be explained, relating to human subjects; choices of buildings and areas of surveys; equipment used and measurement; questionnaires and procedure of the surveys. Results from the surveys will show the profiles of environmental and personal data, as well as the subjective thermal responses (including: expectation, sensation, preference, and adaptation to achieve comfort) of the subjects in their environments.

7.2 Background

This field study is a work following up the previous thermal comfort study in Bangkok, Thailand in 1988, reported by Busch [1990a; 1990b; 1992; 1995]. The environments and the analysis of thermal comfort are considered a decade after the initial surveys in order to examine what changes in the comfort responses have occurred. This study is also to complement the comfort criteria in a sequence of "in-between" zones of the external and the internal to and from the office environments done by Busch.

Thermal enquiries in the field surveys are arranged in series of *expectation*, *sensation*, *preference* and *adaptation*. The four concepts represent a complex interplay in thermal comfort research, thereby searching for the resolute structure of thermal comfort prediction. Fountain et al [1996] suggested that the research should be required to examine the influences of culture and climate, associated with these four concepts. Auliciems [1981] mentioned to explore not only traditional assumptions of physiological responses, but also the recognition of higher levels of mental integration of information flows, i.e., parameters of past cultural and climatic experiences and expectations.

Concerns about the environments and energy consumption have increasingly been realised. Large amounts of energy resources have been used to provide cooling of built environments; sometimes this is merely to provide excessive levels of comfort or convey some levels of prestige for occupants in air-conditioned environments [Cowan 1993; Prins 1992].

Therefore, it is hope that the findings from this research will suggest the optimum comfort conditions, which apply less energy consumption but provide satisfaction to all subjects; and will give design recommendations by passive methods in consideration of built environments with climatic responses.

7.3 Objectives of the field study

The field study aims to contribute to the knowledge of thermal comfort, as one of many research exercises for the well beings of mankind. According to Fanger [1970], the reasons for creating thermal comfort are mainly twofold: first is to satisfy human desires to feel thermally comfortable and second is justified from human performance namely intellectual, manual and perceptive performance at his or her highest range.

Since thermal function of a building could be used as an effective element of design, hypothesised by Heschong [1979], thermal qualities should be included in initial concept and all phases of design. In terms of building services engineering, thermal comfort is one of a number of criteria that have a significant role in facilities management as well as during the design process (be it new build or refurbishment) [Irving 1994].

The investigation will suggest the relationship between thermal expectation and experience, thus producing comprehensive patterns of human thermal behaviour. These patterns will reflect the human physiology and psychological adaptation in responses to the actual environments. The comfort findings could then be used to explain and compare with the other results from other literature of thermal comfort.

Especially in this research — in transitional spaces, it will make recommendations in complementary functions to the whole building project for the optimal conditions in built environments. The suggestions will enhance designers' confidence in thermal quality applied by particular passive means for their architectural design, thereby achieving thermal comfort as a priority.

7.4 Climatic characteristic of Bangkok, Thailand

Thailand is situated in Southeast Asia, which is classified as a hot and humid tropical region. A general characteristic of the climate[1] is an equatorial in the extreme south, and a tropical monsoon in the centre and the north [Pearce and Smith 1984]. There are three seasons yearly, which the rainy season is largely confined to the months of May to October. The winter season is very short and not very cool in the months from November to January, and the summer season is between February and May, and the extremely hot month is in April.

Bangkok (in Figures 7.1 and 7.2), the city in this field study, is the capital city of Thailand. It is situated at latitude of 13°45' north and longitude of 100°28' east, with altitude of 2.00 metres. The climatological data of Bangkok are given in details by Pearce and Smith [1984] and the Royal Thai Meteorological Department [1993; 1994], as follows:

[1] Details of the general climatic characteristics of both equatorial and tropical monsoon can be seen in Chapter Two (see 2.2.2).

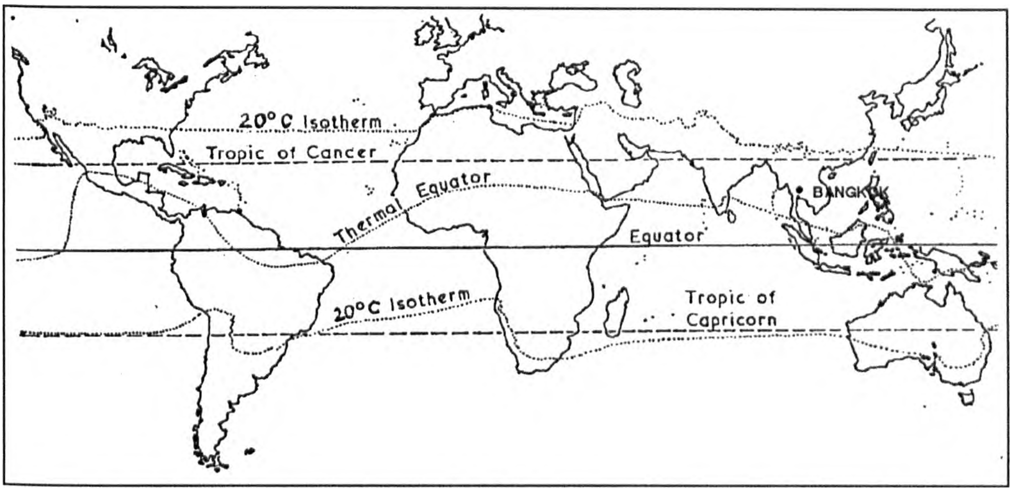


Figure 7.1 *Map of the tropical regions indicating Bangkok.*
(After Oakley 1961)

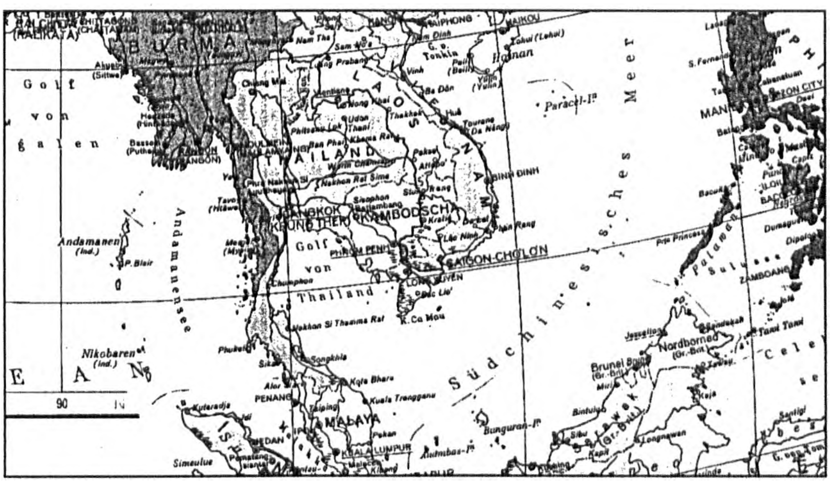


Figure 7.2 *Map of Thailand and its neighbours.*
(After McGraw-Hill International Atlas 1961)

1. Air temperature: mean annual temperature is about 28°C. The mean maximum temperatures are between 31 and 35°C and the mean minimum are between 20 and 25°C. The diurnal range of temperature is around 7-11 K.

2. Relative Humidity: mean relative humidity is relatively high with the maximum between 90 and 94% in the morning, and the minimum between 53 and 70% during the day. The mean annual relative humidity is about 74%.

3. Precipitation: Thailand has abundant but not excessive rainfall in the rainy season. Annual rainfall is around 1500 to 1600 mm and may exceed 400 mm in the wettest month.

4. Sky conditions: sunshine levels are about 9-10 hours a day, except during the months from June to September when in the wet season, at 4-5 hours a day. Cloud cover varies between 50 to 70% and mean cloudiness (0-10) is 7.4.

5. Wind: a general prevailing wind blows from the south with mean speed of 2.5 knots or around 1.3 m/s. The annual winds from south-west come from the India Ocean blowing during summer and from north-east from China and Indo-China during winter.

7.5 Methodology of the field surveys

The "Field Study" of thermal comfort [Nicol 1993] is the methodology used for the surveys. Its principle is to establish thermally comfortable conditions, corresponding to normal human thermal experiences in their daily-life. The method is based on the observations in the actual environments and the procedure is to measure all physical quantities both environmental and individual parameters, and simultaneously to collect the subjective comfort responses of the respondents from the surveyed questionnaires.

7.5.1 Respondents

This field study uses the transverse design survey, thereby collecting a large number of responses to make an assessment. All respondents in the field surveys are of Thai nationality, who are in the actual environments of the buildings surveyed. There is no restriction according to age, gender and any other feature of the subjects; as well as on the clothing to wear or the activities to perform. During the completion of the questionnaires, the respondents are in the vicinity of the equipment used for taking environmental parameters measurements.

The study dealt with four groups of subjects, responding to their individual thermal environment in and around transitional spaces. These four groups are those entering from outdoors into air-conditioned transitional indoor environments (A/C-indoor), those entering from outdoors into naturally-ventilated transitional indoor environments (N/V-indoor), those who are leaving indoor air-conditioned environments to outdoor transitional spaces (A/C-outdoor), and those who are leaving indoor naturally-ventilated environments to outdoor transitional spaces (N/V-outdoor) (also see 1.3; and Figure 1.2).

7.5.2 Building choices and areas studied

All buildings selected for this field study are in Bangkok and the distances between them are not more than 15 kilometres. They are five buildings of two types: two naturally ventilated and three air-conditioned.

Two naturally ventilated buildings are:

1. Faculty of Architecture, Silpakorn University (building no. 1) (in Figure 7.3): a six-floor building of an architectural school and student studios. The outdoor surveyed condition is at the entrance canopy and on the benches at the front of the building. The area has two or three big trees which give shade all day and a fish pool underneath the platform of the canopy as evaporative cooling. The indoor surveyed condition is in a lobby hall, functioning as a foyer to various lecture rooms and a staircase leading to upper levels. There is light breeze passing through the area.

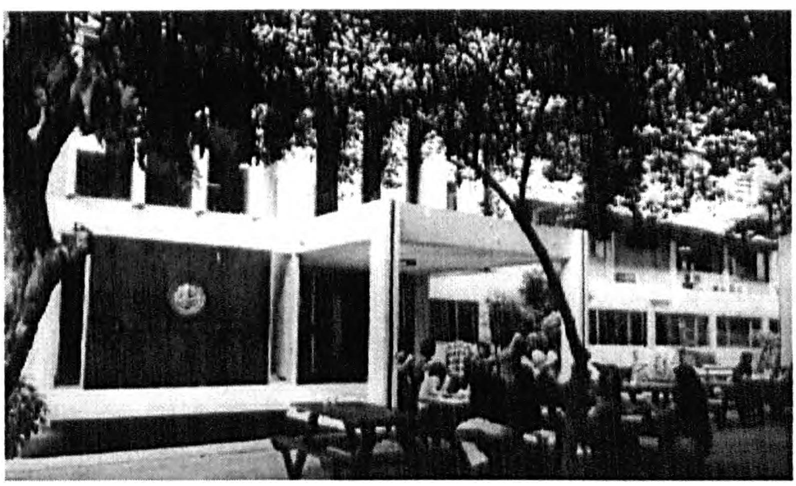


Figure 7.3 *Faculty of Architecture, Silpakorn University.*

2. Office of the Civil Service Commission (building no. 2) (in Figure 7.4): a medium-rise government building. The exterior surveyed condition is at the entrance canopy, which acts as a porch for people arriving the building by car and on foot. If this space is compared with that of the architecture school, here is less pleasant because it is a hard landscape of pavements and no big trees to give shade, but only few bushes. There is air pollution from cars' exhaust, too. During the day-time, the sun-light shines on the platform of the canopy, thereby creating much solar radiation. Many respondents therefore have to avoid the direct sun-light and stay in the shaded area, when they fill in their questionnaires. The indoor surveyed area is in the foyer which leads to various parts of the office, a stairway and an elevator. Light breeze ventilates from the rear of the foyer, which is pleasant.

Figure 7.4 *Office of the Civil Service Commission.*

Three air-conditioned buildings are:

1. SAI Consultants Co. Ltd. (building no. 3) (in Figure 7.5): a small architect office adapted from two units of a row of terrace houses. The indoor condition is fully air-conditioned. The space surveyed is at the entrance hall, which functions as a reception area. The outdoor surveyed condition is totally different from the interior; the direct sun-light shines on the facade, where there is only a small area shaded (on a recessed entrance) and therefore the respondents have to fill their questionnaires on the opposite site of the office.

This building is surveyed only in the cool season and there are a few thermal responses in the analysis.

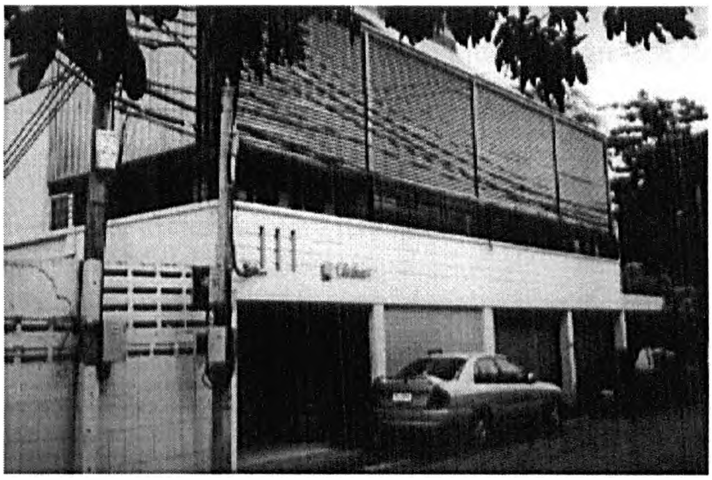


Figure 7.5 *SAI Consultants Co. Ltd.*

2. Sathon Thani Building (building no. 4) (in Figure 7.6): a high-rise office building in a business district centre. The indoor surveyed condition is in the lift-lobby. The surveyed area is not actually hermetic air-conditioning, but the cool air of A/C units indirectly comes from eight elevators of the lobby and from an air-conditioned bank nearby, on the ground floor. The exterior surveyed condition is on a large terrace platform at the front of the building. In the afternoon when the sun moves via south, many respondents have to avoid the direct solar radiation, and fill in their questionnaires in the shaded area.

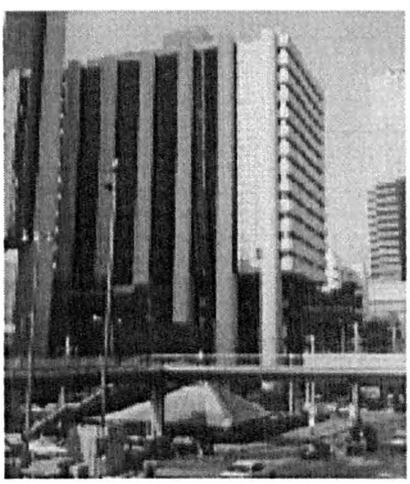


Figure 7.6 *Sathon Thani Building.*

3. Central Department Store, Pinklao Branch (building no. 5) (in Figure 7.7): a medium-rise complex shopping centre and a high-rise office building (at the rear of the complex). The building is fully hermetic air-conditioned. The indoor surveyed condition is in the atrium on the lower ground floor, where it is used as multi-purpose area. The outdoor condition is on the front platform of the building on the ground level. There is no direct sun-light shining on the surveyed area due to the building itself acting as a shading device.

Figure 7.7 *Central Department Store, Pinklao Branch.*

In summary, the area surveyed is "transitional spaces" both inside and outside the buildings. It is considered as transitional in time (i.e., spaces where people pass through). Information on the spaces can be read in Chapter Three. A schematic diagram of the spaces is shown in Figure 7.8.

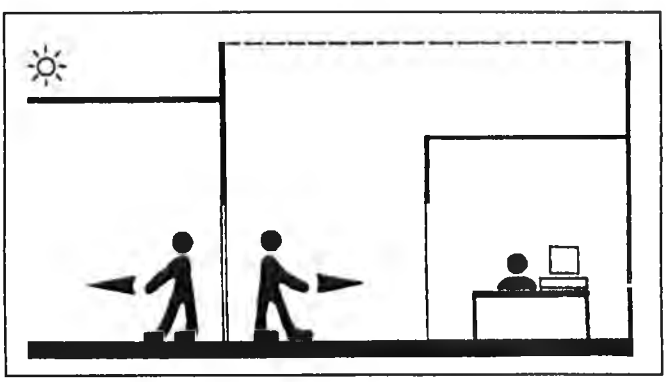


Figure 7.8 *A schematic diagram of the transitional spaces in the field study.*

7.5.3 Equipment and measurement

The measurements of the environmental parameters are taken and later plotted onto climatic data sheets. These physical quantities are air temperature (T_a), globe temperature (T_g), relative humidity (rh) and air velocity (v).

The main pieces of equipment used in the surveys are Skye Data Hog, SDL, a data-logger in which the readings of air temperatures and relative humidities are gathered and stored, automatically. The globe temperatures are taken by using one channel of the data-logger and using a 38-mm-diameter table-tennis ball as the globe. Air velocities are measured by an air-flow meter, Solomat MPM 500e. A detailed description of the instrumentation with accuracy is shown in Appendix A.

The set of equipment is shown in Figure 7.9.

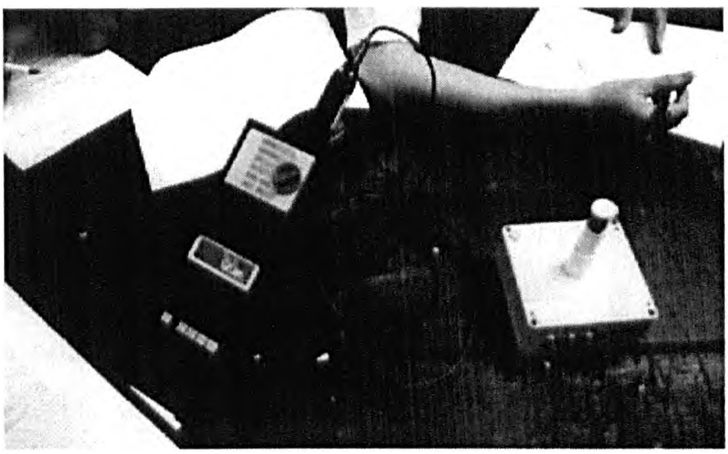


Figure 7.9 *The equipment used in the field surveys.*

The sessions of the field surveys in the cool season are within six days:

- 06 December 1996 at Faculty of Architecture, Silpakorn University;
- 11 December 1996 at Faculty of Architecture, Silpakorn University;
- 12 December 1996 at Office of the Civil Service Commission;
- 13 December 1996 at SAI Consultants Co. Ltd.;
- 09 January 1997 at Sathon Thani Building; and
- 10 January 1997 at Central Department Store, Pinklao Branch.

The sessions of the field surveys in the warm season are within four days:

- 21 April 1997 at Faculty of Architecture, Silpakorn University;
- 23 April 1997 at Office of the Civil Service Commission;
- 24 April 1997 at Sathon Thani Building; and
- 25 April 1997 at Central Department Store, Pinklao Branch.

The individual parameters such as values of clothing insulation and activity level are observed and recorded into the survey forms, and are used in the analysis process. Each item of clothing is transferred into the clo-value according to Table E2 (Thermal insulation of individual pieces of garments) and each activity is transferred into the met-value according to Table A1 (Metabolic rate) of International Standard ISO 7730 [ISO 1994] (see Appendices B and C).

7.5.4 Questionnaires

The questionnaires contain a covering letter explaining the aim of the surveys and every question is translated into the Thai language, based on the previous surveys [Busch 1988]. The special feature in this field study is that it includes an additional question on the thermal "expectation", as the first question. This will give more analysis in terms of time-space comparative study between the expectation and experience of the previous occupied spaces (i.e., either outdoor or indoor environments) to the transitional spaces. Therefore, the questions are arranged in the order of *thermal expectation, sensation, preference* and *adaptation to achieve comfort* of the respondents.

The enquiries in the questionnaires are:

1. subjective rating thermal response:
    - Expectation and Sensation, using a seven-point ASHRAE Scale,
    - Preference, using a three-point McIntyre Scale,
    - Air-Flow and Humidity, using a seven-point scale, and
    - Adaptation, allowing the open answer for the respondents to fill in;
2. activity;

3. clothing; and
4. personal information of the respondents.

The questionnaires are separated into two types (see Appendix D). The first type is used by the respondents entering the buildings (indoor type) and the second for those leaving the buildings (outdoor type). Every question is required the respondents only to tick the appropriate choices, except the part of Adaptation, which is required written comments.

7.5.5 Procedure

The field surveys were conducted within six days in the cool season (December 1996/January 1997) and four days in the warm season (April 1997) in Bangkok, Thailand. The time for the field surveys in each day was not fixed, but within the range of working hours, i.e., between 09:00 and 18:00. The procedure was repeated in every building and was based upon the "Field Study" methodology.

The areas surveyed were transitional spaces of both indoor and outdoor, in the selected buildings. The indoor conditions were entrance hall, foyer, lift lobby or atrium, and for the outdoor conditions, the surveys were taken as a special consideration, regarding the matter of sun-light and therefore, shaded areas, such as under the trees, under the canopy, or the building itself giving shade. This is because the solar radiation intensity would over-ride human sensations.

Teams carrying out the surveys had five persons. Two were in internal spaces and other two at outdoors to hand out the questionnaires to the subjects who just enter transitional indoor spaces or leaving the buildings to transitional outdoor spaces. The remaining one took the environmental measurements. These members are able to give the explanation of each question, if the respondents are in doubt. However, there was no persuasive suggestion from the members to bias the votes in any way on any thermal scales in the surveys.

7.6 Results of the surveys

7.6.1 Profile of the climatic environments

Air temperatures and globe temperatures

In the cool season, air temperatures (T_a) during the last three days (AC + cool), are cooler than those of the first three days (NV + cool), and they are the most cool conditions in this study. Globe temperatures (T_g) were only collected at outdoor conditions. The correlation coefficient of the globe temperatures is found highly correlated with the air temperatures, $r(T_a, T_g) = 0.98$. In the warm season, both air and globe temperatures are higher than those in the cool season, as they should be. The first two days (NV + warm) are the warmest environments of the field surveys. The correlation coefficient of the globe temperatures is found highly correlated with the air temperatures, $r(T_a, T_g) = 0.99$.

Figure 7.10 shows the scatter diagram between air temperature (T_a) and globe temperature (T_g).

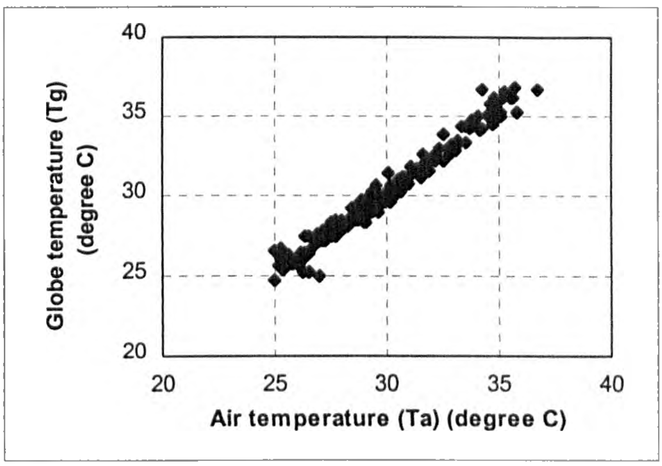


Figure 7.10 *Scatter diagram of air temperature and globe temperature.*

The data of air temperatures from this field study are plotted in Figure 7.11. (Globe temperatures (T_g) are not shown). The numbers presented in the charts indicate the buildings' numbers, and this will apply to Figures 7.12 to 7.15).

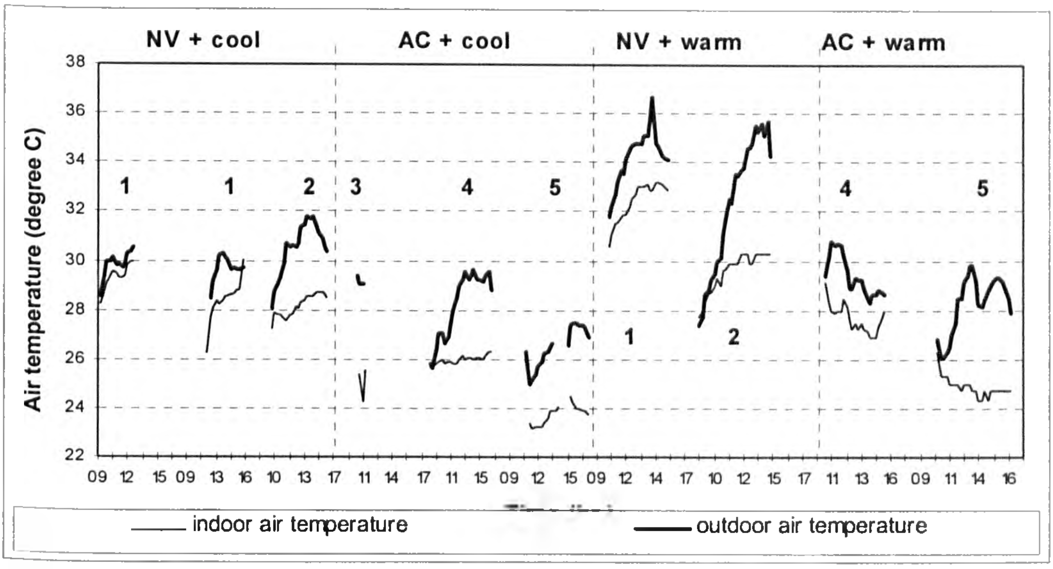


Figure 7.11 *Air temperatures of this field study.*

<u>Humidity</u>

The average of the relative humidity of every group in this study are in-between 45.4 and 65.3%, in which this range is within the comfort zone of 30 to 70% suggested by Brooks [1950] and ISO 7730 [ISO 1994]. However, the upper limit, suggested by Chalkley and Cater [1968], is slightly lower at 65%. So, the mean relative humidity of the outdoor environments of AC + warm group is somewhat beyond the comfort limit. In general, the indoor relative humidities are higher than the outdoor ones. Only the AC + warm has the opposite results, and its outdoor environments are the most humid in this field study. The data of relative humidities from this field study are plotted in Figure 7.12.

Relative humidity, defined as *"the ratio of the actual amount of moisture present, to the amount of moisture the air could hold at the given temperature"* [Koenigsberger et al, 1973], is converted into water vapour pressure. It is usually used in the analysis of thermal comfort research in order to study the exact quantity of the moisture in the air. This actual quantity of water vapour pressure per unit volume of air is dependent on the temperature; the higher the temperature, the greater the capacity to hold water vapour [Chalkley and Cater 1968]. Percentages of the relative humidity (rh) can be calculated into water vapour pressure (P_a), using the following equation given by McIntyre [1980]:

$$P_a = rh\,(fraction) \cdot \exp\,[18.956 - 4030.18 / (T_a + 235)] \qquad (eq.7.1)$$

The data of vapour pressures from this field study are plotted in Figure 7.13.

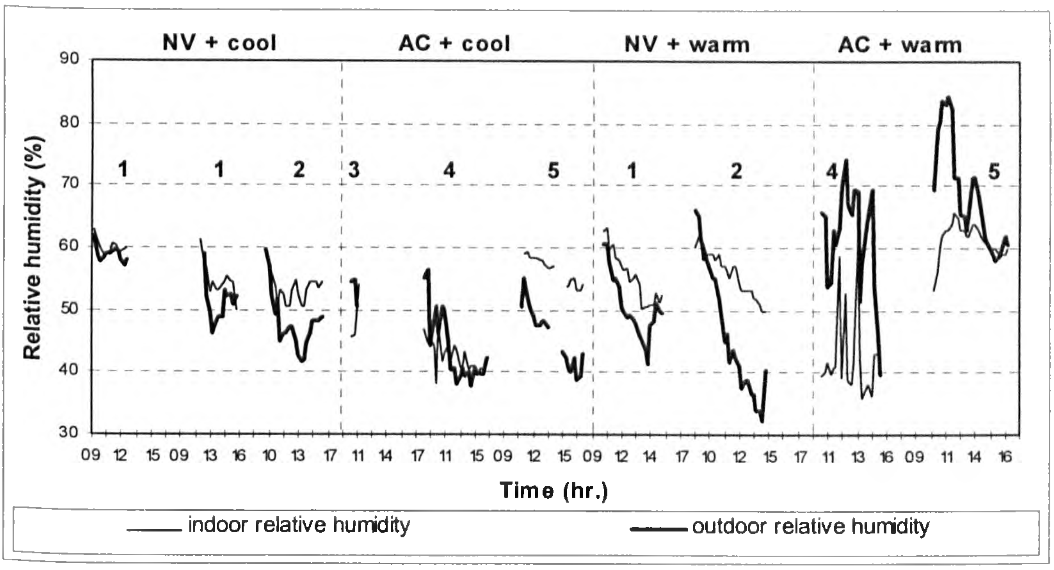


Figure 7.12 *Relative humidities of this field study.*

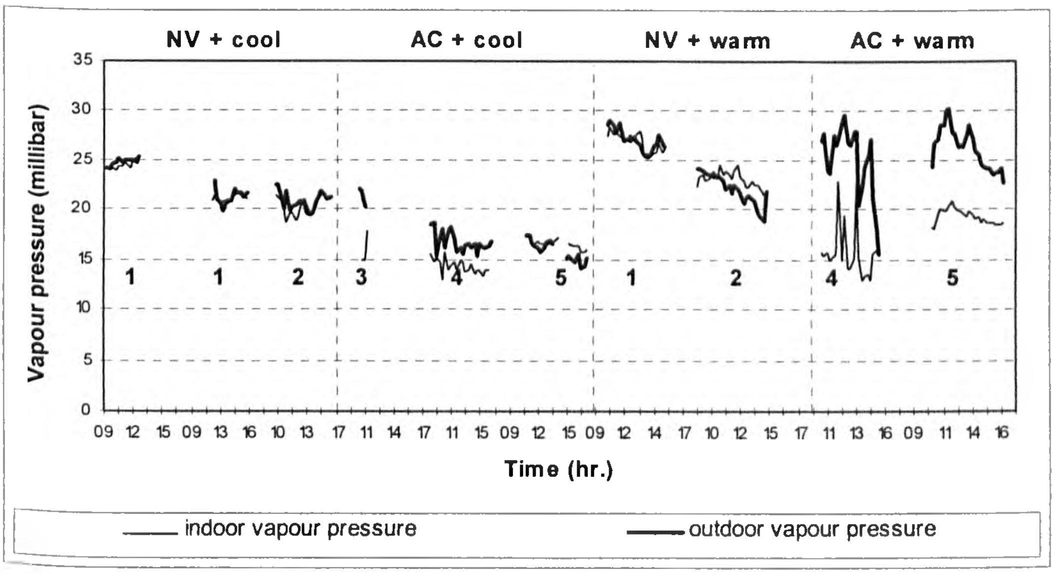


Figure 7.13 *Water vapour pressures of this field study.*

Vapour pressures in the warm season are higher than those in the cool season. The indoor vapour pressures are generally lower than the outdoor ones, which are the opposite results found in relative humidities. The averages of vapour pressure are between 19.0 and 23.2.

Air velocity

Air velocities in indoors and outdoors were different: lower air velocities are experienced in indoor conditions, but in the outdoors, air velocities could be up to 1.9 m/s. This discrepancy was also recognised by Tanabe and Kimura [1994]; Kimura et al [1994]. The data of air velocities from this field study are plotted in Figure 7.14. Nicol et al [1994] suggested that air movement should be expressed as the square root of air velocity, because it is the measure normally used as being the best estimate of the cooling power of air movement. The square root air velocities of this field study are plotted in Figure 7.15.

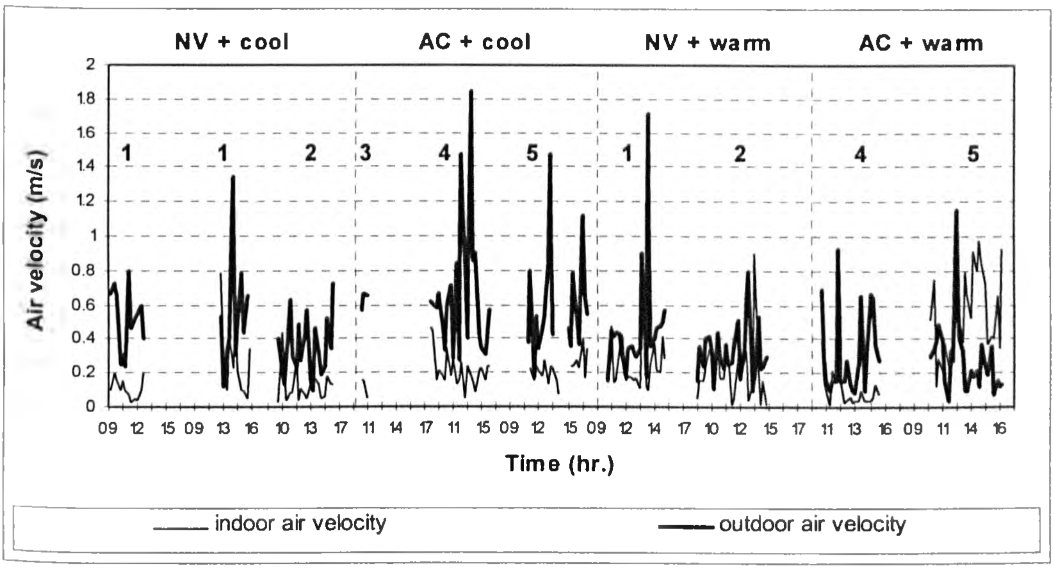


Figure 7.14 *Air velocities of this field study.*

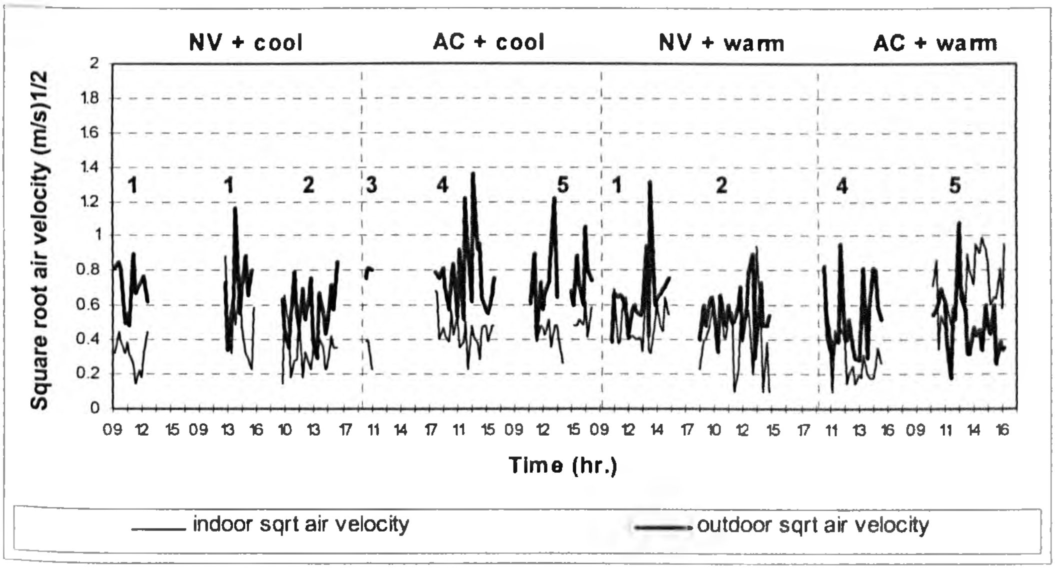


Figure 7.15 *Square root air velocities of this field study.*

When the data of air velocities are squared root, the minimum value will be $0.1(m/s)^{1/2}$. It is clear that the discrepancies between indoors and outdoors ($\sqrt{v}$) are less than those from the measured air velocities (v) due to the mathematical process. The ranges of the square root air velocity of each group are also narrower.

Summaries of the mean values, as well as maximum and minimum (the range of values) are tabulated in Table 7.1 for the cool season, and in Table 7.2 for the warm season.

Table 7.1 *Distribution of climatic data in the cool season.*

Mean and (Range)	A/C indoor	N/V indoor	A/C outdoor	N/V outdoor	All
T_a (°C)	25.0 (23.1-26.3)	28.5 (26.3-30.0)	27.6 (25.0-29.7)	30.1 (28.0-31.8)	27.8 (23.1-31.8)
T_g (°C)	N/A	N/A	27.9 (24.8-30.6)	30.3 (28.2-32.1)	N/A
rh (%)	49.0 (38.1-59.2)	55.6 (49.8-62.9)	45.4 (37.7-56.5)	51.8 (41.6-62.0)	50.5 (37.7-62.9)
P_a (mb)	15.4 (12.8-17.8)	21.7 (18.5-25.4)	16.7 (14.1-22.2)	22.1 (19.5-25.4)	19.0 (12.8-25.4)
v (m/s)	0.21 (0.05-0.47)	0.17 (0.02-0.78)	0.63 (0.18-1.85)	0.44 (0.09-1.35)	0.36 (0.02-1.85)
$\sqrt{v}$ $(m/s)^{0.5}$	0.45 (0.22-0.69)	0.37 (0.14-0.88)	0.77 (0.42-1.36)	0.64 (0.30-1.16)	0.56 (0.14-1.36)

Table 7.2 *Distribution of climatic data in the warm season.*

Mean and (Range)	A/C indoor	N/V indoor	A/C outdoor	N/V outdoor	All
T_a (°C)	26.1 (24.3-29.1)	30.9 (27.7-33.2)	28.8 (26.1-30.8)	33.2 (27.4-36.7)	29.7 (24.3-36.7)
T_g (°C)	26.2 (24.4-28.9)	30.8 (27.5-33.3)	28.9 (26.0-31.1)	33.8 (27.9-36.8)	29.9 (24.4-36.8)
rh (%)	52.9 (36.0-66.0)	55.6 (50.0-63.2)	65.3 (39.8-84.4)	48.5 (32.2-66.3)	55.6 (32.2-84.4)
P_a (mb)	17.7 (12.9-22.9)	24.8 (21.6-28.4)	25.7 (15.6-30.3)	24.4 (18.8-29.1)	23.2 (12.9-30.3)
v (m/s)	0.20 (0.01-1.15)	0.23 (0.01-0.90)	0.44 (0.08-0.98)	0.39 (0.09-1.72)	0.32 (0.01-1.72)
$\sqrt{v}$ $(m/s)^{0.5}$	0.40 (0.10-1.07)	0.45 (0.10-0.95)	0.63 (0.28-0.99)	0.60 (0.30-1.31)	0.52 (0.10-1.31)

7.6.2 Profile of the respondents

Total number of the respondents in this field study are 1143, derived from two seasons: 593 subjects in the cool season and 550 subjects in the warm season. These subjects are categorised into four groups: those who were just entering air conditioned or naturally ventilated indoor environments:

1. A/C-indoor: 254 persons (121 in cool season and 133 in warm season);
2. N/V-indoor: 315 persons (181 in cool season and 134 in warm season);

   and those who had just left those indoor environments to go outside:
3. A/C-outdoor: 281 persons (133 in cool season and 148 in warm season); and
4. N/V-outdoor: 293 persons (158 in cool season and 135 in warm season).

