A STUDY OF HEAT TRANSFER THROUGH CLOTHING ASSEMBLIES

A thesis

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by

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Dedicated to my mother

ABSTRACTS

The work presented in this thesis is devoted to further understanding heat transfer through clothing under different circumstances, in order to provide guidelines for the design and construction of clothing with regard to thermal comfort.

In one part of this work, studies were concentrated on the clothing thermal insulation in windy conditions. In this part, a newly designed cylindrical togmeter and a theoretical model have been developed. The numerical solution derived from the theoretical model agrees well with the experimental findings from the cylindrical togmeter in a wind tunnel. The heat transfer mechanisms involved in the wind induced reduction of clothing thermal insulation have been better understood by examining the experimental and theoretical results. The effects of wind velocity, air permeability and stiffness of the outer fabrics, air permeability and thickness of the inner fibrous battings, and the dimensions of the human body on the clothing thermal insulation have also been examined and discussed. Furthermore, based on the understanding of the mechanism of air penetration into permeable clothing assemblies, methods have been proposed for the design and construction of wind resistant protective clothing by using permeable outer fabrics. These methods were evaluated on the cylindrical togmeter and are believed to have important practical values.

The other part of this work was focused on the development and laboratory use of a fabric manikin. The "skin" of the manikin was made of coated water-proof fabric, and heated water was circulated inside the "body". The arms and legs of the manikin could be moved to simulate walking. The manikin was very cheap to construct when compared with that of a copper manikin and can be widely applied for routine tests for outdoor and military garments subject to some modifications in its design. With this fabric manikin, a series of experiments have been conducted to investigate the effects of body motion, clothing design and environmental conditions on the thermal insulation of clothing. Some useful information for the design of functional clothing and for the prediction of the thermal stress of a clothed person in different environmental conditions has been provided through this investigation.

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Contents

PART-I

BACKGROUND

Chapter 1

General Introduction and Basic Concepts

1.1 Introduction

Clothing, in a broad sense, covers all items which serve to cover the human body. This broad class can be divided into garments, footwear, body decorations, etc. From the functional point of view, it can be regarded as a portable environment which supports the human body's abilities to maintain comfort and life.

The function of clothing had already been of concern since the time of the Ancient Greeks. In today's modern society, this is required to a higher and more refined extent than ever. Today more and more people are involved in many activities in extremes of temperature and other hazardous environments, such as the South Pole, offshores and space, where the function of clothing can be a matter of life or death. For people in temperate and indoor conditions, clothing may have no survival value, but still contributes to the body comfort.

The function of clothing includes many aspects. They can be generally classified into four areas, ie, protection, adornment, status and modesty (Slater 1986). Hence, in the design and construction of functional clothing for use, many factors should be considered. These include the freedom of body movement, appearance, protection from heat, cold, pests, radiation and other physical or chemical hazards. Among these factors, protection from cold or heat to keep the body thermal comfort is the most primary and important one. This is because thermal comfort has the most direct effect on the human body's physical and mental condition and performance.

Thermal comfort, in simple words, implies the maintainance of the body temperature within relatively small limits. Under the conditions where the thermal comfort cannot be achieved by the human body's own ability (i.e. body temperature regulation), such as very cold or hot weather, clothing must be worn to support its temperature regulation by resisting or facilitating the heat exchange between the human body and the environment. The design of effective clothing for thermal comfort should be based on the understanding of the heat transfer through clothing.

The heat transfer through clothing is a very complicated phenomenon. Possible modes of heat transfer through clothing are conduction, convection, radiation and latent heat transfer by moisture transport. These modes of heat transfer are all affected by the geometries of human bodies and clothing systems which can never be exactly described. They are also affected by the conditions of human bodies such as skin temperature, skin wetness, and body movement, the conditions of environment such as wind, radiation, temperature and humidity, and physical properties of clothing and its constituents. The phenonmenon may be further complicated by the buffering effect within clothing and condensation factors. In such a study, it may not be possible to consider all the factors at one time. Researches therefore are carried out by simulating the actual circumstances and taking into account the main human, clothing and environmental factors. Although much work has been done on this topic, the mechanisms under many circumstances are far from understood.

The purpose of this work, as described by the title of the thesis is to study the heat transfer through clothing assemblies. A clothing assembly is an assembly of clothing materials which reflects or simulates some features of actual clothing systems in different environmental conditions. So, in other words, this work is to develop suitable methods to simulate actual circumstances of the human body wearing clothing in order to investigate the mechanisms of heat transfer and apply the understandings to the design and construction of effective clothing in use.

Before discussing the work in further detail, in the following sections of this chapter, some basic concepts need to be introduced.

1.2 Thermal Comfort

Thermal comfort is an emotional or effective experience referring to the subjective state of the observer under a thermal environment. According to ASHRAE's defination, it is "that condition of mind which expresses satisfaction with the thermal environment" (Fanger 1982).

It has been found that the expression of thermal comfort strongly depends on the thermal physiological conditions of the subject. For a person under a long exposure, the physiological conditions for general thermal comfort can be specified as follows: (1), the core temperature (the temperature of the deep central area including the heart, lungs, abdonimal organs and brain) within 36.6°C to 37.1°C; (2), the mean skin temperature (the surface area weighted average skin temperature) within 33°C to 34.5°C for men and 32.5°C to 35°C for women; (3), local skin temperature within 32°C to 35.5°C; (4), temperature regulation active and completely accomplished by vasomotor control of blood flow to the skin, i.e. no sweating and shivering present (Hensel 1981).

Among these four physiological conditions, the first one is the most important. The survival value of the consistency of the core temperature is very evident. Changes of more than 2°C can be dangerous to human life. To achieve this consistency, heat production inside the human body and heat lost from the human body should be balanced. The human body's own ability to maintain this balance is by temperature regulation. In this process, heat lost from the human body is adjusted by changing skin temperatures or sweating rate, and heat production is modified by internal body activities. However, the effect of temperature regulation is limited, if changes of heat lost and heat production are beyond the limits which the body temperature regulation system can cope with, the core temperature cannot be maintained and life can be in danger. Such events are well known in severe weather conditions.

In the sense of thermal comfort, therefore, clothing is used to help the body temperature regulation by maintain the heat balance between the heat production and heat lost.

1.3 Modes of Heat Transfer

Heat can be transfered within the clothing system in the modes of conduction, radiation, convection and latent heat transfer by moisture transport.

CONDUCTION

Conduction is a process in which heat is transfered through a body or from one body to another without appreciable displacement of the parts of the body. From the molecular point of view, the conductive heat is transfered from a faster moving molecule of higher temperature to a slower moving molecule of lower temperature. The process can occure in either solid or fluid. Fourier's Law for the conduction of heat states that the instantaneous rate of heat flow dq is equal to the product of three factors: the area A of the section, taken at a right angle to the direction of heat flow, the temperature gradient $\frac{dT}{dx}$, which is the rate of change of temperature T with respect of the length path x, and a proportionality factor K, known as the thermal conductivity, i.e. $dq = -K \cdot A \cdot \frac{dT}{dx}$. In clothing systems, all components of clothing such as air, fibres and moisture vapor are thermal conductors. The thermal conductivities of wool fibres are about 0.2 W/m/°C, that of air is 0.026 W/m/°C.

RADIATION

Radiation is the heat exchange between a hotter and a colder body by emitting and absorbing radiant energy. Heat exchange by radiation depends only on the temperature and the nature of the surface of the radiating objects. The heat exchange between two gray surfaces is

$$Hr = \sigma \cdot \varepsilon_1 \cdot \varepsilon_2 \cdot (T_1^4 - T_2^4) \cdot A ,$$

where, Hr is the radiant heat exchange in watts, σ is the Stefen-Boltzmann's constant, $\sigma = 5.67 \times 10^{-8} watt/m^2/K^4$, ε_1 and e_2 are the emissivities of the two gray surfaces, T_1 and T_2 are the absolute temperature of the two gray surfaces, and A is the area of the two surfaces.

The radiant heat can transfer directly through clothing spacings from the skin surface into the environment and between clothing materials. The emissivity of skin is about 0.95, that of textile fabrics, e.g. cotton, linen, wool lies between 0.95 and 0.90 (Spencer-Smith 1976).

CONVECTION

Convection is the transfer of heat from one point to another within a fluid, gas or liquid, by the mixing of one portion of the fluid with another. The motion of the fluid may be entirely the result of differences of density due to the temperature differences, as in natural convection; or produced by an external force, as in forced convection. The rate of convection depends on the motion of the fluid and the temperature gradient.

The convection within clothing systems can be caused by the differences of air density at different places, external wind and body motion. When the human body is moving or in strong windy conditions, ventilation is an important way of convective heat transfer through clothing. Ventilation is the exchange of generally hot, wet air within a clothing system and cold, dry air in the environment without passing through fabric layers (Mecheels 1977). It could account for 75% percent of the total heat loss from the human body when the wearer is walking in strong windy conditions (Keighley 1985).