Personal information

All subjects gave their personal information in their survey forms and these demographic data are summarised in percentage, shown in Table 7.3 for the cool season and in Table 7.4 for the warm season (and are graphically shown in Appendix F). All respondents are aged between 8 and 70, with the majority at 20 to 29. There are about the same number of males and females. The bodies of the respondents have the averages of 55-57 kilograms in weight and 164-165 centimetres in height.

While most subjects in A/C buildings are private office workers, those in N/V buildings are students and civil servants. The occupations are related to the incomes of the subjects because workers in the private sectors are better paid than those in government organisations in general. The majority of the respondents have either finished high schools or graduated with bachelor's degrees, as their highest education. The number of the subjects having use of air-conditioning units at home of the N/V data are surprisingly more than those of the A/C data. However, the acclimatisation to air-conditioning could not be considered as of importance because only ten per cent indicated "always" using air-conditioning units, while the rest indicated “no” or “little”.

Table 7.3 *Anthropometric data in percentage in the cool season.*

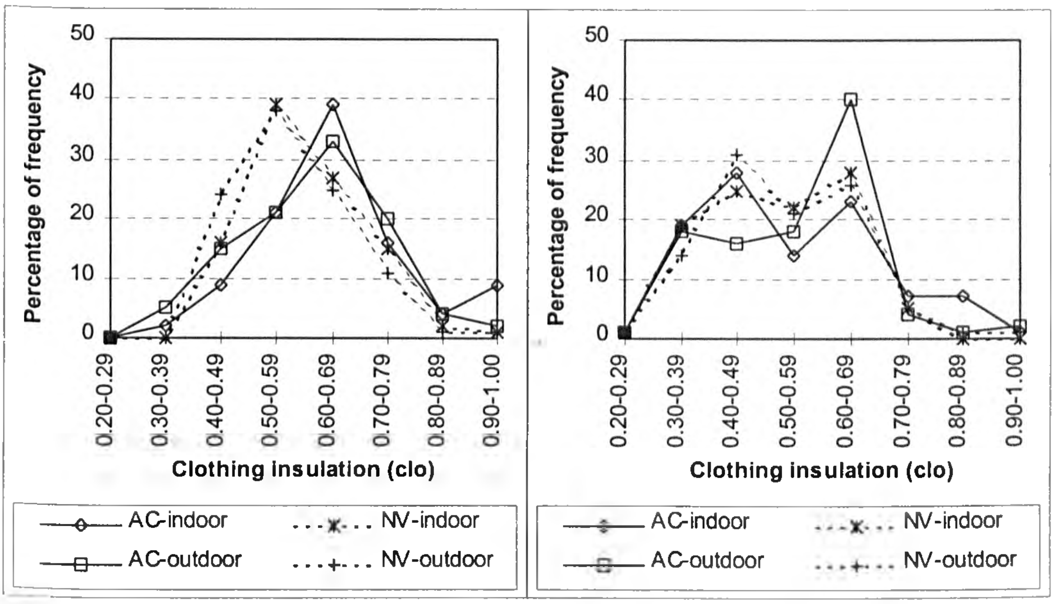
Total respondent = 593		A/C indoor (121)	N/V indoor (181)	A/C outdoor (133)	N/V outdoor (158)
Age 8-68 (year)	8-19	21	25	25	30
	20-29	60	52	53	52
	30-39	14	12	16	6
mean = 24.8	40-49	2	6	5	9
mode = 20.0	50-59	2	4	2	1
	60-68	1	1	0	1
Gender	male	26	53	44	49
	female	74	47	56	51
Weight 30-98 (kg)	30-39	0	1	2	1
	40-49	40	23	28	25
	50-59	39	44	46	40
mean = 54.7	60-69	16	24	18	23
mode = 45.0	70-79	2	4	3	6
	80-89	3	2	1	3
	90-98	0	1	2	1
Height 130-185 (cm)	130-139	0	0	0	1
	140-149	1	1	0	1
	150-159	36	30	34	26
mean = 163.9	160-169	43	38	36	35
mode = 160.0	170-179	17	25	23	28
	180-185	2	6	5	7
Occupation	students	31	65	32	75
	govt. servants	7	26	5	16
	office workers	54	5	51	5
	proprietors	4	1	2	2
	house-wives	1	1	2	1
	others	2	2	8	2
Income (£ per annum)	< £1500	30	51	35	56
	up to £3000	33	20	34	22
	up to £7500	28	18	26	12
	up to £15000	7	3	4	2
	up to £30000	1	1	1	2
	> £30000	1	1	0	2
Highest Education	Compulsory	8	6	13	2
	High school	41	54	49	63
	Bachelors	45	30	37	28
	Post-grad	4	10	1	6
A/C used at home	no	41	30	54	31
	little	45	58	29	54
	always	14	10	17	15

Table 7.4 *Anthropometric data in percentage in the warm season.*

Total respondent = 550		A/C indoor (133)	N/V indoor (134)	A/C outdoor (148)	N/V outdoor (135)
Age	15-19	19	3	8	7
15-70 (year)	20-29	42	52	53	55
	30-39	27	22	26	18
mean = 29.1	40-49	9	21	12	12
mode = 20.0	50-59	2	3	2	6
	60-70	1	0	0	1
Gender	male	56	58	78	56
	female	44	42	22	44
Weight	39	1	1	0	0
39-100 (kg)	40-49	22	19	17	25
	50-59	35	39	50	36
mean = 56.6	60-69	29	33	26	28
mode = 60.0	70-79	9	8	8	7
	80-89	1	0	1	3
	90-100	2	0	0	0
Height	130-139	0	0	0	0
143-184 (cm)	140-149	0	2	1	1
	150-159	20	20	11	28
mean = 165.2	160-169	47	49	49	41
mode = 170.0	170-179	32	26	34	28
	180-185	2	2	5	2
Occupation	students	31	40	18	40
	govt. servants	7	40	2	39
	office workers	52	18	73	15
	proprietors	7	1	4	4
	house-wives	0	0	1	1
	others	3	2	2	3
Income	< £1500	31	33	22	30
(£ per annum)	up to £3000	28	29	34	31
	up to £7500	34	33	38	33
	up to £15000	6	6	6	5
	up to £30000	2	0	0	1
	> £30000	0	0	0	0
Highest Education	Compulsory	8	2	19	10
	High school	40	20	33	29
	Bachelors	44	62	46	53
	Post-grad	9	16	1	9
A/C used at home	no	45	44	62	49
	little	47	46	29	44
	always	8	10	10	7

Individual parameters

The individual parameters of both clothing insulation values (clo-value) and activity levels (met-value) are shown in Figures 7.16 and 7.17, respectively.



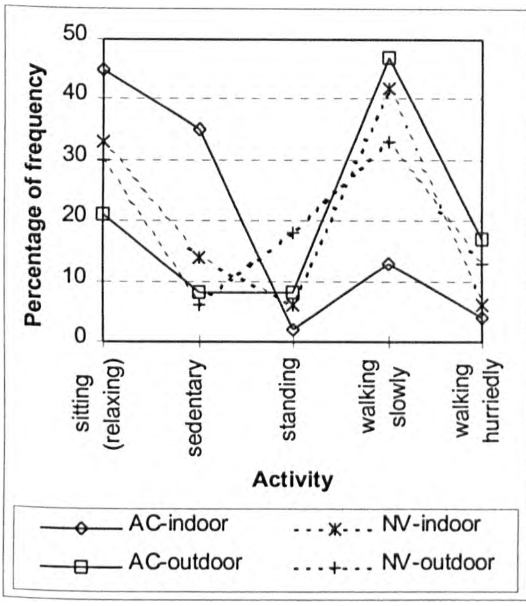
(a) the cool season

(b) the warm season

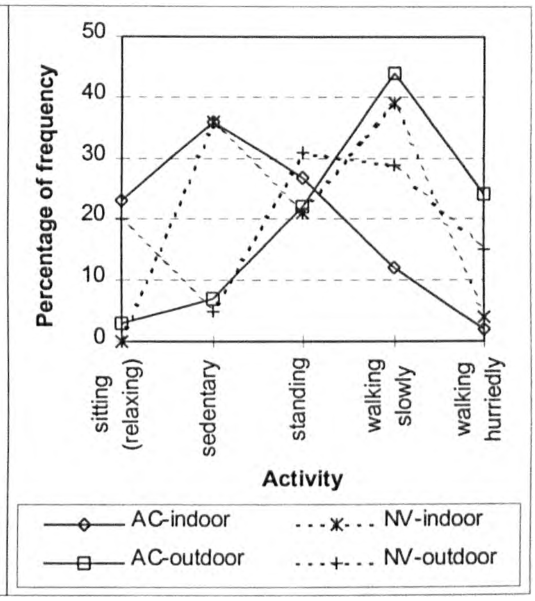
Figure 7.16 *Relative frequency distributions of clothing insulation values.*

From Figure 7.16 (a), the distributions of clothing insulation in the cool season are evidently separated into two groups: the A/C subjects with the peaks at 0.60-0.69 clo, and the N/V subjects at 0.50-0.59 clo. It is apparent that the indoor/outdoor conditions have less effects on the clothing than the conditions of A/C or N/V of the buildings, where the respondents intended to visit. The influence on the decision on the choices of clothing can be attributed to the expectations of the subjects.

From Figure 7.16 (b), the distributions of clothing insulation in the warm season show no distinct peaks, except the A/C-outdoor group, whose peak is at 0.60-0.69 clo. The clo-values of every group are reduced in the warm season. It should be noted that the daily wear clothing may consist of underpants + shirt with short sleeves + light trousers + light socks + shoes (= 0.50 clo) [ISO 1994]. However, this field study reveals that many respondents wore clothing lower than a general average, and the mode value is 0.39 clo.



(a) the cool season



(b) the warm season

***Figure** 7.17 Relative frequency distributions of metabolic rates.*

In Figure 7.17, the activity levels in both seasons are not consistent. Perhaps it is because the areas surveyed are transitional spaces and the respondents are free to engage in any activities. Seemingly, a common activity is "walking slowly", which has a metabolic rate of 1.9 met. The average metabolic rate of A/C-indoor is the lowest one; many subjects in this group performed either sitting (relaxing) (= 1.0 met) or sedentary (= 1.2 met). The observations in the surveys suggest that the environmental conditions did not have influences on the activities the respondents performed.

Mean clothing insulation values and mean metabolic rates of every subject group in both cool and warm seasons are summarised in Table 7.5.

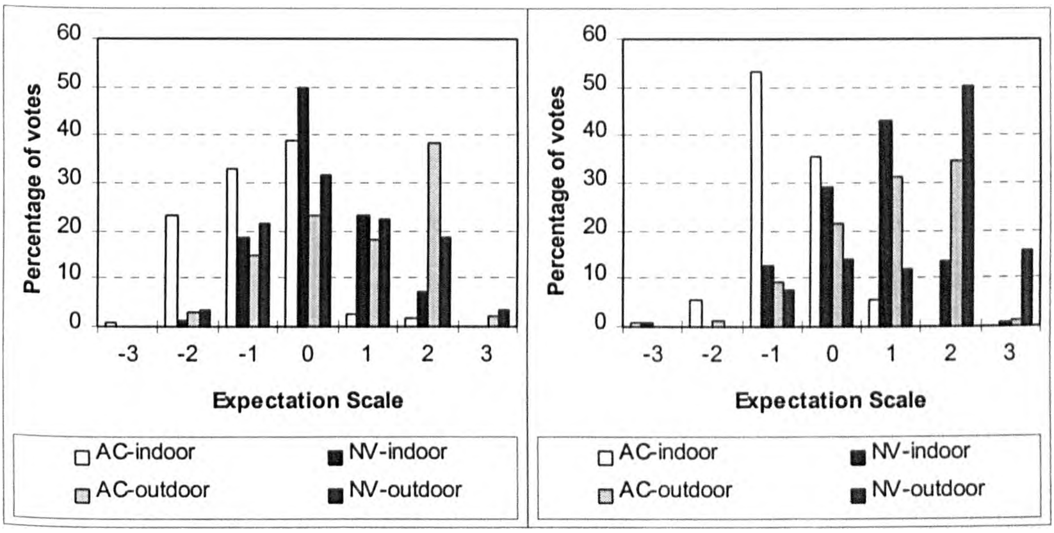
***Table** 7.5 Mean values of individual parameters of this field study.*

Mean individual factors	A/C indoor	N/V indoor	A/C outdoor	N/V outdoor
In the cool season				
mean clo-value	0.65	0.59	0.61	0.57
mean met-value	1.3	1.5	1.7	1.6
In the warm season				
mean clo-value	0.54	0.53	0.56	0.54
mean met-value	1.4	1.6	1.9	1.7

7.7 Thermal responses

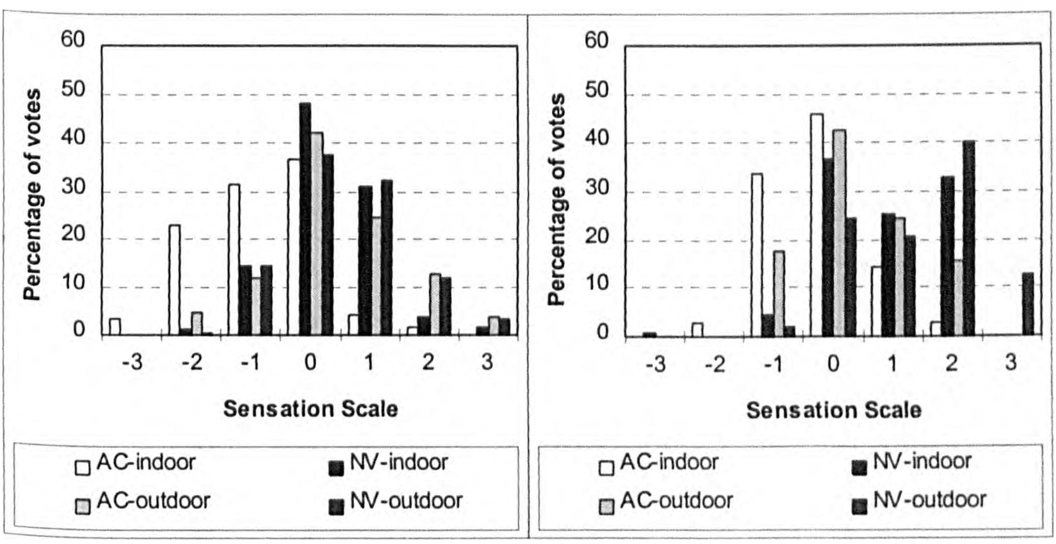
7.7.1 Thermal expectation and thermal sensation

The seven-point ASHRAE scale (-3 = cold, -2 = cool, -1 = slightly cool, 0 = neutral, 1 = slightly warm, 2 = warm, and 3 = hot) is used for the subjects' thermal expectation and sensation responses and their distributions of votes are shown in Figures 7.18 and 7.19, respectively.



(a) the cool season (b) the warm season

Figure 7.18 Relative frequency distributions of thermal expectation votes.



(a) the cool season (b) the warm season

Figure 7.19 Relative frequency distributions of thermal sensation votes.

In the cool season, from Figures 7.18 (a) and 7.19 (a), the expectations and sensations of the A/C-indoor subjects have almost similar patterns of votes and apparently bias on the cool side. More than half of the respondents indicate "-1 to -3" (slightly cool, cool and cold) and about three quarters of votes, the central three categories (slightly cool, neutral and slightly warm). The peaks of both thermal votes are at "0" (neutral).

A large number of votes from the N/V-indoor subjects are on "0" (neutral) in both thermal expectation and thermal sensation scales. More than 90% fall within the central three categories. There is no response on both extreme sides in the expectations but the vote "3" (hot) appears in the sensation scale.

Both outdoor groups, the A/C-outdoor and the N/V-outdoor have their expectation and sensation distributions bias on the warm side. The major vote of thermal expectations of the A/C-outdoor subjects is "2" (warm) and more than half of the responses indicate "1 to 3" (slightly warm, warm and hot). However, in thermal sensations, the peak vote is at "0" (neutral) and the responses in the warm side decrease nearly twenty per cent. It implies that the subjects, who were leaving air conditioned environments to outside, would certainly expect a warmer climate than they actually felt.

The bias distributions of the N/V-outdoor subjects show that nearly half of the expectation and sensation responses are in the warm side. The vote on "0" (neutral) is about one-third and the central three categories proportion is about three quarters.

In the warm season, as shown in Figures 7.18 (b) and 7.19 (b), only the A/C-indoor subjects have their expectation and sensation distributions of votes bias towards the cool side. The peak vote of the group is at "-1" (slightly cool) in thermal expectation, but at "0" (neutral) in thermal sensation scale. More than 90% of the subjects respond within the central three categories. It is interesting to note that there is no vote beyond "1" (slightly warm) in the expectations, but the votes on "2" (warm) appear and the votes on "-3" (cold) disappear in the sensation scale. This implies some respondents felt warmer (in air-conditioned environments) than they had expected.

The expectations of the other three groups are distinctively towards the warm side, with their peaks at either "1" (slightly warm) or "2" (warm). However, the sensations of the A/C-outdoor and the N/V-indoor subjects turn to be "0" (neutral). A proportion of a quarter from the warm side in thermal expectation of the A/C-outdoor subjects transfers to the central three categories in thermal sensations. It explains that the subjects who had been previously in air-conditioned environments expected too warm air out of door.

Both naturally ventilated groups have a majority of votes in the warm side. The distributions bias towards the warm side of the N/V-indoor subjects show a higher proportion of "2" (warm) in thermal sensations than in thermal expectation. It points that the subjects felt warmer (in naturally ventilated buildings) than they had expected.

The majority of both thermal expectation and sensation votes of the N/V-outdoor subjects are "2" (warm). About three quarters indicate "1 to 3" (slightly warm, warm and hot) and there are less than half of the group in the central three categories. The relatively high air temperatures in the warm season apparently showed dramatic effects on thermal responses for the naturally-ventilated experienced subjects.

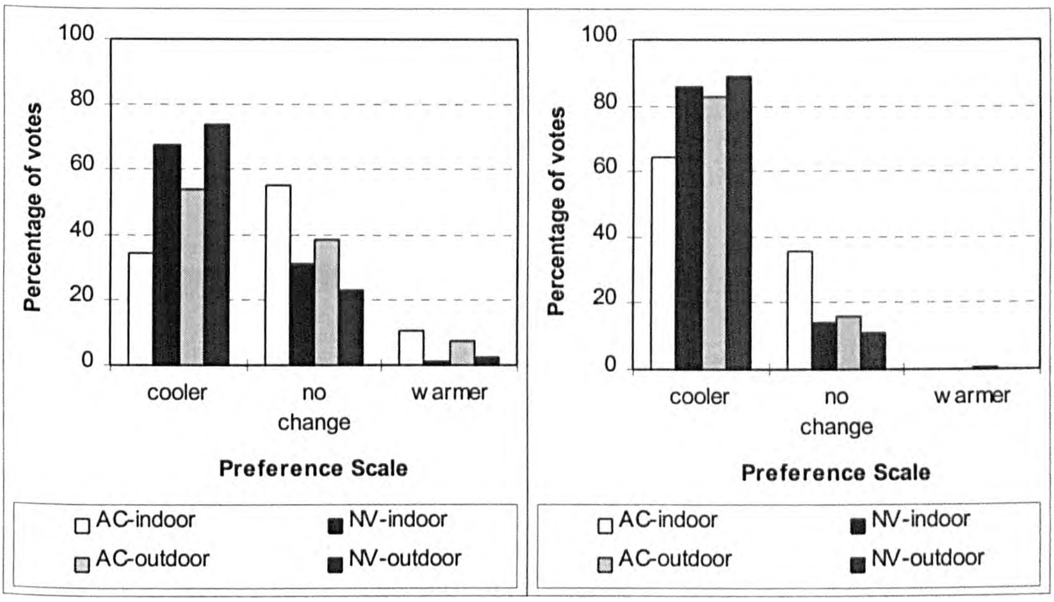
Mean thermal expectation and thermal sensation responses of every group in both cool and warm seasons are summarised in Table 7.6.

Table 7.6 *Mean thermal expectations and sensations of this field study.*

Mean thermal responses	A/C indoor	N/V indoor	A/C outdoor	N/V outdoor
In the cool season				
mean expectation vote	-0.76	0.17	0.81	0.41
mean sensation vote	-0.80	0.27	0.41	0.50
In the warm season				
mean expectation vote	-0.61	0.58	0.93	1.53
mean sensation vote	-0.20	0.84	0.38	1.36

7.7.2 Thermal preference

The three-point McIntyre scale is used for the subjects' thermal preferences and their distributions of votes are shown in Figure 7.20.



(a) the cool season (b) the warm season

Figure 7.20 *Relative frequency distributions of thermal preference votes.*

The proportions of preferring "cooler" in the warm season are significantly larger than those in the cool season. The absence of the vote for "warmer" in the warm season is distinctive. The subjects have the majority of votes for their preferences for "cooler" and "no change", except the A/C-indoor subjects in the cool season, for whom more than half are "no change" and one-third is "cooler". Although this group had the expectations and sensations bias towards the cool side, there are only eleven per cent for "warmer". In the warm season, two-thirds of this group vote for "cooler" and the other third for "no change".

The other three groups, in the cool season, have their preferences "cooler" 54-74%, "no change" 23-38%, and thirteen persons for "warmer". In the warm season, there are more than eighty per cent for "cooler" and about fifteen per cent for "no change". Only one person would like to be in a "warmer" environment.

Mean thermal preference responses of every group in both cool and warm seasons are summarised in Table 7.7.

Table 7.7 *Mean thermal preferences of this field study.*

Mean thermal preference vote	A/C indoor	N/V indoor	A/C outdoor	N/V outdoor
In the cool season	-0.23	-0.67	-0.47	-0.72
In the warm season	-0.65	-0.86	-0.82	-0.89

7.7.3 Adaptation to achieve comfort

The adaptations to achieve comfort are suggested by the respondents themselves writing down on the survey forms. These results demonstrate a range of ideas of adaptations, if they feel warm or cool discomfort, shown in Table 7.8 (see Appendix G for separated seasons).

Table 7.8 *The suggested adaptations by the respondents.*

Adaptation	frequency		
	A/C	N/V	all
When too warm			
1. use A/C	178	182	360
2. stay in a shaded area and expose to N/V or increase air movement	103	212	315
3. take a bath or wash a face	124	103	227
4. have cool drink or ice-cream	43	69	112
5. change or take off some clothes	23	46	69
6. perform less metabolic rate	29	22	51
When too cool			
1. increase clothing insulation	174	150	324
2. increase activity level, i.e., walking or exercise	47	44	91
3. stay in warm area or in the sun	31	32	63
4. stay home	27	25	52
5. close window or turn off A/C	27	23	50
6. have hot drink or food	9	24	33

If the subjects feel warm discomfort, the primary suggestion is "using air-conditioning", and the second is "staying in a shaded area and exposing to natural ventilation" or "increasing air movement". These results assume that the encountered environments of the respondents have effects on their adaptive behaviour: the majority of the respondents in the A/C environments suggest active means, while those in the N/V environments give passive cooling methods. In the cool season, the suggested adaptations also tend to be passive methods, but in the warm season, they are mechanical cooling to achieve comfort (see Appendix G).

If the subjects feel cool discomfort, the foremost idea is "increasing clothing insulation" by putting on their jackets or casual suits or some other clothing and the second is "increasing activity level". The results show that the adaptation by using clothing is significantly relevant to the cool environments.

It should be noted that the passive means, for instance, using control namely opening windows to increase air ventilation, or using shading devices to prevent direct sun-light (i.e., environmental adjustment), could have been provided in the initial stage of architectural design. Other suggestions focus on the subjects' personal adaptations (i.e., behavioural adjustment and psychological adaptations) [Brager and de Dear 1998; Humphreys and Nicol 1998].

7.8 Summary

A study of thermal environments in transitional spaces of selected A/C and N/V buildings in Bangkok has been carried out in both cool and warm seasons. The methodology used for the field surveys was based on Nicol's "Field Study" of thermal comfort, and was explained in this chapter. Results of this field study categorised the subjects into four groups: those entering air-conditioned indoor environments (A/C-indoor); those entering naturally-ventilated indoor environments (N/V-indoor); those who were leaving air-conditioned environments to outdoor (A/C-outdoor); and those who were leaving naturally-ventilated environments to outdoor (N/V-outdoor).

The A/C-indoor subjects were in the coolest environments, while the N/V-outdoor subjects in the warmest ones. In terms of air movement, the indoor groups experienced lower air velocities than the outdoor groups. Like many field studies, the activities and clothing of the subjects were not controlled. However, since the field surveys were conducted in transitional spaces of buildings, main activities were standing or walking, rather than sedentary work. Clothing insulation values of the subjects in the air-conditioned environments were slightly higher than those in the naturally-ventilated ones; and the clo-values in the cool season were also somewhat higher than those in the warm season.

Subjective thermal responses were represented by four concepts: *expectation*, *sensation*, *preference*, and *adaptation to achieve comfort.* The patterns of the responses of thermal expectations and thermal sensations were fairly similar in every group, except those of the A/C-outdoor subjects, who seemingly expected warmer air out of door than their actual feeling. The A/C-indoor subjects had bias of votes on the cool side, but the naturally-ventilated subjects (i.e., both N/V-indoor and N/V-outdoor), on the warm side. Thermal preferences of all groups were consistent for "cooler" environments. In the warm season, all subjective thermal responses expressed their expectations and sensations warmer and their wants to be "cooler" than in the cool season. The suggested adaptation actions when too warm were mainly environmental adjustments (e.g., using air-conditioning, increasing air movement, or staying in a shaded area), but the actions when too cool related to individual or behavioural adaptations (e.g., increasing clothing insulation or increasing activities).

The analysis of the results will be discussed in the next chapter. Various statistical techniques will be used to investigate the relationship between comfort criteria and parameters affecting comfort; and to establish comfortable conditions: neutral temperatures and thermal acceptability.

Chapter 8

ANALYSIS OF THE FIELD STUDY DATA

"The fundamental distinction between the heat balance and adaptive models is their underlying basis or cause for a shift in comfort temperatures. The former permits only adjustments to heat balance variables such as clothing or air velocity, whereas the adaptive model is premised on changing the expectations of building occupants."

R. de Dear [1994b]

8.1 Introduction

This chapter will deal with the analysis of the results from the field surveys and will establish neutral temperatures and thermal acceptability of the subjects in transitional spaces of tropical buildings in Bangkok. The analysis of the data aims to investigate the relationships between the measured environmental variables, and the reported variables such as the individual parameters and the subjective thermal responses. The methodology of the analysis is a replication from the literature of thermal comfort research in Pakistan by Nicol et al [1994]. Basically, the analysis uses scatter diagram to show the relationships between two variables, and uses correlation coefficient technique to examine the strength and direction between two variables in terms of linear relationship.

To establish the neutral temperatures, this study uses various statistical techniques such as simple linear regression, probit regression, and Griffiths' value. The first two techniques give expected, neutral and preferred temperatures of all subjects combined (analysed from the votes in thermal expectation, sensation and preference scales, respectively); and the last technique allows the calculation for the neutral temperatures of each subject group.

Thermal acceptability of the subjects is investigated through two subjective thermal responses: the preferences of "no change"; and the sensation responses of "0" (neutral) and of the central three categories. The range of thermal acceptability is estimated by quadratic analysis technique, and assumes as the 80% or more of the subjects voting within the central three categories of thermal sensation scale.

Finally, this chapter will examine the effects of humidity and air movement on human comfort. The methodology used was proposed by Nicol [1974], using probit technique to differentiate two groups of data and to make a comparison by the combined effect with air temperatures. In terms of humidity, it will study through water vapour pressure unit; and in terms of air movement, through the unit of square root air velocity.

8.2 Relationships between variables

8.2.1 With mean air temperatures

The variables to be examined in the relationships with the main thermal index — air temperature, are: thermal responses and individual parameters. Figures 8.1, 8.2 and 8.3 show the scatter diagrams of mean thermal expectations, sensations and preferences, respectively, of eight sub-groups (four subject groups in the cool season and other four in the warm season), as a function of mean air temperatures.

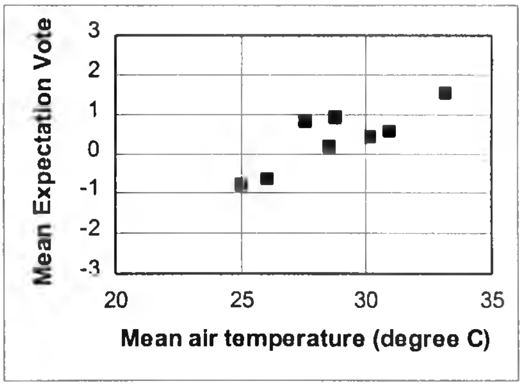


Figure 8.1 *Mean expectations against mean air temperatures.*

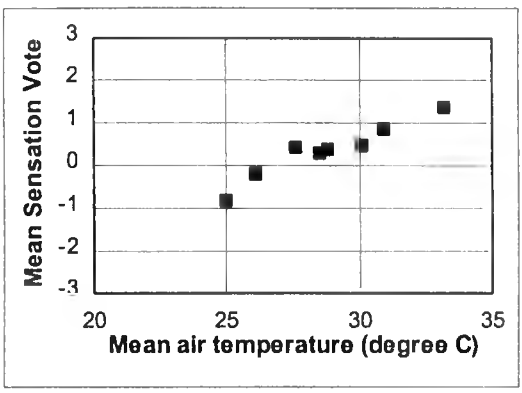


Figure 8.2 *Mean sensations against mean air temperatures.*

The variations of mean expectation and mean sensation votes with mean air temperatures are of fairly similar patterns and they show positive relationships; the higher the temperatures, the warmer the expectations and the sensations. The ranges of the mean expectations and sensations are in-between "-1" and "2" (slightly cool to warm) on the ASHRAE scale, at mean air temperatures between 25.0°C and 33.2°C.

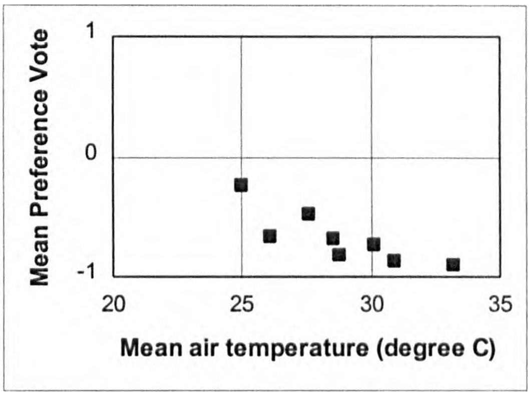


Figure 8.3 *Mean preferences against mean air temperatures.*

The variation of mean thermal preferences with mean air temperatures is of opposite direction (from the thermal expectation and sensation responses); it shows a negative relationship. The range of the mean preference votes is between "0" and "-1" (no change to cooler) on the McIntyre scale.

The scatter diagrams in Figures 8.1 to 8.3 show good relationship between the mean thermal responses and the mean air temperatures. It is clear that the subjects had awareness of their thermal responses in relation to air temperatures.

Figures 8.4 and 8.5 show the scatter diagrams of the reported individual variables namely mean clo-values and mean met-values, respectively, of eight sub-groups as a function of mean air temperatures.

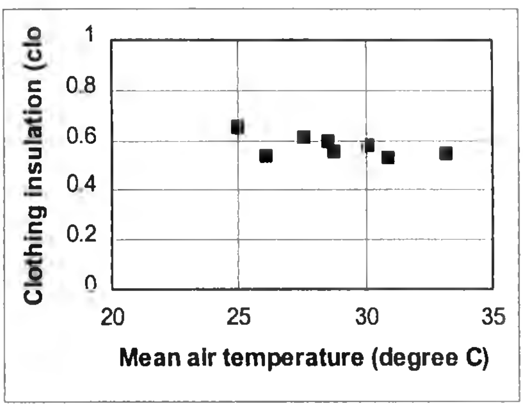


Figure 8.4 *Mean clothing values against mean air temperatures.*

The variation of mean clothing insulation values with mean air temperatures is not distinct, but it has a somewhat tendency to be a negative relationship. The mean clothing insulation values are gathering around 0.5 to 0.7 clo.

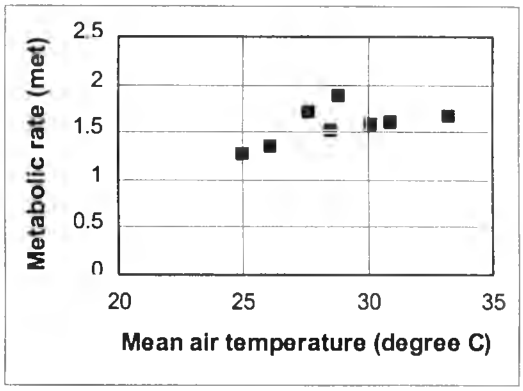


Figure 8.5 *Mean metabolic rates against mean air temperatures.*

The variation of mean metabolic rates with mean air temperatures shows some positive relationship. This is quite surprising because of the relationship between increasing air temperatures and higher levels of activities by subjects. This phenomenon may not be explained by the adaptive hypothesis, but the functions of transitional spaces. The mean metabolic rates are ranged from 1.3 to 1.9 met.

8.2.2 Between thermal responses

The scatter diagram in Figure 8.6 shows the relationship between mean thermal expectations and sensations; and in Figure 8.7, between thermal sensations and thermal preferences.

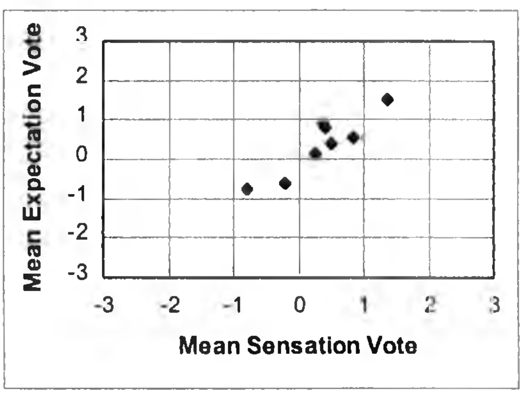


Figure 8.6 *Mean expectations against mean sensations.*

The positive relationship between mean expectations and mean sensations is obvious and nearly perfect. The scatter diagram between mean sensations and mean preferences shows some negative and quite strong relationship. Both relationships between thermal responses have similar patterns to those of the plots against the mean air temperatures.

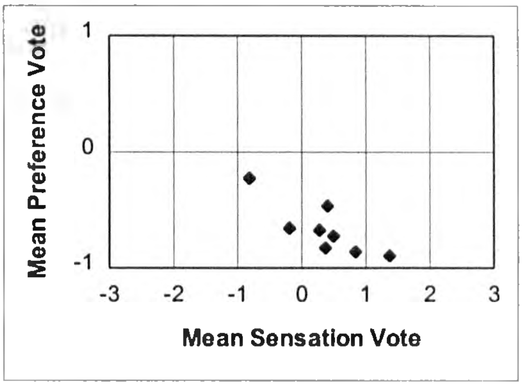


Figure 8.7 *Mean preferences against mean sensations.*

8.2.3 With thermal sensation responses

The following scatter diagrams show the tendencies of the environmental and personal variables at a particular sensation vote to the next. Mean values of air temperatures, vapour pressures, and square root air velocities at each sensation category are presented in Figures 8.8, 8.9 and 8.10, respectively. The numbers of the subjects are also included.

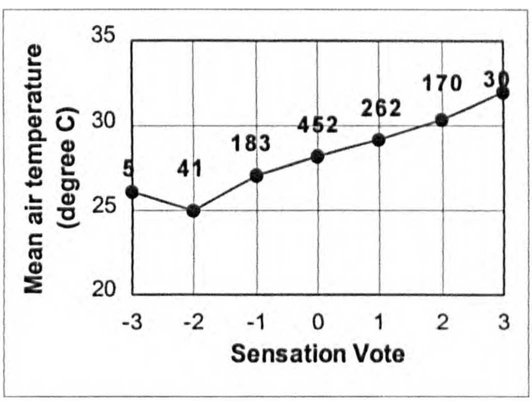


Figure 8.8 *Mean air temperatures at each sensation vote.*

The relationships between the environmental factors and thermal sensation responses are positive. Quite strong relationships occur at both air temperature and vapour pressure diagrams. However, the directions are somewhat opposite at the end tails of the "-3" (cold) vote. This may be caused by too small number of the subjects voting for "cold" in hot-humid climate like Bangkok, and thereby resulting in some misleading of the analysis.

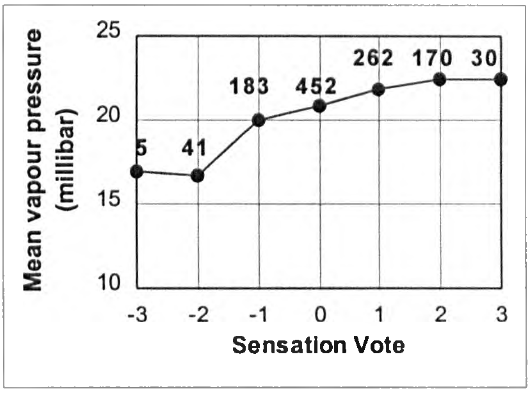


Figure 8.9 *Mean vapour pressures at each sensation vote.*

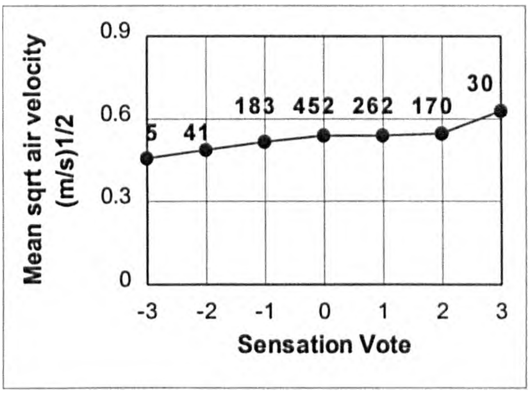


Figure 8.10 *Mean square root air velocities at each sensation vote.*

The positive relationship between air movement and sensation of warmth is also unexpected. It is quite controversial to a general belief that natural ventilation can reduce warm discomfort in tropical architecture (see Chapter Two). Further analysis of the effects of environmental variables will be discussed in this chapter.

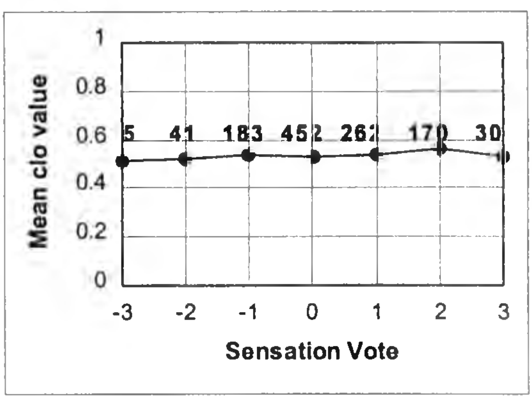


Figure 8.11 *Mean clothing values at each sensation vote.*

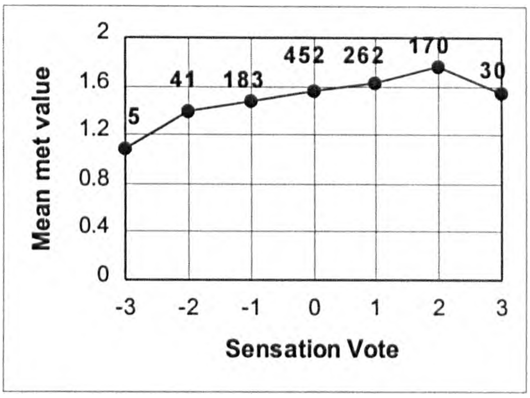


Figure 8.12 *Mean metabolic rates at each sensation vote.*

Figures 8.11 and 8.12 show mean clothing insulation values and mean metabolic rates, respectively, plotted at each thermal sensation vote. The relationship of thermal sensation votes with the clothing values, and with the metabolic rate are not available. The plotted mean clo-values are all around 0.5, and for the met-values, around 1.5-1.7. This should consider the actual cause/effect of the personal parameters' variations with the subjective thermal responses. It is possible to have some kind of adaptive feedback system involved, and therefore no relationship presented.