LATENT HEAT TRANSFER

Latent heat transfer is a process in which heat is carried from one place to another by the movement of a substance which absorbs or dissipates heat by a change of phase. Latent heat transfer is the only way of body cooling when heat produced inside the human body cannot be totally lost by conduction, radiation and convection. In this case, sweat is produced at the surface of skin and heat is lost by evaporation of liquid sweat into moisture vapor which then passes into the environment.

1.4 Heat Transfer Through Clothing

As already mentioned, heat can be transfered through clothing by conduction, radiation, convection and latent heat transfer by moisture transmission. Radiation, conduction and convection are dominated by the temperature difference between the skin surface and the environment, and are therefore grouped as dry heat transfer. On the other hand, latent heat transfer is achieved by moisture transmission which is drived by the difference in partial water vapour pressure between the skin surface and the environment.

1.4.1 Dry Heat Transfer Through Clothing

The dry heat transfer through a clothing system can be described by

$$H_d = \frac{10\cdot(T_s - T_a)}{R_c + R_s} , \qquad (1.1)$$

Where, T_s is the skin temperature(°C), T_a is the ambient temperature(°C), H_d is the rate of dry heat transfer through clothing (W/m^2), R_c is the thermal insulation of the clothing, and R_s is the the thermal insulation of the clothing surface. R_c and R_s are expressed in tog units. The tog unit was developed by Clulow & Rees (1968). 1 tog = 0.1°C m^2/Watts (ISO unit). American counterparts would like to express the thermal insulation in clo value. This is a unit which was developed based on human physiological factors. 1 clo means the amount of clothing worn for a normal sitting-resting man to keep thermal comfort in a normal ventilated room. From biophysical data, a common conversion between Tog unit and Clo value is that, 1 clo = 1.55 togs (Burton & Edholm 1955).

Formula (1.1) only represents the main principles involved in the dry heat transfer through clothing. In actual circumstances, R_c and R_s are related to many factors within the human body-clothing-environment system.

1.4.2. Latent Heat Transfer Through Clothing

The latent heat transfer through a clothing system can be described by

$$H_l = \frac{c \cdot (P_s - P_a)}{W_c + W_s} , \qquad (1.2)$$

where, H_l is the rate of latent heat transfer through clothing (W/m^2), P_s is the partial water vapour pressure at the skin surface, Pa is the partial water vapour pressure in the environment, c is the evaporative heat at the skin temperature, c = 2.44 KJ/g at 35°C, W_c is the resistance to water vapour transfer of the clothing, and Ws is the resistance to water vapour transfer of the clothing surface. The units of partial water vapour pressure and the resistance should be correspond.

Instead of the resistance to water vapour transfer, Woodcock (1962) introduced a parameter i called "the permeability index" to describe the water vapour transfer properties of clothing. It can be defined as follows,

$$i = \frac{c \cdot R}{10 \cdot S \cdot W} ,$$

where, R is the total thermal insulation of the clothing system in tog unit, $R = R_c + R_s$, W is the total resistance to water vapour transfer, $W = W_c + W_s$. S is obtained from the temperature Tw of the wet bulb thermometer and is given by

$$S = \frac{T_a - T_w}{P_w - P_a} ,$$

where, Pw is the saturated water vapour pressure at temperature Tw. At high wind velocities, S = 2.0°C/mmHg.

i was claimed as a dimensionless factor which described the efficiency of water vapour transfer through clothing. i ranges from 0, for a clothing system totally resistant to the water vapour transfer, to 1 for an ideally permeable clothing system which has no more impedence than the wet bulb thermometer at high wind velocities. With this new index, therefore, Formula (1.2) can be written as

$$H_l = \frac{10 \cdot i \cdot S \cdot (P_s - P_a)}{R_c + R_s} \quad . \qquad (1.3)$$

Similarly to the dry heat transfer, here, Wc, Ws and i are dependent on many factors in the human body-clothing-environment system.

1.4.3. Simultaneous Dry and Latent Heat Transfer

When dry and latent heat transfer exist simultaneously, from formula (1.1), (1.2) and (1.3), the overall heat transfer H can be estimated by

$$H = \frac{10 \cdot (T_s - T_a)}{R_c + R_s} + \frac{c \cdot (P_s - P_a)}{W_c + W_s} \quad , \qquad (1.4)$$

or

$$H = \frac{10}{R_c + R_s} \cdot \{(T_s - T_a) + i \cdot S \cdot (P_s - P_a)\} \quad . \qquad (1.5)$$

In the above formule, dry and latent heat transfer are treated independently, and this only describes the main principles invovled in the heat transfer through clothing. Under many circumstances, by using the above formule, the heat transfer may well be underestimated due to the effect of buffering and condensation (Spencer-Smith 1976).

Buffering happens when clothing materials absorb or desorb moisture vapour from the boundaries. The absorption or desorption involves heat lost to or gain from the boundary. The effect can increase the thermal comfort of a wearer when his environmental condition changes, e.g. moving from dry, warm indoor into cold, wet outdoor, or he starts sensible perspiration.

Condensation happens when the partial water vapour pressure within the clothing is higher than the saturated one which is determined by the local temperature. The condensation of water vapour into liquid water will release latent heat of vaporization which is 2.44 KJ/g of vapour. In contrast, the evaporation of the condensed water will absorb heat. Supposing moisture is condensed in the central layers of clothing, some of this condensed moisture may wick back to the inner, warmer layers where it can be re-evaporated at the expense of its latent heat. This water vapour will later recondense in the cooler layers giving up its latent heat at a place further away from the skin. This cycling of moisture between warmer and cooler parts of the clothing provides an extra mode of heat transfer between the body and the environment (Rees 1971). Condensation can result in extra chill for a person working in a cold environment, and therefore should be eliminated as much as possible.

1.5 The Outline of the Present Work

The main principles involved in the heat transfer through clothing have been described by Formula (1.1), (1.2), (1.3), (1.4) and (1.5), however, the actual picture of heat transfer is much more complicated and not well understood because of the many factors within the human body-clothing-environment system and the many interactions between these factors. Work on this subject is necessary to investigate the effects of these factors and interactions on the heat transfer through clothing and apply the results in the design and construction of effective clothing for use. The development of research methods for such work and the recent understanding of this problem are to be reviewed in the next chapter. The present researches concentrated on the studies of the wind effect on the clothing thermal insulation, and investigations into some typical clothing systems under different environmental conditions and walking speeds with a newly developed fabric manikin. The present researches are to to be reported in Part-II and Part-III of this thesis.

Chapter 2

Literature Review

2.1 Introduction

Because of the importance of clothing for thermal comfort, studies of heat transfer through clothing have been of historical interest. During and after the Second World War, due to military reasons, researches in this area were much intensified. In recent years, because of the increase of outdoor pursuits and the expansion of the industries which require employees to work in severe environmental conditions, much further work has been carried out.

Comprehensive surveys of literature in this area have been presented by many workers from 1930s up to present (Marsh 1931, Morris 1953, Mak 1980, Blyth 1984). In all these presentations, methods available were classified into four groups according to Marsh's suggestion, ie, disc methods, constant temperature methods, cooling methods and miscellaneous methods. In my opinion, this classification is no longer convenient any more, because many new methods have been developed over the last sixty years, and it is not logical to put these new methods into the miscellaneous group. Since all methods are attempting to simulate the actual features of clothing materials, clothing items or even the whole clothing systems on the human body under different conditions, here, the various methods available are classified into three categories according to the method by which the simulation is attempted. These three categories are experimental simulations, theoretical simulations and wearer trials. Within the experimental simulations, the existing methods are classified according to the extent to which the reality is simulated. These experimental methods are flat plate methods, cylinderical methods and manikins.

In this chapter, the development and the advantages and disadvantages of various existing methods are to be reviewed. In addition, the present views concerning the effects of the various factors within the human body-clothing-environment system on the heat transfer through clothing are to be discussed. The application of these theories in the design and construction of effective clothing are also noted.

2.2 Methods for the Study of Heat Transfer Through Clothing

2.2.1 Experimental Simulations

The full understanding of the phenomenon of the heat transfer through clothing requires the knowledge of the thermal behaviour of the clothing materials and clothing systems as a whole. The simplest experimental approach to this problem is by using a flat plate method in which clothing materials or simple clothing assemblies are covered on a heated flat surface and the heat transfer through the materials or assemblies are observed. Because the geometry of a flat surface is very simple, these methods have the advantage in evaluating the thermal properties of the materials or assemblies, but have problems in applying the results to the actual clothing systems in use. For this reason, various cylindrical methods were developed, which take into the consideration that a human body approximately consists of many cylindrical forms. Hence, the cylindrical methods provide better simulations than flat plate methods. Yet, the findings from these cylindrical methods are still unable to analysis the heat transfer between different parts of a clothed human body, and heat transfer induced by the body motion. Based on the above considerations, in recent years, manikins have been developed and applied. In the following sections, the developments of these experimental simulations are to be discussed.