8.3 Correlation coefficients

The further analysis of the data is tested by bivariate correlation, using the Pearson's product moment correlation coefficient (r). It is a statistical technique used to explore the relationship between two variables in order to reveal the strength and the direction of one variable to the other. A correlation coefficient always lies between plus one and minus one inclusive. If a correlation coefficient is "-1", it interprets a perfect negative linear correlation; if "+1", a perfect positive linear correlation; and if "0", there is no correlation or non-linear relationship [Caswell 1996]. In other words, a negative correlation implies that an increase in one variable corresponds to a decrease in the other or vice versa, while a positive correlation implies increases or decreases of both variables at the same time.

Nicol et al [1994] stated that the square of the correlation coefficient gives a measure of the proportion of variations from one variable to explain the variations of the other. For example, a correlation of 0.5 between comfort and temperature implies that the square $[(0.5)^2 = 0.25]$ or 25% of the statistical variance of comfort vote is explained by the variance of temperature.

In this study, the correlation coefficient technique is used for all subjects combined, subjects in the cool and warm seasons, and between subject groups (A/C-indoor; N/V-indoor; A/C-outdoor; and N/V-outdoor).

8.3.1 Between environmental variables

Table 8.1 *Correlation coefficients between environmental variables.*

Subject	no.	$T_a : T_g$	$T_a : P_a$	$T_a : \sqrt{v}$	$P_a : \sqrt{v}$
All	1143	0.99***	0.59***	0.14***	0.07*
Cool	593	0.98***	0.70***	0.12**	-0.11**
Warm	550	0.99***	0.41***	0.22***	0.32***
A/C-indoor	254	0.99***	-0.22***	-0.26***	0.18**
N/V-indoor	315	0.99***	0.73***	0.18**	0.16**
A/C-outdoor	281	0.97***	0.63***	-0.29***	-0.34***
N/V-outdoor	293	0.98***	0.13*	*0.06*	*0.09*

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and *italic* = not significant.

The correlation coefficients between air temperatures (T_a) and globe temperatures (T_g) of every group are extremely high (r = 0.97 to 0.99). The high correlation between T_a and T_g is usually expected in field studies of thermal comfort; and presumably, these two indices can be used instead for each other (see 5.2.3).

Between air temperatures (T_a) and vapour pressures (P_a), the correlations are relatively high, except two subject groups: the A/C-indoor (which also shows a negative relationship, possibly caused by the controls of air-conditioning) and the N/V-outdoor. Generally speaking, in this region, it is expected a combination of highly hot and highly humid climate. The comparatively high correlation is in the N/V-indoor subjects and the combined subjects of the cool season.

Square root air velocities ($\sqrt{v}$) do not appear to be well and consistently correlated with other variables (i.e., both T_a and P_a), and they show no significant relationships in the N/V-outdoor group.

8.3.2 Between thermal responses

Table 8.2 *Correlation coefficients between thermal responses.*

Subject	no.	Sensation : Expectation	Sensation : Preference
All	1143	0.50***	-0.44***
Cool	593	0.51***	-0.47***
Warm	550	0.45***	-0.34***
A/C-indoor	254	0.25***	-0.42***
N/V-indoor	315	0.37***	-0.45***
A/C-outdoor	281	0.34***	-0.31***
N/V-outdoor	293	0.50***	-0.37***

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and *italic* = not significant.

All correlation coefficients between thermal responses are highly significant ($p < 0.001$). The correlation coefficients between sensation and expectation responses show some degrees of positive relationships, implying the similar direction of both thermal votes. On the other hand, between sensation and preference responses are correlated in some degrees of negative relationships; the subjects would like to be "cooler" when they feel warm.

Comparatively, the higher correlations are in the cool season and in the naturally-ventilated groups. The high positive relationships between the sensations and the expectations in the naturally-ventilated groups explain a better realisation of the subjects to their environments, whereas those in the climate controlled rooms by air-conditioning may not expect and realise which conditions of indoor air they would experience. The negative relationships between the sensations and the preferences are higher in the indoor environmental groups. The degrees of preferences for "cooler" of the subjects inside the built environments may be explained by psychological feedback in relation to the fundamental application for tropical architecture.

8.3.3 With air temperatures

Table 8.3 *Correlation coefficients of subjective thermal responses and individual variables with air temperatures*

Subject	no.	T_a : E	T_a: S	T_a : P	T_a : clo	T_a : met
All	1143	0.46***	0.50***	-0.32***	*-0.05*	0.23***
Cool	593	0.31***	0.42***	-0.33***	-0.18***	0.27***
Warm	550	0.53***	0.52***	-0.21***	*0.02*	0.15***
A/C-indoor	254	*0.09*	0.30***	-0.26***	0.26***	0.18**
N/V-indoor	315	*0.07*	0.14*	*-0.07*	*-0.11*	0.25***
A/C-outdoor	281	0.16**	0.18**	-0.35***	0.12*	0.29***
N/V-outdoor	293	0.39***	0.46***	-0.17**	*0.01*	-0.13*

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and *italic* = not significant.

The correlation coefficients between subjective thermal responses and air temperatures of all subjects and of subjects between seasons are higher than those between individual groups. The directions of the correlation are logical; when air temperatures increase, the subjects vote their expectations and sensations to be warm, and their preferences for "cooler".

The strength of the correlation coefficients between T_a and sensations is somewhat better than that between T_a and expectations, and that between T_a and preferences. Nicol et al [1994] stated that the preference generally shows a slightly lower correlation with temperature than does comfort (sensation). The positive relationships of T_a with expectations and with sensations in the warm season are slightly higher than those in the cool season, but the negative relationship of T_a with preferences in the cool season are higher than that in the warm season. Between individual subjects, the correlation of the N/V-outdoor group is higher than the other groups.

The correlation coefficients between the reported individual variables and air temperatures are low and not consistent. The correlations between T_a and clo-values are significant only in the groups of subjects in the cool season and the A/C-indoor subjects. The somewhat small and negative relationship (r = -0.18) of the subjects in the cool season gives a sign that when air temperatures decrease, clothes to be worn increase or vice versa. This is a kind of the adaptive method by changing clothing in relation to thermal environments and it is apparently a coincidence with the suggested adaptation by the subjects in the case of "cool discomfort" (see 7.7.3).

8.3.4 With thermal sensation responses

Table 8.4 *Correlation coefficients of environmental and individual variables with thermal sensations.*

Subject	no.	S : T_a	S : P_a	S : $\sqrt{v}$	S : clo	S : met
All	1143	0.50***	0.28***	0.07*	*0.04*	0.19***
Cool	593	0.42***	0.24***	0.09*	*-0.00*	0.26***
Warm	550	0.52***	0.18***	0.09*	*0.08*	*0.06*
A/C-indoor	254	0.30***	0.14*	*-0.05*	0.14*	*0.05*
N/V-indoor	315	0.14*	0.12*	*0.01*	0.15**	*0.11*
A/C-outdoor	281	0.18**	*-0.03*	*-0.06*	0.12*	*0.10*
N/V-outdoor	293	0.46***	*0.11*	*-0.09*	*0.05*	*0.09*

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and *italic* = not significant.

The correlation coefficients between air temperatures and thermal sensations are repeated in Table 8.4 for comparison. The sensations are well correlated with air temperatures (T_a), and slightly correlated with vapour pressures (P_a) for all subjects and for subjects between seasons. These results may be affected by the high correlations between air temperatures and vapour pressures (see Table 8.1).

Between thermal sensations and metabolic rates are slightly correlated for all subjects combined and for subjects in the cool season. These positive relationships are quite similar to those between T_a and met-values. The relationship between sensations and clo-values is not significant. This should consider the cause/effect between these variables.

Davies and Davies [1995] suggested to use a pattern of correlation to discuss the influences of thermal environments and the adjustments of subjective personal factors or individual controls to thermal sensation responses (see 5.5.3). By this means, it will show whether the adaptive feedback process occurs in a particular field work. However, many results of the correlation with the individual variables in this field study are not statistically significant, and therefore a pattern of the correlation cannot be created to discuss. The suggestion is that future research should increase the number of data of the relevant factors for analysis, and should include individual controls in the field surveys.

8.3.5 With thermal expectation and thermal preference responses

Table 8.5 *Correlation coefficients of individual variables with thermal expectations and preferences.*

Subject	no.	E : clo	E : met	P : clo	P : met
All	1143	*-0.01*	0.21***	*-0.01*	-0.11***
Cool	593	*-0.05*	0.21***	*0.02*	-0.12**
Warm	550	*0.03*	0.19***	*-0.05*	*-0.02*
A/C-indoor	254	*-0.06*	*0.03*	*-0.04*	*0.02*
N/V-indoor	315	*0.04*	*0.06*	*-0.00*	*-0.03*
A/C-outdoor	281	*-0.01*	*-0.08*	*-0.08*	-0.13*
N/V-outdoor	293	0.14*	0.15**	*-0.04*	*-0.08*

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and *italic* = not significant.

Nearly all correlation coefficients in Table 8.5 are not significant. Only the expectations of all subjects combined are slightly correlated with met-values. The correlations between thermal responses with clo-values are not statistically significant at all. These results are quite similar to the correlation analysis with thermal sensations.

8.4 Establishing neutral temperatures

Several techniques of statistical analyses are used to establish neutral temperatures of each subject group and of whole samples in this field study. Two common and powerful analysis methods are *simple linear regression* and *probit regression* (see 5.2.2). Both analyses, nowadays, can be processed by using a statistic computer package namely SPSS (Statistical Package for the Social

Sciences). Its high efficiency gives a researcher the ability to carry out complex analyses in a straightforward and convenient manner.

This programme can also be used for *multiple regression analysis*, using not only air temperatures, but also water vapour pressures and square root air velocities as independent variables. However, this analysis for this field study does not reach a statistical significance and cannot give the neutral conditions. Therefore, there will be no report in this thesis.

An alternative technique to establish neutral temperatures is a calculation model proposed by Griffiths [1990]. The *Griffiths' value* is suitable for field studies in which there are a small number of data or there is unreliable regression coefficient values from the regression analysis. This model assumes a regression coefficient as a constant value (see 5.3.5).

This field study also establishes thermal acceptability in order to provide an information of a range of "correct" or "suitable" temperatures as a complement to a single reported neutral temperature. It uses quadratic regression analysis for the process.

8.4.1 Simple linear regression analysis

Simple linear regression analysis is performed on thermal expectation, sensation and preference responses against air temperatures (T_a). The mean thermal votes are used as dependent variables, instead of all votes, for the reasons of better goodness of fit (R^2) and the custom in reporting on thermal comfort field studies. These mean votes are also weighted by the number of the subjects [Busch 1990].

The scatter diagrams and the regression lines of thermal expectation and thermal sensation of all subjects are presented in Figure 8.13, and those of thermal preference, in Figure 8.14. For the cool and warm seasons, the analyses are shown in Appendix E.

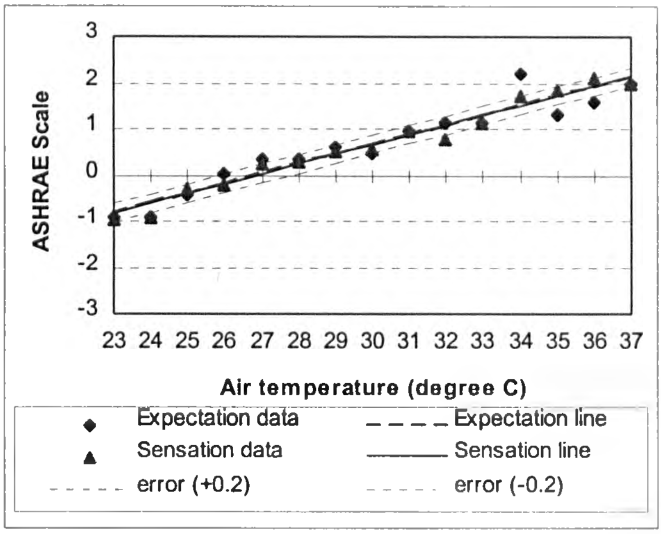


Figure 8.13 *Simple linear regression analysis of expectation and sensation with the band of instrumentation errors ±0.2 ℃ (see Appendix A).*

As shown in Figure 8.13, the slopes of expectation and sensation lines are identical at 0.21/°C, in which is about as steep as the slope of 0.22/°C found by Humphreys [1976] from a world-wide field studies review, but less than the slope of 0.33/°C by Fanger [1970] from his climate chamber experiments. It is suggested that the smaller the regression coefficient (slope), the better the adaptability to thermal variations of respondents [Humphreys 1976]. The expectation line gives the intercept (constant value) of -5.60 and R^2 of 0.88, and the sensation line gives the intercept of -5.69 and R^2 of 0.95.

The regression lines can be used to estimate the neutral temperatures by applying the knowledge of linear equation (see eq. 5.1). Therefore, the expected temperature and the neutral temperature can be calculated from the following equations:

thermal expectation (=0) = $0.21\ T_n - 5.60$ (eq. 8.1)

$T_n = 5.60 / 0.21 = 26.7°C$

thermal sensation (=0) = $0.21\ T_n - 5.69$ (eq. 8.2)

$T_n = 5.69 / 0.21 = 26.9°C$

From Figure 8.14, the analysis on thermal preference gives a very shallow regression coefficient and an unreliable result. The negative regression coefficient is -0.06; and the constant value is 1.10 and R^2 is 0.78.

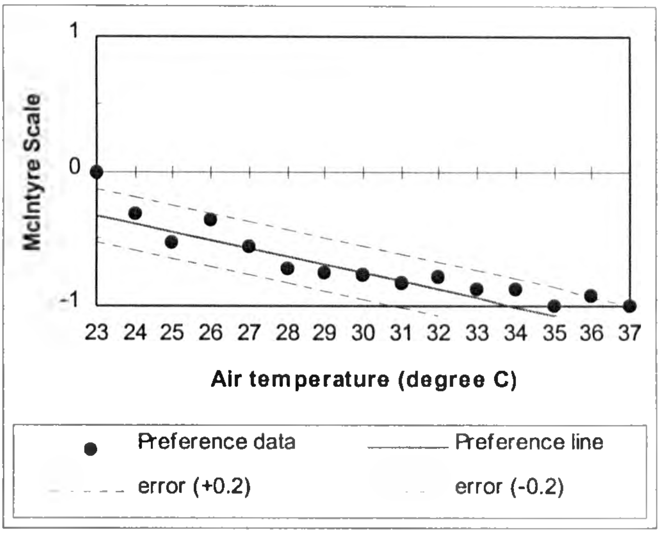


Figure 8.14 *Simple linear regression analysis of preference with the band of instrumentation errors ±0.2 °C (see Appendix A).*

The preferred temperature can be calculated from the following equation:

thermal preference (=0) = (-0.06) T_n + 1.10 (eq. 8.3)

T_n = 1.10 / 0.06 = 17.8°C

The simple linear regression analysis is only able to apply to all subjects, but fails to give the results for each subject group. It is because the analysis sometimes does not reach the significance level, or the regression coefficient is too shallow and cannot give a reliable neutral temperature. Therefore, the comparisons between each group are not available. Some results of the analysis in the cool, warm and combined seasons, are tabulated in Table 8.6.

Table 8.6 *Simple linear regression analysis of mean votes of all subjects.*

Scales	Slope	Intercept	R^2	T_n (°C)
In the cool season				
Expectation	0.16	-4.39	0.53	26.7
Sensation	0.21	-5.60	0.75	27.1
Preference	-0.09	1.87	0.83	21.6
In the warm season				
Expectation	0.23	-6.14	0.87	26.7
Sensation	0.20	-5.40	0.91	26.5
Preference	-0.03	0.06	0.69	2.0
In combined seasons				
Expectation	0.21	-5.60	0.88	26.7
Sensation	0.21	-5.69	0.95	26.9
Preference	-0.06	1.10	0.78	17.8

The expected temperatures in both seasons are identical at 26.7°C, while the neutral temperature in the cool season is 27.1°C and that in the warm season is 26.5°C. It is surprising that the neutral temperature in the warm season is lower than that in the cool season, despite the fact that air temperatures in the warm season are comparatively much higher. In the combined seasons, all subjects have the expected temperature at 26.7°C, and the neutral temperature at slightly higher 26.9°C.

The preferred temperatures are very low at 17.8°C and 21.6°C, in the combined and cool seasons, respectively; and unrealistic 2.0°C in the warm season. The reason for this unusual result may be arrived from the bias of the votes towards "cooler" and "no change" preferences, thereby leading to a non-normal distribution (not bell-shaped curve). As a consequence, the result could only be interpreted as an expression of preferring a cooler thermal environment of the respondents.

8.4.2 Probit regression analysis

The probit technique is used to analyse all thermal responses of all subjects, subjects between seasons and each subject group. An example of the probit analysis of thermal sensation of all subjects is shown in Figures 8.15 and 8.16.

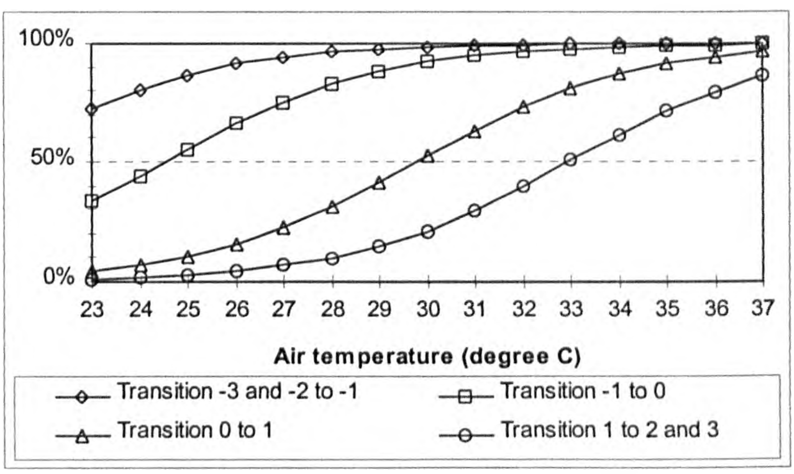


Figure 8.15 Cumulative distributions of thermal sensation responses.

As seen in Figure 8.15, there are three transition temperatures determined at three intersections between the cumulative distributions curves and the 50% line. The transition temperature from "slightly cool" to "neutral" (transition -1 to 0) is approximately at 24.5°C; from "neutral" to "slight warm" (transition 0 to 1) at 29.5°C; and from "slightly warm" to "warm or "hot" (transition 1 to 2 and 3) at 33.0°C. These transition temperatures imply the category width: the "neutral" category is 5 K and the "slightly warm" category is 3.5 K.

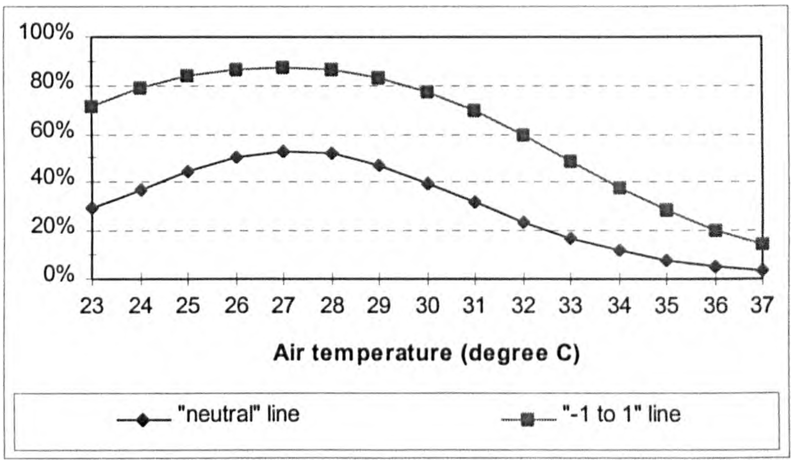


Figure 8.16 *Probit analysis of thermal sensation of all subjects.*

The curves in Figure 8.16 are re-drawn from Figure 8.15, in order to re-present the maximum proportions of votes in "neutral" and "central-three-category". The peaks of the curves can then be assumed as the neutral temperature of the group population [Humphreys 1976]. The peak of the "neutral" line is at 27.2°C, while that of the "-1 to 1" line is somewhat lower at 26.9°C.

Another example of the probit analysis of thermal preference of all subjects combined, is shown in Figures 8.17 and 8.18.

As seen in Figure 8.17, there is only one transition temperature determined from "no change" to preference for "cooler", at approximately 26.0°C, which is about 1 K lower than the neutral temperature. The subjects in the tropical climates are able to tolerate to a relatively high temperature but somehow prefer a cooler air than their neutral temperature. The proportion of the subjects "wanting cooler" is much larger than the other groups. The subtraction of two transition lines in Figure 8.17, is re-drawn in Figure 8.18, indicating the proportion of preference "no change". The peak of the curve, as the preferred temperature, is at 21.4°C.

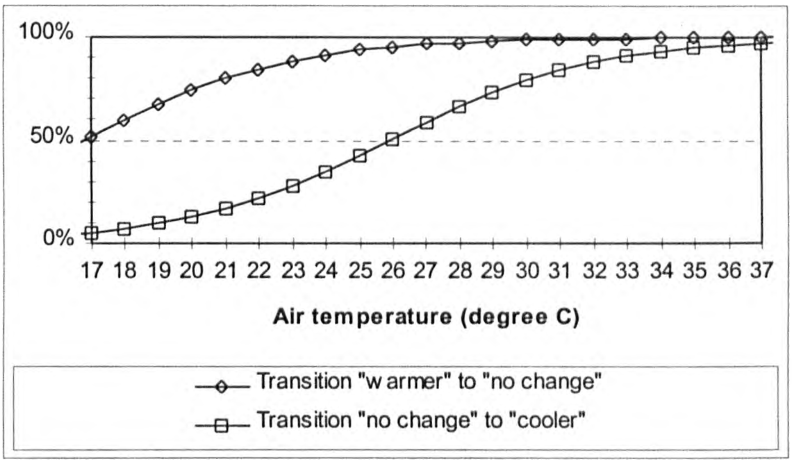


Figure 8.17 *Cumulative distributions of thermal preference responses.*

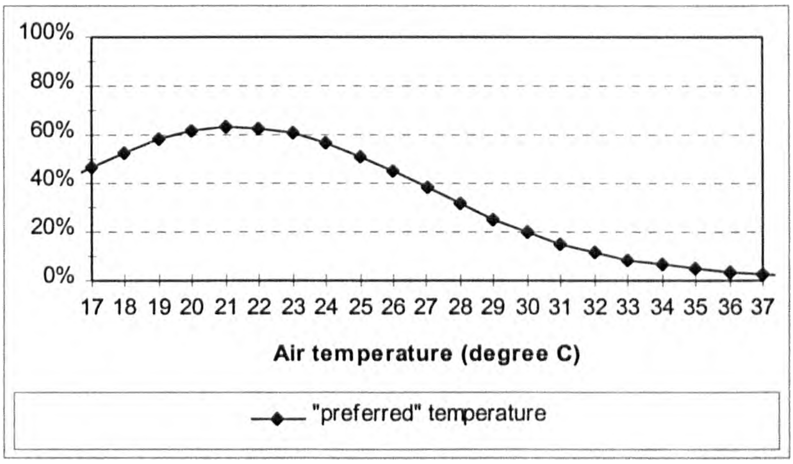


Figure 8.18 *Probit analysis of thermal preference of all subjects.*

The probit technique is also applied to analysis of thermal expectation, sensation and preference of all samples in the cool and warm seasons (see Appendix I). Like the simple linear regression analysis, the probit regression analysis is not able to give full results of the neutral temperatures of each subject group. This is due to two main reasons: the result is not statistically significant and the regression coefficient is too small.

It should be noted that, although the property and the process of both analyses are different, the assumptions underlying both methods are identical. The assessments of both techniques are free from auto-correlation, meaning that the variables such as sensation of warmth affected by the subjects' actions or adjustments, are not considered in the analysis [Humphreys 1976]. Therefore, when the results of the analysis are interpreted, the effects of the environmental or individual factors are indeed hidden in the findings.

Table 8.7 *Probit regression analysis of all subjects and each subject group.*

Scales	All	A/C indoor	N/V indoor	A/C outdoor	N/V outdoor
In the cool season					
Expectation "-1 to 1"	26.1	28.3	N/A	22.8	N/A
Expectation "neutral"	26.9	28.6	N/A	24.2	N/A
Sensation "-1 to 1"	27.4	27.5	N/A	25.5	N/A
Sensation "neutral"	27.0	27.3	N/A	26.0	N/A
Preference "no change"	22.2	22.3	N/A	23.5	N/A
In the warm season					
Expectation "-1 to 1"	25.9	N/A	N/A	N/A	N/A
Expectation "neutral"	27.9	N/A	N/A	25.2	26.0
Sensation "-1 to 1"	25.5	26.3	N/A	N/A	N/A
Sensation "neutral"	26.9	27.0	N/A	26.6	25.8
Preference "no change"	N/A	N/A	N/A	N/A	N/A
In combined seasons					
Expectation "-1 to 1"	25.9	N/A	N/A	20.6	23.7
Expectation "neutral"	27.4	N/A	N/A	22.6	27.6
Sensation "-1 to 1"	26.9	26.7	N/A	24.8	N/A
Sensation "neutral"	27.2	27.0	N/A	26.3	26.3
Preference "no change"	21.4	22.5	N/A	23.9	N/A

The summary of the probit analysis of all subjects and each subject group, separated into the cool, warm and combined seasons, is shown in Table 8.7. In the cool season, the expected temperature and the neutral temperature of all subjects is quite similar (26.9-27.0°C); but in the warm season, the expected (27.9°C) is 1 K higher than the neutral (26.9°C). When considering the results from the wider categories of "-1 to 1", the neutral temperatures are quite controversial, like the findings from the simple regression analysis. The neutral temperature in the warm season (25.5°C) is about 2 K lower than that in the cool season (27.4°C). The expected temperature in the warm season (25.9°C) is also slightly lower than that in the cool season (26.1°C). The preferred temperature for "no change" is 22.2°C in the cool season but is not available in the warm season. In the combined seasons, all subjects have neutral temperature at 27.2°C, and preferred temperature at 21.4°C.

The neutral temperatures of individual subject group are only available in certain analyses. The expected and neutral temperatures of the A/C-indoor subjects are higher than those of the other groups, although air temperatures of this group are much lower. The neutral temperatures of every group are clustered around 25-27°C and the preferred temperatures are approximately 22-24°C. However, the comparatively wide range of the expected temperatures (around 21-29°C) are much different.

8.4.3 Griffiths' value

Both simple regression and probit analysis fail to establish the neutral temperatures in certain cases namely those of each subject group. The alternative method by using a calculating model is introduced — the Griffiths' value [1990] (see 5.3.5). It uses mean comfort vote and mean air temperature as variables, and assumes a regression coefficient of 0.33/°C. The previous research using this model were by Nicol et al [1994] and by Malama [1997] which reported thermal comfort in Pakistan, and in Zambia, respectively.

The Griffiths' model is written as the following equation (see 5.3.5):

$$T_n = T_i + (0 - C_m) / a^* \qquad \text{(eq. 5.13)}$$

where T_n = neutral temperature (or comfort temperature)

T_i = mean internal temperature

0 = "neutral" category in seven-point comfort scale

C_m = mean subjective comfort vote

and a^* = regression coefficient of 0.33/°C.

By applying this model, the neutral temperatures of all samples and each subject group in the cool, warm and combined seasons can be calculated, and they are shown in Table 8.8.

Table 8.8 *Neutral temperatures calculated from Griffiths' value.*

	All	A/C indoor	N/V indoor	A/C outdoor	N/V outdoor
In the cool season					
Mean comfort vote	0.14	-0.80	0.27	0.41	0.50
Mean air temperature	27.8	25.0	28.5	27.6	30.1
Neutral temperature	27.4	27.4	27.7	26.4	28.6
In the warm season					
Mean comfort vote	0.60	-0.20	0.84	0.38	1.36
Mean air temperature	29.7	26.1	30.9	28.8	33.2
Neutral temperature	27.9	26.7	28.4	27.6	29.1
In combined seasons					
Mean comfort vote	0.36	-0.48	0.51	0.39	0.90
Mean air temperature	28.8	25.6	29.7	28.2	31.7
Neutral temperature	27.7	27.1	28.2	27.0	29.0

It is clear that the Griffiths' value is a useful model to estimate the neutral temperatures of all samples, and simultaneously every individual subject group. The neutral temperature of all subjects in the combined seasons is 27.7°C, which is slightly higher than that found in simple regression (26.9°C) and probit analysis (27.2°C).

The neutral temperatures of every subject group varies, according to the outdoor temperatures and the actual warmth votes of the subjects. The lowest neutral temperature in the cool season is in the A/C-outdoor group (26.4°C), and that in the warm season is in the A/C-indoor group (26.7°C). The highest neutral temperatures in both cool and warm seasons are in the N/V-outdoor group (28.6°C and 29.1°C, respectively). In the combined seasons, the neutral temperatures of the A/C groups are around 27°C, while those in the N/V groups are 1-2 K higher. The findings suggest the variable such as mean comfort (sensation) vote as a significant parameter for the Griffiths' value.

8.4.4 Thermal acceptability

The analysis to establish thermal acceptability is to provide a range of "correct" or "suitable" temperatures for a particular environment, or to give a broader indication of the acceptable temperatures than a single reported neutral temperature. Thermal acceptability is closely related to the concept of a "comfort zone" (see 4.4.4). A small dissimilarity can be claimed that the thermal acceptability is concerned with the concept of acceptable temperatures which are derived from the subjective thermal responses in the field, but the comfort zone is the consideration of a complex relationship between environmental parameters namely T_a, MRT, rh and v, as a whole, and the human body at rest. Research which has been reviewed shows that "thermal acceptability" has continued to be widely debated [Busch 1990], whilst the concept of comfort zone was firmly established by Olgyay [1963] and Givoni [1969].

In general, there are four means to arrive thermal acceptability for the respondents:

1. a direct question whether the encountered environment is acceptable;

2. the conventional method considering thermal sensation votes within the central three categories of the seven-point ASHRAE scale, i.e., "-1 to 1";

3. the 80% of the respondents who are satisfied by their environments (or 20% of Predicted Percentage of Dissatisfied - PPD) [ISO 7730-1994]; and

4. thermal preference responses for "no change" category of the three-point McIntyre scale, assuming satisfaction without any desire to "cooler" or "warmer".

Unfortunately, this field study did not ask the direct question on thermal acceptability to the respondents, and therefore, there is no analysis by the first means. By using the other three methods, both ASHRAE and McIntyre scales are considered. Figure 8.19 shows the percentages of all subjects in the cool, warm, and combined seasons, comparing the responses for "no change" preference; for "neutral" sensation; and for "central-three-category" on the sensation scale.

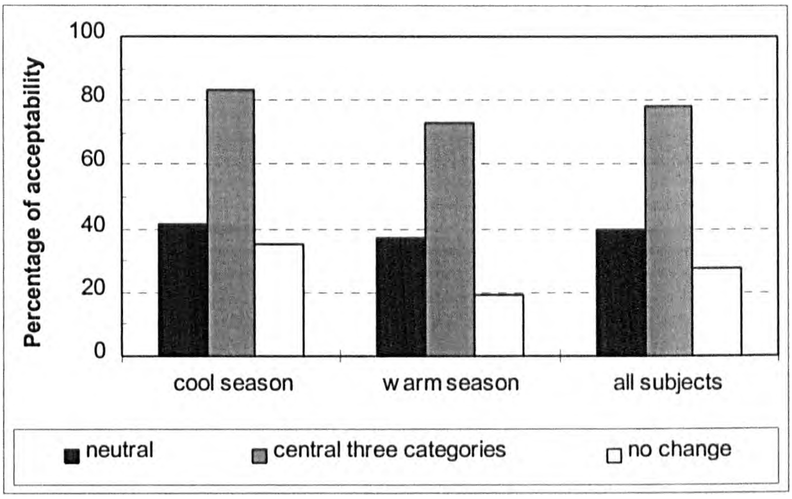


Figure 8.19 *Comparison of thermal acceptability.*

In the combined seasons, the proportion of respondents who indicate "no change" on the preference scale is only 27.6%, while the votes for "neutral" on the sensation scale are 39.5%, and for "central three categories" a much higher 78.4%. Seemingly, the "no change" is not the acceptable category for the subjects in this field study.

Using the percentage distributions of both responses from ASHRAE and McIntyre scales, the cross-tabulation between thermal sensations and thermal preferences of all responses is shown in Table 8.9. (The cross-tabulations between the sensation and the preference scales in both cool and warm seasons are shown in Appendix J).

Table 8.9 *Cross-tabulation between thermal sensation and preference scales of all subjects.*

Sensation	Preference			Total
	"cooler"	"no change"	"warmer"	
-3	0	60.0	40.0	0.4
-2	22.0	53.7	24.4	3.6
-1	44.8	50.8	4.4	16.0
0	62.5	36.1	1.3	39.5
1	89.7	9.2	1.1	22.9
2	94.1	5.3	0.6	14.9
3	96.7	3.3	0	2.6
Total	69.8	27.6	2.6	100.0

Note: Percentages are calculated by row, within each sensation scale vote.

As seen in Table 8.9, nearly seventy per cent of the whole sample indicate "cooler" and there is almost an absence for "warmer". The majority of the cool side (-1 to -3) in the sensation prefer "no change", and the majority of the warm side (1 to 3) prefer "cooler". These findings are quite similar to those found in tropical classrooms by Kwok [1998]. This shows that the preference scale is a more stringent measure of ideal condition than the sensation scale, as also found by Busch [1990a; 1992]. Kwok [1998] claimed that a standard based only on a measure of neutral temperature by thermal sensation analysis may be inappropriate for the people in the tropics. Further discussion to investigate the relationship between neutrality and preference is in the next chapter (see 9.4.3).

The range of thermal acceptability is determined by using the 80% or above of the respondents voting within the central three categories on the sensation scale as criteria. A quadratic regression technique is used to estimate the curve lines. The analysis of all subjects is shown in Figure 8.20, and that of each subject group in Figure 8.21.

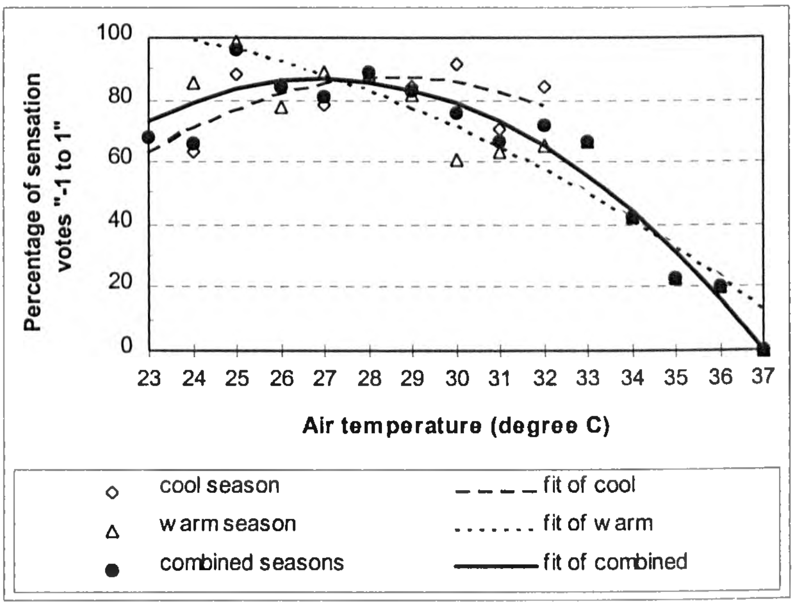


Figure 8.20 *Thermal acceptability of all subjects.*

Thermal acceptability of all subjects is ranged between 24.2 and 29.8°C, which is still within the comfort zone of 21.0-30.0°C, defined by Olgyay [1963]. In the cool season, the thermal acceptability is between 25.5 and 31.7°C, while in the warm season, the lower boundary of thermal acceptability is undefined and the upper boundary is comparative low at 28.7°C. It is surprising that the acceptable temperatures in the warm season are lower than those in the cool season.

The upper acceptable temperature from this field study is much higher and beyond the warm boundary of summer comfort of 26.0°C defined by ISO 7730 [1994] and ASHRAE 55 [1992]. Although the thermal index used in this study (air temperature — T_a) is different from that applied in the ISO Standard (operative temperature — T_o) and the ASHRAE Standard (new effective temperature — ET*), it has been argued that either complicated or simple indices do not give much different explanations of thermal comfort [Humphreys 1994].

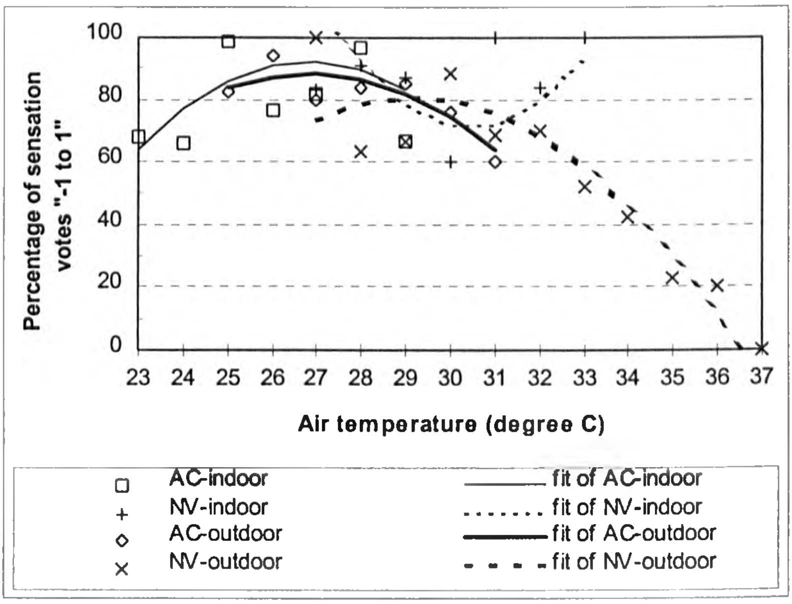


Figure 8.21 *Thermal acceptability of each subject group.*

From Figure 8.21, thermal acceptabilities of the air-conditioned buildings (either indoor or outdoor) are fairly similar to each other and are in good agreement with the acceptability of all subjects. The curvilinear of the A/C-indoor subjects crosses the 80% line at 24.3 and 29.4°C, and that of the A/C-outdoor subjects at 24.4 and 29.3°C.

The thermal acceptability of the N/V-indoor subjects is not logical; the parabolic curve is upside down, implying that the majority of the subjects are satisfied when air temperatures are either higher than 32.1°C or lower than 28.8°C. For the N/V-outdoor subjects, the thermal acceptability is very narrow

(≈ 1.2 K) and comparatively high (from 28.6 to 29.8°C). This is because the votes in the central-three-category are extremely low, and therefore, the curvilinear line virtually misses the 80% line.

If considering the thermal acceptability in the cool and warm seasons (see Appendix K), only the A/C-outdoor group can be assessed. In the cool season, the acceptability is 22.7-27.3°C, and in the warm season, 24.5-29.9°C. For the other groups, the parabolic fit-curves are not logical (being upside down), or not statistically significant, or do not reach the 80% line.

8.5 Humidity and air movement on human comfort

The effects of humidity and air movement on comfort are investigated by a comparative technique. The methodology used for analysis in this study is replicated the previous work by Nicol [1974]. The probit analysis is used to regress two different groups of data at each binned air temperature, which subsequently compare with each other and with the base case (of the combined subjects voting "-1 to 1" — see Figure 8.16). It is believed that the findings are able to show the significant influences of both groups of high/low humidity and high/low air movement on human comfort.

8.5.1 The combined effect of air temperature and humidity

The investigation of the effect of humidity is studied through the variations of water vapour pressure (P_a), which is the moisture content of air[1]; and is usually used in the analysis of thermal comfort research in order to study the exact quantity of the moisture in the air [Chalkley and Cater 1968] (see 7.6.1). To obtain fairly equal number of data for comparison, the subjects are divided into two groups: those with low water vapour pressure (P_a less than 21 millibar) and

[1] Vapour pressure is the pressure exerted by the molecules of vapour contained in air. Enables the rate of diffusion of vapour through materials of construction to be estimated [Burberry 1983; 1992].

those with high water vapour pressure (P_a exceeded 21). The property of these two groups is shown in Table 8.10.

Table 8.10 *Comparison of two different water vapour pressure groups*

	$P_a < 21$	$P_a > 21$
Number of subjects	547	596
Mean T_a (°C)	27.0	29.9
Mean rh (%)	50.2	57.1
Mean P_a (millibar)	17.8	24.0
Mean met-value	1.50	1.66
Mean clo-value	0.55	0.53
Mean thermal sensation vote	0.05	0.65
Mean thermal preference vote	-0.55	-0.79

The number of subjects in the less water vapour pressure group ($P_a < 21$) is slightly lower than the other group ($P_a > 21$), and they experience comparatively lower mean air temperature (approximately 3 K) and perform somewhat lower mean metabolic rate. The clo-values of both groups are fairly similar. Mean thermal sensation of the subjects in the less humid environments is "neutral", and that of the subjects in the high humid environments is near "slightly warm". However, mean thermal preferences of both groups are similar, for "cooler".

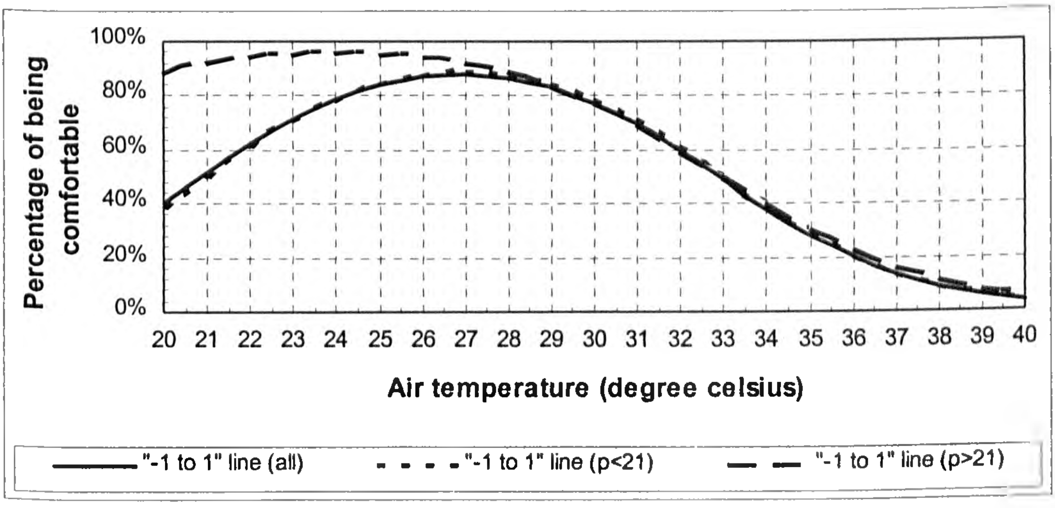


Figure 8.22 *Probit analysis : the effect of humidity.*

The probit analysis, used to examine the effect of humidity on comfort, is shown in Figure 8.22. The curves show the proportional percentages of the subjects who vote within the central-three-category on thermal sensation scale, indicating their comfort at different air temperatures. One curve includes the observations of $P_a < 21$ millibar and the other of $P_a > 21$ millibar. The base case of the combined population is also shown for comparison.

The curve of the $P_a < 21$ group (dot line) is nearly identical to that of the whole subject (full line), which shows its peak or the maximum percentage of the comfortable votes (neutral temperature) at approximately 27.0°C. The other curve of the $P_a > 21$ group (dash line) appears to have more subjects being comfortable at around 28.0°C and below. The maximum of comfortable subjects (neutral temperature) of this group is at approximately 24.0°C. More than half of the subjects are comfortable, if the air temperatures are not beyond 33.0°C, regardless of high or low water vapour pressure. The range of 80% comfortable (thermal acceptability) of the $P_a < 21$ group is approximately between 24.5°C and 29.5°C. For the $P_a > 21$ group, the upper limit of the 80% comfortable range is around 29.5°C, but the lower limit is undefined.

At low air temperatures (i.e., below 28°C), high water vapour pressure has increased effects on subjects being comfortable. However, it should be noted that this finding is arrived from the combined effect with air temperature, which the $Pa < 21$ group has experienced relatively lower mean air temperature of approximately 3 K.

8.5.2 The combined effect of air temperature and air movement

The investigation of the effect of air movement is using the same method of analysis as that of the effect of humidity. The variations of the air movement to test here is applying the unit of square root air velocity ($\sqrt{v}$) (see 7.6.1). The subjects are divided into two groups: those with $\sqrt{v}$ less than 0.5 $(m/s)^{1/2}$ (i.e., air velocities less than 0.25 m/s), and those with $\sqrt{v}$ more than 0.5 $(m/s)^{1/2}$. The property of these two groups is shown in Table 8.11.

Table 8.11 *Comparison of two different square root air velocity groups.*

	$\sqrt{v} < 0.5$	$\sqrt{v} > 0.5$
Number of subjects	558	585
Mean T_a (°C)	28.1	28.9
Mean v (m/s)	0.14	0.52
Mean $\sqrt{v}$ $(m/s)^{0.5}$	0.36	0.70
Mean met-value	1.53	1.63
Mean clo-value	0.55	0.53
Mean thermal sensation vote	0.48	0.24
Mean thermal preference vote	-0.67	-0.67

Both subject groups experience quite similar mean air temperatures, and are clothed fairly similar mean clo-value. The subjects with less air movement ($\sqrt{v} < 0.5$) perform somewhat lower mean metabolic rate. On subjective thermal responses, the subjects of high air movement group ($\sqrt{v} > 0.5$) have mean thermal sensation close to "neutral", and the other group, between "neutral" and "slightly warm". Mean thermal preference votes of both groups are identical (for "cooler").

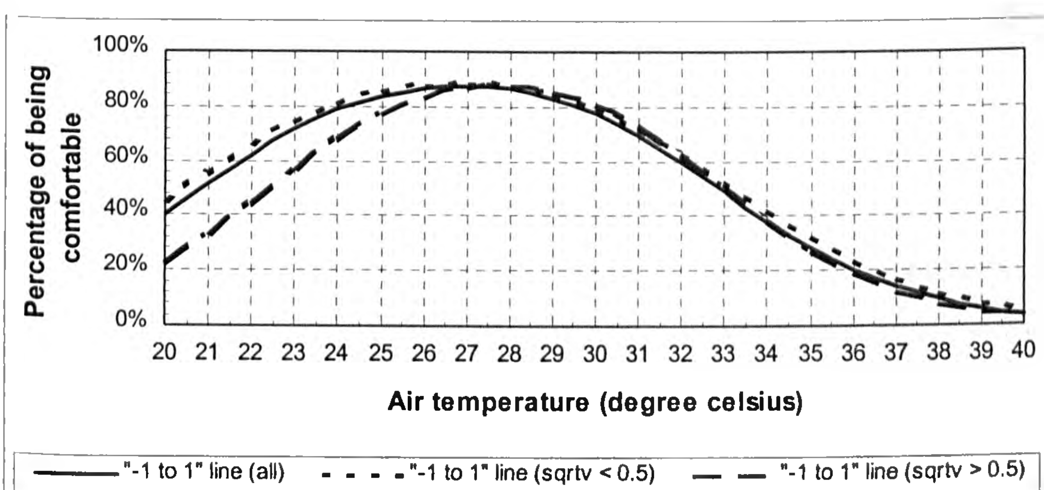


Figure 8.23 *Probit analysis: the effect of air movement.*

The probit analysis in Figure 8.23 shows the combined effect of air temperature and air movement on human comfort. The curves show the proportional percentages of comfortable subjects (who vote the central-three-category on thermal sensation scale) at each air temperature. Two curves of the $\sqrt{v} < 0.5$ group and the $\sqrt{v} > 0.5$ group, compare to each other and to the base case of "-1 to 1" line of the whole subject.

The curve of the $\sqrt{v} < 0.5$ group (dot line) is nearly identical to that of the combined population (full line); and shows its maximum percentage of comfort votes (neutral temperature) at approximately 27.0°C. The range of 80% comfortable (thermal acceptability) is approximately between 24.0°C and 29.5°C. The other curve of the $\sqrt{v} > 0.5$ group (dash line) has its peak (neutral temperature) at a slightly higher air temperature of 28.0°C, and there is a higher but narrower range of 80% comfortable (thermal acceptability) at around between 25.5°C and 30.0°C.

It should be noted that, at high air temperatures (i.e., above 30°C), high air movement does not have effects on comfort (does not extend the comfort zone or give the sense of more comfortable conditions) to the subjects in this study, which is not in agreement with general literature. Worse, at low air temperatures (i.e., below 26°C), high air movement can reduce the number of subjects voting comfortable. The explanation to this finding may be contributed to the combined effect with air temperature, despite a slightly higher mean air temperature (only 1 K) of the $\sqrt{v} > 0.5$ group!

8.6 Summary

The analysis of field study data, using scatter diagram and correlation coefficient techniques, has revealed that there are some relationships between environmental parameters and subjective thermal responses, but none is found consistent and significant with the reported personal parameters. The positive relationship between air temperatures and thermal sensations is significant and most strong ($r = 0.50$) for the combined subjects. The relationships between air temperatures and expectations are also positive, but those between air temperatures and preferences are negative.

Vapour pressures are second well correlated with air temperatures or with thermal sensations, but square root air velocities are not. The relationships between air temperatures or thermal sensations and metabolic rates are slightly low and positive. Only relationship between air temperature and clothing insulation value in the cool season (r = -0.18) gives a sign of adaptation by changing clothing in relation to the thermal environments of a little cooler.

To establish the neutral temperatures (T_n), the simple linear regression and the probit analysis can be used to estimate for all subjects (in the cool, warm and combined seasons), but fail to give T_n of each subject group. The neutral temperature of all subjects is approximately at 27.2°C; the expected temperature (calculated from the seven-point expectation scale) is somewhat lower at 27.1°C; and the preferred temperature (from the three-point preference scale) is much lower and cannot be calculated for the warm season. In the cool season, the preferred temperature is approximately 21.9°C.

Using Griffiths' method, the neutral temperatures (T_n) of individual subject groups can be established. The air-conditioned groups have T_n at approximately 27.0°C, regardless of either indoor or outdoor environmental conditions. The N/V-indoor subjects have T_n at 28.1°C; and the N/V-outdoor subjects, at 28.9°C.

Thermal acceptability is analysed by using the quadratic regression technique. Assumed at 80% or above of the subjects voting the central three categories on thermal sensation scale, the range of acceptable temperatures of the combined subjects is between 24.2°C and 29.8°C, in which the upper boundary is extended beyond the summer comfort range recommended by the standards. The thermal acceptability of the air-conditioned environmental groups is approximately 24-29°C, regardless of either indoor or outdoor, and that of the N/V-outdoor is very narrow (28.6-29.8°C), but that of the N/V-indoor group is not available due to unrealistic. It is also shown that thermal preference is a more stringent measure than thermal sensation in the tropics.

This chapter has also analysed the combined effects of air temperatures with humidity and with air movement upon human comfort. At low air temperatures (i.e., below 28°C), there are more number of subjects being comfortable if high water vapour pressure; and surprisingly, if low air movement. The comfortable conditions of the low water vapour pressure group and of the low air movement group, are nearly identical to those of the whole subject.

The analysis of this field study data gives more understanding of the comfortable conditions in relation to both environmental and personal factors. Some findings are in good agreement with the literature or the previous research in the tropical climates, but some are not. The next chapter will further investigate and discuss the comfort issues, and will compare with other findings, including the standard criteria — the PMV-PPD models, other world-wide findings, and the adaptive models.

Chapter 9

DISCUSSION OF THE RESULTS

"We do not seek to "Tell Anyone What To Do", but more to lay down a structure for the purpose. We hope that local researchers will use the results for a wide range of purposes and at the same time make them available to others interested in the development of the (adaptive) model, and in better understanding of thermal comfort in buildings."

F. Nicol [1993]

9.1 Introduction

This chapter will discuss the comfort issues, aiming at investigating the possibility and actually applying thermal comfort theory, to field study and to practice. Previous research which produced standards and several models, will be compared with the findings of comfortable conditions in this field study. The PMV-PPD models and the Adaptive Models have been the main interest of thermal comfort study and will be the main criteria to be explored for this thesis. Other previous models such as Humphreys' and Auliciems' are also considered.

The relationships between thermal expectation, sensation and preference responses will be clarified to distinguish their characteristics and the significance of their roles in thermal comfort. These thermal responses produce the expected, neutral and preferred temperatures, respectively, which can be used in real-life situations. With the application of the adaptive theory, human comfort can be achieved by various kinds of environmental and behavioural adjustments/adaptations through the considering in both physiological and psychological means.

Finally, this chapter will conclude with one of the methodologies used to improve an acceptable thermal environment — the use of adaptive errors [Baker and Standeven 1996]. This will show the effects of cumulative revision or bias towards improving comfort. By altering the input data of environmental and individual parameters little by little, the results of thermal acceptability will show a dramatic increase.

9.2 Neutral temperatures and thermal acceptability

This field study of thermal comfort in transitional spaces in buildings in Bangkok used many methods of statistical analyses to establish neutral temperatures and thermal acceptability of all subjects and each subject group. The most common method — simple linear regression analysis, and the second best known — probit regression analysis were used to determine the neutral temperatures for all subjects. The Griffiths' model was introduced to estimate the neutral temperatures for all subjects and for every individual subject groups. Finally, the quadratic regression was used to analyse the thermal acceptability. These neutral temperatures and thermal acceptability are graphically summarised in Figure 9.1.

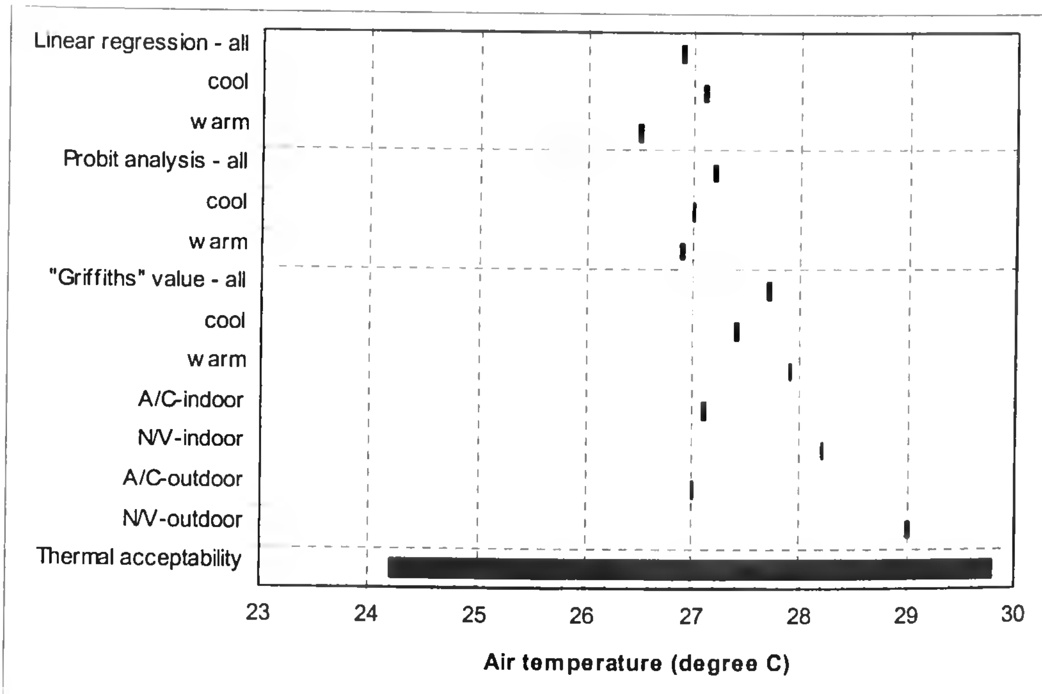


Figure 9.1 *Neutral temperatures and thermal acceptability in this study.*

The neutral temperatures of all subjects in the cool, warm and combined seasons, are scattered around 27.2°C ± 0.7 K. For all subjects in the combined seasons, the neutral temperatures by linear regression is 26.9°C; by probit analysis is 27.2°C; and by Griffiths' value is 27.7°C. It is interesting to note that the neutral temperatures in the cool season from linear regression and probit analysis are higher than those in the warm season. Higher neutral temperatures in the cool season were also found in tropical upland housing in Zambia [Malama et al 1998] and in UK office environments [Oseland 1998].

The neutral temperatures of each subject group calculated by the Griffiths' value are variable. In the air-conditioned buildings, the A/C-indoor subjects who were in the air-conditioned environments have the neutral temperature of 27.1°C, which is fairly similar to that of the A/C-outdoor subjects (27.0°C) who experience the naturally ventilated environments. Some previous field-study research, for example, in UK office environments [Oseland 1998] and in the tropical classrooms in Hawaii [Kwok 1998], found that the neutral temperatures in the air-conditioned rooms were higher than those in the naturally-ventilated rooms.

It is claimed that these anomalies of thermal sensation responses resulted from the effects of thermal *preferences*, *expectations* and *experiences* in thermal environments of subjects [Oseland 1998]. Other explanations considered the results of the neutral temperatures and regression coefficients in terms of *adaptation* [Malama et al 1998]; and the clustering of the majority of thermal sensation responses over *a narrow range of experienced air temperatures* [Kwok 1998].

In the naturally ventilated buildings, the neutral temperatures are 28.2°C in the N/V-indoor subjects and 29.0°C in the N/V-outdoor subjects. These two groups have relatively high neutral temperatures as expected because their encountered environments were of high air temperatures. In this field study, the subjects (of all groups) were exposed to a comparatively wide range of air temperatures (between 23.1°C and 36.7°C), and this affected a wide range of thermal acceptability (between 24.2°C and 29.8°C).

9.3 Comparison the neutral temperatures

9.3.1 Comparison to the standards

The neutral temperatures and thermal acceptability in transitional spaces in Bangkok are compared with the standards and other results from tropical climates. The neutral temperature of 27.2°C in this study is higher than the recommendations of the upper summer comfort temperature of 26.0°C, by both ISO 7730 [1994] and ASHRAE 55 [1992] Standards. Even more, the range of the thermal acceptability of 5.6 K (24.2-29.8°C) in this study is wider than that of approximately 3.0 K (23.0-26.0°C) of the Standards.

The universal standards, which have been applied across all building types, climate zones and populations, are crucially much different to the other reported results [Parsons 1994]. Busch [1990b] mentioned that currently, air-conditioned buildings in the tropics and elsewhere have been designed according to criteria based on comfort studies of white, male, college-age responses (from the West). Kempton and Lutzenhiser [1992] also stated that the standards ignore the importance of cultural, climatic, social and contextual dimensions of comfort, thereby leading to an exaggeration of the need for air conditioning. De dear and Brager [1998] suggested that people in warm climate zones prefer warmer indoor temperatures than those living in cold climates, and this is the basis of the adaptive hypothesis.

9.3.2 Comparison to other results in tropical regions

When compared with other findings from tropical climates, the results of this study are quite similar to those from the naturally-ventilated environments. This may be explained by the thermal environments of the majority of the subjects in free-running conditions (or the environments without any controls) namely A/C-outdoor, N/V-indoor and N/V-outdoor.

The neutral temperature of 27.2°C is very similar to that of 27.4°C of the previous research of Thai workers in naturally ventilated offices [Busch 1992]. It is also similar to that of 27.5°C of Indian subjects [Sharma and Ali 1986]; that of 27.9°C of Pakistani subjects of summer season [Nicol et al 1994]; that of 26.5°C in Indonesian office workers [Karyono 1996a]; and that of 27.4°C and 26.8°C in A/C and in N/V classrooms, respectively, in Hawaii [Kwok 1998].

Other findings gave relatively high neutral temperatures but in the same level as the upper boundary of thermal acceptability in this study. Among these are the neutral temperature of 28.3°C from Malaysian subjects in Malaysia (climate chamber study) [Abdulshukor 1993]; that of 28.5°C from Singaporean residents in naturally ventilated apartments [de Dear et al 1991c]; that of 28.0-31.6°C (the latter temperature applied with fan of 0.45 m/s) in housing in Dhaka, Bangladesh [Mallick 1996]; and that of 31.1°C in Roorkee, India [Nicol 1974].

9.3.3 Comparison to Humphreys' and Auliciems' models

The application of both Humphreys' and Auliciems' models is based on the earlier stage of the adaptive model, which considered *acclimatisation* as a factor affecting thermal comfort (see 5.3.1). They showed the relationship between the indoor comfort temperatures and the prevailing (internal or external ambient) temperatures. As a consequence, the comparison of only two indoor groups namely the A/C-indoor and the N/V-indoor will be concerned. The input data of mean indoor (T_i) and mean outdoor (T_m) temperatures are derived from field measurements. The results of the neutral temperatures (T_n) as the outputs will justify the best predictors of the models.

The equations of Humphreys' models (see 5.3.2) are:

$$T_{n,i} = 2.56 + 0.831\ T_i \qquad \text{(eq. 5.3)}$$

$$T_{n,m} = 11.9 + 0.534\ T_m \qquad \text{(eq. 5.4)}$$

The equations of Auliciems' models (see 5.3.3) are:

$$T_{n,i\&m} = 0.48\ T_i + 0.14\ T_m + 9.22 \qquad \text{(eq. 5.6)}$$

$$T_{n,m} = 0.31\ T_m + 17.6 \qquad \text{(eq. 5.7)}$$

$$T_{n,i} = 0.73\ T_i + 5.41 \qquad \text{(eq. 5.8)}$$

The calculated neutral temperatures in the combined seasons are shown in Table 9.1.

Table 9.1 *Neutral temperatures from Humphreys' and Auliciems' models.*

	A/C indoor	N/V indoor
Griffiths' value	27.1	28.2
(eq. 5.3) Humphreys' model ($T_{n,i}$)	23.8	27.2
(eq. 5.4) Humphreys' model ($T_{n,m}$)	27.0	28.8
(eq. 5.6) Auliciems' model ($T_{n,i\&m}$)	25.5	27.9
(eq. 5.7) Auliciems' model ($T_{n,m}$)	26.3	27.4
(eq. 5.8) Auliciems' model ($T_{n,i}$)	24.1	27.1

Compared with the neutral temperatures of both A/C-indoor (27.1°C) and N/V-indoor (28.2°C) groups from the Griffiths' value of this field study, the calculated neutral temperature from eq. 5.4 of Humphreys' model ($T_{n,m}$) is the best predictor for the A/C-indoor group, and eq. 5.6 of Auliciems' model ($T_{n,i\&m}$) for the N/V-indoor group. The discrepancies of the neutral temperatures are less than 0.8 K. The second best predicting tool for the A/C-indoor group is eq. 5.7 by Auliciems ($T_{n,m}$) and for the N/V-indoor group is eq. 5.4 by Humphreys ($T_{n,m}$). The neutral differences are less than 1.2 K.

9.3.4 Comparison to the PMV-PPD models

The PMV model (see 4.4.3) was originally applied to a steady-state condition, where human subjects were exposed for a long period of time to a constant thermal condition at a constant metabolic rate [Fountain and Huizenga 1996b; 1997]. Although the results from this field study and those predicted by the PMV model do not compare well, because the environmental conditions were dynamic as in the transitional spaces, it is assumed at a particular moment to be predicted by the PMV equation, using the mean values of all parameters as input variables. The PMV values in this field study are determined by a thermal comfort prediction tool — "WinComf" on Windows [Fountain and Huizenga 1996a].

Before anything else, it should be noted that there are limitations of this comfort prediction tool which may give an error to predicted results [Fountain and Huizenga 1996a]. The model can work best only for sedentary humans wearing light clothing, in thermal conditions of the ASHRAE comfort zone and without air movement. The farther away the input data, the more error the results. The expected error in the PMV is approximately half of a thermal sensation scale value if within the ASHRAE comfort zone, and it increases by around one third of a scale value for each degree Celsius change in effective temperatures [Doherty and Arens 1988].

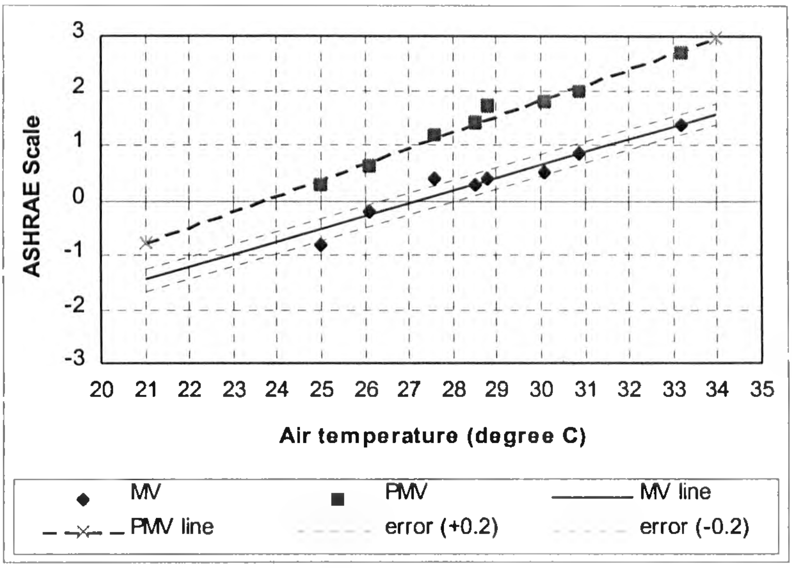


Figure 9.2 *Comparison of the PMV and the actual mean vote (MV) with approximate errors ±0.2 °C.*

Figure 9.2 shows the scatter diagram of eight individual subject groups (each four in the cool and warm seasons), and the regression lines of the PMV model and the actual mean vote (MV). The PMV of the N/V-indoor group in the warm season is extremely high (+2.69) and it is the most doubtful result because its value is much farther away from neutral (beyond +2 — see 4.4.3). The regression coefficient of the PMV is 0.29/°C, and is slightly higher than that of the actual mean vote (MV) of 0.23/°C. The category width of the actual mean vote (MV) is about 4.3 K, while the PMV has a width of 3.5 K.

The neutral temperature of the actual mean vote (MV) is estimated at 27.3°C, whereas the predicted temperature from the PMV is 23.7°C. The discrepancy of 3.6 K is recognised to be a reason for the disagreement between the standard model and the reported thermal comfort for the subjects in this study; and it is slightly higher than an average of 3.0 K found in many research investigation [Humphreys 1994a].

Like this study, much research in tropical regions showed that the PMV index *overestimated* the actual thermal sensation votes and gave *lower* neutral temperatures. In Jakarta, the predicted neutral temperature from the PMV was 25.6°C, while the observed was 26.5°C: the discrepancy of 0.9 K [Karyono 1996b]. Chan et al [1998] found that the PMV model gave the predicted neutral temperature lower than the observed by approximately 1.5 K in Hong Kong, and the gradients of the PMV were lower than the actual mean vote of approximately 3/8°C per sensation unit in summer and 5/7°C per sensation unit in winter.

In contrast, some research in temperate climates showed the opposite results: the PMV *underestimated* the actual thermal sensation votes and gave *higher* neutral temperatures. In the UK, Oseland [1992;1993] found that the reported neutral temperature in homes was about 5.0 K lower than the predicted. Further studies showed that the discrepancy was 5.0 K in winter and 3.0 K in summer [Oseland 1994b]. Another study, using longitudinal surveys of office workers in climate chambers, offices and homes, showed that the differences of the neutral temperatures between the reported and the predicted were up to 1.0 K [Oseland 1995]. A recent study revealed that the predicted neutral temperature was significantly 3.0 K higher than the observed in naturally ventilated offices in summer [Oseland 1998].

Schiller [1990] found that the office workers in the San Francisco Bay Areas gave neutral temperatures lower than the PMV by 2.4 K, which was explained by the preference of the subjects for "cooler" conditions. However, when the revised input data including the clo-value of chair (clo = 0.15) and the met-value of 1.2, were used, the discrepancy between the measured and the predicted was only 0.2 K [Brager et al 1994].

Besides, some other research found that the neutral temperatures calculated from the PMV model and the observed data were in good agreement. Among these are Thai office environments [Busch 1990a; 1990b]; thermal comfort in offices in Townsville, in the northern tropical area of Australia [de Dear and Fountain 1994]; tropical classrooms of Hawaii [Kwok 1998]; and housing in tropical upland climates, Zambia [Malama et al 1998].

According to Fanger [1970], the PMV model can be modified to calculate the predicted percentage of dissatisfied or the PPD, in order to state the number of subjects who are decidedly dissatisfied with their thermal environments. The PPD index is based on the assumption that the votes outside the central-three-category of thermal sensation scale represent dissatisfaction (or the opposite of thermal acceptability).

The comparison between the PPD and the reported percentage of dissatisfaction, or the actual votes of +2, +3, -2 and -3 from the field surveys, is shown in Figure 9.3. Also, the comparison includes the combined preference votes for "cooler" and "warmer", in the assumption that the subjects would like to change their thermal environments.

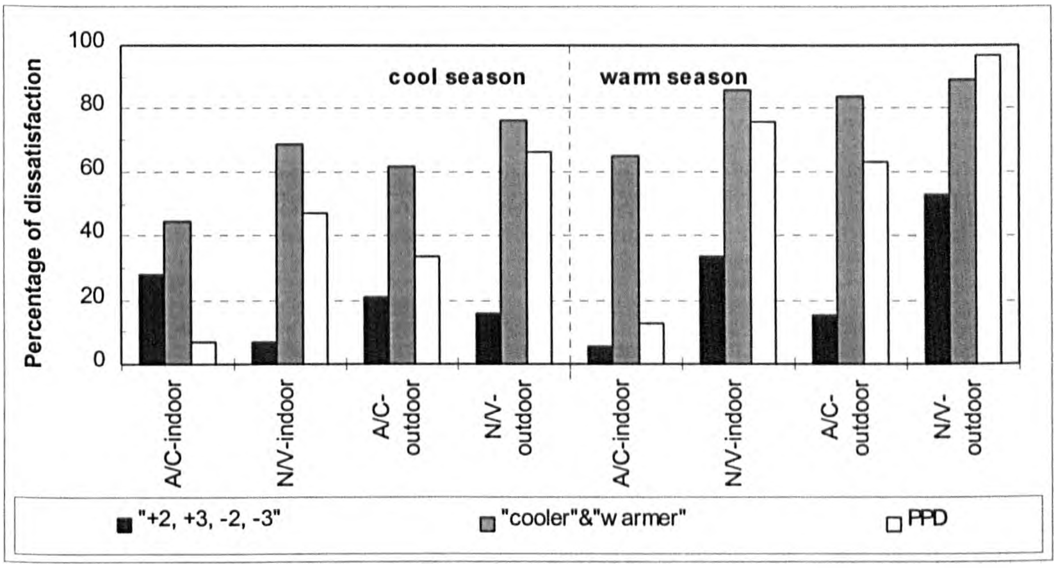


Figure 9.3 *Comparison of the actual percentage of dissatisfaction (±2 & ±3), the preference for "cooler" & "warmer" and the PPD.*

Note that at comparatively low percentages of sensation ±2 and ±3, the actual dissatisfaction of the subjects in this field study is much lower than the expressions for the combined thermal preference to be "cooler" and "warmer", and the results of the PPD index.

In the cool season, the subjects obviously experienced better thermal conditions and were more satisfied than in the warm season. The PPD results show that the A/C-indoor groups in both cool and warm seasons are the most acceptable conditions of thermal comfort (PPD = 7, and PPD = 13, respectively), while the N/V-outdoor group in the warm season has the least satisfaction (PPD = 97).

Baker and Standeven [1996] explained that it is possible to use the effects of *adaptive errors* (see 4.6.1) to reduce the PPD in the comfort equation. The method is to bias towards improving comfort, such as by assuming lower room air and radiant temperatures, or lower metabolic rates and clothing insulation (due to occupant interactions), or increasing air speed. By altering the input data little by little, the results of the PPD will show a dramatic reduction. An example of the use of the adaptive errors for the N/V-indoor subjects in the warm season, is shown in Table 9.2.

Table 9.2 *Effects of the adaptive errors on the N/V-indoor subjects in the warm season.*

	Actual case	Adapted case
Air temperature (°C)	30.9	29.0
Mean radiant temperature (°C)	30.9	29.0
Relative humidity (%)	55.6	50.0
Air velocity (m/s)	0.23	0.35
Clothing (clo)	0.53	0.39
Activity (met)	1.61	1.20
PPD (%)	77	20

As seen in Table 9.2, the impact on comfort of the adaptive errors is considerable. For example, if there is an installation of fans (of 2.25 m/s, as mentioned in Busch's research [1990b; 1992]), it would be assumed that the mean air velocity becomes 0.35 m/s and the air and mean radiant temperatures is approximately 2-3 K lower (approximation according to Humphreys [1976]). The predicted percentage dissatisfaction (the PPD) of this adapted case can be reduced to around 25%. There would also be a 20% reduction on metabolic rate, if the subjects change their activities from "walking" or "standing" to "sitting (relaxing)" for a moment, and finally a further 10% reduction on clothing insulation values would derive from the changing of clothing to the lowest possible ensemble (0.39 clo). It is clear that a significant total reduction in the PPD from 77% to 20% can be achieved. The further application of the *adaptive errors* to reduce the PPD will be given and discussed later (see 9.5.3).

9.4 Expectation, sensation and preference

9.4.1 Relationship between thermal responses

The relationship between thermal expectation and thermal sensation is positive with the correlation coefficient of $r = 0.50$, and the relationship between thermal sensation and thermal preference is negative with $r = -0.44$ for all subjects (see 8.3.2). Considering the subjects in each season, the correlations in the cool season are stronger than those in the warm season; and considering the subjects individual groups, the strongest positive relationship between expectation and sensation is the N/V-outdoor group, and the strongest negative relationship between sensation and preference is the N/V-indoor group.

For the purpose of comparisons, all thermal responses are calculated to give some degrees of *standardisation*. Because the different thermal responses have different interval scales, they are processed by dividing their values by the range of categories and thus the standardised mean thermal responses will always lie between plus one and minus one [Humphreys 1976]. In this field study, both mean expectation and mean sensation votes are divided by three (because this is the maximum vote permitted), while mean preference vote is divided by one. When the expectation and sensation responses are standardised, the values are relatively small, compared with the preference, as seen in Table 9.3.

Table 9.3 *Standardised mean thermal responses.*

	A/C indoor	N/V indoor	A/C outdoor	N/V outdoor
In the cool season				
Expectation responses	-0.25	0.06	0.27	0.14
Sensation response	-0.27	0.09	0.14	0.17
Preference response	-0.23	-0.67	-0.47	-0.72
In the warm season				
Expectation responses	-0.20	0.19	0.31	0.51
Sensation response	-0.07	0.28	0.13	0.45
Preference response	-0.65	-0.86	-0.82	-0.89

Theoretically, it is possible to state that if the value of any standardised mean vote is at or near zero, the subjects will be satisfied with their thermal environments, either expected or experienced. On the other hand, any value away from zero gives a measure of the degree of thermal environmental stimuli affecting the subjects' dissatisfaction, either warm or cool discomfort.

The comparison of the standardised mean thermal responses (from Table 9.3) is graphically re-presented in Figure 9.4.

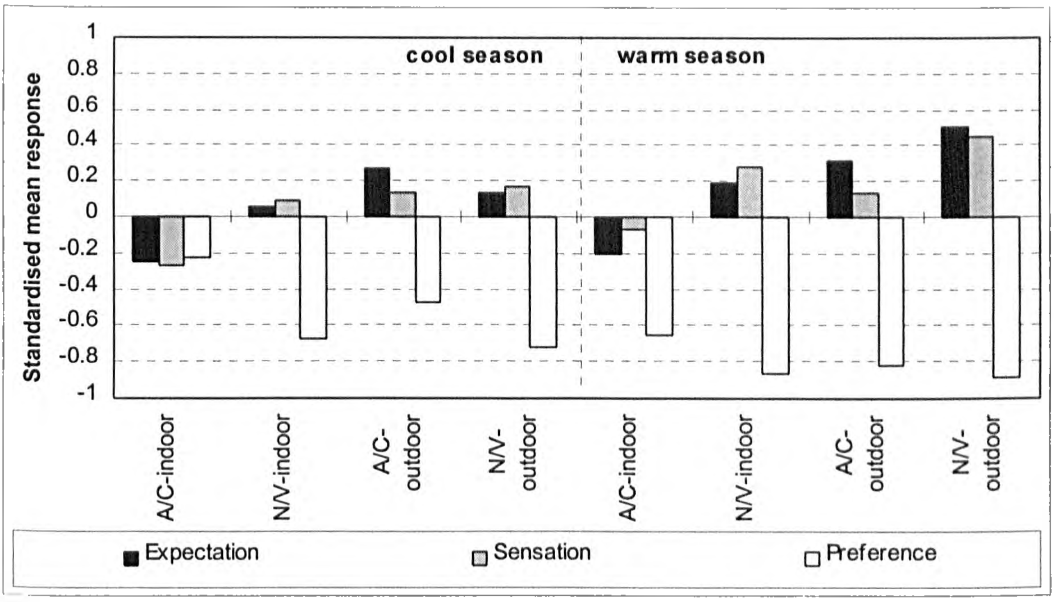


Figure 9.4 *Comparison of standardised mean thermal responses.*

By comparing the expectation and sensation standardised means, the analysis aims for the past and present *experiences* of the subjects in thermal environments; and by comparing sensation and preference standardised means, for the possibility of subjects' *compensation* between their "neutral" and "preferred" thermal environments. This comparative idea is initially inspired from a part of the hypothetical model of psycho-physiological warmth perception by Auliciems [1981] to explore the complexity of human responses under thermal stress (see 5.5.2).