Flat Plate Methods

The earliest version of this kind of method which have been applied to clothing materials was developed by Lees and Chorlton in 1896. The apparatus consisted of a flat cylindrical vessel, a plate at the bottom of the vessel, and a plate hung below the vessel. The temperature within the flat vessel was controlled at 100 °C by passing steam through it. Samples were sandwiched between the upper and lower plates. Temperatures at the lower surface of the upper plate and the upper surface of the lower plate were measured with thermometers. The thickness of the sample was obtained by measuring the distance between the pegs projecting from the edges of these two plates. This method was later improved by Lees (1898), and became well known as the Lees' disc method by which thermal conductivities of various materials were evaluated.

When the Lees' disc method was applied to textile fabrics, the contact thermal insulation between the fabric and the discs, and the pressure applied on the fabrics could affect the final results. This problem was noted by Rood (1921), who tackled it by using multiple fabric layer techniques and specifying the pressure applied on the fabrics.

In the Lees' disc method, no guard ring was used to prevent heat loss in the directions other than through the sample. This might be reasonable in his work, since the discs and the samples were thin and the surface area was large. However, this was not satisfactory in later work. Sale (Marsh 1931) hence developed a new disc method with a guard ring on it. In addition, his method employed only one single hot plate, the sample was exposed to the conditioned air and the temperature of the hot plate was controlled at body temperature. This arrangement was regarded as a good simulation of actual clothing in use and was recommended as a standard.

Later, in order to take the water vapor transmission into account, methods which allow simultaneous dry and latent heat transfer through clothing were developed. In 1941, Rees developed a flat plate method in which fabrics were placed on a hot, porous plate which was covering on a water dish. Modern versions of this kind were developed throughout the world (Blyth 1984, Farnworth 1986, Mecheels & Umbach 1977).

In the above methods, heat transfer through the clothing were measured in the same way, i.e. measuring the power input into the testing system. However, Niven's flat plate method (1962) is very different in this aspect. His method combined the flat plate guard ring technique and the cooling principle. The time taken for the hot plate which covered the specimen to drop its temperature from 50°C to 49.5°C was chosen as a measure of the rate of heat transfer through the specimen.

The most commonly used flat plate method nowadays is the disc togmeter, which was first developed by Clulow & Rees (1968). The togmeter used a standard plate of known thermal insulation in between the hot plate and the specimen so that the thermal insulation of the specimen could be determined by comparing the temperature difference across the specimen and across the standard plate. This method was adopted as a British Standard in 1971 (BS. 4745).

Cylindrical Methods

The simplest method of this kind may be the use of a Kata-thermometer upon which the specimen is wrapped. The time taken for a definite temperature drop is a measure of the thermal insulating properties of the specimen or the heat transfer through the specimen. This method was used by Bachmann in 1928. The problem of the use of a Kata-thermometer is that the surface area is too small to obtain a reliable and consistent measurement.

In fact, before Bachmann, some cylindrical methods of bigger sizes than a Kata-thermometer had already been developed (Priestman 1921). These methods employed the same cooling method because of its simplicity. However, since the 1930s, most cylindrical methods have used the constant temperature method, in which the temperature of the cylindrical body was controlled at a constant level similar to the human body temperature, and the heat supplied to maintain the constant temperature was measured. These methods were used by Marsh in 1931 and Niven & Babbitt in 1938.

Argus' apparatus (1935) was a different one. He used a heated cylinder-like zinc tank with two convex and two concave sides to simulate the shape of the human body. Clothing specimens were used to the tank. He expressed his results as the percentage insulation (PI) which was defined as follows.

$$PI=\frac{t}{T}x100\%$$

where, T is the temperature drop between the hot water inside the tank and the other surface of the tank when the tank is not covered with the specimen, and t is the temperature drop when the tank is covered with the specimen.

In order to study the latent heat transfer, sweating cylindrical apparatus were also developed. Woodcock (1962) covered his cylindrical apparatus with a layer of linen which was kept wet by absorbing water from a water reservoir. Specimens were wrapped on the layer of linen. The moisture transfer properties of the specimen were expressed in a Permeability Index.

More recently, Mak (1980) taking the advantage of the disc togmeter design, and applied it in the development of a cylindrical togmeter. This cylindrical apparatus had an internally heated cylinder and an enclosing layer of known thermal conductivity on which the specimen was covered. The thermal insulation of the specimen as a function of the angular position could be evaluated. This apparatus was especially useful for studies in windy conditions. The only critisms of his cylindrical togmeter were that the size was too small and heat loss from the ends of the cylindrical apparatus was not prevented.

Manikins

The total number of existing manikins are still small because of their high cost. The earliest manikin, which can be found in the literature, was employed by the Royal Air Force Institute of Aviation Medicine (Kerslake 1964). It consisted of sixteen independently controlled sections. Each section was arranged to reproduce the skin temperature. Heat lost from the manikin due to forced ventilation was investigated. Later in the U.S. Army Research Institute of Environmental Medicine (Fonseca 1970), a similar heated sectional copper manikin was also developed. With this manikin, sweating was also simulated by wearing a coverall type of "skin" which was made of "T-shirt" material and wetted in advance. The uneven wetness of the "skin" after a period of testing was a problem for such sweating simulation. The above two manikins cannot simulate walking and were regarded as of the first generation.

The second generation movable manikins were later developed in Germany (Mecheels 1977), Denmark (Olesen et al. 1983) and Japan (Hanada 1979). Amongst them, copper manikin "Charlie" in the Hohenstein Institue in Germany was the most famous one. However, none of these manikins was successful in simulating sweating.

Manikins of the third generation, which are aimed to simulate sweating and sophisticated body motions are still being developed.

There are reports on the development of such manikins, but still no experimental results.

2.2.2 Theoretical Simulations

The fundamental feature of the theoretical simulations is that it applies physical principles in a mathematical model which takes into account some or many characteristics of actual clothing in use. With the worldwide application of computers, these research methods have a great potential in the further advance of this area.

Many theoretical models have been developed for the solution of heat transfer through clothing over last few years. In 1983, Farnworth presented a model of the combined conductive and radiative heat transfer through fibrous insulating materials. By comparing the theoretical results with the experimental ones, convective heat transfer through low density battings in still air was found to be of little importance. Later in 1986, he developed another model for the heat transfer by conduction, radiation and vapor transport in multi-layered clothing assemblies. This model was applied to display the effects due to condensation or evaporation of water within clothing and absorption or desorption by hygroscopic materials. More recently, attempts have been made to develop models which consider the main features of the human body-clothing-environment system (Imre et al. 1987, Imre et al. 1988). Results from such models can directly analyse the contribution of clothing to body thermal comfort.

2.2.3 Wearer Trials

Wearer trials can be used for studying different properties of clothing by means of subjective judgements or objective measurements. When these methods are applied to the study of heat transfer through clothing, results are determined objectively.

The rate of dry heat transfer (Hd) from the human body is determined by solving the heat balance equation, i.e.

$$Hd = M-W-Cr-Er-E-S \quad \text{(watts/m2)}$$

where, M is the body metabolism which can be determined from oxygen uptake, W is the external work, Cr and Er are the respiratory heat loss by convection and evaporation respectively, E is the skin evaporative heat loss which can be determined from the body weight loss, and S is the body heat storage.

The thermal insulation of the clothing (Rc) , clothing surface (Rs) and the clothing system (R) can be calculated as

$$Rc=\frac{Ts-Tc}{Hd}, \quad Rs=\frac{Tc-Ta}{Hd}, \quad R=\frac{Ts-Ta}{Hd},$$

where, Ts is the mean skin temperature, Tc is the mean temperature of the clothing surface, and Ta is the ambient temperature.

If the partial water vapor pressure at the skin surface, at the clothing surface and in the environment can be measured, the resistance to water vapor transfer of the clothing (Wc), the clothing surface (Ws) and the system (W) can also be calculated, i.e.

$$Wc=\frac{Ps-Pc}{E}, \quad Ws=\frac{Pc-Pa}{E}, \quad W=\frac{Ps-Pa}{E},$$

where, Ps and Pc are the mean partial water vapor pressure at the skin surface and the clothing surface, and Pa is the ambient partial water vapor pressure.

During recent years, many workers have used wearer trials to investigate the heat transfer through clothing under different circumstances (Belding et al. 1947, Vogt et al. 1983, Nielsen et al. 1985). This method is regarded as the most realistic as it takes all human factors into account. The disadvantage of this kind of method is that it is time consuming, expensive and inconsistent. It is also limited to the restriction that human subjects prefer to be thermally comfortable during the tests.

2.3 Factors
Related to the Heat Transfer Through Clothing

2.3.1 Human Factors

Body Posture

The heat transfer through clothing is influenced by body posture by changing the effective surface area, the geometry of the clothing and the entraped air layers. For standard clothing, with measurements on a thermal manikin, Olesen, et. al. (1983) found that the clothing thermal insulation of a sitting person was 8-18% lower than that when standing. Similar results were also reported by Nielsen, et al. (1985) from the measurements from wearer trials.

Body Motion

Body motion sets up convection currents within the clothing system, and therefore increases heat flow rate through clothing and reduces the clothing thermal insulation. "Bellows action", "pumping effect" and "ventilation" are common terms to describe the exchange of the hot air within the clothing and cold air in the environment, which is induced by body motion. The effects of body motion have long been recognized. Belding, et al. (1947), from the studies on two human subjects at the Harvard Fatigue Laboratory, reported that the thermal insulation value of an Arctic Uniform was reduced from 2.7 clo with the subjects standing, to 1.3 clo for level walking at 6.4 km/hr. However, little additional work was conducted until recently, when the need for such data became essential to improve the modelling techniques for predicting environmental stress and tolerance for active men. In recent years, clothing insulation values during bicycling and walking were studied by several workers (Vogt et al. 1983, Nielsen et al. 1985, Micheels et al. 1977). Much of this work is just data capturing, and the understanding of the mechanism of the effect of body motion on the heat transfer through clothing was limited.

Body Geometry

The curvature of the body surface can affect the clothing thermal insulation. By considering a cylinder covered with insulating materials, it was found that the effective thermal insulation provided by a given material of a given thickness becomes smaller as the radius of the cylinder is reduced (Rees 1971). This explained the greater difficulty in keeping the arms and legs warm compared with the trunk in cold weather.

The shape of the human body can also affect the effective area of the radiant heat lost from the body (Kerslake 1972).

Skin Wetness

The latent heat lost is affected by the skin wetness. Mecheels & Umbach (1977) suggested the following formula to account this effect. That is

$$Hl=\frac{d(Pss-Pa)}{W} ,$$

where, Hl is the latent heat transfer by evaporation, Pss is the saturated water vapor pressure at the skin surface, Pa is the ambient partial water vapor pressure, W is the resistance to water vapor transfer of the clothing system, and d is a so-called "perspiration discomfort factor'. d is directly related to the skin wetness. It was assumed that d=0.1 when the perspiration is insensible, and d=1.0 when the skin is totally wetted.

The skin wetness can also affect the dry heat transfer, since the absorption of liquid sweat or moisture by clothing materials can change the thermal properties of the materials, and can induce a buffering effect and even condensation under certain conditions.

Skin Temperature

The skin temperature is a governing factor in the heat transfer through clothing. The changes in its magnitude and distribution around the body surface regulate the heat lost from the human body. However, its effect on the thermal insulating properties of clothing is small due its small variability.

2.3.2 Clothing Factors

Fibre Type

Textile clothing materials whether of woven, knitted or non-woven construction are disperse systems consisting of textile fibres, air and moisture. Air has a very low thermal conductivity and offers a high resistance to conductive heat transfer. Textile fibres are much better conductors of heat than air - the thermal conductivity of wool fibres is about 10 times and of cotton fibres about 25 times that of air. Because the fibres occupy only a small fraction of the total volume in a textile fabric except for very tight fabrics, the differences in fibre type are of minor importance for the dry heat transfer and the thermal insulation (Rees 1971). Comparatively, the effect of fibre type is more evident for pile fabrics than others, since in pile fabrics heat is transfered in parallel with the fibre arrangement (Bogaty et al. 1957, Brook & Keighley 1980).

As far as the latent heat transfer is concerned, clothing materials made of hygroscopic fibres behave differently from those clothing materials made of hydrophobic fibres due to the buffering effect.

Thickness and Compression Resistance of Clothing Materials

The relationship between the thickness of clothing materials and the thermal insulation has been investigated by many workers (Mak 1980). It has been universally agreed that the thermal insulation of clothing materials are proportional to their thickness. On this basis, the compression of clothing materials will reduce the thermal insulation due to the loss of thickness. Mak (1980) investigated the thermal insulation of polyester battings under different pressures. It was found that the rate of reduction of the thermal insulation with increasing pressure was the maximum at the lowest pressure, and minimal at the highest pressure. Clothing such as sleeping bags are subjected to compression in use, the compression resistance of clothing materials is thus very important to retain the thermal insulating properties of clothing.

Air Permeability of Clothing Materials

The air permeability of clothing materials is directly related to the resistance to water vapor transmission. The lower the air permeability, the higher the resistance to water vapor transmission. So, when latent heat transfer is important for thermal comfort, clothing made of materials of low air permeabilities are not desirable. However, the air permeability is also directly related to the resistance to air penetration in windy conditions. To minimize the heat lost by air penetration, clothing for use in cold and windy conditions should have an outer cover of as low a permeability as possible (Larose 1947).

Bulkiness of Clothing Materials

Many workers (Speakman & Chamberlain 1930, Rees 1941, Mak 1980) have examined the effect of bulk density on the thermal insulation of clothing materials. It has been agreed that, in order to obtain the maximum thermal insulation, the structure of clothing materials should be neither so open that it allows too much radiation and convection or so close that it allows too much conduction.

Clothing Design and Fit

When fabrics are made into clothing and worn on the body, there are air gaps between layers of fabrics and openings around the body depending on the design and fit of the clothing. It has been reported that as much as 75% of the total heat can be lost through openings at the places like the neck, the waist, the wrists and ankles by bellows action when the body is moving in windy conditions (Keighley 1985). This heat lost can be reduced for well designed and fitted clothing, and this is important for clothing used in cold environment. The effects of openings and fit of clothing on the thermal insulation of clothing in windy conditions were studied by Fonseca & Breckenridge (1965) on a cylindrical apparatus. It was shown that the thermal insulation of a fabric system increases when a "seal" was formed at the bottom opening of the system. This finding was further proved by the comparative tests on a manikin with a open clothing system and a closed clothing system (Fonseca 1975).

3.3.3 Environmental Factors

Environmental Temperature

The environmental temperature is a governing factor of heat transfer through clothing. Apart from that, it can also affect the clothing thermal insulation. This is because, first, the conductivities of fibres and air are related to the temperature; second, the proportion of the radiant heat transfer over the ~~the~~ total varies with the temperature difference between the skin and the environment (Mecheels 1971). In addition, in a cold environment, condensation is likely to occur, and this can also reduce the thermal insulation of clothing (Martin 1987).

Humidity

The humidity of the environment is a very important factor in determining the latent heat transfer by moisture transmission through clothing. This is because the driving force of the water vapor transmission is the difference between the water vapor pressure at the skin surface and that in the environment which is strongly related to the relative humidity by the relation RH=Pa/Pss, where Pa is the partial water vapor pressure in the environment and Pss is the saturated partial water vapor pressure at the environmental temperature. So, the increase in the humidity in the environment can reduce the latent heat transfer through clothing.

The ambient humidity can also influence the dry heat transfer by increasing the moisture or water content in the clothing. It has already been shown that the thermal insulation of clothing materials markedly reduces when the moisture content in the clothing materials increases from 0 to 75% (Black & Matthew 1934). Hoge, et al.(1964) explained that water was likely to be in the form of liquid and the thermal contacts between fibres are improved by the increased water content at the surface of fibres. Condensation may be another reason for the reduction in the thermal insulation of clothing materials, and this has been observed (Martin 1987).

Wind

Wind can have the most destructive effect on the thermal insulation of a clothing system by air penetration, compression of the clothing materials and the removal of the surface still air layer. Spencer-Smith (1977) examined the effects of streamlined and turbulent air flow on the surface thermal insulation of different fabrics placed on a hot plate. It was found that the reduction in the surface thermal insulation was proportional to the wind velocity to the power of 0.7 in the case of turbulent air flow, and to the square root of the wind velocity in the case of streamlined air flow. The case of the turbulent air flow was regarded to be similar to the case of a clothed man in wind.

The surface thermal insulation of a clothed man in wind was investigated by Winslow, et al.(1939), and a useful empirical formula was given, i.e.

$$Rs = \frac{1}{0.61+0.19\sqrt{V}} \quad \text{(clo)},$$

where, Rs is the surface thermal insulation in clo value, V is the wind velocity in cm/sec.

The effect of air penetration on the clothing thermal insulation was studied by Larose (1947) who conducted a series of experiments of clothing assemblies, which consisted of a layer of wind resistant outer fabric and a layer of thick underlying fabric, with a hot plate method in a wind tunnel. He found that the air penetration had little effect at low wind velocities but was important at high wind velocities. Later in 1965, Fonseca, et al. studied the mechanism of wind penetration, and they found that an air space between the outer wind break layer and the inner clothing would allow air that penetrates the wind break layer in the windward side to loose its momentum and drift to the leeward without penetrating the inner clothing.

The compression of clothing is induced by the dynamic air pressure imposed on the clothing surface arising from air movement (Yankilovich 1972). The effect of such compression on the clothing thermal insulation must be equivalent to that of the compression induced by other forces, which has been discussed previously.

Ambient Radiation

Men are in a thermal radiant environment. Thermal radiation not only comes from the sun or a radiator, but from any heated objects such as the ground surface, a wall, boiler, etc. The radiant field around a clothed man is an important factor in determining the heat lost from the human body. It was found that the heat gain from the direct and reflected radiation at the South Pole was up to 200-400 kcal/m^2hr, and was equivalent to raising temperature of the environment by 8 - 20^{o}C, depending on the wind (Chrenko & Pugh 1961).