As seen in Figure 9.4, only the A/C-indoor groups in both seasons exhibit all thermal responses in the cool side. The subjects experience comparatively cooler environments in the cool season than in the warm season and there is no possibility of compensation because their neutrality and preference are in the same side. It should be noted that the demand for "cooler" preference of the

A/C-indoor group in the warm season is more or less similar to the other groups in naturally-ventilated environments.

The subjects in the N/V-indoor group in the cool season apparently experience their thermal environments with the least stimuli. The levels of expectation and sensation are very small on the standardised mean response scale, implying an expression of the most satisfactory environment in this field study. However, when considering the group's compensation, the amount for "cooler" shows as large as that in the N/V-outdoor groups, which have past and present experiences of the most warm environments. The compensation between the neutrality and preference of both groups shows that the subjects would like to be in far "cooler" environments.

For the A/C-outdoor groups in both seasons, the expected (or past) experiences of the warmth sensation are more influential than the present. The subjects have standardised mean expectations more than sensations. The preference of the group in the cool season apparently is less demanding for "cooler".

9.4.2 The expected, neutral, and preferred temperatures

The expected, neutral and preferred temperatures, analysed by simple linear regression (see 8.4.1) and by probit analysis (see 8.4.2) are recapped in Table 9.4.

Table 9.4 *The expected, neutral and preferred temperatures of this study.*

	All	cool season	warm season
Linear regression			
Expected temperature	26.7	26.7	26.7
Neutral temperature	26.9	27.1	26.5
Preferred temperature	17.8	21.6	2.0
Probit analysis			
Expected temperature	27.4	26.9	27.9
Neutral temperature	27.2	27.0	26.9
Preferred temperature	21.4	22.2	N/A

The expected temperatures are fairly similar to the neutral temperatures, but the preferred temperatures are extremely low. This may be explained by the different interval of the scales used in the field surveys (between the ASHRAE and the McIntyre scales) as well as the bias of the subjects towards the preference for "cooler" environments.

In the cool season, the expected temperatures are slightly lower than the neutral temperatures, but in the warm season, the subjects expected somewhat higher temperatures than their neutral. The average of the expected and the neutral temperatures is around 27.0°C. The preferred temperature in the cool season averages at approximately 21.9°C, but that in the warm season cannot be calculated by both regression techniques.

An alternative method to arrive the preferred temperature is to integrate the smallest number of the subjects who like to be "cooler" and "warmer", against air temperatures. Previous researchers who used this method were Schiller et al [1988]; de Dear and Fountain [1994]; Donnini et al [1997]; Chan et al [1998]; Kwok [1998]. The preferred temperature of all subjects in this field study is shown in Figure 9.5.

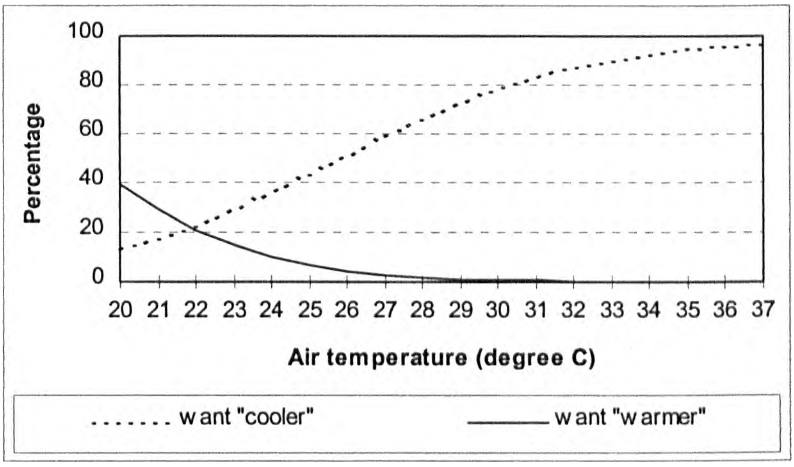


Figure 9.5 *The preferred temperature of all subjects.*

The preferred temperature from Figure 9.5 is approximately 22.0°C, which is not different from that in the cool season, but is lower than the average expected and neutral temperatures of around 5 K. Compared with other field studies, the discrepancy of this study is much greater. The findings in office buildings in the San Francisco Bay Areas [Schiller et al 1988]; in Townsville [de Dear and Fountain 1994]; in cold climates of southern Quebec [Donnini et al 1997]; and in Hong Kong [Chan et al 1998], showed similar results of the lower preferred temperatures than the neutral temperatures of 0.4-1.0 K. Much higher discrepancies were found in Hawaii's classrooms of 2.5 K in naturally ventilated; and of 4.2 K in air-conditioned [Kwok 1998]. These are supported by the statement that: *"... the preferred temperature is below the comfort temperature in hot conditions ... "* [Nicol et al 1994].

On the contrary, in temperate climates like England, Fox et al [1973] found that the elderly subjects preferred "warmer" than a reported neutral temperature. Humphreys [1976]; Hunt and Gidman [1978] reported their subjects in England preferred a state of above "comfortable" or at "comfortably warm" on the Bedford scale.

These results support the argument by McIntyre [1980] that although it is generally assumed that the neutral temperatures are the optimum for a group, there is evidence of the preferred temperatures being above or below. McIntyre [1978a; 1982]; Rohles [1980] reported that during the summer season, people prefer conditions somewhat cooler than neutral, but in the winter season, they prefer somewhat warmer than neutral. It also assumes that people in the cool or moderate climates might prefer a "warmer" environments than they experience, but on the other hand, people in the tropical or warm climates would like to be "cooler" than they experience.

9.4.3 Interplay between neutrality and preference

The relationship between *neutrality* and *preference* is one of the most significance in thermal comfort studies. This is because it is not necessary for comfort that the subjects have "neutral" sensation, they must rather have the preference for "no change", as mentioned above and seen in previous research [Busch 1992; Nicol et al 1994]. The proportion of subjects preferring "cooler" could be far more than those preferring "no change", although the majority of the subjects voted "neutral" sensations (see 8.4.4). These findings showed the contradiction in thermal sensations as opposed to thermal preferences. The issue of the conflict connotation was discussed by Fisk [1981].

The analysis which investigate the interplay between these two thermal responses, uses Busch's methodology for examining the relationship [Busch 1992]. Shown in Figures 9.6 and 9.7, the curves represent the percentage of all respondents and of four subject groups, respectively, who prefer to be either "warmer" or "cooler". The intersection between two curves implies the optimum state of the subjects' preference on the sensation scale. (The analyses in the cool and warm seasons are shown in Appendix L).

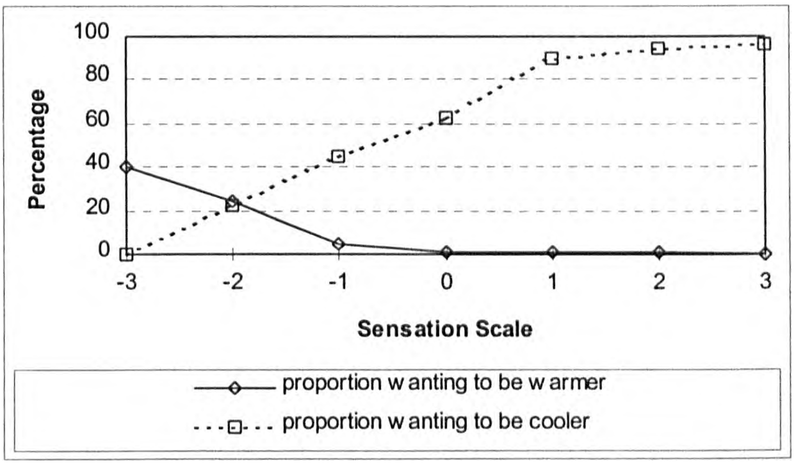


Figure 9.6 *Interplay between sensation and preference scales of all subjects.*

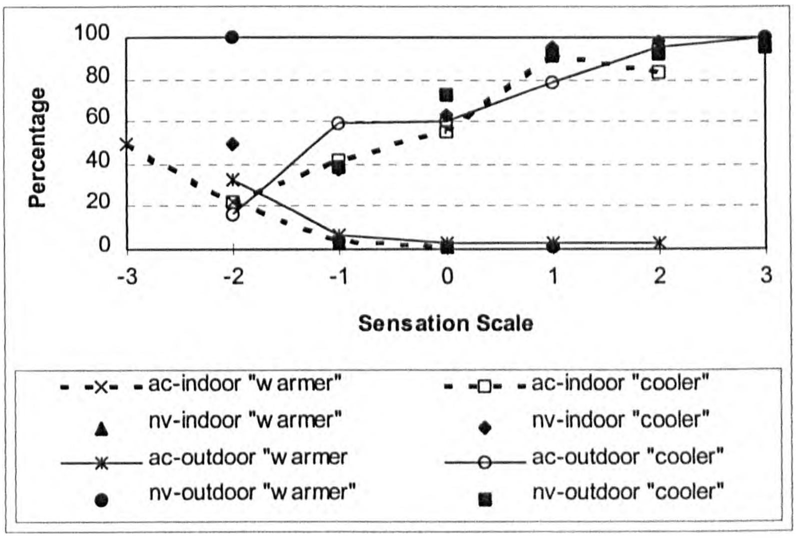


Figure 9.7 *Interplay between sensation and preference scales of individual subject group.*

From Figure 9.6, the intersection is at "-2", meaning that all subjects prefer to be "cool", rather than "slightly cool" or "neutral". At the "0" (neutral) sensation category, only one per cent of the subjects would like to be "warmer", but 62.5% for "cooler". In the previous research, Busch [1992] found that the Thai subjects in both air-conditioned and naturally ventilated office environments preferred to be closer to "slightly cool" than "neutral".

From Figure 9.7, only the curves of the A/C-indoor and the A/C-outdoor subjects give intersections, and therefore no curves for the preferences of the naturally ventilated groups are shown. The preferences of these air-conditioned groups lie between "-1" and "-2" (slightly cool to cool) on thermal sensation scale. McIntyre [1980] explained the difficulties in terms of connotation of the words *"warm"* and *"cool"* that in a cool climate, people describe their preferred state as "warm" because the word "cool" implies an undesirable state; whereas in a hot climate, "cool" becomes the desirable state.

9.4.4 Comparison thermal sensation responses to other research

The thermal sensation values of each subject group are compared with the earlier field studies' findings, compiled by Humphreys [1976]. The comparison uses the standardised mean values as the dependent variable against mean air temperatures as independent variable. The simple linear regression analysis gives statistical information, of which the regression equation [Humphreys 1976] is:

$$\text{standardised mean sensation} = -0.244 + 0.0166\, T_a \qquad \text{(eq. 9.1)}$$

where T_a = mean air temperature.

The standardised mean sensation votes of this study (from Table 9.3) are analysed by the same technique and their data are weighted by the number of each subject group. The fit line can be written in terms of the regression equation as:

$$\text{standardised mean sensation} = -2.123 + 0.0778\, T_a \qquad \text{(eq. 9.2)}$$

Both findings from Humphreys [1976] and from this study are compared and shown in Figure 9.8.

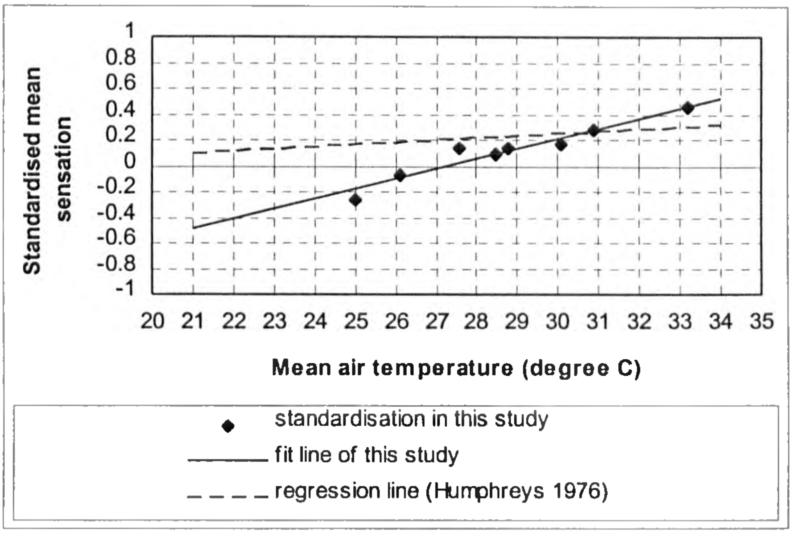


Figure 9.8 *Comparison of standardised mean sensation responses between this study and the world-wide results by Humphreys (1976).*

The regression coefficient from this study is a little steeper than that found by Humphreys. This shows no significant difference of the sensitivity of the subjects in this field study and other subjects world-wide. The tail of the fit line in this study, which is in the minus value, is probably influenced by the A/C-indoor groups of both seasons. It should be noted that at mean air temperatures below 30.5°C, all standardised sensation values are lower than the regression line by Humphreys, implying that the subjects in Bangkok would have the sensation somewhat cooler than others.

9.5 The application of the adaptive theory

9.5.1 Suggested adaptations and correlation analysis

The suggested adaptations to achieve comfort by subjects themselves, were categorised into two groups: those when too warm and those when too cool (see 7.7.3). The major actions relating to warm environments included adjustments of the environmental factors (i.e., using A/C, increasing air movement), whereas the actions to cool environments included adjustments of the personal factors (i.e., changing clothing, adjusting postures or activities). These suggested adaptations are sub-groups of the conceivable adaptive actions [Humphreys and Nicol 1998] and the generic thermal adaptations [de Dear and Brager 1998].

Due to the dominance of hot and humid climates in Bangkok, the relationship between environmental factors and subjective thermal responses were quite strong and highly significant (see 8.2.1; 8.3.3). In particular, the correlation coefficients between air temperatures and thermal sensation votes of all subjects in the cool, warm and combined seasons were (r = 0.42), (r = 0.52), and (r = 0.50), respectively. It explains the main cause of comfort/discomfort in this study that the warmth of environments was affected by a main factor, which is the air temperature.

Another analysis on reported personal variables such as clothing values revealed that although the relationships between air temperatures and clothing insulation values were weak, the correlation coefficient of all subjects in the cool season (r = -0.18) implied the increasing clothing values of the subjects, as an adaptive action. This kind of the adaptive action has been found in temperate or cold climate zones [Davies and Davies 1995]; or in the cool season of some tropical climates such as in Pakistan [Nicol et al 1994] and in Zambia [Malama 1997].

If the adaptive actions in thermal comfort studies are examples of the *complex adaptive system*, at the present there is no formal mathematical framework to probe the properties of, and to form the basic insight for this theory [Casti 1996]. Nonetheless, the proposal to apply several interacting time series and the actions of intelligent agents making decisions on limited information has been suggested in this light to establish the comfort temperature [Nicol and Humphreys 1973; Humphreys and Nicol 1998].

Further work on a modelling which includes the application of simultaneous equations or multivariate statistical regression, is in progress at the Martin Centre, Cambridge University (under the supervision of Dr Nick Baker) [Humphreys and Nicol 1998]; and another analysis which aims to create an adaptive algorithm for temperature control (namely in many European climatic zones), is under development at Oxford Brookes University [Nicol and Sykes 1998].

9.5.2 The use of the Adaptive Model

The relationship between neutral temperatures[1] and mean air temperatures of each subject group (see 8.4.3) is analysed by simple linear regression technique, shown in Figure 9.9. These data are weighted by the number of the subjects in each group. The regression line can be written as an equation:

regressed neutral temperature = $19.1 + 0.30\,T_a$ (eq. 9.3)

where T_a is mean air temperature of a group of subjects exposed to.

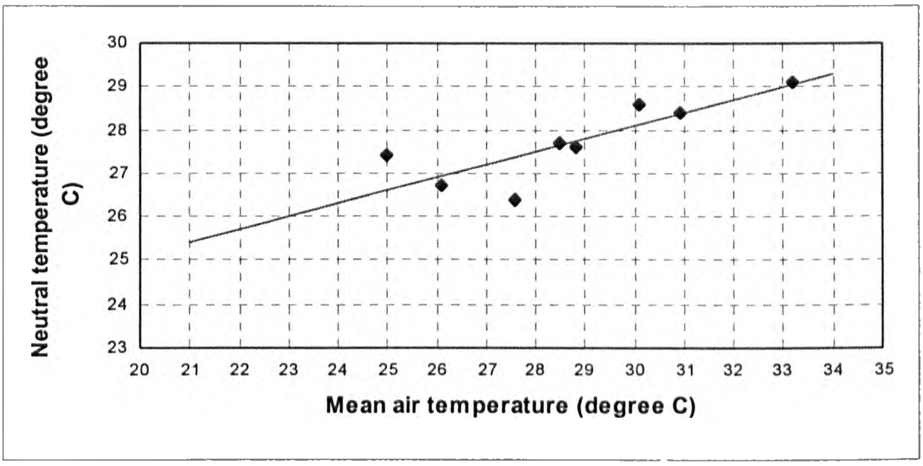


Figure 9.9 *Relationship between neutral temperatures and mean air temperatures.*

The range of the interpolated mean air temperatures between 25.0°C and 33.2°C, gives the neutral temperatures at approximately 26.6°C to 29.1°C. This relationship is statistically highly significant, and supports the adaptive principle of the subjects' comfort in relation to their experiences in thermal environments.

From ASHRAE Research Project 884 (see 5.3.4), de Dear and Brager [1998] proposed the Adaptive Models for an adaptive comfort standard. The predicted comfort temperature (T_n) therefore will be arrived at from the knowledge of mean indoor temperature (T_i) or mean outdoor temperature (T_m) in terms of linear relationships (see 5.3.4; 5.5.7).

---

[1] Neutral temperatures of eight subject groups (each four in the cool and in the warm seasons) calculated from Griffiths' value.

Two models which are applicable for naturally ventilated environments, are:

$$T_n = 15.47 + 0.35\, T_i \qquad \text{(eq. 5.10)}$$

$$T_n = 18.9 + 0.26\, T_m \qquad \text{(eq. 5.12)}$$

These models have regression coefficients (0.35/°C and 0.26/°C) quite similar to that found in this study — eq. 9.3 (0.30/°C). The application of both models is to predict indoor comfort temperatures, and therefore only two groups of the A/C-indoor[2] and the N/V-indoor subjects are calculated. The comparison of the results from these two models and those from the model established in this study (eq. 9.3), is shown in Table 9.5.

Table 9.5 *Comparison of the model in this study (eq. 9.3) and the Adaptive Models (de Dear and Brager 1998).*

	A/C indoor	N/V indoor
In the cool season		
(eq. 9.3) Regression model of this study	26.6	27.7
(eq. 5.10) Adaptive Model (T_i = variable)	24.2	25.4
(eq. 5.12) Adaptive Model (T_m = variable)	26.1	26.7
In the warm season		
(eq. 9.3) Regression model of this study	26.9	28.4
(eq. 5.10) Adaptive Model (T_i = variable)	24.6	26.3
(eq. 5.12) Adaptive Model (T_m = variable)	26.4	27.5
In the combined seasons		
(eq. 9.3) Regression model of this study	26.8	28.0
(eq. 5.10) Adaptive Model (T_i = variable)	24.4	25.9
(eq. 5.12) Adaptive Model (T_m = variable)	26.2	27.1

The Adaptive Model, which uses mean outdoor temperature as variable (eq. 5.12), gives the predicted neutral temperature closer to T_n calculated from this study (eq. 9.3) in both A/C-indoor and N/V-indoor groups. The discrepancies are approximately up to 1.0 K. The findings show the significant

[2] It is assumed that the models for naturally-ventilated environments are more suitable, although the A/C-indooor subjects experienced air-conditioned environments.

effect of factor such as mean outdoor temperature upon the comfort conditions, as previous models by Humphreys (eq. 5.4) and by Auliciems (eq. 5.6) (see 9.3.3).

To obtain a more accurate result of the predicted neutral temperature (T_n) from these Adaptive Models, two modifications should be considered: firstly, the variables should be the composite thermal indices such as the operative temperature (T_o) and the new effective temperature (ET*) for eq. 5.10 and eq. 5.12, respectively; and secondly, the model should be applied to subjects with sedentary activity like much of the previous research in office environments. Therefore, the comparison in this study must be very careful carried out since they are not very exact findings.

9.5.3 The effect of the adaptive errors

Further discussion on the adaptive theory is to investigate the effect of the *adaptive errors*, proposed by Baker and Standeven [1996]. Its application is the cumulative revision or bias towards improving comfort, as mentioned above (see 4.6.1; 9.3.4). The basic rules are to adjust the input data for the adapted cases, which expect that the adapted results (adapted PMV and adapted PPD) will be the satisfactory environments for subjects. It will give a general view of how to adjust/adapt factors to achieve human comfort. In this study, an example of some adjustments is proposed, shown in Table 9.6.

Table 9.6 *Rules to adjust the input data for the adapted cases.*

Variables	Cool season	Warm season
Air temperature (°C)*	reduce 2.0°C	reduce 2.0°C
Air velocity (m/s)*,+	increase 0.1 m/s	increase 0.1 m/s
Relative humidity (%)	50% or below	50% or below
Metabolic rate (met)	1.2 met	1.2 met
Clothing insulation (clo)	0.5 clo	0.4 clo

Note: * A/C-indoor groups in both seasons use the existing temperatures and air velocities.

+ A/C-outdoor group in the cool season uses the existing air velocities.

It is believed that, with the use of a passive cooling control namely by increasing natural ventilation or using a fan, the mean values of the environmental variables can be adjusted as shown in Table 9.6. The alterations of the personal variables, regarding between seasons, should also be considered to improve comfort.

The comparison of the adapted results (the adapted PMV) with the regression lines of the PMV and the actual mean vote (MV), is shown in Figure 9.10; and the comparison of the adapted PPD with the PPD and the percentages of the actual thermal dissatisfaction (from the votes of "±2 and ±3" on thermal sensation scale, and from the votes of "cooler" and "warmer" on thermal preference scale), is shown in Figure 9.11.

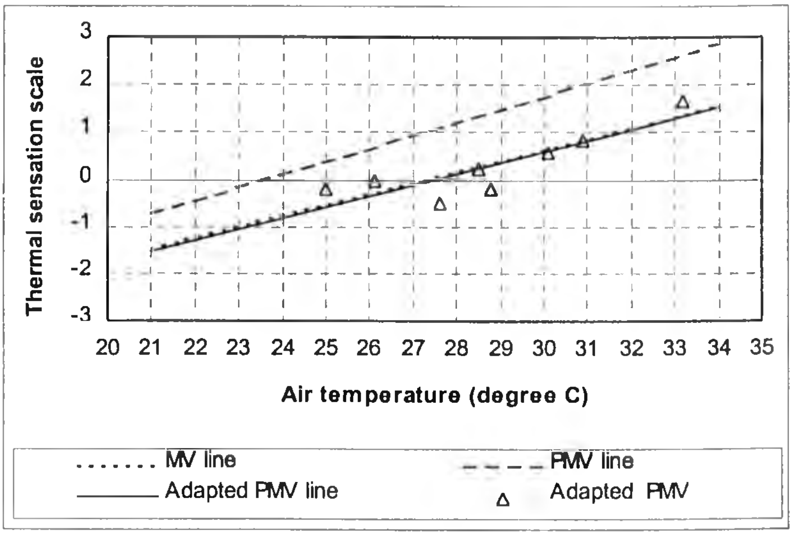


Figure 9.10 *Comparison between the actual mean vote (MV), the PMV and the adapted PMV.*

As seen from Figure 9.10, the adapted PMV regression line is nearly identical to the MV line. The regression coefficient of the adapted PMV is 0.24/°C, which is very similar to that of the actual mean vote (MV) of 0.23/°C. Both analyses give the neutral temperature at approximately 27.5°C. This finding is significantly different from that of the PMV and shows the effects of the adaptive errors in "rectifying" the PMV model.

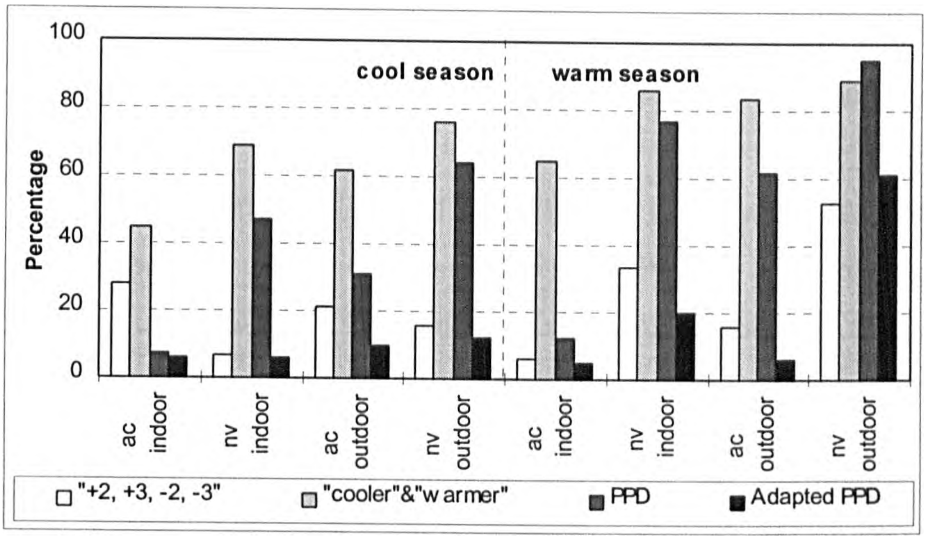


Figure 9.11 *Comparison between the actual dissatisfactions (±2 and ±3; "cooler" & "warmer"), the PPD and the adapted PPD.*

From Figure 9.11, overall results of the adapted PPD are significantly smaller (at approximately lower than 20%, except that of the N/V-outdoor subjects in the warm season — at 61%). The adjustments of the input data have an effect upon improving thermal acceptability, which reduces the PPD up to nearly 60%. The relative effects of the adjusted environmental variables are generally higher than those of the personal variables. For example, in the warm season, the effects of the environmental factors on the N/V-indoor and the A/C-outdoor subjects, can reduce approximately 30% from the PPD values, while those of the personal factors, around 25%. Only two groups of the A/C-indoor subjects in both seasons are not much affected from the adjustments, because there are no changes on mean values of air temperature and air velocity. The adapted PPD results are generally slightly better than the actual dissatisfied votes of "±2 and ±3" for thermal sensation, and much better than those of "cooler" and "warmer" on thermal preference scale.

An example of research which used the PMV index approach to human comfort conditions and building energy savings, is by Yang and Su [1997]. Two experiments were made (in Taiwan), by introducing the use of increased air velocity as a key factor to reduce the heat of the environments due to solar radiation. The first experiment, performed on a long-distance bus, showed that without air velocity, the measured sensations of the subjects were either "warm" or "hot" (PMV = 0.93 to 2.07). Using a portable electric fan boosting with 0.72 m/s air velocity, the measured sensations of the subjects became either "cool" or "comfortable" (PMV = -1.07 to 0.38).

The second experiment, carried out in the test rooms at the National Sun Yat Sen University, indicated that the "very hot" (PMV > 2.0) conditions of indoor climate were directly influenced by solar radiation penetrated through the curtain wall. In order to maintain the PMV within ± 0.5, an intelligent controller, developed to adjust the indoor air velocity automatically, was introduced. It was a passive cooling strategy, which successfully achieved comfort with significant energy savings. In this full-scale experiment, the energy that could be saved was around 30%, compared with the conventional indoor environmental control.

9.6 Summary

The neutral temperatures and thermal acceptability of this field study have been discussed. The average of the neutral temperature is approximately 27.2°C and its range of the acceptable temperatures is between 24.2°C and 29.8°C. The comfortable conditions in the cool season are slightly higher than those in the warm season, as found in some other research. When compared to the standards [ISO 7730-1994; ASHRAE 55-1992], these findings are much higher, like many findings from research in tropical regions.

In terms of the Adaptive Model, the regression equation, showing the relationship between neutral temperatures (T_n) and prevailing temperatures (T_a), can be written as:

$$T_n = 19.1 + 0.30\, T_a \qquad \text{(eq. 9.3)}$$

The model was analysed by using the neutral temperatures of individual subject groups in both cool and warm seasons. These results were calculated by Griffiths' value (eq. 5.13). It should be noted that the results from this model are in good agreement with Humphreys' model [1978], which uses the monthly mean outdoor temperatures as variables (eq. 5.4).

On other thermal responses, the subjects' expectations are very similar to their sensations, but their preferences are significantly different and definitely demanding for "cooler" environments. The preferred temperature is approximately 22.0°C. Many research suggested that the consideration of thermal comfort should be the collaboration between the neutrality found in the sensation scale and the preference statements of the subjects.

Finally, in comparisons with the PMV-PPD models, the actual responses in the sensation and preference scales are not quite matched to the predicted ones. This chapter suggests to use the effects of the *adaptive errors* in order to improve comfort [Baker and Standeven 1996]. With the use of passive cooling control and the changes of subjects' activity and clothing, the adapted cases show significantly better comfort findings. Next chapter will discuss more about other applications, which can be used in practice. The criteria of architectural design will be given.

Chapter 10

APPLICATIONS FROM RESEARCH TO PRACTICE

"A good thermal design for a building originates during the sketch design stage. ... Building designers usually prefer simplified thermal analysis procedures because these provide short simulation times and are usually easy to use."

E. H. Mathews et al. [1991a]

10.1 Introduction

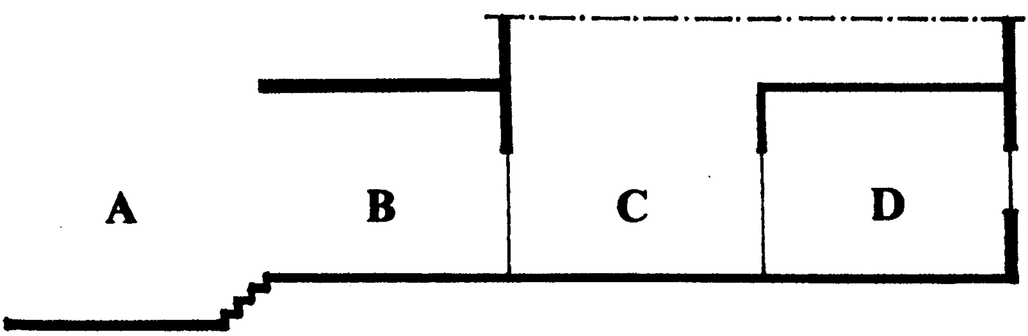
This chapter focuses on the application of the research findings to use in practice. The study of thermal comfort has suggested the neutral temperatures of Thai subjects in transitional spaces of various environments: air-conditioned/naturally-ventilated and indoor/outdoor. These results will be compared with the previous research in Thai office environments. Arranged in a series of spaces approaching to and from in tropical architecture, thermal quality will be considered.

In terms of thermal performance of the transitional spaces, a thermal simulation programme — Quick, will be used to study various effects of parametric changes. The investigations include some of the design criteria suggested earlier in this thesis namely orientation, conditions of exposure, volume of the spaces, thermal mass, and ventilation effects.

This chapter will summarise with a brief design recommendations for transitional spaces in tropical architecture.

10.2 Sequence of the spaces in tropical architecture

An inherent space in tropical architecture is *transitional space*, whose significance and characteristics have been discussed in Chapter Three. It is now appropriate to apply the findings of thermal quality found in this study into the spaces.



outdoor environment	transitional outdoor space	transitional indoor space	office environment

Figure 10.1 *A sequence of spaces in tropical architecture - an office building. (Repeated Figures 1.2; and 3.23)*

Figure 10.1 (replicated from Figures 1.2; and 3.23) is an example of non-domestic architecture such as an office building. The sequence of the approach is arranged from the completely outdoor to the transitional spaces of outdoor (with shade — i.e., canopy or entrance platform) and indoor (i.e., entrance hall, lobby area, foyer or atrium), and finally, to the main function of the building — workspace. The spaces of transitions such as space B and space C are obviously a significant feature in tropical architectural design if consideration of thermal quality in buildings is of priority.

Using the findings of the measured outdoor air temperatures and reported neutral temperatures of all subjects combined and of each category group (of both indoor/outdoor and air-conditioned/naturally-ventilated environments) from this study, and comparing with the previous research of thermal comfort in Thai office environments by Busch [1992], the possible sequence of the encountered temperatures is shown in Table 10.1.

Table 10.1 *The temperatures in the sequence of spaces for comfort.*

Condition	Outdoor environment* (A)	Transition outdoor** (B)	Transition indoor** (C)	Office environment^{+} (D)
A/C	25.6-28.2	27.0	27.1	24.7
N/V	29.7-31.7	29.0	28.2	27.4
Combined	28.8	27.7		25.0

Note: * mean air temperatures from the field survey.

** neutral temperatures calculated from Griffiths' value.

$^{+}$ neutral temperatures from Busch [1992].

It is clear that if the transitional spaces have air temperatures controlled or variably maintained at approximately reported neutral temperatures, they can be functioned as a *mitigation feature* for thermal environments in the tropical architecture of hot and humid climates like Bangkok, and possibly elsewhere. These spaces act as a buffer zone between a very dynamic outdoor environments (which are sometimes too hot) and an environment around the work-station which is occupied by sedentary subjects. Therefore, these findings suggest a design for an optimum condition that could give the building occupants a chance to adapt their thermal sensations to be comfortable as they move between outside and inside, and vice versa.

10.3 Thermal performance of transitional spaces

Thermal performance of transitional spaces in this thesis is studied by using a thermal analysis program — QUICK [Mathews et al 1991b]. It has been developed at the Centre for Experimental and Numeric Thermoflow in South Africa. The program is a basic and very user-friendly computer simulation, especially for naturally-ventilated buildings.

A case study of a transitional space, which will be used as a base-case in this parametric study, is a fundamental cubic form, shown in Figure 10.2.

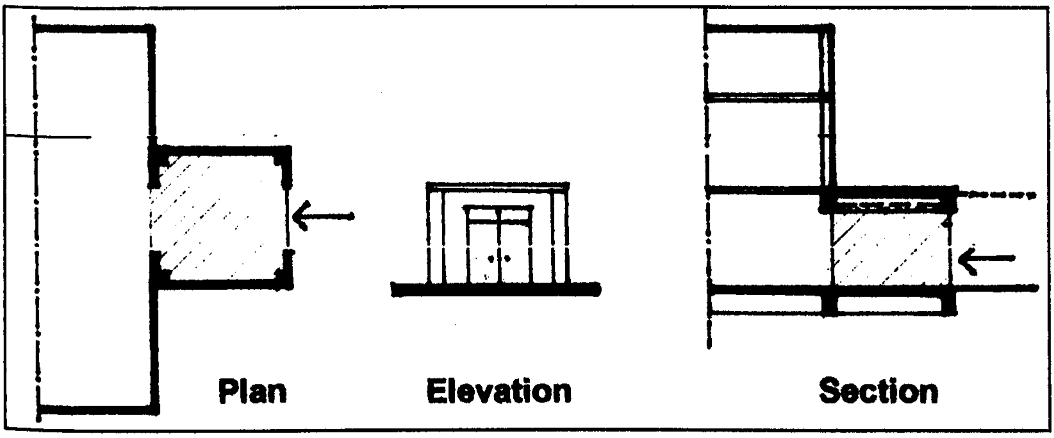


Figure 10.2 A case study of a transitional space in the simulation.

The space is 4.0 m * 4.0 m, with 3.0 m high. The main structure is concrete, the external walls are of brickwork and the internal, plywood. In the flat roof, there is 100 mm of air space and gypsum plaster board for insulation. A door at the main entrance is made of glass, which is able to open for natural ventilation.

The climatic data of Bangkok in the database were collected from the Royal Thai Meteorological Department [1996; 1997]. The data consist of the mean values of air temperature, relative humidity, and radiation of a 24-hour of a cool day (December 1996) and another 24-hour of a warm day (April 1997). It should be noted that the data of air movement will be used as a ventilation variable to be analysed in the simulation.

Mallick [1994] stated that it is difficult to isolate the exclusive effect of one single aspect to another, in the measurement of thermal performance in an existing building. Therefore, it is a beneficial feature of thermal simulation programmes that allow study of the effects of changes in one of design criteria while others remain constant. In this study, the effects of parameters investigated are:

1. orientation;
2. (roof/floor) exposure to outdoor;
3. elongation;
4. ceiling height;
5. thermal mass; and
6. ventilation.

The results of the simulated indoor temperatures are considered in two parts according to the analysis periods: firstly, twenty-four hours for general basis, and secondly, between 9:00 and 18:00 for working hours.

The simulations discussed in this section will be only of warm days, in which the effects of parametric changes are of significant importance in order to build the recommendations for building design criteria. For those of cool days, many results are already within a range of comfort zone or thermal acceptability, and the effects of the parametric changes are of similar patterns to those warm-days analyses, and do not significantly alter the comfort conditions. The patterns of thermal performance in a cool day are shown in Appendix M.

10.3.1 The effect of orientation

The simulation of the four cardinal orientations (north; south; east; and west) is shown in Figure 10.3.

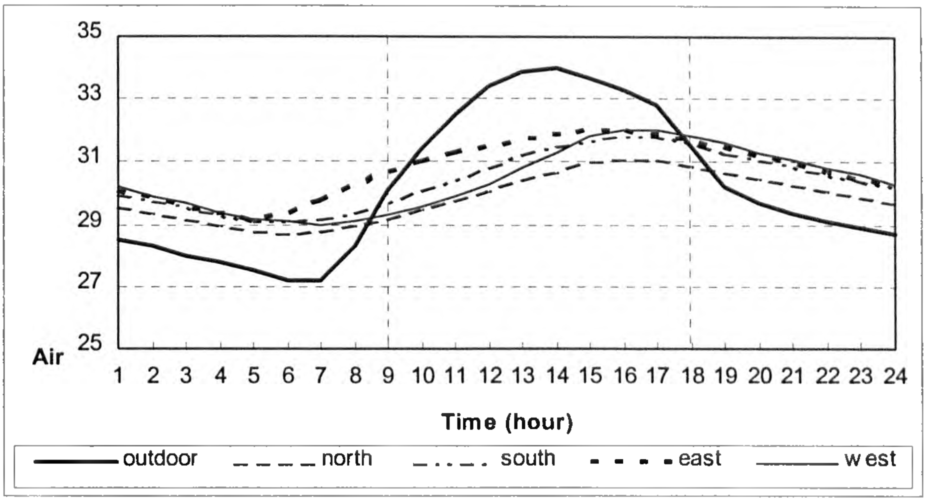


Figure 10.3 *Effects of orientation in a warm day.*

The best thermal performance is in the case of north orientation or a transitional space that has a north entrance, whereas the worst is that with east orientation. The discrepancy of the simulated indoor temperatures between two cases is approximately 1-2 K during working hours. These findings are in good agreement with the fact that, in the north hemisphere like Bangkok, the sun moves across from east to west via the south, and therefore, rooms on the north side will be given shades nearly all of the day, resulting in comparatively lower air temperatures.