The radiant heat lost from the clothing surface can be estimated by

$$Hr = A \cdot \varepsilon \cdot \sigma \cdot (Tc^4 - Tmr^4) \quad ,$$

where, A is the effective radiant surface area, ε is the emissivity of the clothing surface, σ is the Stefen-Boltzman's constant, Tc is the surface temperature of the clothing, Tmr is the mean radiant temperature of the environment. Hr is the radiant heat lost (watts). Tmr can be assessed by using a globe thermometer.

PART-II

CLOTHING THERMAL INSULATION IN WINDY CONDITIONS

Chapter 3

Experimental Investigations on Clothing Thermal Insulation in Windy Conditions

3.1 Introduction

In this part, we are going to concentrate on the study of the wind effect on clothing thermal insulation, or in other words, the heat transfer through clothing in windy conditions. This is a topic which has attracted many workers over last 60 years. Early work (Vernon 1926, Black & Matthew 1934) employed very simple experimental methods, and the understanding of this problem was very limited. Since 1940s, because of military reasons, more work was carried out. However, most of these studies considered clothing assemblies which covered only flat surfaces (Rees 1941, Larose 1947, Niven 1962, Spencer-Smith 1977). As pointed out by Yankelevich (1972), these approaches are not adequate in view of the dynamic air pressure distribution which, for a flat surface differs from that at the surface of a cylinder of a human trunk or limbs.

Clothing in actual windy conditions is very complex. The wind, clothing and human body system can never be described in simple terms. An appropriate approach to this problem should be conducted under the condition which is of the main feature of the clothing systems worn on human bodies in windy conditions. On this basis, a cylindrical apparatus is preferable because of its good approximation to the trunk or limbs of a human body. In addition, in order to describe the windy conditions clearly, the experiments can be conducted in a free air stream. Cylindrical apparatuses have been applied by early workers. However, some of these apparatuses (Augus 1935, Niven & Babbitt 1940) could only measure the overall effect of wind on the clothing thermal insulation, comparisons between different clothing assemblies based on these results can be misleading (Fonseca & Breckenride 1965).

In this work, a better performing cylindrical togmeter was designed and constructed on the lines of the Mak's (1980) version with some modifications, and the study was aimed to improve the understanding of this problem by clarifying the mechanisms involved. The clothing assemblies under investigation consisted of two layers, outer wind resistant fabrics and inner polyester battings. Such a clothing assembly was believed to be a good representation of the clothing usually worn in windy conditions. A series of experiments were conducted for clothing assemblies covered with different outer fabrics in a wind tunnel where the air flow was essentially linear.

3.2 Apparatus

3.2.1 Cylindrical Togmeter

The cylindrical togmeter for this study is shown in Fig.3.1. It consisted of two hollow cylinders. The inner one, 122mm in diameter, was made of Aluminum, the outer one made of Vicuclad. Since the outer diameter of the Vicuclad cylinder could affect the

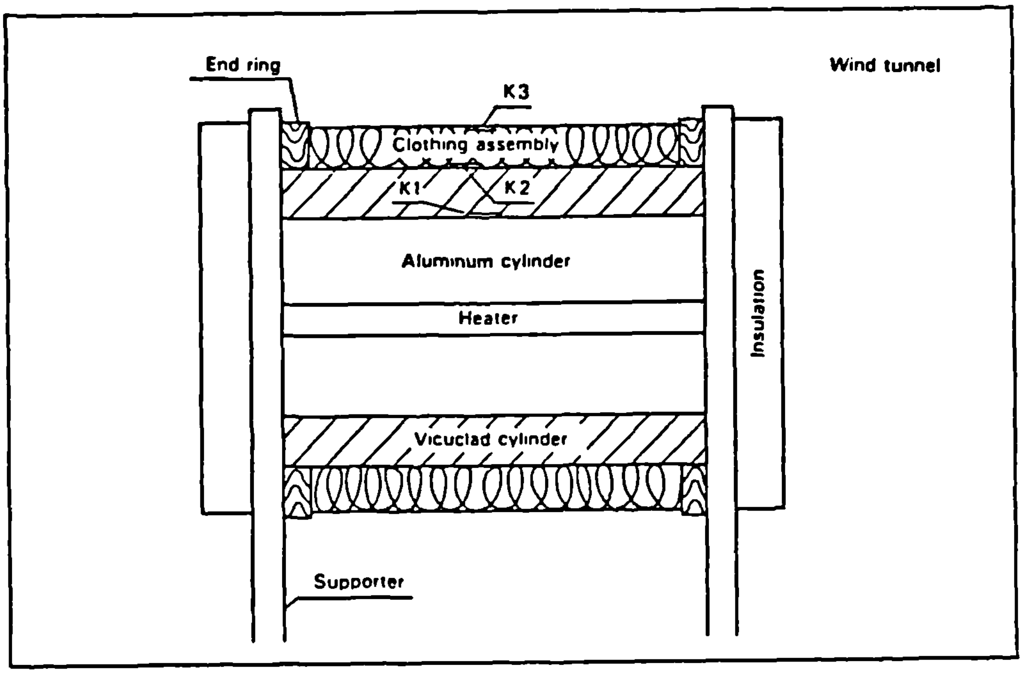


FIGURE 3.1 Diagram of the Cylindrical Togmeter.

final results (Yankelevich 1972), it was designed to be 180mm, which was about the weighted average diameter of different parts of an average man, thus ensuring that the results from the apparatus would be representative of those from a human body. The longitudinal hole at the center of the Aluminum cylinder was bored for an electric tubular heater. Because Aluminum is highly conductive to heat transfer, the inner cylinder acted as an internal heat source. While, the hollow Vicuclad cylinder acted as a standard reference for test specimens covered on the cylinder. Since heat loss from the ends of the togmeter was not desirable, the ends were covered by thick high insulating materials.

At the surface of the Aluminum and Vicuclad cylinders, two grooves were cut from one side to the middle center at corresponding positions and two thermocouples K1 and K2 were inserted. These two thermocouples plus another one K3 sewed on the outer surface of the specimen were connected to a multiple channel chart recorder by which temperatures were recorded. Thermocouple K1 was also connected to an adjustable temperature controller to control the temperature of the heat source. On the rotation of the cylinder, temperatures at different angular positions relative to wind direction could be measured, and the corresponding tog values could be calculated.

3.2.2 Wind Tunnel

The cylindrical togmeter, described above, was supported about a horizontal axis in the centre of a wind tunnel (see Plate. 3.1). The moving air was generated by a propeller fan and its

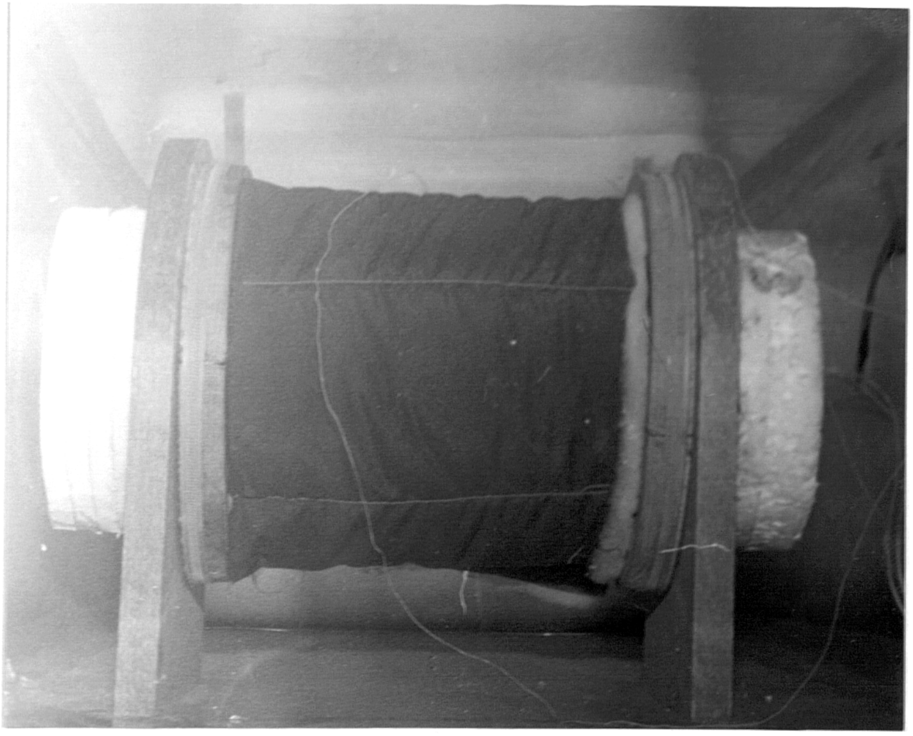


Plate 3.1 A Sample under Test in the Wind Tunnel

velocity was adjustable. To ensure the wind velocity distribution in the upper half and the lower half of the cylindrical togmeter to be symmetrical, the wind velocity distributions adjacent to the outer surfaces of clothing assemblies (about 4 mm beyond the surface) were checked by fixing the probe of an anemometer on the surface. The results are shown in Fig. 3.2. The magnitude of the wind velocity in the wind tunnel was described by the mean value of the 9 measurements at the cross section at least 10 cm away from the togmeter, where preliminary experiments showed that the linearity was not influenced by the togmeter.

3.3 Calibration

3.3.1 The Conductivity of the Standard Vicuclad Cylinder

The Vicuclad cylinder was the standard reference for the clothing assemblies tested. Its conductivity should be determined in advance. There are many methods for determining the conductivity of such a kind of material. Here the comparative method was used. By measuring the tog value of a flat Vicuclad plate on a standard disc togmeter in the department and the thickness on a Shirley Thickness Gauge, the conductivity was calculated as follows,

$$K = 10 \cdot \frac{d}{R} ,$$

where, K was the conductivity, d was the thickness of the plate, R was the tog value of the plate.

Mean tog value and thickness from the nine measurements at different places throughout the surface of the plate were taken

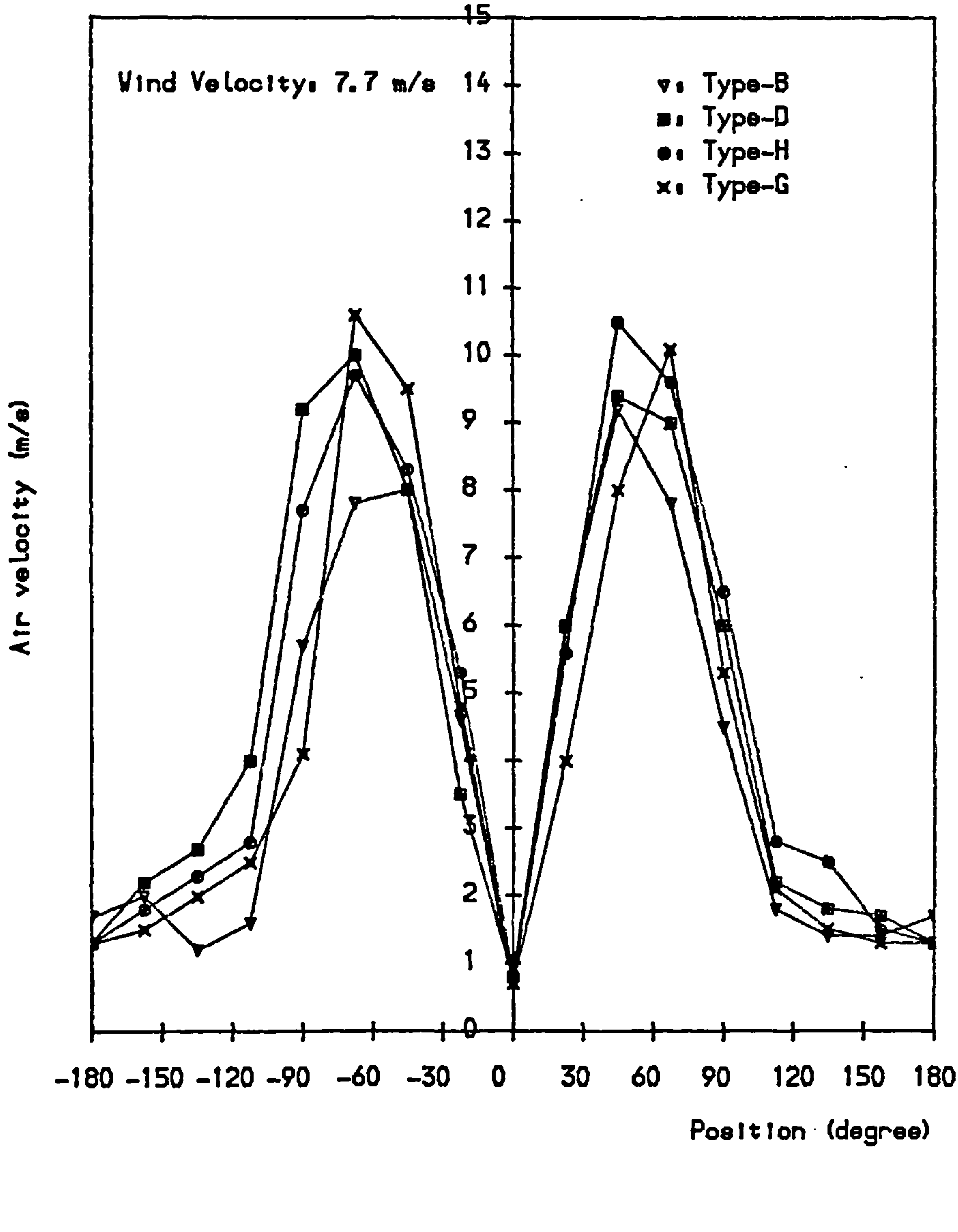


FIGURE 3.2 Air Velocity Distribution Near the outer Surface of Clothing Assemblies.

for this calculation. The conductivity determined by this method was 0.17 W/m °C.

3.3.2 Temperature Measurement

The basic principle of the temperature measurement using thermocouples is that the temperature difference between two junctions of a thermocouple can induce a voltage, and the magnitude of this voltage is proportional to the temperature difference. By keeping the hot junction in the place where the the temperature is to be measured and the cold junction in ice water mixture which has a temperature of 0 °C, and connecting the voltage output to a chart recorder, the movement of the pen on the chart recorder away from its original position is proportional to the temperature to be measured.

In this work, in order to determine the proportionality, the hot junctions of the thermocouples were kept in hot water at fixed temperatures and measured by a mercury thermometer. The temperature variation per unit division of the pen movement Δ was calculated as follow,

$$\Delta = \frac{\text{temperature change measured by mercury thermometer}}{\text{numbers of divisions of the pen movement}} \quad .$$

The Δ value determined for thermocouples K1, K2 and K3 respectively were

K1, $\Delta_1 = 0.61^{\circ}C/div$,

K2, $\Delta_2 = 0.61^{\circ}C/div$,

K3, $\Delta_3 = 0.58^{\circ}C/div$.

With these known Δ values, the temperature to be measured could be easily calculated from the number of the divisions of the pen movements from a reference position which indicated a known temperature.

3.4 The Expression of Results

The effective clothing insulation and surface insulation of a clothing assembly at an angular position relative to the wind direction were expressed in convectional tog units. They were calculated as follows.

$$R_c(\theta) = \frac{T_2(\theta) - T_3(\theta)}{H(\theta)} \cdot 10 \quad , \tag{3.1}$$

and $$R_s(\theta) = \frac{T_3(\theta) - T_a}{H(\theta)} \cdot 10 \quad , \tag{3.2}$$

where, $R_c(\theta)$ was the clothing insulation in tog units at "θ" angle position, $R_s(\theta)$ was the surface insulation in tog units at the same position, T_a was the ambient temperature, $T_2(\theta)$ and $T_3(\theta)$ were the outer surface temperature of the Vicuclad cylinder and the clothing assembly at the angular position "θ", and $H(\theta)$ was the rate of heat loss from the outer surface of the Vicuclad hollow cylinder at the same position in $W/m^2/sec$.

By approximating the heat flow through the Vicuclad cylinder and the clothing assembly to be radial, in the steady state conditions, $H(\theta)$ could be calculated as follow (Eckert et al. 1972),

$$H(\theta) = K_v \cdot \frac{T_1(\theta) - T_2(\theta)}{r_2 \cdot Ln(r_2/r_1)} \quad , \tag{3.3}$$

where, r_1 and r_2 were the inner and outer radii of the Vicuclad cylinder, $T_1(\theta)$ was the inner surface temperature of the Vicuclad cylinder at "θ" angle position, Kv was the conductivity of Vicuclad, Kv = 0.17 W/m°C.

In this cylindrical togmeter, r_1 = 0.061 m, r_2 = 0.09 m, therefore, from Eq.(3.1), Eq.(3.2) and Eq.(3.3), we can have

$$R_c(\theta) = 2.06\cdot\frac{T_2(\theta) - T_3(\theta)}{T_1(\theta) - T_2(\theta)} \quad , \qquad (3.4)$$

and $$R_s(\theta) = 2.06\cdot\frac{T_3(\theta) - T_a}{T_1(\theta) - T_2(\theta)} \quad . \qquad (3.5)$$

Eq.(3.4) and Eq.(3.5) were used for the calculation of $R_c(\theta)$ and $R_s(\theta)$ in the experiments.

3.5 Sample Specifications and Experimental Procedure

3.5.1 Sample specifications

The clothing assemblies tested in these experiments consisted of two parts, inner polyester battings and outer wind resistant fabrics. All of them were cut into 210mm wide and 680mm long pieces. By controlling these two parameters, samples were expected to have very similar expansion or compression when they were covered on the cylindrical togmeter. Velcro was used to stick two ends of such an assembly together when it was fitted on the togmeter. Since, for such samples under test, there was a possibility that air can pass into or out of the clothing assemblies from the edges, which was not desirable, preliminary experiments were carried out to compare the results of the samples which were prepared according to the above instructions and those in which the edges were sealed. No significant difference were found. This justified the above preparation of samples in future tests.

The same polyester battings were used for different samples. Its thickness was 20.0mm, weight 160 g/m^2 and air permeability per unit thickness $1.8x10^{-3}m^3/m$ /Pa/sec. The thickness was measured by a Shirley Thickness Gauge under a pressure of 0.2 g/cm^2. The air permeability per unit thickness was the product of the measured permeability of the compressed batting on a Permeability Tester and its thickness.