Generally speaking, the rooms on the north orientation should be functioned as living or working spaces while the periphery of these rooms should be the service zones (i.e., kitchen, bathroom, storage, or mechanical rooms) and the transitional spaces (i.e., entrance hall, circulation areas, shaded terrace, and veranda).

In the case of the east orientation or the transitional spaces with the east entrance (thick dot line), its simulated indoor temperatures rapidly increase in the morning and stay steady in the afternoon with the highest temperature at approximately 32°C during 15:00-16:00 hour. Then, the temperatures start declining during the evening and through the night. The following simulation analyses will use the transitional space with the east entrance as a base-case, for comparisons.

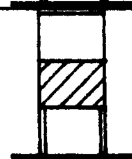
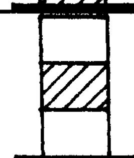
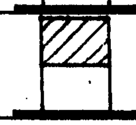
It should be noted that, for the south and west orientations, the rapidly increasing temperatures are in the late morning and in the afternoon, respectively.

It is particular in the case of transitional spaces that has the west entrance. Its temperatures are most high for the twenty-four hours analysis basis.

10.3.2 The effect of (roof/floor) exposure

There are six different cases of transitional spaces for simulating the effect of roof and floor exposure. For the roof, it considers each of which is exposed to the outdoor environments. For the floor, the considerations are both the exposure to outdoor environments (i.e., on stilts) and the floor level (either on ground contact or in the intermediate level). These six cases are classified in Table 10.2, and their simulated results are shown in Figure 10.4.

Table 10.2 *Case studies of (roofs/floors) exposures in the simulation.*

Case	Roof: exposed to outdoor	Floor: exposed to outdoor	Floor: intermediate level	Image
1	yes	no	no	
2	yes	yes	yes	
3	no	yes	yes	
4	no	no	no	
5	no	no	yes	
6	yes	no	yes	

It is clear that the roof exposure to outdoor environments will gain direct solar radiation and it is the cause of the major problem of high simulated indoor temperatures during the working hours, as seen in the cases 1, 2 and 6. The other cases which have another floor above or false-roof, perform better (lower simulated indoor temperatures such as in cases 3, 4 and 5).

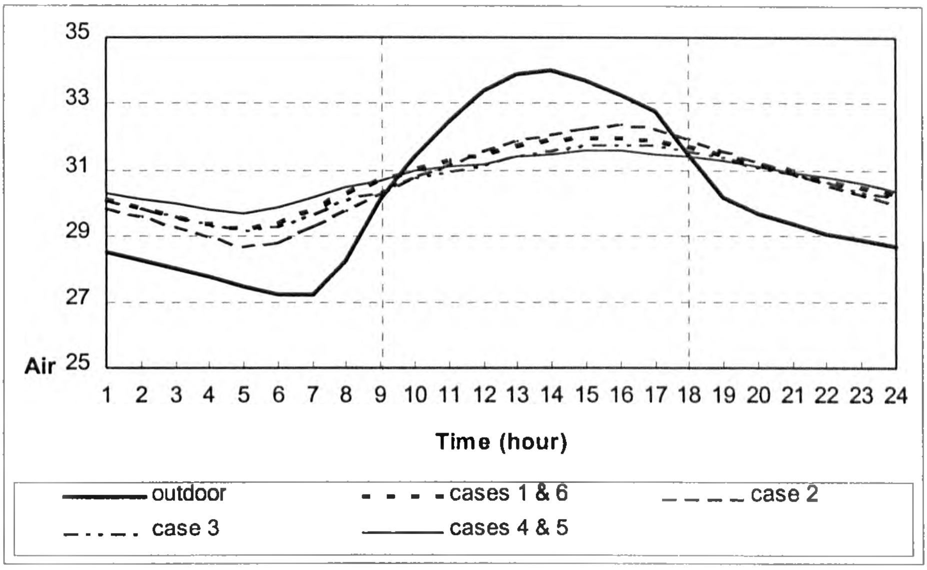


Figure 10.4 *Effects of (roof/floor) exposure in a warm day.*

The simulation of the case studies with floor on ground contact or those in intermediate level have similar results and produce thermal conditions better than those with floor on stilts. However, the simulated indoor temperatures of all cases are not more than 0.5 K different.

10.3.3 The effects of elongation and ceiling height

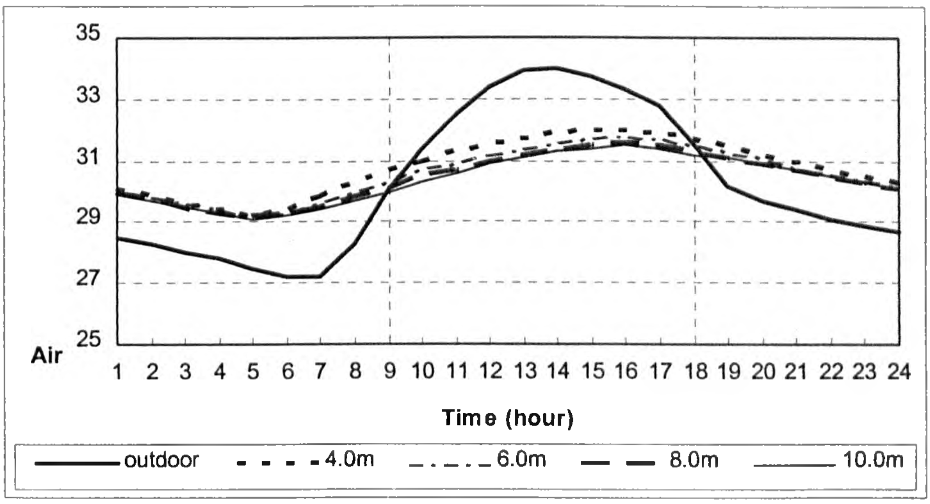


Figure 10.5 *Effects of elongation in a warm day.*

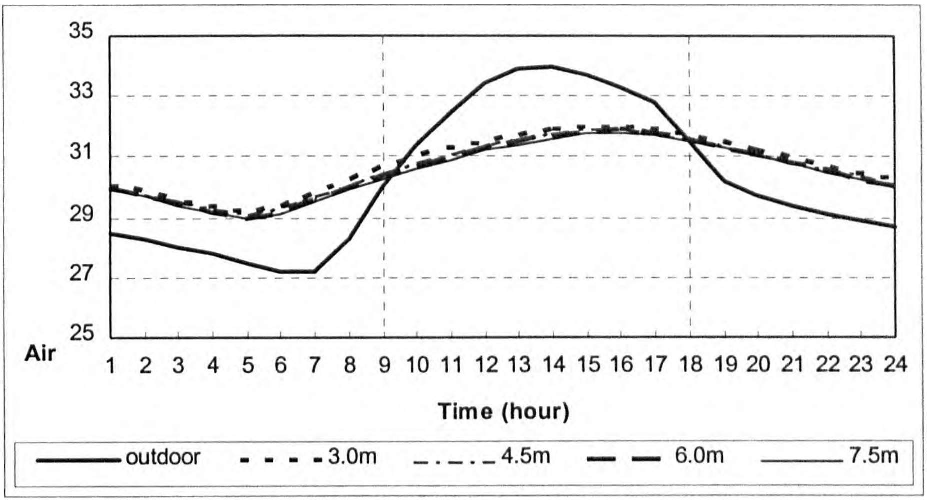


Figure 10.6 *Effects of ceiling height in a warm day.*

Both effects of elongation and ceiling height of transitional spaces are simulated and their results are shown in Figures 10.5 and 10.6, respectively. They show that the increasing volumes of the spaces either horizontally or vertically, can reduce the simulated indoor temperatures. The effectiveness by the elongation of the transitional spaces to decrease indoor temperatures during the working hours, seems somewhat better than that by the increasing of ceiling height, although not much different really.

When applied to architectural design, the length of the journey to approach to the main function of a building should be considered. It affects the building occupants in thermal perception whether there is a smooth transition between inside and outside. This space can be regarded as a mitigation feature in tropical architecture (see 10.2).

To increase the height of the ceiling is another feature in order to improve thermal performance. It applies the fact of the thermo-dynamic basis that hot air will drift to the spaces at high level, causing comparatively lower air temperatures in the occupied spaces. A further suggestion for a strategy of passive cooling is to apply *stack effect* in the design: an opening at the low level will let the natural air in, and a vent on the top level will ventilate hot air out. The combined effect of the ceiling height and the stack effect should be studied in the future.

10.3.4 The effect of thermal mass

The effect of thermal mass is studied by altering the thickness of the external wall (made of brickwork). The wall thickness of the base-case is 150 mm, and the other cases are 300 mm, 500 mm, and 500 mm with an air space of 100 mm. The results of the simulated indoor temperatures are shown in Figure 10.7.

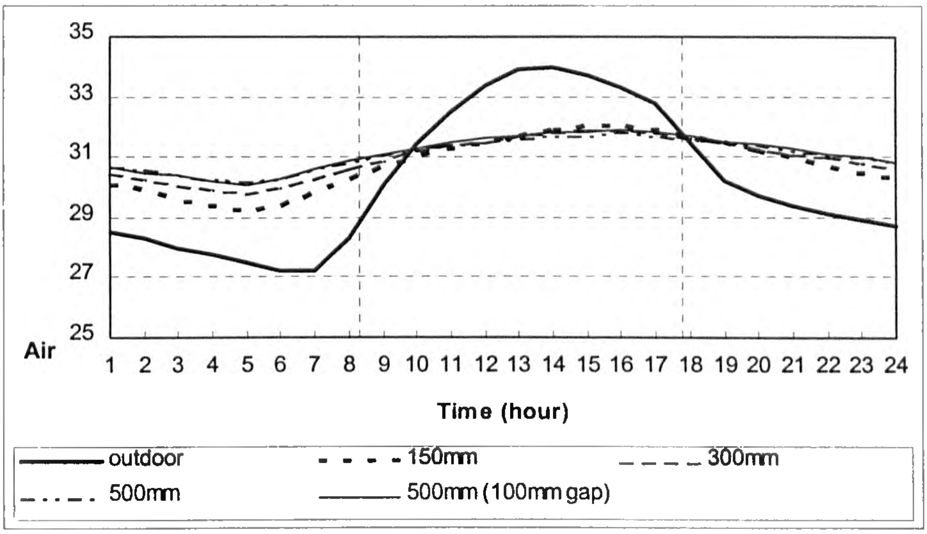


Figure 10.7 Effects of wall thickness in a warm day.

During the working hours, the differences of the wall thickness do not have significant effects on the simulated indoor temperatures. The discrepancy of the indoor temperatures among these four configurations is less than 0.1 K.

Low thermal mass, like 150 mm wall thickness, has relatively low indoor temperatures during the night and in the morning, but high temperatures in the afternoon. A more massive material (or thicker wall) has the thermal characteristics in the opposite direction. It is interesting to note that, despite similar thickness of 500 mm, the thermal performance of the wall with a 100 mm airspace is somewhat better than that of the wall without airspace. Further suggestion is to use light materials such as very thin walls (e.g., just timber partition) in the simulation analysis.

Seemingly, the effect of thermal mass is only of benefit to architectural design in certain climatic zones. It is applicable in the relation between the duration of the day-time and the period of the time lag of material. In this case of hot and humid climate, it is generally recommended that light materials should be used for all elements of its architecture.

10.3.5 The effect of ventilation

The effect of ventilation analysed in this simulation program arises from natural ventilation using outdoor air. The rates of the ventilation are entered in terms of air change per hour (ach). The base-case is the simulation without ventilation, and the other cases are entered with 2, 8 and 20 ach. The results are shown in Figure 10.8.

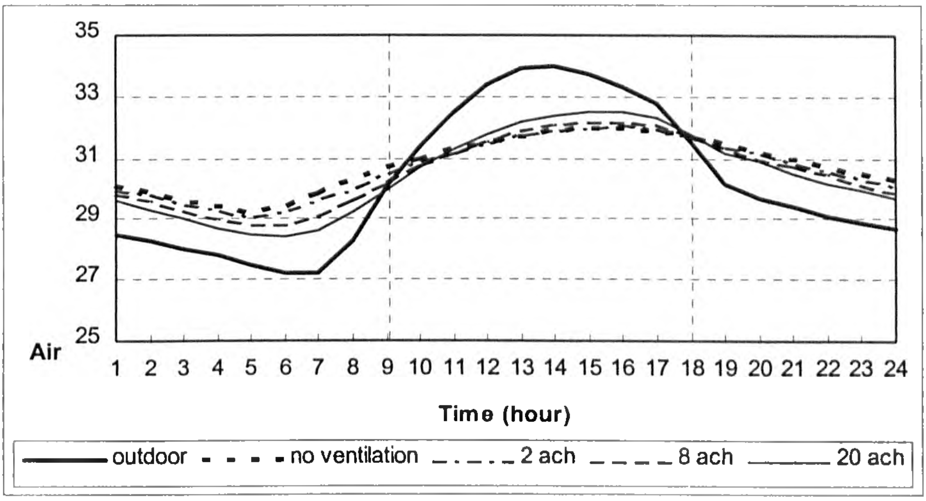


Figure 10.8 *Effects of ventilation in a warm day.*

Ventilation effects on the simulated indoor temperatures are dependent on to the outdoor air temperatures. When outdoor temperature is high, the indoor temperature is rising, but when outdoor temperature is relatively low, the result is declining. It should be realised that the temperatures in this particular climate of the dominant heat in the tropics are used as a ventilation source.

Due to the comparative high outdoor temperatures during working hours, the simulation from the case of high ventilation rates such as 20 ach, produces the highest indoor temperature, while the case without ventilation has relatively lower. However, it is questionable about the validity of this simulation programme, with respect to vent rates. Especially, it may not be possible to establish accuracy at high vent rates.

Baker [1988] suggested that comfort is attainable at air speeds of between 1 and 2 m/s, just low enough to be practical, and fairly easily obtained from the prevailing wind conditions. This can be applied to the case of a ventilation rate of 2 ach, which thermally performs better than other case (including that without ventilation). Further simulation is suggested to use other sources of passive cooling such as evaporative cooling or forced ventilation by using a fan.

10.4 Summary

The study in this chapter suggested the recommendations on the application from research to practice. The sequence of the approach to and from tropical architecture via transitional spaces is given. By arranging the results of the neutral temperatures of the previous research in Thai office environments in Bangkok [Busch 1992] with the findings of indoor/outdoor transitional spaces from this study, a series of the neutral temperatures is demonstrated. It can be stated that the transitional spaces are able to function as buffer zones between outdoor environments and workspaces. It is therefore useful as a mitigation feature for tropical architecture.

Thermal performance of a transitional space is studied by using a computer simulation program — QUICK [Mathews et al 1991b]. Various effects such as orientation, exposure to outdoor, elongation, ceiling height, thermal mass and ventilation are performed. General recommendations for the architectural design in passive means are given. These include: transitional spaces that have east entrance; less exposure to outdoor environments; increasing spaces either horizontally or vertically; light materials applied; and practical ventilation of prevailing wind (natural ventilation).

Chapter 11

CONCLUSIONS

11.1 General conclusions

This thesis has looked at tropical architecture, especially at an elemental and inherent space — transitional space — from the point of view of thermal comfort. The main methods used have been: firstly, literature reviews of both tropical architecture and thermal comfort studies, forming up analytical framework; secondly, a field study of thermal comfort by surveys of the actual buildings in relation to the occupants giving their subjective thermal responses; and finally, thermal simulation modelling using QUICK programme to build design recommendations.

The study is aiming to clarify the significant feature of tropical buildings that should be designed by the considerations of local climates as an intrinsic factor. This thesis has used some buildings in Bangkok as case studies.

The first part (Chapters Two and Three) has reviewed the relevant literature on tropical architecture and transitional spaces. It has identified the typical and distinctive characteristics of its architecture, depending upon various factors affecting its design. This is in particular — culture and climate. It is clear that the two types of architecture, traditional and contemporary, have responded with different questions/purposes.

However, there is a particular feature in both types which has a distinct significance and characteristic in hot and humid regions, and that is the transitional space. The "in-between" spaces in buildings enable the smoothness of a series of parts of a journey which is taken from exterior to interior, or vice versa, or give options for adaptability to occupants experiencing thermally less severe of high air temperatures and high solar radiation. Satisfaction is the main aim in comfort.

The second part (Chapters Four, Five and Six) has taken account of literature on thermal comfort, and has given some case studies. It has showed that the trends of research in thermal comfort have been studied through "Field-

Studies" methodology and applied adaptive theory. This involves the satisfactory states with thermal environments, physiologically and psychologically.

In the classic theory, the thermal balance between the human body and its surroundings has dominated the thermal comfort study, giving both environmental and individual factors as main contributors to establish the comfort equations, and later the thermal standards. Nevertheless, there have been many arguments between the findings from field work and the standards. The considerations of the adaptive theory in relation to the proposal of the Adaptive Models are therefore an alternative. They demonstrate the relationship between the conditions of prevailing temperatures and the comfort or neutral temperatures, especially in the "free-running" buildings.

From various case studies, it seems constant neutral temperatures were found in chamber studies, and in contrast, the neutral temperatures varied in field studies, identifying the thermal requirement of man in different places and climatic regions. Regarding thermal preference, the human subjects in warm climates prefer lower temperatures than the neutral temperatures, while those in cold climates are opposite.

The final part (Chapters Seven to Ten) which is the main part of this thesis, has described the observation and analysis of the field study of thermal comfort conducted in transitional spaces in selected buildings in Bangkok, and has given discussions and design recommendations. The subjects in the field surveys experienced various thermal environments: air-conditioned/naturally-ventilated and indoors/outdoors, and the subjective thermal responses were represented by four concepts: expectation, sensation, preference, and adaptation to achieve comfort.

In general, the responses of thermal expectations and thermal sensations were fairly similar in every group, except those of the A/C-outdoor subjects, who expected warmer air out of doors than actual felt. The A/C-indoor showed the patterns of both thermal responses on the cool side, while the rest, on the warm side. Thermal preferences of all subjects were consistently for "cooler" environments. It has been suggested that the consideration of thermal comfort should be the collaboration between the neutrality and the preference. The suggested adaptation actions were: using air-conditioning, increasing air movement, or staying in a shaded area, if too warm; and were increasing clothing insulation or increasing activities, if too cool.

The statistical techniques such as simple linear regression and probit analysis have given the findings of comfortable conditions of all subjects: the neutral temperature of approximately 27.2°C; the expected temperature of somewhat lower 27.1°C; and the preferred temperature of much lower 21.9°C (this only calculated using the cool season data). Using the Griffiths' method, the neutral temperatures of individual subject groups have been established: the A/C groups of approximately 27.0°C; and the N/V groups of 28.0-29.0°C. Thermal acceptability of all subjects analysed by using quadratic regression technique has given at a range of temperatures between 24.2°C and 29.8°C, which are much higher than the recommendations in the standards.

The analysis of the combined effects of air temperatures with humidity and with air movement upon human comfort has not shown significant findings, but surprisingly controversial. At low air temperatures, there are more number of subjects being comfortable, if high water vapour pressure, and if low air movement.

The findings of neutral temperatures (T_n) from this study are comparatively in good agreement with various results from previous research, especially those in tropical regions. In terms of the Adaptive Models, they have shown the good relationship between climate and comfort, like Humphreys' model [1978], which uses the monthly mean outdoor temperatures as variables.

Finally, this thesis has suggested some techniques to improve thermal comfort and to apply the results from research to practice. It also suggested the recommendations of design criteria to improve thermal performance of transitional spaces in buildings in tropical climates. Firstly, the effects of the adaptive errors [Baker and Standeven 1996] has been introduced. With the use of passive cooling control and the changes of subjects' activity and clothing, the adapted cases have shown better comfort findings. Secondly, to apply the results of this study with the previous work of Thai office workers [Busch 1992] in terms of a sequence of the approach to and from tropical architecture, the transitional spaces have functioned as buffer zones (a mitigation feature) between outdoor environments and workplaces. Finally, a computer simulation program — QUICK [Mathews et al 1991b] has been used to analyse thermal performance of a transitional space. Various effects have been performed and general recommendations have been given.

11.2 Design recommendations

The design recommendations from this thesis are:

1. Transitional spaces should be applied in hot and humid tropical architecture. These "in-between" spaces are able to act as buffer zones, giving the building occupants a chance to adapt their thermal sensations to be comfortable as they move between outside and inside, and vice versa. It is therefore useful as a mitigation feature to alleviate the thermal stress which may occur.

2. The recommended neutral temperatures (T_n) in transitional spaces can be estimated from the knowledge of prevailing temperatures (T_a). The regression equation can be written as:

   $$T_n = 19.1 + 0.30\,T_a \qquad \text{(eq. 9.3)}$$

   $$\text{where} \quad 25.0 \le T_a \le 33.2$$

   This model is derived from the relationship between climate and comfort, of which is the theoretical basis of the adaptive principle. The upper comfort boundary can be extended up to 30.0°C, which is much beyond the recommendations by the standards.

3. The use of passive cooling control is suggested to improve comfort. Its cumulative effects of the adaptive errors (i.e., reducing air temperature, and increasing air velocity) show significantly better findings. Human subjects should also be allowed to adjust their activity and their clothing. It is clear

that subjects in tropical climates prefer "cooler" environments (possibly, than their expectations and neutrality).

4. A computer simulation program has investigated various effects of parametric changes in terms of thermal performance of a transitional space. It gives general recommendations for the architectural design criteria, which consider passive means:

   - It is clear that the space in the north orientation is the best thermal performance and it should be functioned as a main area for living or working. Therefore, transitional spaces can be oriented towards the east direction or other sides, serving as buffer zones.

   - The exposure of the roof to outdoor environments can create high indoor temperature due to direct solar radiation. It is suggested to have another floor above or to install a false roof. In the case of floors, the cooling effect can gain from ground contact (not floor on stilts). It should be noted that this finding is arrived from the simulation from only the working hours.

   - Increasing volume of the spaces by elongation or increasing ceiling height can reduce the indoor temperatures. The length of the journey to approach to the main functions of a building affects thermal perception of building occupants because of the smoothness of transition between inside and outside. A vertical increase of the height of the ceiling with a vent on the top level to ventilate hot air out (i.e., stack effect) can improve thermal performance.

   - Light materials are generally suggested to use in tropical architecture. Thermal mass may be applicable in some cases only if the duration of the day-time and the period of the time-lag of materials are considered.

- Finally, the effects of ventilation show that air speeds obtained from the prevailing wind conditions (i.e., ventilation rate of 2 ach) are just enough to be practical to achieve comfort.

11.3 Suggestions for future research

There are some suggestions for future research in relation to this thesis, which will be a great deal of advantages to contribute to the knowledge of building science subjects, in particular to thermal environmental study. These are:

- In doing a field study of thermal comfort by transverse design survey, the number of subjects are of importance. Various statistical analyses need a lot of input data for giving significant and reliable results. Further field surveys to be added to this study will increase the confidence in analysis and the reliability of comfort findings.

- Another suggested field study by longitudinal design survey is of equal importance. Subjects may give their thermal responses in a series of moving spaces or changing spaces during the day and between the days or the months. This will expect comfort findings in terms of the consistency of individuals, and the patterns of adaptability in dynamic environments. In addition, analysis using time-sequence hypothesis will provide a set of non-static neutral temperatures which relate to various factors affecting comfort.

- There is a need to further study and investigate the impact of various methods of adaptations and to establish adaptive thermal comfort standards. The adaptive models should include both physiological (i.e., personal adjustments, thermal control strategies) and psychological (i.e., acclimatisation, expectation, sensitivity to thermal environments) parameters, forming algorithm solutions.

- Future research will be useful for architects or building designers in practice if there is a serious link between the findings from thermal comfort study and thermal performance, derived from either simulation analyses or physical measurements. Design criteria (of both comfort and architecture) in particular regions and climates will be independent and suitable for locality. This may include comparative energy analysis to show double benefits of energy savings and comfortable conditions.

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Appendices

Appendix A
Instrumentation in the field surveys

Humidity and Temperature Sensors — Skye Data Hog SDL

Humidity Sensor

Measurement range	:	0-100% rh
Operating temperature	:	-20°C to +70°C (units for extended temperature range available)
Capacitance	:	typically 500pf at 25°C and 75% rh
Limit temperature	:	-40°C to +140°C (performance not guaranteed at extremes)
Pressure	:	0.04 to 30 Bars
Time response	:	typically 10s between 10 and 75% rh for 90% of the step
Linearity deviation	:	typically 2.5% rh between 10 and 90% rh — cancalled in electronics to give linear output
Hysteresis	:	better than 0.5% rh
Reversible drift	:	1 day at 97% rh maximum of 2% rh 1 week at 97% rh maximum of 3% rh
Stability	:	typically 5% in 2 years
Accuracy (inc. electronics)	:	better than 2%

Temperature Sensors

Measurement range	:	-20°C to +70°C (units for extended temperature range available)
Accuracy - PRT's	:	standard units to BS 1904 and DIN 43760 (1/3rd DIN)max. error at 0°C = +0.05°C (1/5th & 1/10th DIN available to order)
Accuracy - thermistors	:	standard Fenwal type 10 K ohms at 25°C - curve matched. Accuracy 0.2°C max. error over 0°C to 60°C

Air Flow Meter — Solomat MPM 500e

Multifunction Environmental Instrument

Usage conditions	:	-0°C / 50°C (<80% RH)
Storage conditions	:	-20°C / 65°C without battery
Average	:	the average of a continuous set of measurements can be calculated by the processor.
Powering	:	batter type of 9 volt PP3 (IEC no. 6LR61)

<u>Hotwire Probe 228MS/GN (Air Speed Measurement)</u>

Range/Resolution	:	1.00 / 40.00 m/s
Accuracy	:	2% rdg ± 0.15 m/s
Temperature range	:	-10°C / 70°C

Appendix B
Metabolic rates of different activities

(After ISO 7730 1994)

Activity	Metabolic rates	
	W/m^2	met
Reclining	46	0.8
Seated, relaxed	58	1.0
Sedentary activity (office, dwelling, school, laboratory)	70	1.2
Standing, light activity (shopping, laboratory, light industry)	93	1.6
Standing, medium activity (shop assistant, domestic work, machine work)	116	2.0
Walking on the level:		
2 km/h	110	1.9
3 km/h	140	2.4
4 km/h	165	2.8
5 km/h	200	3.4

Appendix C
Clothing insulation values

(After ISO 7730 1994)

Garment description		Thermal insulation clo
Underwear	Panties	0.03
	Underpants with long legs	0.10
	Singlet	0.04
	T-shirt	0.09
	Shirt with long sleeves	0.12
	Panties and bra	0.03
Shirts - Blouses	Short sleeves	0.15
	Light-weight, long sleeves	0.20
	Normal, long sleeves	0.25
	Flannel shirt, long sleeves	0.30
	Light-weight blouse, long sleeves	0.15
Trousers	Shorts	0.06
	Light-weight	0.20
	Normal	0.25
	Flannel	0.28
Dresses - Skirts	Light skirts (summer)	0.15
	Heavy skirts (winter)	0.25
	Light dress, short sleeves	0.20
	Winter dress, long sleeves	0.40
	Boiler suit	0.55
Sweaters	Sleeveless vest	0.12
	Thin sweater	0.20
	Sweater	0.28
	Thick sweater	0.35
Jackets	Light, summer jacket	0.25
	Jacket	0.35
	Smock	0.30
High-insulative, fibre-pelt	Boiler suit	0.90
	Trousers	0.35
	Jacket	0.40
	Vest	0.20

(Continue.)

Garment description		Thermal insulation
		clo
Outdoor clothing	Coat	0.60
	Down Jacket	0.55
	Parka	0.70
	Fibre-pelt overalls	0.55
Sundries	Socks	0.02
	Thick, ankle socks	0.05
	Thick, long socks	0.10
	Nylon stockings	0.03
	Shoes (thin soled)	0.02
	Shoes (thick soled)	0.04
	Boots	0.10
	Gloves	0.05

Appendix D
Questionnaires

Thermal comfort survey in Thailand

- Type A: use when entering the building
- Type B: use when leaving of the building
- Thai versions

Thermal comfort survey in Thailand
(Type A: use when entering the building)

Subject code number: .... Date: ....
Building: .... Time: ....

Please make a mark " x " in the box which relates to your feeling.

1.1 What sensation did you expect to feel before coming in this building?

cold	cool	slightly cool	neutral	slightly warm	warm	hot

1.2 How do you actually feel at this moment?

cold	cool	slightly cool	neutral	slightly warm	warm	hot

1.3 Would you like to be ...

cooler	no change	warmer

1.4 How do you feel at this moment in terms of air flow?

much too still	too still	slightly still	just right	slightly breezy	too breezy	much too breezy

1.5 How do you feel at this moment in terms of humidity?

much too dry	too dry	slightly dry	just right	slightly humid	too humid	much too humid

1.6 What do you do, if you feel too hot or too cold, to make yourself more comfortable? Please mark " x " next to any action you have taken today.

too hot	too cold
1.	1. ....
2.	2. ....
3.	3. ....

1.7 Is there a sudden or gradual change in environmental conditions between the inside and outside of the building?

sudden	gradual	little / no change

2.1 How did you travel here?

- ☐ on foot
- ☐ by air-conditioned car, or bus
- ☐ by naturally-ventilated car, or bus
- ☐ by boat
- ☐ other (specify) ....

2.2 How long did the journey take?

.... minutes.

2.3 What activity do you normally do when you are in this building?

- ☐ sitting - passive work
- ☐ walking - relaxed
- ☐ sitting - active work
- ☐ walking - fast
- ☐ standing - relaxed
- ☐ working hard
- ☐ standing - working
- ☐ other (specify) ....

3.1 What clothes are you wearing at the moment?

- ☐ T-shirt
- ☐ shorts
- ☐ short sleeved shirt / blouse
- ☐ trousers
- ☐ long sleeved shirt / blouse
- ☐ short skirt
- ☐ vest
- ☐ long skirt
- ☐ sweater
- ☐ short socks
- ☐ jacket
- ☐ long socks
- ☐ casual suit
- ☐ tights
- ☐ formal suit
- ☐ sandals / slippers
- ☐ tie
- ☐ shoes
- ☐ head-dress / cap
- ☐ boots
- ☐ other (specify) ....

3.2 Do you feel comfortable with your clothes?

- ☐ yes
- ☐ no

3.3 If you do not feel comfortable, which of the clothes would you take off or put on to achieve comfort?

take off .... put on ....

4.1 Age .... (years)

4.2 Gender ☐ male ☐ female

4.3 Weight .... (kilograms)

4.4 Height .... (centimetres)

4.5 Occupation

- ☐ student
- ☐ proprietor
- ☐ government service
- ☐ house-wife
- ☐ private office worker
- ☐ other (specify) ....

4.6 Income per month

- ☐ lower than 5,000 Baht
- ☐ 25,000 - 50,000 Baht
- ☐ 5,000 - 10,000 Baht
- ☐ 50,000 - 100,000 Baht
- ☐ 10,000 - 25,000 Baht
- ☐ more than 100,000 Baht

4.7 Education

- ☐ compulsory or vocational
- ☐ bachelor
- ☐ secondary school
- ☐ post-graduate

Thermal comfort survey in Thailand
(Type B: use when leaving of the building)
Subject code number: .... Date: ....
Building: .... Time: ....

Please make a mark " x " in the box which relates to your feeling.

1.1 What sensation did you expect to feel after going out this building?

cold	cool	slightly cool	neutral	slightly warm	warm	hot

1.2 How do you actually feel at this moment?

cold	cool	slightly cool	neutral	slightly warm	warm	hot

1.3 Would you like to be ...

cooler	no change	warmer

1.4 How do you feel at this moment in terms of air flow?

much too still	too still	slightly still	just right	slightly breezy	too breezy	much too breezy

1.5 How do you feel at this moment in terms of humidity?

much too dry	too dry	slightly dry	just right	slightly humid	too humid	much too humid

1.6 What do you do, if you feel too hot or too cold, to make yourself more comfortable? Please mark " x " next to any action you have taken today.

too hot
1. ....
2. ....
3. ....

too cold
1. ....
2. ....
3. ....

1.7 Is there a sudden or gradual change in environmental conditions between the outside and inside of the building?

sudden	gradual	little / no change

2.1 What activity did you do in the last 15 minutes?

☐ sitting - passive work	☐ walking - relaxed
☐ sitting - active work	☐ walking - fast
☐ standing - relaxed	☐ working hard
☐ standing - working	☐ other (specify) ....

2.2 What activity do you do when you are going out the building?

☐ sitting - passive work	☐ walking - relaxed
☐ sitting - active work	☐ walking - fast
☐ standing - relaxed	☐ working hard
☐ standing - working	☐ other (specify) ....

3.1 What clothes are you wearing at the moment?

☐ T-shirt	☐ shorts
☐ short sleeved shirt / blouse	☐ trousers
☐ long sleeved shirt / blouse	☐ short skirt
☐ vest	☐ long skirt
☐ sweater	☐ short socks
☐ jacket	☐ long socks
☐ casual suit	☐ tights
☐ formal suit	☐ sandals / slippers
☐ tie	☐ shoes
☐ head-dress / cap	☐ boots
☐ other (specify)	

3.2 Do you feel comfortable with your clothes?

☐ yes ☐ no

3.3 If you do not feel comfortable, which of the clothes would you take off or put on to achieve comfort?

take off .... put on ....

4.1 Age .... (years)

4.2 Gender ☐ male ☐ female

4.3 Weight .... (kilograms)

4.4 Height .... (centimetres)

4.5 Occupation

☐ student	☐ proprietor
☐ government service	☐ house-wife
☐ private office worker	☐ other (specify) ....

4.6 Income per month

☐ lower than 5,000 Baht	☐ 25,000 - 50,000 Baht
☐ 5,000 - 10,000 Baht	☐ 50,000 - 100,000 Baht
☐ 10,000 - 25,000 Baht	☐ more than 100,000 Baht

4.7 Education

☐ compulsory or vocational	☐ bachelor
☐ secondary school	☐ post-graduate

แบบสอบถามเกี่ยวกับความรู้สึกของท่าน ต่อสภาวะอากาศ TYPE A

ชื่อ .... วันที่ ....

อาคาร .... เวลา ....

โปรดทำเครื่องหมาย "X" ในช่องว่างที่สอดคล้องกับความรู้สึกของท่าน

1.1 ก่อนที่ท่านจะเข้ามาในอาคารนี้ ท่านคาดหวังว่าท่านจะรู้สึกอย่างไร

หนาวมาก	หนาว	หนาวเล็กน้อย	กลาง	ร้อนเล็กน้อย	ร้อน	ร้อนมาก

1.2 ในขณะนี้ ท่านรู้สึกอย่างไร

หนาวมาก	หนาว	หนาวเล็กน้อย	กลาง	ร้อนเล็กน้อย	ร้อน	ร้อนมาก

1.3 ในขณะนี้ ท่านอยากจะให้อุณหภูมิเป็นอย่างไร

เย็นลง	ไม่เปลี่ยนแปลง	ร้อนขึ้น

1.4 ท่านรู้สึกอย่างไรเกี่ยวกับ เรื่องการเคลื่อนไหวของอากาศ

อากาศนิ่งมากเกินไป	อากาศนิ่งเกินไป	อากาศนิ่งไปเล็กน้อย	กำลังพอดี	อากาศเคลื่อนไหวไปเล็กน้อย	อากาศเคลื่อนไหวเกินไป	อากาศเคลื่อนไหวมากเกินไป

1.5 ท่านรู้สึกอย่างไร เกี่ยวกับ เรื่องความชื้นในอากาศ

แห้งมากเกินไป	แห้งเกินไป	แห้งไปเล็กน้อย	กำลังพอดี	ชื้นไปเล็กน้อย	ชื้นเกินไป	ชื้นมากเกินไป

1.6 ถ้าหากท่านรู้สึกร้อนเกินไปหรือหนาวเกินไป ท่านจะทำอย่างไรเพื่อให้รู้สึกสบายขึ้น และ โปรดทำเครื่องหมาย "X" หลังคำตอบ ที่ท่านได้กระทำไปในวันนี้ด้วย

ร้อนเกินไป

1...

2...

3...

หนาวเกินไป

1...

2...

3...

1.7 ท่านคิดว่า มีการเปลี่ยนแปลงระหว่างสภาพอากาศ ภายในและภายนอก อย่างไร

เปลี่ยนทันที	ค่อยๆเปลี่ยน	เปลี่ยนเล็กน้อย/ไม่เปลี่ยนแปลง

2.1 ท่านเดินทางมาที่อาคารนี้โดยวิธีใด

- ☐เดิน
- ☐รถยนต์หรือรถโดยสารปรับอากาศ
- ☐รถยนต์หรือรถโดยสาร ไม่ติดเครื่องปรับอากาศ
- ☐เรือ
- ☐อื่น ๆ (โปรดระบุ)..

2.2 ท่านใช้เวลาในการเดินทางนานเท่าไร

.... นาที

2.3 โดยปกติ ท่านทำกิจกรรมอะไรต่อไปนี้ ในอาคารนี้

☐นั่งเล่น	☐เดินเล่น
☐นั่งทำงาน	☐เดินอย่างรีบเร่ง
☐ยืน	☐ทำงานหนัก
☐ยืนทำงาน	☐อื่น ๆ (โปรดระบุ).................................

3.1 โปรดทำเครื่องหมาย "X" หน้ารายการเครื่องแต่งกาย ที่ ท่านกำลังสวมใส่อยู่ ขณะนี้ โปรดดูรายการทั้งหมด ก่อนตอบ

☐เสื้อยืด	☐กางเกงขาสั้น
☐เสื้อเชิ้ตแขนสั้น	☐กางเกงขายาว
☐เสื้อเชิ้ตแขนยาว	☐กระโปรงสั้น
☐เสื้อเสวตเตอร์	☐กระโปรงยาว
☐เสื้อแจ็คเก็ต	☐ถุงเท้าสั้น
☐สูทลำลอง	☐ถุงเท้ายาว
☐สูทมาตรฐาน	☐ถุงน่อง
☐เน็คไท	☐รองเท้าแตะ
☐หมวก	☐รองเท้าผ้าใบ
☐เสื้อกล้าม	☐รองเท้าหนัง

☐อื่น ๆ (โปรดระบุ)...

3.2 ท่านรู้สึกสบายกับเครื่องแต่งกายที่สวมใส่อยู่ ใช่หรือไม่

☐ใช่ ☐ไม่ใช่

3.3 หากท่านรู้สึกไม่สบายกับเสื้อผ้าที่สวมใส่อยู่ท่านคิดว่าเครื่องแต่งกายชิ้นใดที่ท่านจะถอดออกหรือสวมใส่เพิ่ม

ถอดออก.. ใส่เพิ่ม..

....

....

4.1 อายุ...............................(ปี)

4.2 เพศ...............................(ชาย,หญิง)

4.3 น้ำหนัก..(กิโลกรัม)

4.4 ส่วนสูง..(เซ็นติเมตร)

4.5 อาชีพ

☐นักเรียน/นักศึกษา	☐ประกอบอาชีพส่วนตัว/เจ้าของกิจการ
☐ข้าราชการ รัฐวิสาหกิจ	☐แม่บ้าน
☐พนักงานบริษัทเอกชน	☐อื่น ๆ (โปรดระบุ)..