In order to study the effect of the properties of the outer fabrics on the clothing and surface insulation, different types of outer fabrics were used in the construction of the clothing assemblies. The specifications of these outer fabrics are listed in Table 3.1. They were measured according to British Standards (thickness, B.S.2544: 1954; air permeability, B.S.3217: 1960; threads per inch, B.S.2862: 1957; yarn tex, B.S.2865: 1957; weight, B.S.2471: 1954; stiffness, B.S.3356: 1961; cover factor, Booth 1968; properties of knitted fabrics, B.S.5441: 1977).

3.5.2 Experimental Procedure

The experiments were conducted in an air conditioned room of dry bulb temperature 20±1°C and relative humidity 65±2%. Samples were kept in the room for at least 24 hours before testing. The experimental procedure for testing a certain sample can be

Table. 3.1 Specifications of Outer Fabrics

Fabric Type	Description	Thickness (mm)	Air permeability ($m^3/m^2/sec/Pa \times 10^{-8}$)	Warp(wale) density(in^{-1})	weft(course) density(in^{-1})	yarn length per loop (in)	warp Tex	weft Tex	cover factor (%)	weight (mg/cm^2)	average bending length (cm)	flexural regidity ($mg \cdot cm$)	bending modulus $\times 10^3$ ($mg \cdot cm/mm^3$)
A	cotton 1x1 rib weft knit	0.49	36.5	20	31	0.22	26.2		46.9	14.4	-	-	-
B	cotton double knit	0.94	16.9	29	61	0.15	22.4		90.8	29.2	1.2	50.5	0.0073
C	cotton plain woven	0.19	1.89	77	129	-	20.2	5.5	72.7	10.4	2.3	126.5	2.2
D	nylon filament plain woven	0.24	0.59	39	67	-	20.2	23.2	61.0	10.2	2.5	159.4	1.3
E	nylon plain woven	0.10	0.12	95	95	-	8.4	8.4	64.6	7.5	1.5	25.3	3.1
F	nylon plain woven neopren coated	0.13	0	87	106	-	-	-	100	10.3	0.9	7.3	0.39
G	nylon plain woven neopren coated	0.28	0	76	65	-	-	-	100	15.2	1.5	51.3	0.27
H	cotton ventile unfinished	0.23	0.10	120	93	-	13.0	20.4	83.7	17.5	1.7	86.0	0.65
I	cotton ventile finished	0.41	0	77	67	-	36.8	49.7	90.4	32.4	4.4	2780.0	5.0
J	nylon plain woven neoprene coated	0.37	0	33	53	-	-	-	100	22.2	1.9	152.3	0.37

summarized as follows;

(1) Cover the sample around the togmeter neatly.

(2) Sew Thermocouple K3 on the outer surface of the sample and be sure it is at the same angular position as K1 and K2.

(3) Turn on the fan.

(4) Wait until K1, K2, and K3 are registering stable temperatures.

(5) Record T1, T2 and T3 when stable temperatures are registered.

(6) Calculate the thermal insulation at this position with Eq.(3.4) and Eq.(3.5).

(7) Rotate the cylinder to another angular position and follow the procedure from (4) to (6) to measure the effective insulation at this new position.

Since the upper half and lower half of the system were designed to be symmetrical, only the thermal insulation of the upper half of the assemblies were investigated in these experiments. The Angles relative to the wind direction which were investigated were 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5° and 180°.

By following the above procedure, three repeat tests were carried out for several samples, and the results were found to be reproducible. The coefficients of variation were found to be within 5%.

3.6 Results and Discussion

3.6.1 Clothing Thermal Insulation in Still Air

In order to study the wind effects on the clothing thermal insulation, the thermal insulation in still air was measured. The measurements were taken at three positions, 90°, 0° and -90°. The mean values from these three measurements were believed to give reasonable account of the overall clothing insulation in still air, since the effects of the weight of the clothing assembly and natural convection on the mean values were eliminated. The results are listed in Table 3.2. As can be seen, the differences in the thermal insulation between different clothing assemblies were small except for assembly B for which the outer fabric was significantly thicker than others. This comfirmed the success of sample preparation.

Table 3.2 Clothing insulation in still air for assemblies covered with different outer fabrics.

\assembly position\	A	B	C	D	E	F	G	H	J	H
0°	2.50	2.87	2.48	2.45	2.48	2.18	2.35	2.52	2.58	2.49
90°	2.40	2.73	2.40	2.25	2.40	2.04	2.19	2.41	2.45	2.40
-90°	2.58	2.95	2.59	2.58	2.59	2.40	2.50	2.56	2.60	2.60
mean	2.49	2.85	2.49	2.43	2.49	2.21	2.35	2.50	2.54	2.50

3.6.2 Clothing Insulation in Windy Conditions

Clothing assemblies covered with different outer fabrics were investigated at wind velocities of 4.5 m/s and 7.7 m/s. The results are plotted in Fig. 3.3 and Fig. 3.4. It can be seen that, for all kinds of clothing assemblies, the lowest thermal insulation was found in the windward areas, and the highest one in the leeward areas. The thermal insulation of different assemblies in the leeward areas are similar and somewhat higher than that in still air except for the assemblies covered with highly permeable knitted outer fabrics. The thermal insulation of permeable assemblies in the windward areas ranks conformablly to the air permeabilities of the outer fabrics. This reveals that, for permeable clothing assemblies, air penetration is the main mechanism involved in the wind induced reduction in the thermal insulation. For impermeable clothing assemblies, the low thermal insulation in the windward areas and high one in the leeward areas must be caused by the compression and expansion of the assemblies due to the air pressure imposed on the clothing surface which arises from the air movement. Interestingly, the average thermal insulation of these impermeable clothing assemblies are strongly related to the stiffness of the outer fabrics (see Fig. 3.5). This may be because assemblies of stiffer outer fabrics are more difficult to compress or expand.

To see the effect of wind velocity on the clothing thermal insulation, clothing assemblies covered with three typical outer fabrics were tested at wind velocities of 2.9m/s, 4.5m/s, 7.7m/s and 10.2m/s. These three outer fabrics are highly permeable outer fabric (type-B), moderately permeable outer fabric (type-D) and impermeable outer fabric (type-J). The results are shown in Fig. 3.6, 3.7 and 3.8. As can been seen, in the windward areas, the

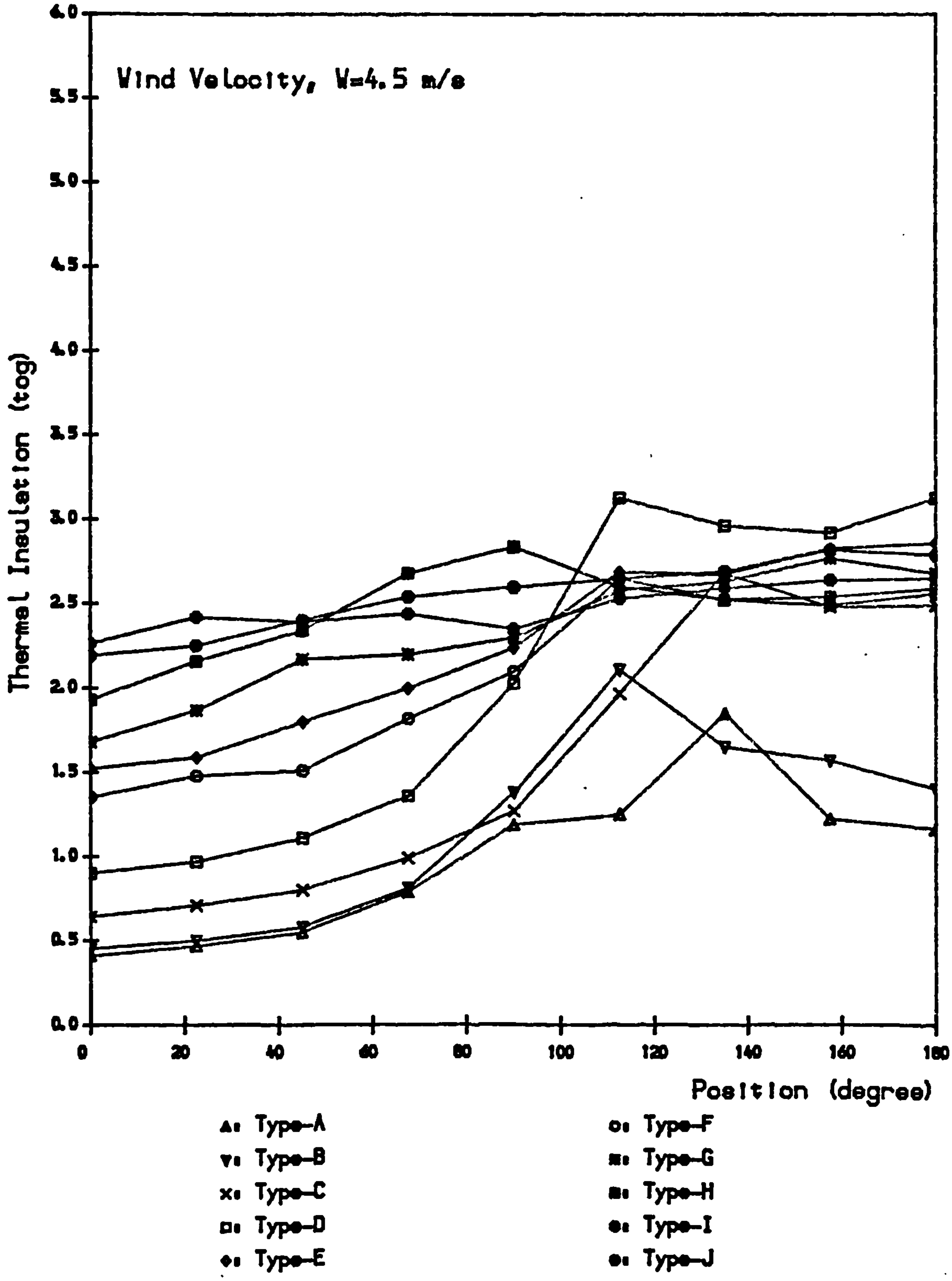


FIGURE 3.3 Thermal Insulation Distributions for clothing assemblies with different outer fabrics.