4.6 รายได้ต่อเดือน

☐ต่ำกว่า 5,000 บาท	☐25,000 - 50,000 บาท
☐5,000 - 10,000 บาท	☐50,000 - 100,000 บาท
☐10,000 - 25,000 บาท	☐มากกว่า 100,000 บาท

4.7 การศึกษาสูงสุด

☐การศึกษาภาคบังคับ	☐ปริญญาตรี
☐มัธยมปลาย/ประกาศนียบัตรวิชาชีพ	☐ปริญญาโท/เอก

4.8 ท่านใช้เครื่องปรับอากาศที่บ้านหรือไม่

☐ไม่ได้ใช้

☐ใช้เพียงเล็กน้อย

☐ใช้ตลอดเวลา

แบบสอบถามเกี่ยวกับความรู้สึกของท่าน ต่อสภาวะอากาศ TYPE B

ชื่อ .... วันที่ ....

อาคาร .... เวลา ....

โปรดทำเครื่องหมาย "X" ในช่องว่างที่สอดคล้องกับความรู้สึกของท่าน

1.1 ก่อนที่ท่านจะออกมาจากอาคารนี้ ท่านคาดหวังว่าท่านจะรู้สึกอย่างไร

หนาวมาก	หนาว	หนาวเล็กน้อย	กลาง	ร้อนเล็กน้อย	ร้อน	ร้อนมาก

1.2 ในขณะนี้ ท่านรู้สึกอย่างไร

หนาวมาก	หนาว	หนาวเล็กน้อย	กลาง	ร้อนเล็กน้อย	ร้อน	ร้อนมาก

1.3 ในขณะนี้ ท่านอยากจะให้อุณหภูมิเป็นอย่างไร

เย็นลง	ไม่เปลี่ยนแปลง	ร้อนขึ้น

1.4 ท่านรู้สึกอย่างไรเกี่ยวกับ เรื่องการเคลื่อนไหวของอากาศ

อากาศนิ่งมากเกินไป	อากาศนิ่งเกินไป	อากาศนิ่งไปเล็กน้อย	กำลังพอดี	อากาศเคลื่อนไหวไปเล็กน้อย	อากาศเคลื่อนไหวเกินไป	อากาศเคลื่อนไหวมากเกินไป

1.5 ท่านรู้สึกอย่างไรเกี่ยวกับ เรื่องความชื้นในอากาศ

แห้งมากเกินไป	แห้งเกินไป	แห้งไปเล็กน้อย	กำลังพอดี	ชื้นไปเล็กน้อย	ชื้นเกินไป	ชื้นมากเกินไป

1.6 ถ้าหากท่านรู้สึกร้อนเกินไปหรือหนาวเกินไป ท่านจะทำอย่างไรเพื่อให้รู้สึกสบายขึ้น และ โปรดทำเครื่องหมาย "X"หลังคำตอบ ที่ท่านได้กระทำไปในวันนี้ด้วย

ร้อนเกินไป

1..

2..

3..

หนาวเกินไป

1..

2..

3..

1.7 ท่านคิดว่า มีการเปลี่ยนแปลงระหว่างสภาพอากาศ ภายในและภายนอก อย่างไร

เปลี่ยนทันที	ค่อยๆเปลี่ยน	เปลี่ยนเล็กน้อย/ไม่เปลี่ยนแปลง

2.1 ท่านทำกิจกรรมอะไรต่อไปนี้ ในอาคาร เมื่อ 15 นาทีที่ผ่านมา

☐นั่งเล่น ☐เดินเล่น

☐นั่งทำงาน ☐เดินอย่างรีบเร่ง

☐ยืน ☐ทำงานหนัก

☐ยืนทำงาน ☐อื่น ๆ (โปรดระบุ)..................................

2.2 ท่านทำกิจกรรมอะไรต่อไปนี้ เมื่อท่านออกมาจากอาคาร

☐นั่งเล่น	☐เดินเล่น
☐นั่งทำงาน	☐เดินอย่างรีบเร่ง
☐ยืน	☐ทำงานหนัก
☐ยืนทำงาน	☐อื่น ๆ (โปรดระบุ).................................

3.1 โปรดทำเครื่องหมาย "X" หน้ารายการเครื่องแต่งกาย ที่ ท่านกำลังสวมใส่อยู่ ขณะนี้ โปรดดูรายการทั้งหมด ก่อนตอบ

☐เสื้อยืด	☐กางเกงขาสั้น
☐เสื้อเชิ้ตแขนสั้น	☐กางเกงขายาว
☐เสื้อเชิ้ตแขนยาว	☐กระโปรงสั้น
☐เสื้อเสวตเตอร์	☐กระโปรงยาว
☐เสื้อแจ็คเก็ต	☐ถุงเท้าสั้น
☐สูทลำลอง	☐ถุงเท้ายาว
☐สูทมาตรฐาน	☐ถุงน่อง
☐เน็คไท	☐รองเท้าแตะ
☐หมวก	☐รองเท้าผ้าใบ
☐เสื้อกล้าม	☐รองเท้าหนัง

☐อื่น ๆ (โปรดระบุ)..

3.2 ท่านรู้สึกสบายกับเครื่องแต่งกายที่สวมใส่อยู่ ใช่หรือไม่

☐ใช่ ☐ไม่ใช่

3.3 หากท่านรู้สึกไม่สบายกับเสื้อผ้าที่สวมใส่อยู่ท่านคิดว่าเครื่องแต่งกายชิ้นใดที่ท่านจะถอดออกหรือสวมใส่เพิ่ม

ถอดออก... ใส่เพิ่ม...
....
....

4.1 อายุ..............................(ปี)

4.2 เพศ..............................(ชาย,หญิง)

4.3 น้ำหนัก..(กิโลกรัม)

4.4 ส่วนสูง..(เซ็นติเมตร)

4.5 อาชีพ

☐นักเรียน/นักศึกษา	☐ประกอบอาชีพส่วนตัว/เจ้าของกิจการ
☐ข้าราชการ รัฐวิสาหกิจ	☐แม่บ้าน
☐พนักงานบริษัทเอกชน	☐อื่น ๆ (โปรดระบุ)...

4.6 รายได้ต่อเดือน

☐ต่ำกว่า 5,000 บาท	☐25,000 - 50,000 บาท
☐5,000 - 10,000 บาท	☐50,000 - 100,000 บาท
☐10,000 - 25,000 บาท	☐มากกว่า 100,000 บาท

4.7 การศึกษาสูงสุด

☐การศึกษาภาคบังคับ	☐ปริญญาตรี
☐มัธยมปลาย/ประกาศนียบัตรวิชาชีพ	☐ปริญญาโท/เอก

4.8 ท่านใช้เครื่องปรับอากาศที่บ้านหรือไม่

☐ไม่ได้ใช้

☐ใช้เพียงเล็กน้อย

☐ใช้ตลอดเวลา

Appendix E
Climatic data of the field surveys

Date = 6 December 1996 (cool)

Place = Faculty of Architecture, Silpakorn University (N/V)

	Indoor				Outdoor			
Time	Ta	Tg	rh	v	Ta	Tg	rh	v
09:20	28.21		62.9	0.10	28.53		62.0	0.67
09:40	28.71		61.0	0.20	29.41		58.7	0.73
10:00	29.02		60.0	0.15	29.98		57.8	0.65
10:20	29.34		58.7	0.10	29.94		58.5	0.25
10:40	29.55		59.0	0.15	30.14		58.9	0.31
11:00	29.49		59.2	0.10	29.79		59.0	0.24
11:20	29.32		60.5	0.07	29.84		59.2	0.80
11:40	29.32		60.4	0.02	29.75		59.6	0.46
12:00	29.40		58.8	0.05	29.88		59.3	0.52
12:20	29.79		59.4	0.03	30.26		57.9	0.55
12:40	29.92		59.6	0.10	30.38		57.1	0.60
13:00	29.97		60.0	0.20	30.53		58.1	0.40

Date = 11 December 1996 (cool)

Place = Faculty of Architecture, Silpakorn University (N/V)

	Indoor				Outdoor			
Time	Ta	Tg	rh	v	Ta	Tg	rh	v
12:00	26.25		61.3					
12:20	27.74		57.5		28.43	29.17	59.1	
12:40	28.07		56.6	0.78	29.16	29.58	52.1	0.53
13:00	28.39		52.9	0.26	29.63	29.74	49.6	0.12
13:20	28.21		54.6	0.10	30.20	30.50	46.4	0.34
13:40	28.4		53.3	0.42	30.27	30.41	48.4	0.41
14:00	28.51		53.3	0.23	30.12	30.04	48.9	1.35
14:20	28.58		54.1	0.63	30.07	29.79	49.0	0.31
14:40	28.63		54.6	0.22	29.62	29.31	53.3	0.49
15:00	28.60		55.4	0.10	29.73	29.58	52.1	0.79
15:20	28.81		54.4	0.09	29.62	29.75	52.4	0.44
15:40	28.82		54.4	0.05	29.66	29.30	51.0	0.65
16:00	30.03		49.8	0.35	29.73	29.65	52.1	

Date = 12 December 1996 (cool)

Place = Office of the Civil Service Commission (N/V)

	Indoor				Outdoor			
Time	Ta	Tg	rh	v	Ta	Tg	rh	v
10:00	27.24		59.7	0.02	28.04	28.20	59.6	0.41
10:20	27.85		56.9	0.44	28.70	28.68	57.2	0.21
10:40	27.84		55.7	0.24	29.08	28.88	52.3	0.13
11:00	27.77		53.8	0.03	29.33	29.39	49.3	0.28
11:20	27.61		50.2	0.08	29.90	30.06	52.0	0.63
11:40	27.59		53.2	0.08	30.70	31.05	45.0	0.30
12:00	27.84		52.6	0.29	30.58	31.04	46.4	0.24
12:20	27.77		50.7	0.03	30.60	30.59	46.4	0.49
12:40	28.16		50.5	0.11	30.53	30.4	47.2	0.27
13:00	28.05		53.2	0.07	30.70	30.85	47.2	0.43
13:20	28.33		54.9	0.05	31.37	31.58	44.9	0.57
13:40	28.42		52.6	0.13	31.47	31.39	42.7	0.15
14:00	28.51		50.7	0.17	31.78	31.87	41.6	0.09
14:20	28.57		50.5	0.17	31.72	32.07	42.2	0.46
14:40	28.58		53.0	0.13	31.75	31.65	44.6	0.32
15:00	28.74		54.4	0.05	31.40	31.61	46.4	0.19
15:20	28.73		54.6	0.06	31.16	31.38	48.4	0.24
15:40	28.73		54.3	0.18	30.85	31.18	48.3	0.52
16:00	28.64		53.5	0.13	30.53	30.69	48.3	0.34
16:20	28.47		54.3	0.13	30.41	30.50	48.9	0.73

Date = 13 December 1996 (cool)

Place = SAI Consultants Co., Ltd. (A/C)

	Indoor				Outdoor			
Time	Ta	Tg	rh	v	Ta	Tg	rh	v
10:20			45.5	0.15	29.35	28.92	54.3	0.57
10:40	25.41		46.1	0.16	29.07	28.82	54.7	0.67
11:00	24.21		49.8	0.05	29.02	28.32	50.5	0.65
11:20	25.60		54.1					

Date = 9 January 1997 (cool)

Place = Sathon Thani Building (A/C)

	Indoor				Outdoor			
Time	Ta	Tg	rh	v	Ta	Tg	rh	v
09:20	25.68		46.9	0.45	25.84	25.72	55.1	0.61
09:40	25.72		44.7	0.16	25.65	26.23	56.5	0.58
10:00	25.84		45.3	0.22	26.39	27.40	44.4	0.67
10:20	25.90		44.3	0.18	27.07	27.72	48.7	0.48
10:40	26.01		38.1	0.15	27.03	27.25	50.5	0.33
11:00	25.85		47.5	0.34	26.61	26.71	46.4	0.60
11:20	25.93		41.6	0.18	26.88	27.55	50.5	0.71
11:40	25.88		43.0	0.29	27.51	28.32	49.8	0.28
12:00	25.81		44.3	0.13	27.96	28.40	45.0	0.85
12:20	25.81		41.9	0.15	28.50	29.25	40.4	0.27
12:40	26.00		44.4	0.26	28.94	29.77	40.7	1.48
13:00	26.17		43.7	0.05	29.24	30.02	38.1	0.91
13:20	25.96		40.8	0.24	29.58	30.59	39.3	0.40
13:40	26.08		41.0	0.18	29.23	29.98	40.7	1.85
14:00	26.06		43.3	0.14	29.41	30.07	39.4	0.86
14:20	26.01		40.4	0.08	29.65	30.19	40.0	0.91
14:40	26.08		41.2	0.22	29.25	29.65	37.7	0.42
15:00	26.06		41.2	0.23	29.23	30.04	40.8	0.34
15:20	26.00		39.3	0.15	29.10	29.54	40.2	0.31
15:40	26.17		40.8	0.24	29.37	29.66	39.7	0.44

Date = 10 January 1997 (cool)

PLACE = Central Department Store, Pinklao Branch (A/C)

	Indoor				Outdoor			
Time	Ta	Tg	RH	v	Ta	Tg	RH	v
11:00					26.33	26.47	50.5	0.38
11:20	23.41		58.9	0.23	25.00	24.80	55.1	0.80
11:40	23.14		59.2	0.15	25.18	25.58	51.8	0.18
12:00	23.25		58.5	0.24	25.37	25.37	50.4	0.53
12:20	23.27		58.5	0.22	25.72	25.80	49.0	0.34
12:40	23.26		58.4	0.18	25.89	26.07	47.5	0.46
13:00	23.41		57.9	0.27	26.20	26.41	47.7	0.53
13:20	23.55		58.1	0.13	26.35	26.46	48.3	0.83
13:40	23.88		57.3	0.24	26.50	26.44	48.3	1.48
14:00	23.88		56.9	0.23	26.65	26.71	47.4	0.43
14:20	23.88		56.9	0.15				
14:40	24.06		57.2	0.07				
15:40					26.58	27.39	43.3	0.47
16:00	24.49		53.9	0.24	27.37	27.59	42.3	0.36
16:20	24.26		53.8	0.24	27.50	27.48	40.6	0.78
16:40	23.98		54.7	0.27	27.48	27.59	40.1	0.52
17:00	23.95		55.2	0.23	27.39	27.42	42.5	0.37
17:20	23.90		53.2	0.40	27.38	27.51	38.7	1.12
17:40	23.87		53.2	0.17	27.31	27.25	39.4	0.66
18:00	23.74		54.1	0.35	26.85		42.9	0.55

Date = 21 April 1997 (warm)

Place = Faculty of Architecture, Silpakorn University (N/V)

	Indoor				Outdoor			
Time	Ta	Tg	rh	v	Ta	Tg	rh	v
10:30	30.5	30.5	62.7	0.22	31.8	32.0	60.8	0.15
10:45	31.0	30.8	63.2	0.48	32.2	32.6	60.5	0.45
11:00	31.5	31.1	59.6	0.14	32.7	32.9	57.8	0.42
11:15	31.5	31.4	60.5	0.15	33.2	33.5	54.9	0.44
11:30	31.8	31.6	58.5	0.34	33.7	34.5	55.1	0.43
11:45	31.9	31.5	57.9	0.43	33.5	33.3	53.8	0.32
12:00	31.9	32.0	57.2	0.16	34.1	35.0	50.5	0.18
12:15	32.2	32.2	56.4	0.18	34.5	35.1	49.9	0.34
12:30	32.5	32.2	56.7	0.17	34.7	35.4	48.9	0.36
12:45	32.7	32.4	54.6	0.16	34.8	36.2	49.2	0.32
13:00	33.0	33.0	55.1	0.17	34.8	35.4	48.7	0.30
13:15	33.0	32.9	55.7	0.11	34.8	34.7	47.8	0.35
13:30	33.0	33.1	54.1	0.65	35.1	35.2	46.1	0.90
13:45	33.1	33.1	50.1	0.12	35.1	35.0	45.2	0.18
14:00	32.9	33.0	50.4	0.10	35.8	35.2	43.6	1.72
14:15	32.9	33.2	50.7	0.25	36.7	36.7	41.4	0.36
14:30	33.2	33.3	50.8	0.38	34.8	35.3	47.7	0.41
14:45	33.2	33.3	50.8	0.22	34.7	34.5	48.1	0.46
15:00	33.1	32.8	52.9	0.20	34.3	34.2	51.2	0.48
15:15	33.0	32.9	51.2	0.42	34.2	34.1	49.8	0.50

Date = 23 April 1997 (warm)

Place = Office of the Civil Service Commission (N/V)

	Indoor				Outdoor			
Time	Ta	Tg	rh	v	Ta	Tg	th	v
09:00	27.7	27.5	60.0	0.05	27.4	27.9	66.3	0.16
09:15	28.0	27.8	62.0	0.16	27.7	28.5	65.3	0.36
09:30	28.3	28.1	61.0	0.16	28.6	29.3	61.4	0.24
09:45	28.7	28.4	58.0	0.24	28.8	29.3	60.2	0.40
10:00	28.7	28.7	59.0	0.34	29.2	29.6	57.9	0.42
10:15	29.0	28.7	59.0	0.33	29.5	30.7	57.0	0.33
10:30	29.3	29.0	59.0	0.12	30.0	30.3	55.1	0.11
10:45	29.0	29.0	58.0	0.40	30.1	31.4	55.1	0.44
11:00	29.6	29.3	59.0	0.17	31.1	31.8	51.8	0.30
11:15	29.6	29.3	57.0	0.17	31.6	32.6	49.5	0.23
11:30	29.9	29.6	57.0	0.30	32.5	33.9	45.0	0.37
11:45	29.9	29.6	56.0	0.32	32.4	32.9	46.4	0.25
12:00	29.9	29.6	55.0	0.01	33.5	34.3	41.9	0.26
12:15	29.9	29.9	57.0	0.05	33.4	34.3	43.8	0.37
12:30	30.3	30.2	57.0	0.30	33.7	34.2	42.3	0.51
12:45	30.3	30.2	54.0	0.15	33.8	34.7	41.1	0.17
13:00	30.3	30.2	53.0	0.29	34.6	34.9	37.6	0.35
13:15	29.9	29.9	53.0	0.33	34.6	35.8	38.8	0.62
13:30	29.9	29.9	53.0	0.04	34.8	35.7	38.7	0.80
13:45	30.3	30.2	53.0	0.13	35.5	36.2	36.4	0.09
14:00	30.3	30.2	52.0	0.90	35.3	36.5	36.4	0.19
14:15	30.3	29.9	52.0	0.21	35.6	36.1	33.9	0.54
14:30	30.3	30.2	51.0	0.01	35.1	36.0	33.9	0.23
14:45	30.3	30.2	50.0	0.15	35.7	36.8	32.2	0.24
15:00	30.3	30.2	50.0	0.01	34.3	36.7	40.4	0.30

Date = 24 April 1997 (warm)

Place = Sathon Thani Building (A/C)

	Indoor				Outdoor			
Time	Ta	Tg	rh	v	Ta	Tg	rh	v
10:30	29.1	28.3	39.3	0.39	29.4	30.3	65.8	0.69
10:45	28.3	28.2	40.1	0.17	30.2	30.7	65.1	0.29
11:00	28.0	28.3	41.6	0.10	30.8	30.6	53.8	0.16
11:15	27.9	28.0	39.7	0.01	30.6	30.2	54.3	0.09
11:30	28.0	28.2	40.8	0.21	30.7	31.1	62.8	0.16
11:45	28.0	28.2	41.0	0.14	30.6	30.7	60.6	0.16
12:00	28.5	28.9	58.8	0.22	30.2	29.6	63.4	0.93
12:15	28.1	28.0	39.1	0.17	29.6	29.0	70.0	0.16
12:30	27.6	27.9	52.9	0.02	28.9	29.0	74.4	0.16
12:45	27.2	27.2	38.9	0.04	28.9	29.1	67.2	0.27
13:00	27.5	27.8	38.2	0.06	29.3	29.4	65.5	0.13
13:15	27.2	27.8	42.1	0.02	29.2	29.1	69.4	0.09
13:30	27.5	28.2	61.9	0.04	29.2	29.3	69.1	0.08
13:45	27.2	27.3	42.3	0.03	28.9	28.5	51.5	0.26
14:00	27.1	27.2	36.0	0.10	28.5	28.4	57.8	0.66
14:15	26.9	27.3	37.5	0.04	28.3	28.4	63.1	0.09
14:30	26.9	27.3	38.2	0.03	28.6	28.7	65.5	0.37
14:45	26.9	27.1	36.3	0.03	28.6	28.9	69.3	0.67
15:00	27.3	27.2	43.0	0.06	28.8	28.6	53.9	0.64
15:15	27.7	27.8	43.0	0.13	28.7	28.8	45.9	0.37

Date = 25 April 1997 (warm)

Place = Central Depaartment Store, Pinklao Branch (A/C)

	Indoor				Outdoor			
Time	Ta	Tg	rh	v	Ta	Tg	rh	v
10:45	26.3	26.9	53.0	0.30	26.8	26.0	69.4	0.51
11:00	25.3	25.7	56.0	0.34	26.1	26.0	79.3	0.75
11:15	25.3	25.7	60.0	0.39	26.1	26.2	80.5	0.12
11:30	25.3	25.3	62.0	0.49	26.3	26.7	83.9	0.29
11:45	25.0	25.3	63.0	0.39	26.5	26.6	83.0	0.22
12:00	25.0	25.0	63.0	0.15	27.0	27.8	84.4	0.38
12:15	25.0	25.0	64.0	0.03	27.5	28.5	82.6	0.24
12:30	25.0	25.0	66.0	0.33	28.5	28.7	71.5	0.35
12:45	24.7	25.0	65.0	0.27	28.5	28.5	71.4	0.36
13:00	25.0	25.0	63.0	1.15	29.1	29.3	65.5	0.60
13:15	25.0	25.0	63.0	0.41	29.4	29.9	65.1	0.52
13:30	25.0	24.7	62.0	0.33	29.8	30.3	62.9	0.38
13:45	24.7	24.7	62.0	0.10	29.8	30.0	65.7	0.80
14:00	24.7	24.4	64.0	0.10	29.1	28.7	71.3	0.65
14:15	24.3	24.4	64.0	0.22	28.2	28.4	71.3	0.52
14:30	24.3	24.4	63.0	0.18	28.1	28.4	68.5	0.92
14:45	24.7	24.4	62.0	0.21	28.4	28.6	66.2	0.80
15:00	24.3	24.4	61.0	0.12	28.8	29.1	61.9	0.98
15:15	24.7	24.7	61.0	0.37	29.0	29.3	60.9	0.85
15:30	24.7	24.7	60.0	0.24	29.2	29.3	59.6	0.73
15:45	24.7	24.7	60.0	0.19	29.3	29.6	59.1	0.37
16:00	24.7	24.7	60.0	0.36	29.3	29.3	57.9	0.42
16:15	24.7	24.7	59.0	0.07	29.1	29.0	58.7	0.41
16:30	24.7	24.7	59.0	0.15	28.9	28.8	59.6	0.66
16:45	24.7	24.7	59.0	0.12	28.5	28.5	61.9	0.34
17:00	24.7	24.7	60.0	0.13	27.9	27.6	60.5	0.93

Appendix F

Demographic information

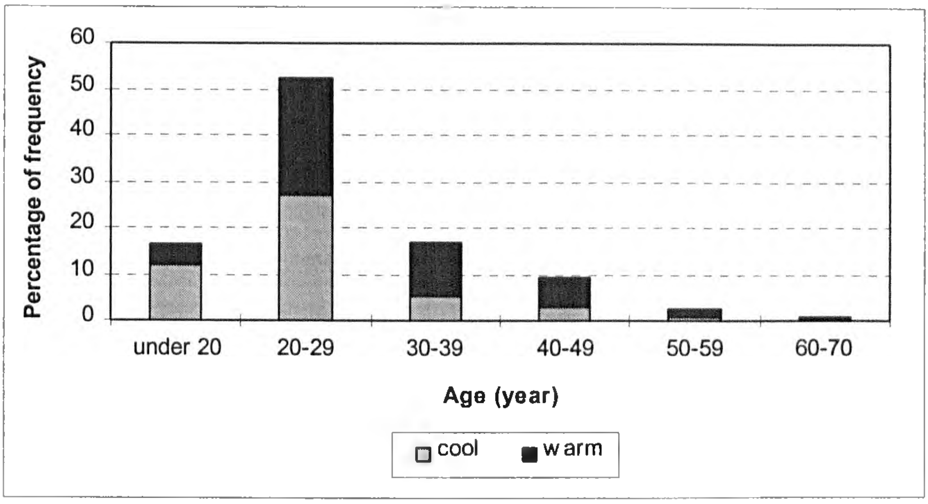

Figure F.1 Percentage distribution of the respondents' age.

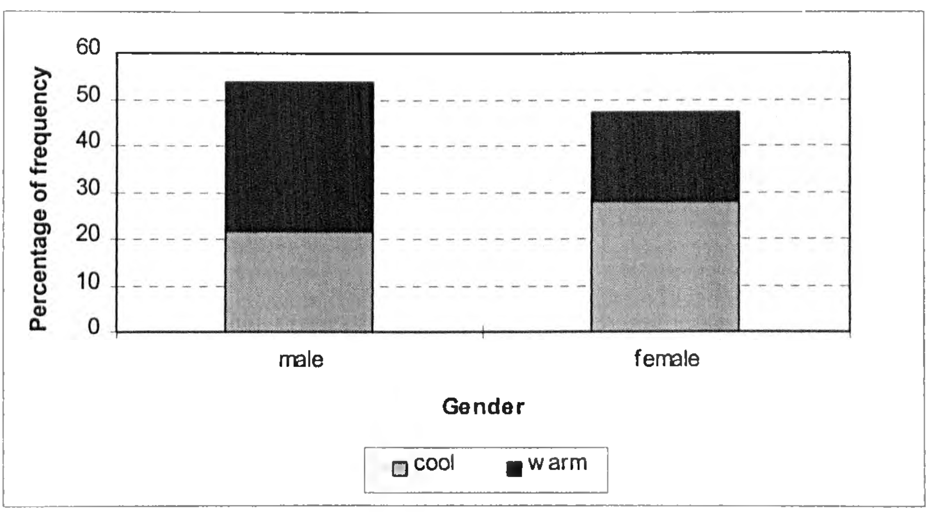

Figure F.2 Percentage distribution of the respondents' gender.

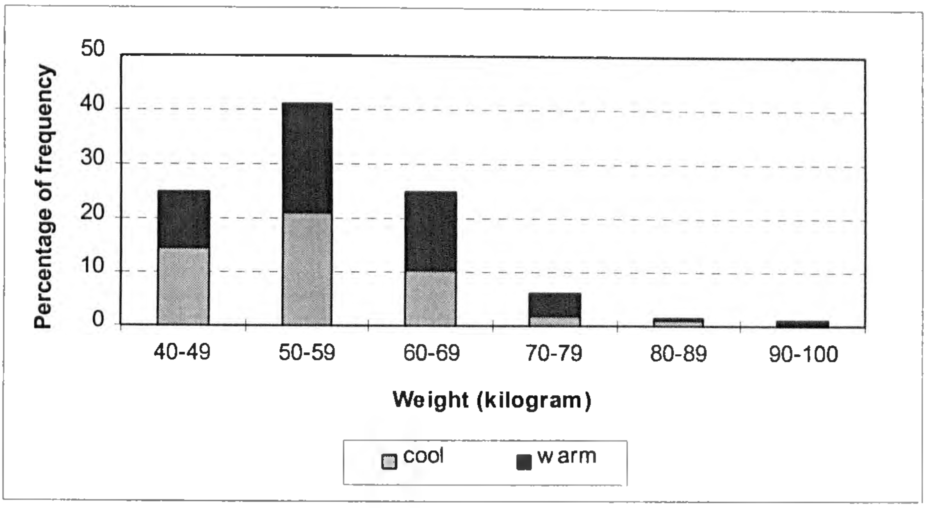

Figure F.3 Percentage distribution of the respondents' weight.

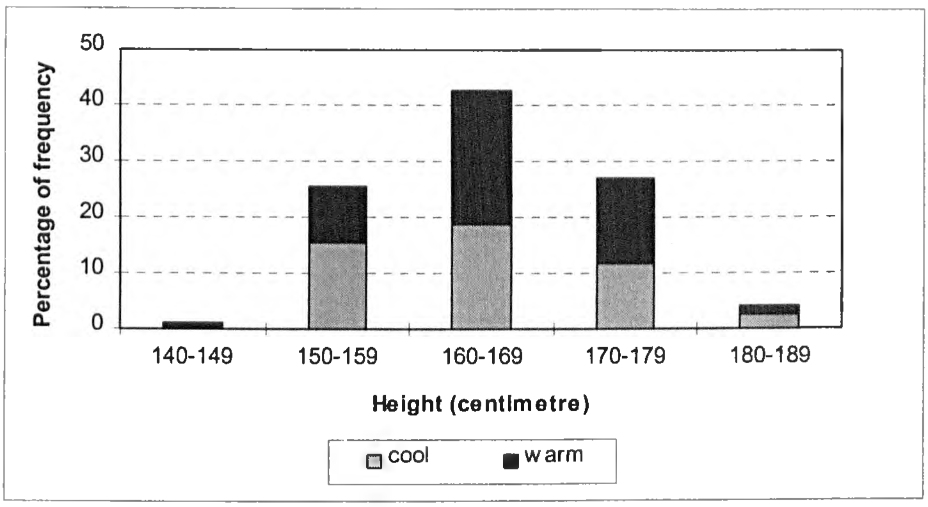

Figure F.4 Percentage distribution of the respondents' height.

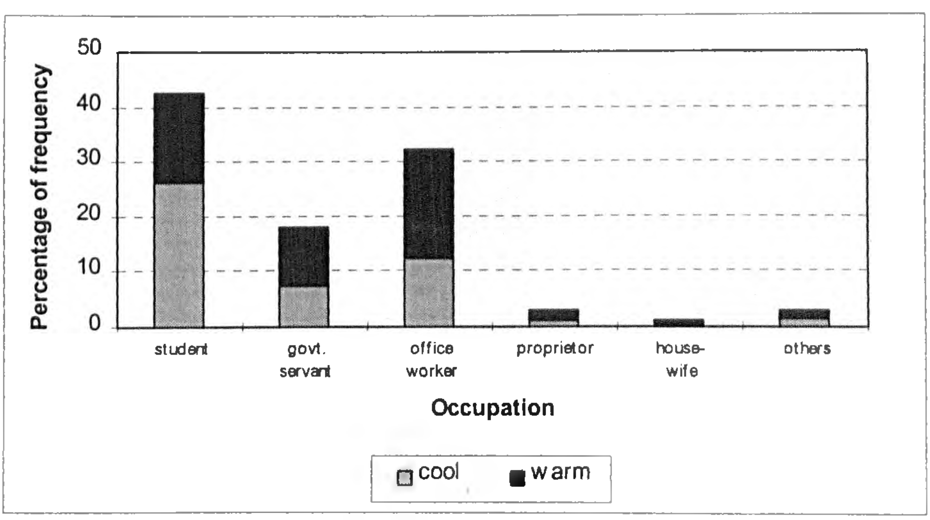

Figure F.5 Percentage distribution of the respondents' occupation.

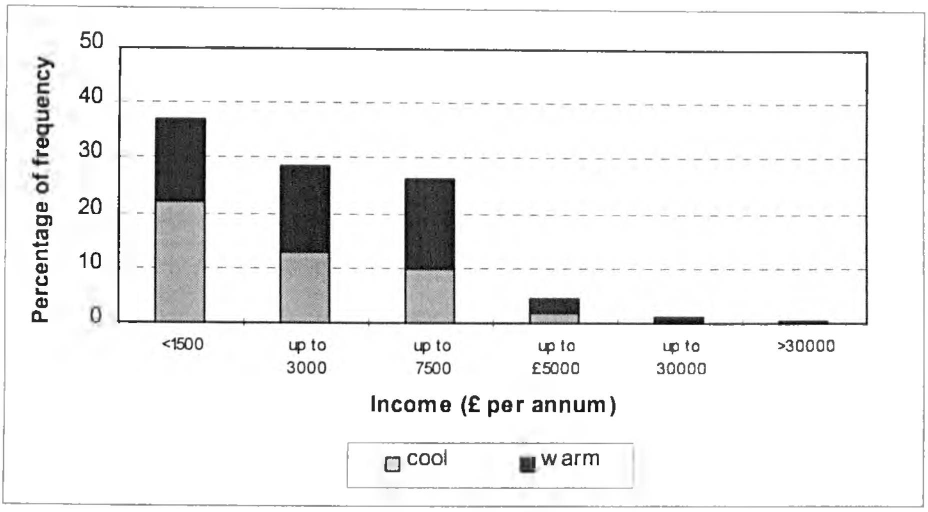

Figure F.6 Percentage distribution of the respondents' income.

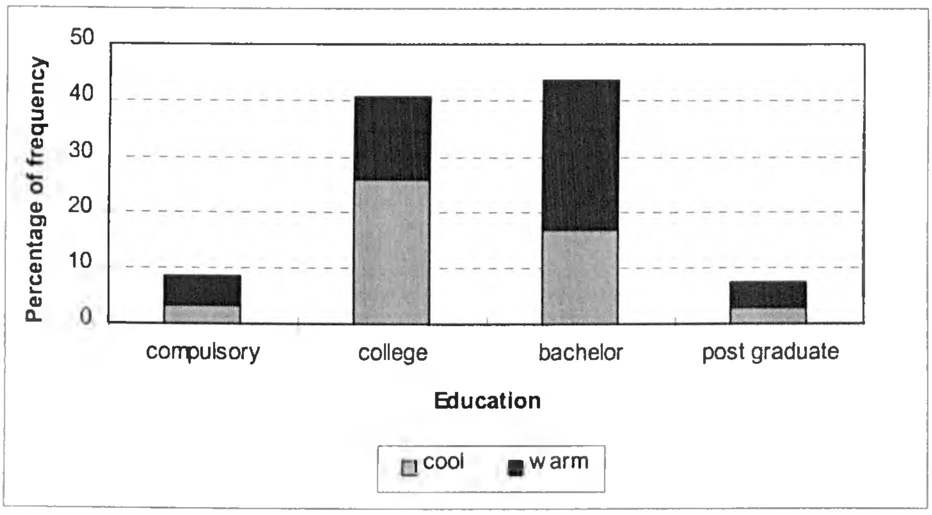

Figure F.7 Percentage distribution of the respondents' education.

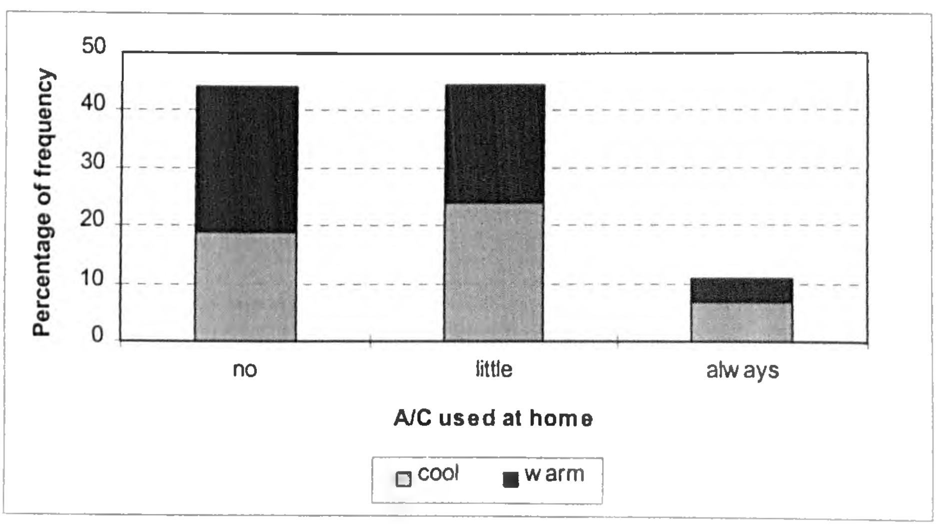

Figure F.8 Percentage distribution of air-conditioning used at home.

Appendix G
Suggested adaptation

In the cool season

Adaptation	frequency		
	A/C	N/V	all
When too warm			
1. stay in a shaded area and expose to N/V or increase air movement	47	152	199
2. use A/C	70	80	150
3. take a bath or wash a face	44	56	100
4. have cool drink or ice-cream	30	51	81
5. change or take off some clothes	13	37	50
6. perform less metabolic rate	0	0	0
When too cool			
1. increase clothing insulation	72	91	163
2. increase activity level, i.e., walking or exercise	24	30	54
3. stay in warm area or in the sun	20	23	43
4. close window or turn off A/C	15	15	30
5. have hot drink or food	6	20	26
6. stay home	3	13	16

In the warm season

Adaptation	frequency		
	A/C	N/V	all
When too warm			
1. use A/C	108	102	210
2. take a bath or wash a face	80	47	127
3. stay in a shaded area and expose to N/V or increase air movement	56	60	116
4. perform less metabolic rate	29	22	51
5. have cool drink or ice-cream	13	18	31
6. change or take off some clothes	10	9	19
When too cool			
1. increase clothing insulation	102	59	161
2. increase activity level, i.e., walking or exercise	23	14	37
3. stay home	24	12	36
4. stay in warm area or in the sun	11	9	20
5. close window or turn off A/C	12	8	20
6. have hot drink or food	3	4	7

Appendix H

Simple linear regression analysis

In the cool season

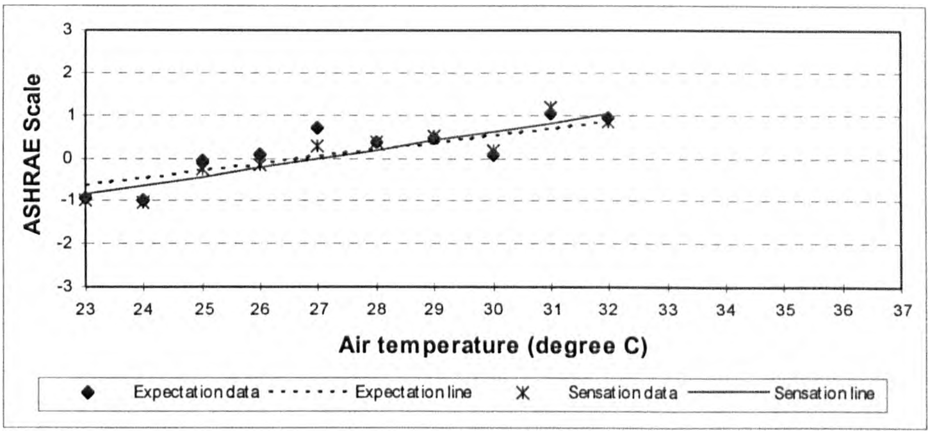

Figure H.1 Scatter diagrams and linear regression lines of thermal expectation and sensation using the ASHRAE scale on air temperature of all subjects.

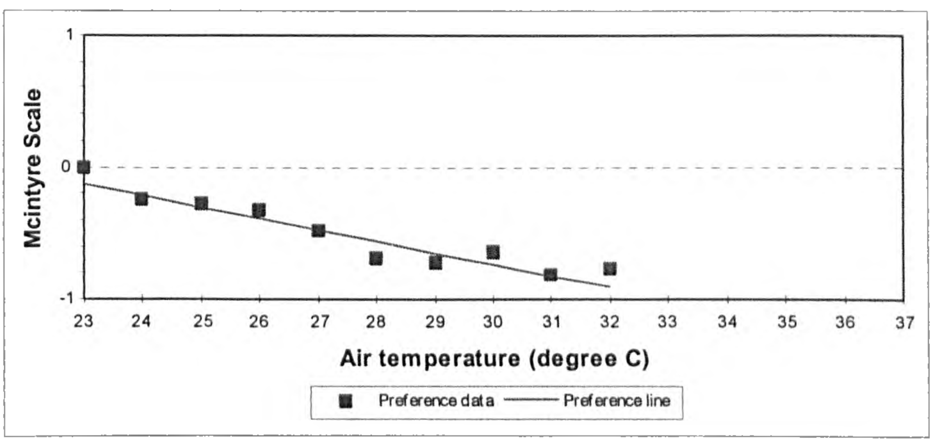

Figure H.2 Scatter diagram and linear regression line of thermal preference using the McIntyre scale on air temperature of all subjects.

In the warm season

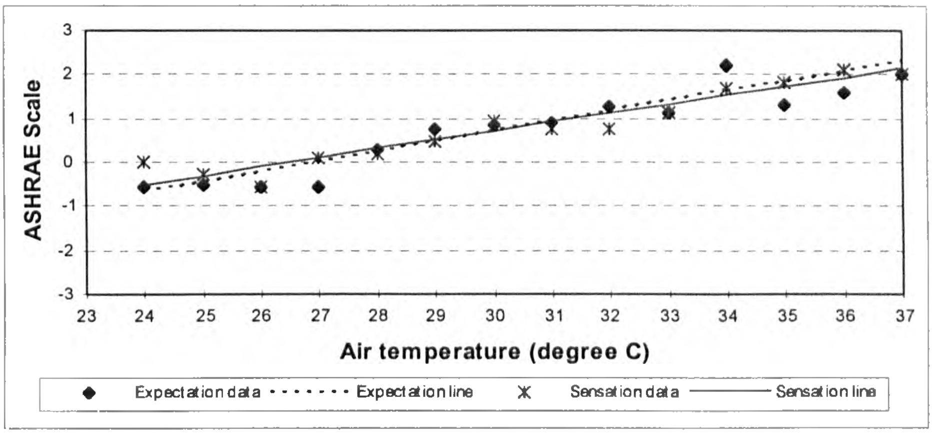

Figure H.3 Scatter diagrams and linear regression lines of thermal expectation and sensation using the ASHRAE scale on air temperature of all subjects.

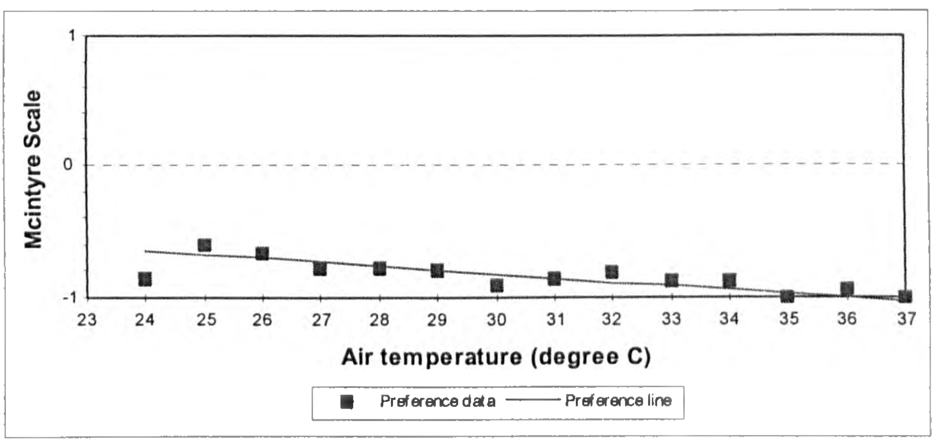

Figure H.4 Scatter diagram and linear regression line of thermal preference using the McIntyre scale on air temperature of all subjects.

Appendix I

Probit regression analysis

In the cool season

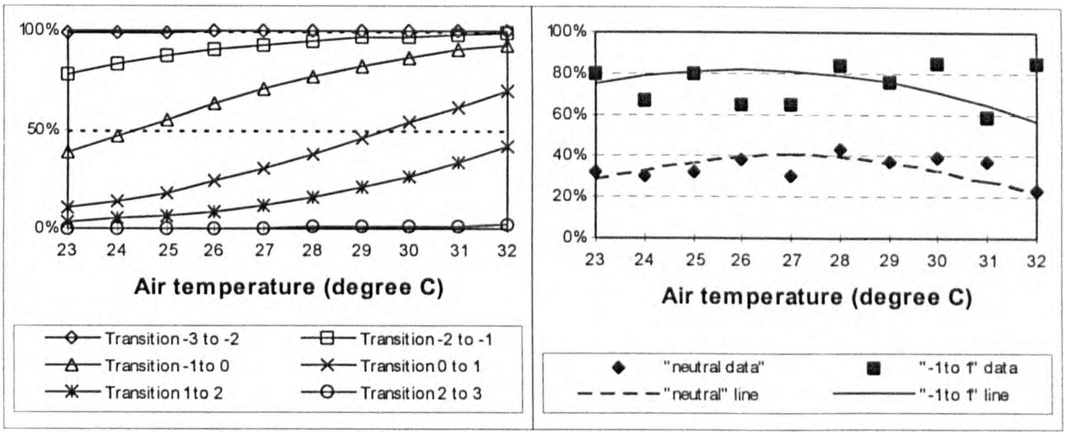

Figure I.1 Probit analysis of thermal expectation of all subjects.

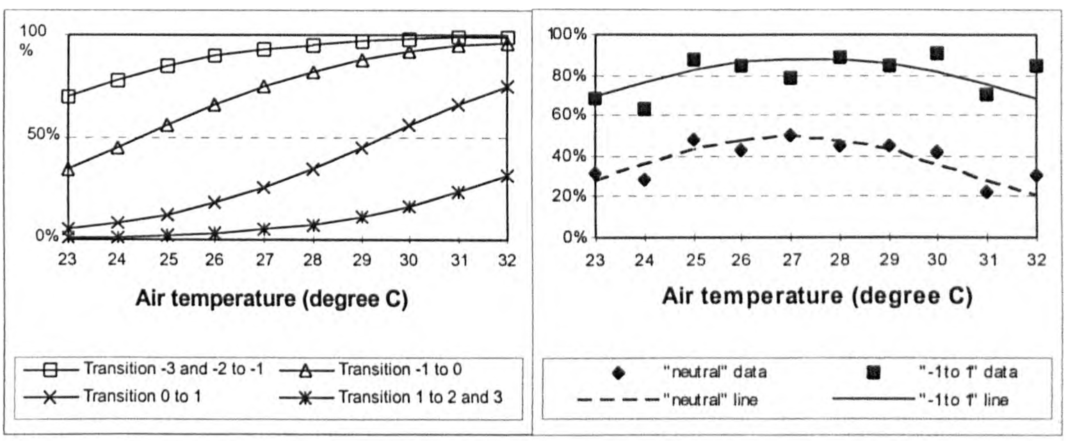

Figure I.2 Probit analysis of thermal sensation of all subjects.

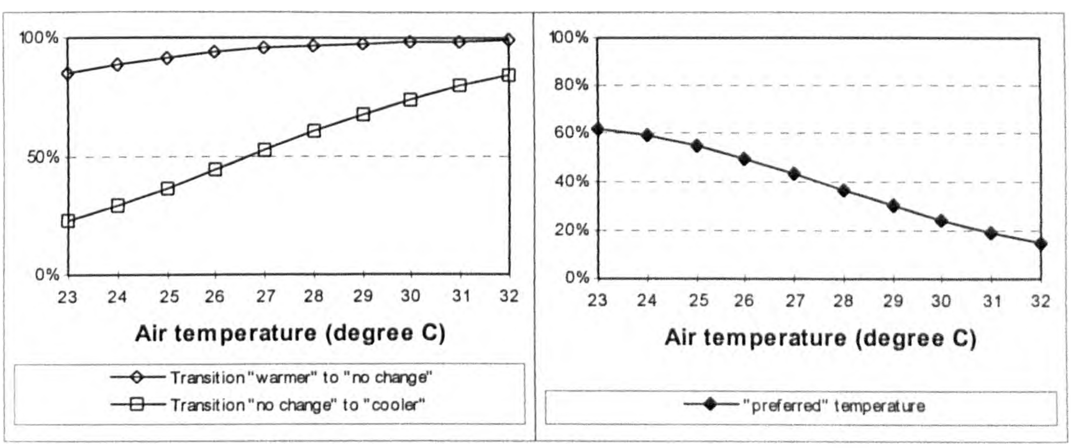

Figure I.3 Probit analysis of thermal preference of all subjects.

In the warm season

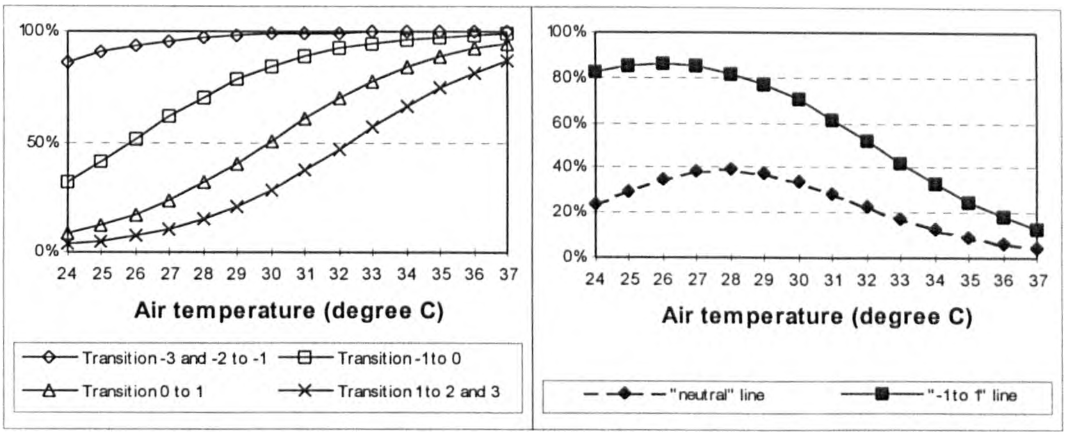

Figure I.4 Probit analysis of thermal expectation of all subjects.

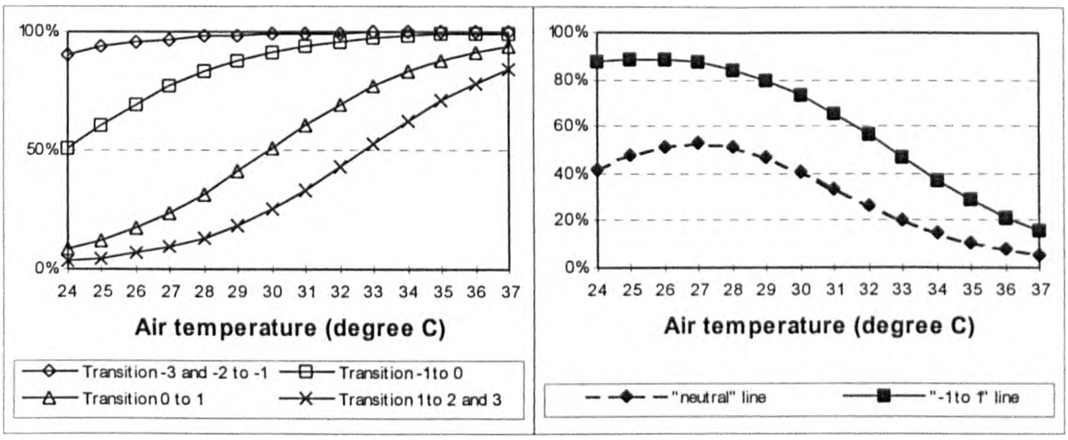

Figure I.5 Probit analysis of thermal sensation of all subjects.

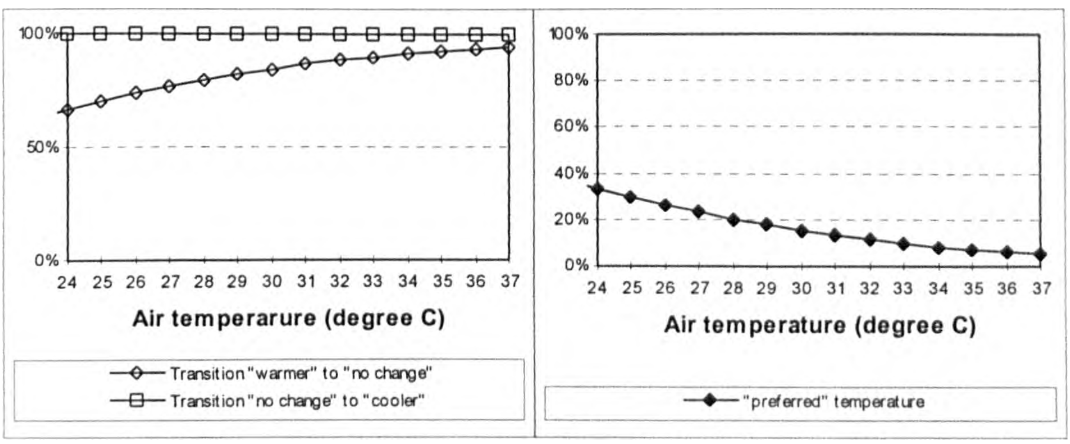

Figure I.6 Probit analysis of thermal preference of all subjects.

Appendix J

Cross-tabulations of sensation and preference

In the cool season

Sensation Scale	% Preference Scale			Total
	"cooler"	"no change"	"warmer"	
-3	0	50.0	50.0	0.7
-2	18.9	54.1	27.0	6.3
-1	34.0	59.2	6.8	17.4
0	53.9	43.7	2.4	41.4
1	86.2	11.7	2.1	24.5
2	91.1	6.7	2.2	7.6
3	100.0	0	0	2.2
Total	59.6	35.5	4.9	100.0

Note: percentages are calculated by row, within each sensation scale vote.

In the warm season

Sensation Scale	% Preference Scale			Total
	"cooler"	"no change"	"warmer"	
-3	0	100.0	0	0.2
-2	50.0	50.0	0	0.7
-1	58.8	40.0	1.3	14.5
0	72.8	27.2	0	37.5
1	94.0	6.0	0	21.3
2	95.2	4.8	0	22.7
3	94.1	5.9	0	3.1
Total	80.7	19.1	0.2	100.0

Note: percentages are calculated by row, within each sensation scale vote.

Appendix K

Thermal acceptability

In the cool season

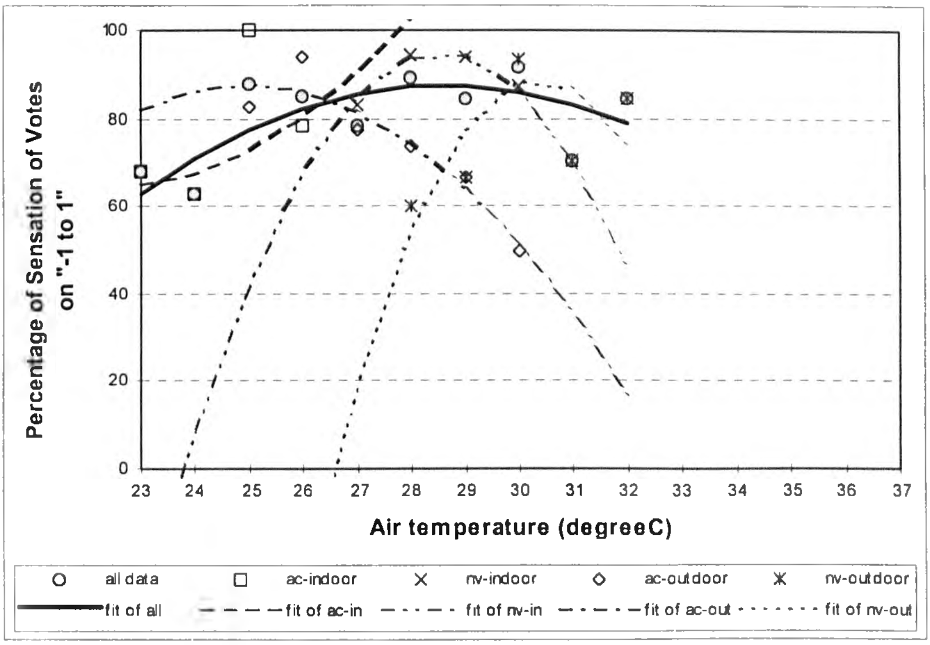

Figure K.1 Quadratic regression analysis of all subjects and each subject group.

In the warm season

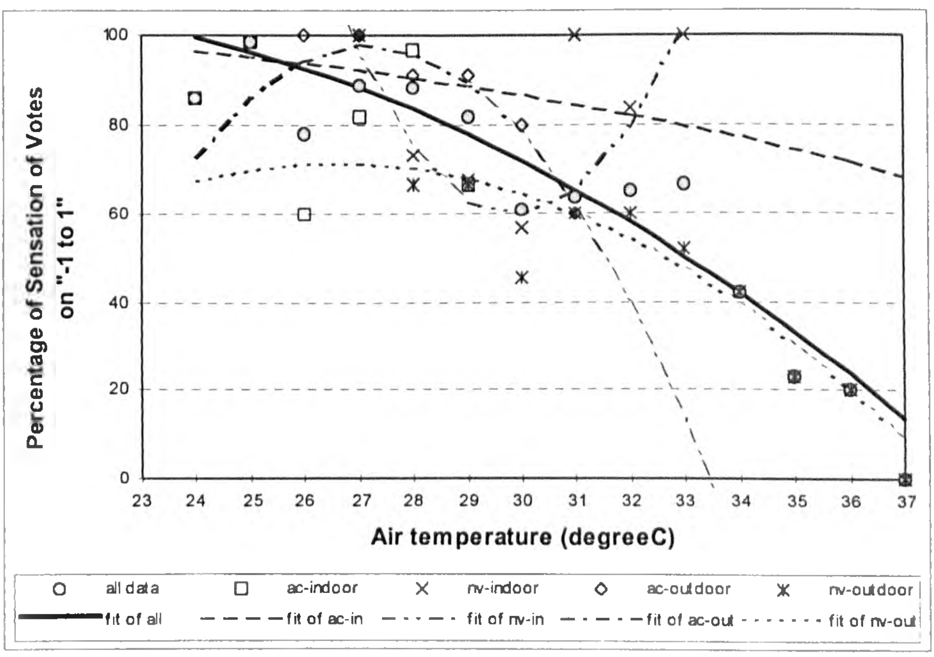

Figure K.2 Quadratic regression analysis of all subjects and each subject group.

Appendix L

Tne interplay between neutrality and preference

In the cool season

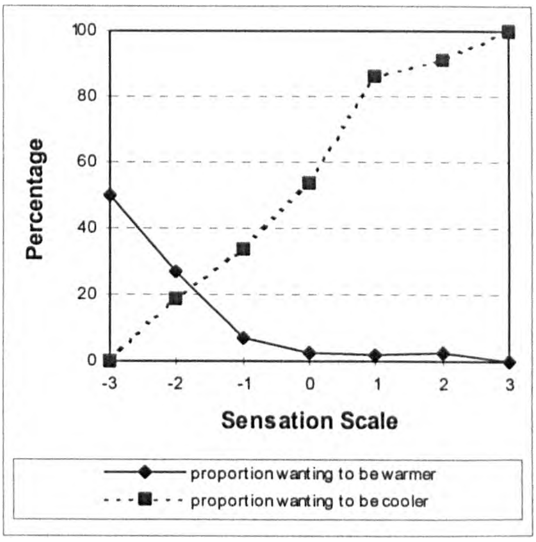

Figure L.1 Interplay between sensation and preference scales of all subjects.

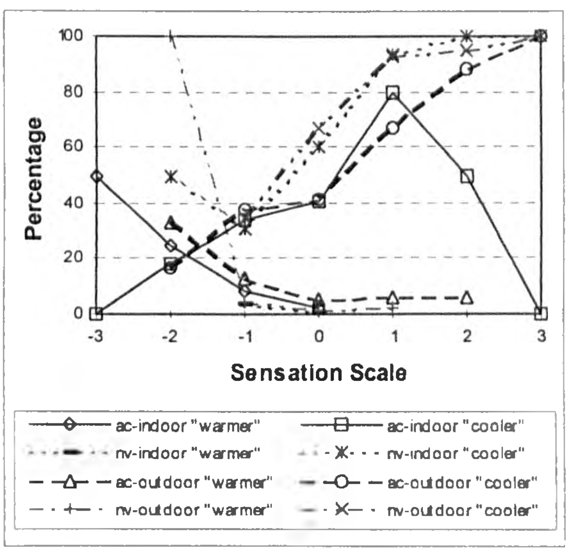

Figure L.2 Interplay between sensation and preference scales of individual subject group.

In the warm season

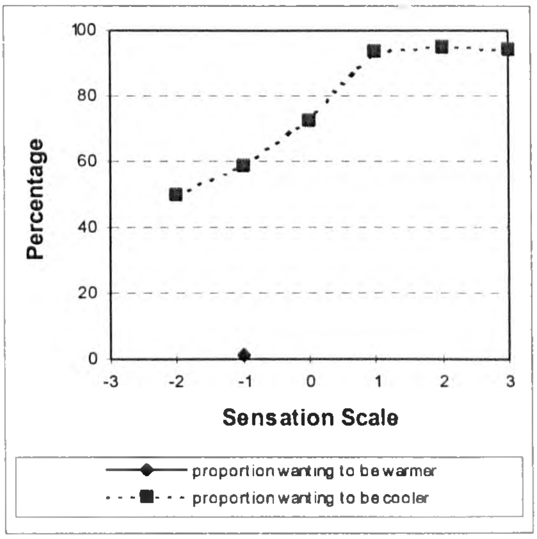

Figure L.3 Interplay between sensation and preference scales of all subjects.

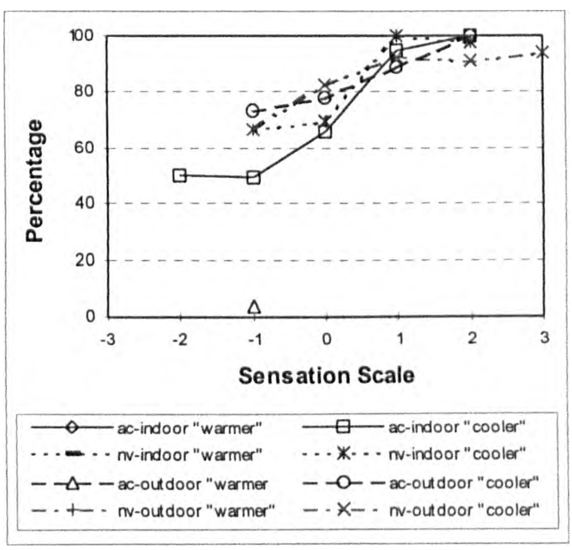

Figure L.4 Interplay between sensation and preference scales of individual subject group.

Appendix M

Thermal performance of a cool day

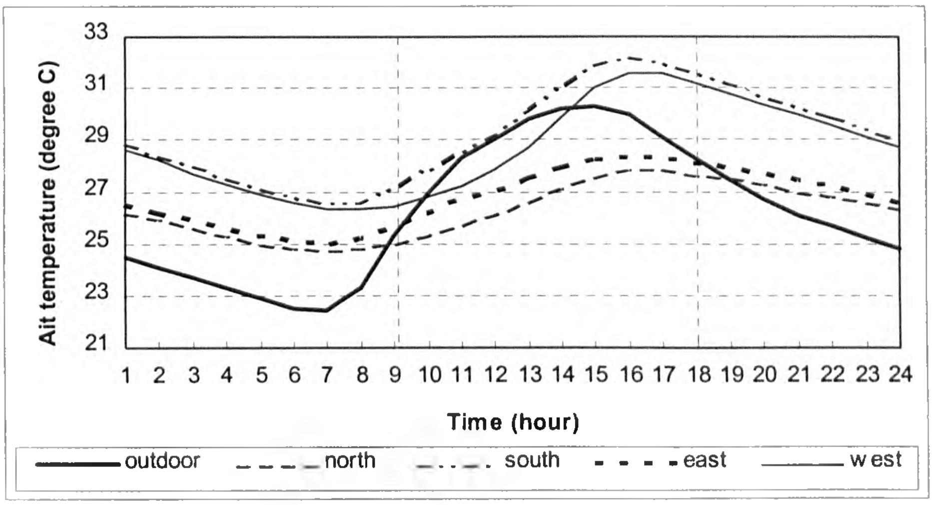

Figure M.1 Effects of orientation in a cool day.

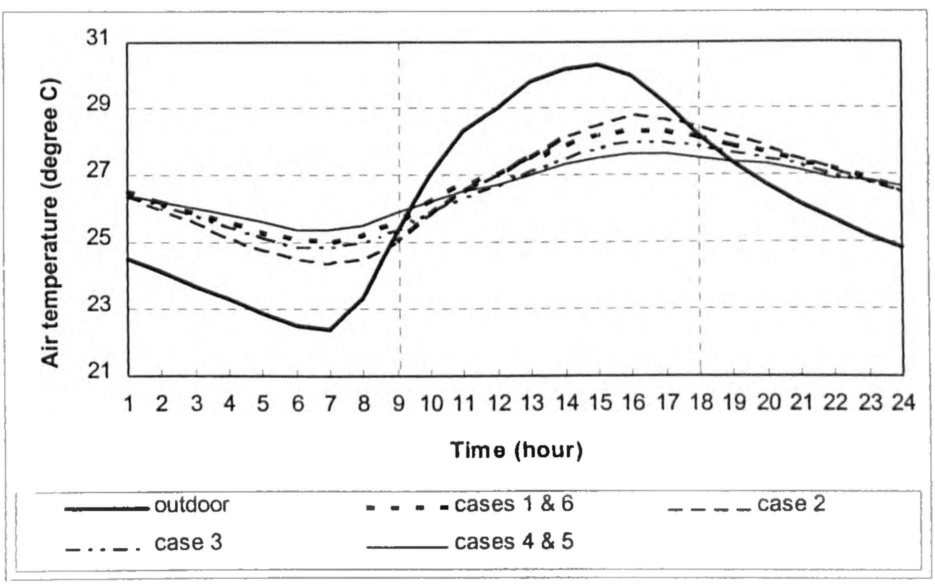

Figure M.2 Effects of (roof/floor) exposure in a cool day.
(details of each case—see Table 9.8).

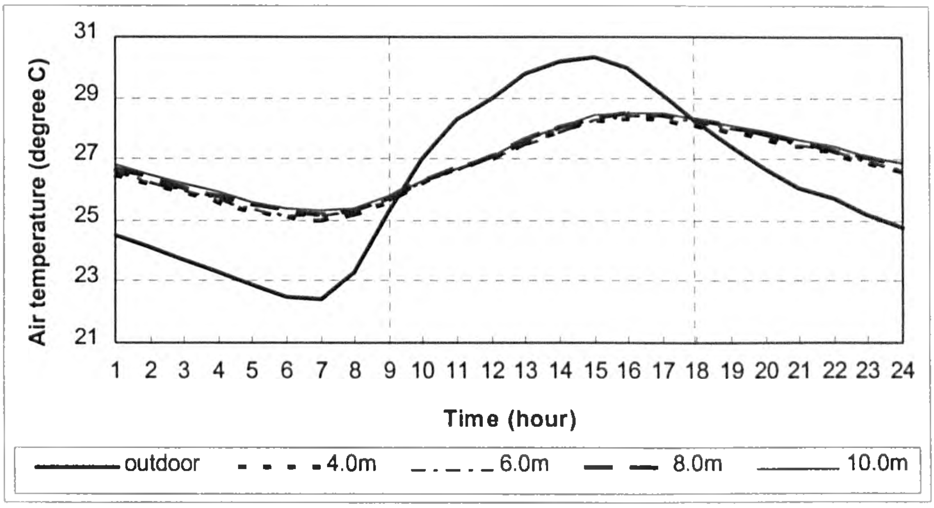

Figure M.3 Effects of elongation in a cool day.

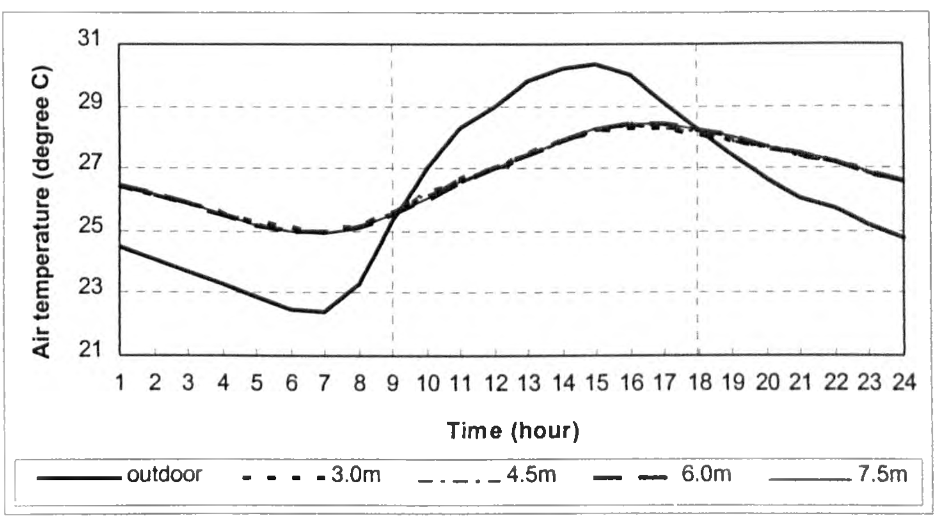

Figure M.4 Effects of ceiling height in a warm day.

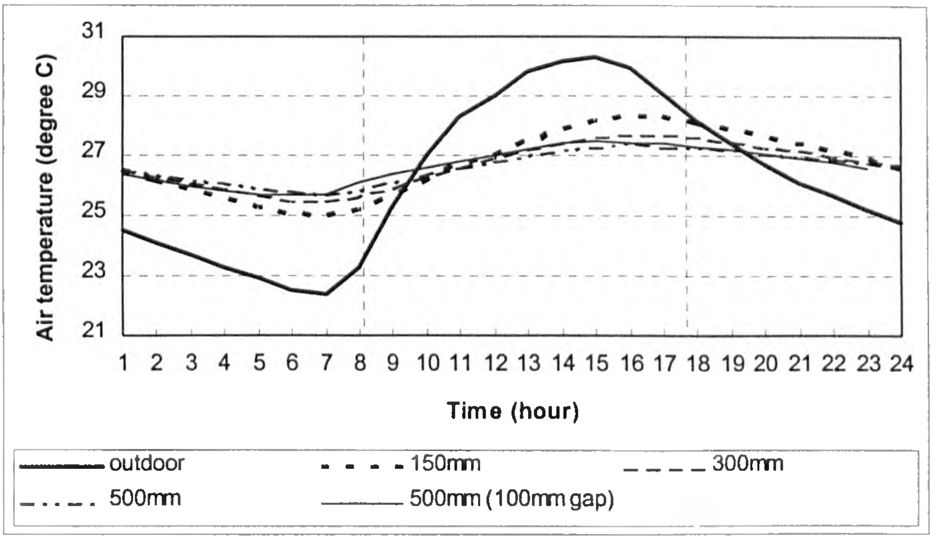

Figure M.5 Effects of wall thickness in a cool day.

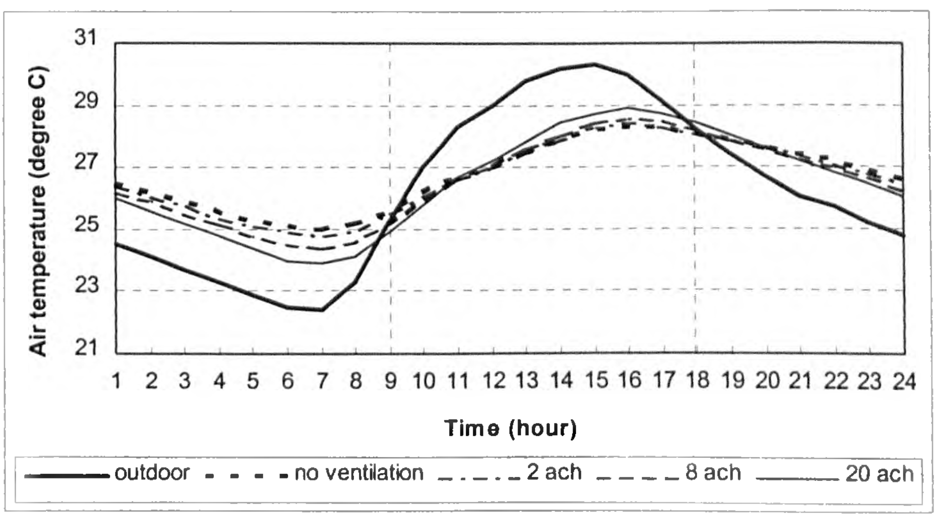

Figure M.6 Effects of ventilation in a cool day.

Appendix N
Climatic data in hot and humid tropical region

(After Pearce and Smith 1984)

Asia

Region		Location		Temperature (°C)		Relative humidity (%)	
Country	City	Longitude	Latitude	max.	min.	max.	min.
Bangladesh	Chittagong	22°21'N	91°50'E	26-32	13-25	76-87	58-86
Burma	Rangoon	16°46'N	96°11'E	29-36	18-25	71-89	52-88
Cambodia	Phnom Penh	10°33'N	104°55'E	30-35	21-25	85	70
Hong Kong	Hong Kong	22°18'N	114°10'E	17-31	13-26	73-87	60-78
India	Bombay	18°54'N	72°49'E	32-38	12-23	70-85	61-83
Indonesia	Jakarta	6°11'S	106°50'E	29-31	23-24	90-95	61-75
Malaysia	Kuala Lumpur	3°07'N	101°42'E	32-33	22-23	95-97	58-66
Philippines	Manila	14°35'N	120°59'E	30-34	21-24	85-93	55-74
Singapore	Singapore	1°18'N	103°50'E	30-32	23-24	76-82	70-78
Sri-Lanka	Colombo	6°05'N	79°52'E	29-31	22-25	71-80	66-78
Taiwan	Hengch'un	22°00'N	120°45'E	24-31	17-25	75-93	60-76
Thailand	Bangkok	13°45'N	100°28'E	31-35	20-25	90-94	53-70
Vietnam	Ho Chi Minh	10°47'N	106°42'E	31-35	21-24	63-79	56-80

Australia

Region		Location		Temperature (°C)		Relative humidity (%)	
Country	City	Longitude	Latitude	max.	min.	max.	min.
Australia	Townsville (Queensland)	19°14'S	146°51'E	24-31	15-24	63-73	58-70

America

Region		Location		Temperature (°C)		Relative humidity (%)	
Country	City	Longitude	Latitude	max.	min.	max.	min.
USA.	Miami (Florida)	25°48'N	80°12'W	23-31	16-24	73-82	62-70

Africa

Region		Location		Temperature (°C)		Relative humidity (%)	
Country	City	Longitude	Latitude	max.	min.	max.	min.
Cameroon	Douala	4°03'N	9°41'E	27-30	22-23	94-96	74-86
Burundi	Bujumbura	3°23'S	29°21'E	28-31	17-20	82	55
Congo	Brazzaville	4°15'S	15°15'E	28-32	17-22	77-89	54-71
Equatorial Guinea	Malabo (Fernando Po)	3°46'N	8°46'E	29-32	19-22	95	85
Gabon	Libreville	0°23'N	9°26'E	28-32	20-23	85-94	69-79
Ghana	Accre	5°33'N	0°12'W	27-31	22-24	95-97	61-77
Guinea	Conakry	9°31'N	13°43'W	28-32	22-24	83-94	63-87
Ivory Coast	Abidjan	5°19'N	4°01'W	28-32	22-24	93-96	71-82
Kenya	Mombasa	4°03'S	39°39'E	27-31	22-25	75-85	63-76
Liberia	Monrovia	6°18'N	10°48'W	27-31	22-23	87-95	76-86
Nigeria	Lagos	6°27'N	3°24'E	28-32	23-26	81-87	65-80
Sierra Leone	Freetown	8°30'N	13°14'W	28-31	23-25	80-91	67-82
Somali	Mogadishu	2°02'N	45°21'E	28-31	23-26	78-85	75-80
Zaire	Kisangani	0°26'N	25°14'E	28-31	19-21	95-97	63-75

South America

Region		Location		Temperature (°C)		Relative humidity (%)	
Country	City	Longitude	Latitude	max.	min.	max.	min.
Brazil	Belem	1°27'S	48°29'W	30-32	22-23	96-98	80-91
	Rio de Janeiro	22°55'S	43°12'W	24-29	17-23	82-87	66-74
French Guiana	Cayenne	4°56'N	52°27'W	29-33	23-24	73-86	69-83
Guyana	Georgetown	6°50'N	58°12' W	29-31	23-24	83-93	69-75
Panama	Balboa Heights	8°57'N	79°33' W	29-32	22-23	81-91	78-92
Surinam	Paramaribo	5°49'N	55°09' W	29-33	22-23	87-92	66-80
Venezuela	Maracaibo	10°39'N	71°36' W	32-34	23-25	78-84	60-63

Appendix O

Publications and seminar presentations

1. **Jitkhajornwanich, K, A C Pitts, A Malama and S Sharples** [1998] "Thermal comfort in transitional spaces in the cool season of Bangkok" *ASHRAE Transactions.* Vol. 104 pt. 1B, pp. 1181-1193. Also in *Field Studies of Thermal Comfort and Adaptation.* ASHRAE Technical Data Bulletin. A collection of papers from the ASHRAE Winter Meeting in San Francisco, California, January 1998. Vol. 14 no. 1, pp. 112-124.

2. **Jitkhajornwanich, K and A C Pitts** [1998] "Thermal comfort in indoor and outdoor transitional spaces of buildings in Bangkok" *Environmentally Friendly Cities.* Proceedings of PLEA'98, Lisbon, Portugal, June 1998, pp. 357-360.

3. **Jitkhajornwanich, K and A C Pitts** [1998] "Transitional spaces as mitigation feature for thermal environments of buildings in hot and humid tropical regions" *Renewable Energy — Energy Efficiency, Policy and the Environment.* Proceedings of World Renewable Energy Congress V, Florence, Italy, September 1998, pp. 1328-1331.

4. **Jitkhajornwanich, K and A C Pitts** [?] "Interpretation of thermal responses of four subject groups in transitional spaces of buildings in Bangkok" *Building and Environment.* In process.

5. **Jitkhajornwanich, K and A C Pitts** [1997] "The comparison of thermal comfort in transitional spaces and in office environments of Bangkok, Thailand" *Synopses of Presentations.* Third UK Thermal Comfort Group Meeting, held at the School of Architecture, Oxford Brookes University, on 1st September 1997. Unpublished paper.

6. **Jitkhajornwanich, K and A C Pitts** [1998] "The effect of humidity and air movement upon thermal comfort in a warm climate" *Presentation Abstracts.* Fourth UK Thermal Comfort Group Meeting, held at the School of Mechanical Engineering, Applied Energy and Optical Diagnostics Group, Cranfield University, on 2nd September 1998. Unpublished paper.