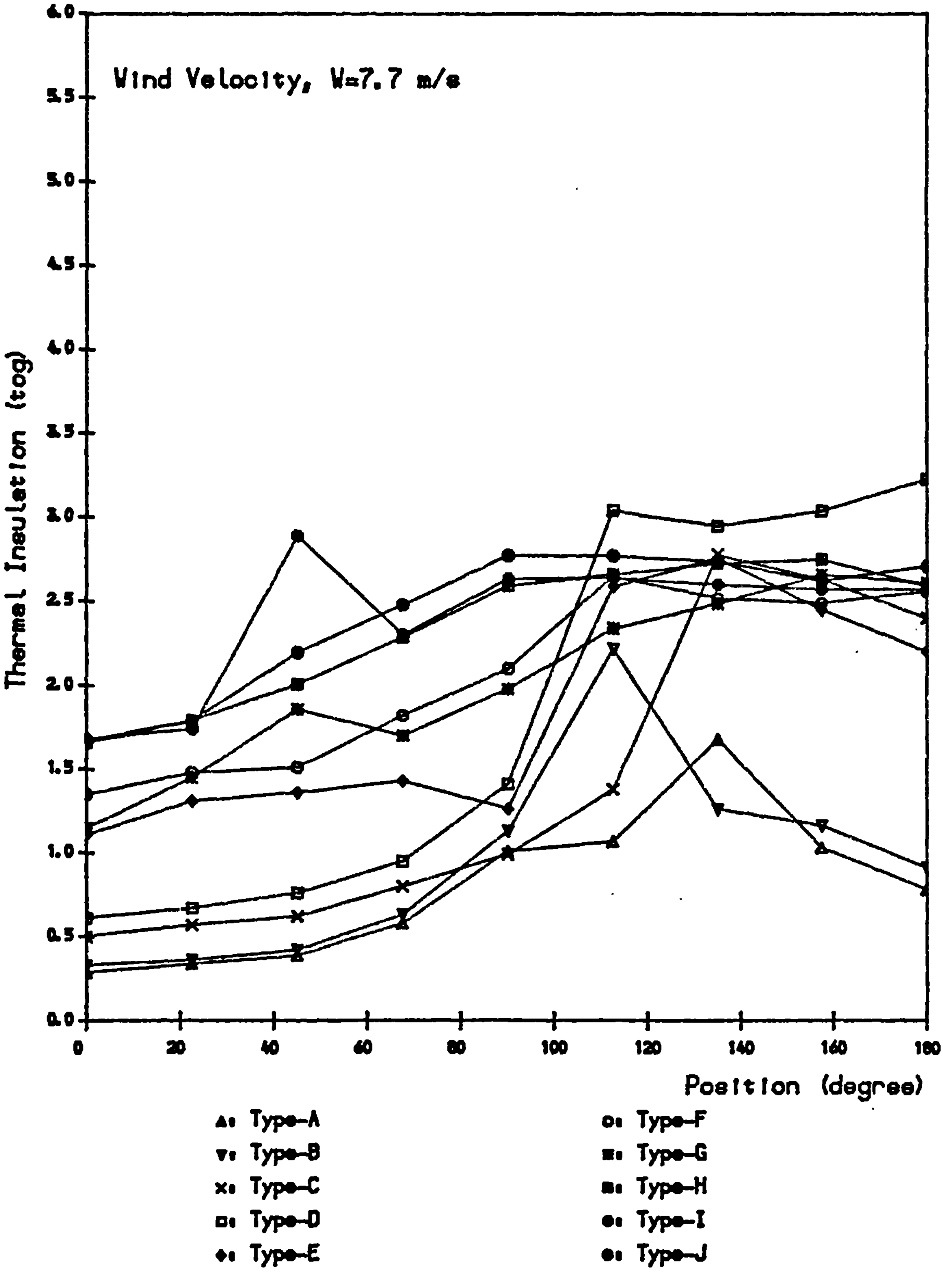


FIGURE 3.4 Thermal Insulation Distributions for clothing assemblies with different outer fabrics.

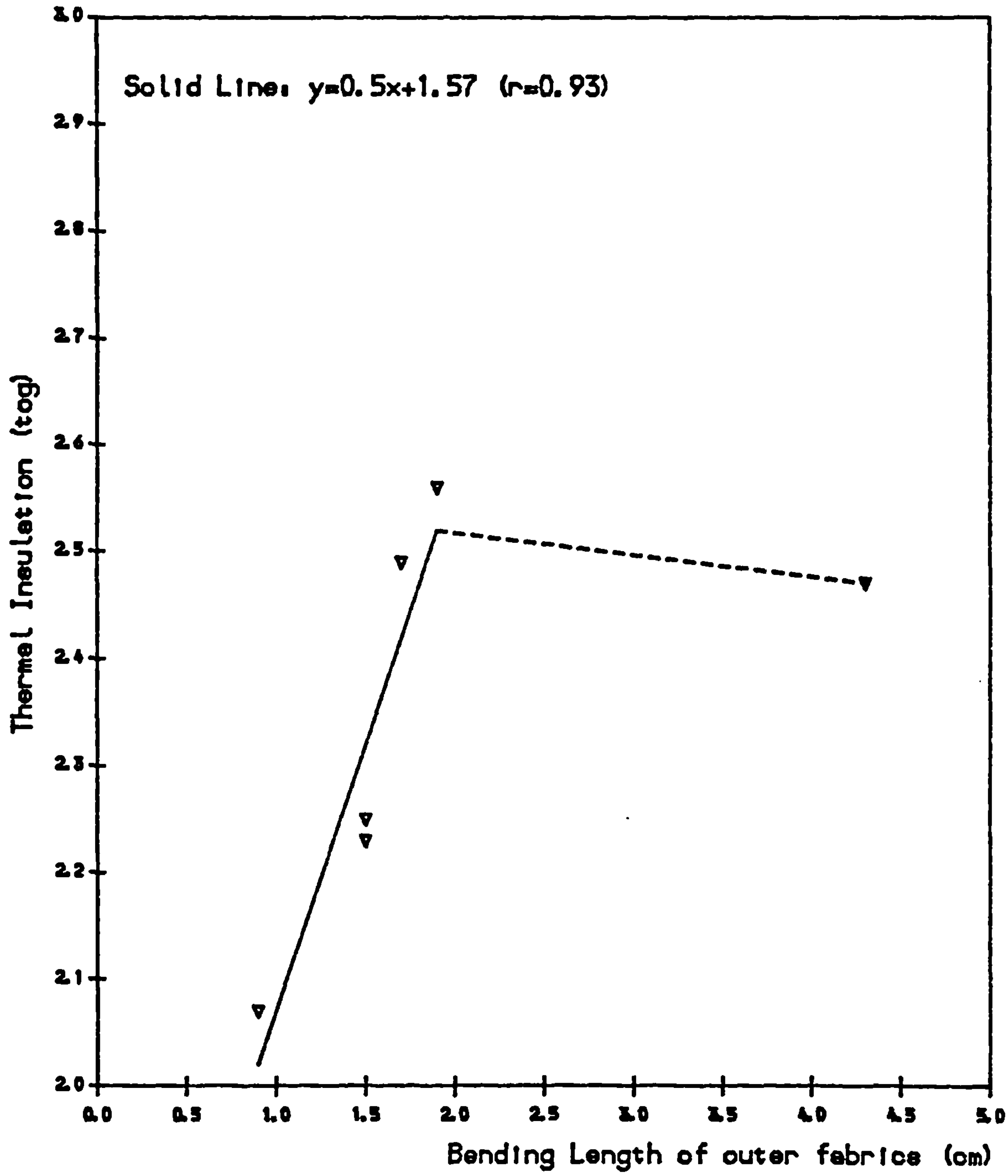


FIGURE 3.5 The Effect of Fabric Stiffness on Clothing Thermal Insulation.

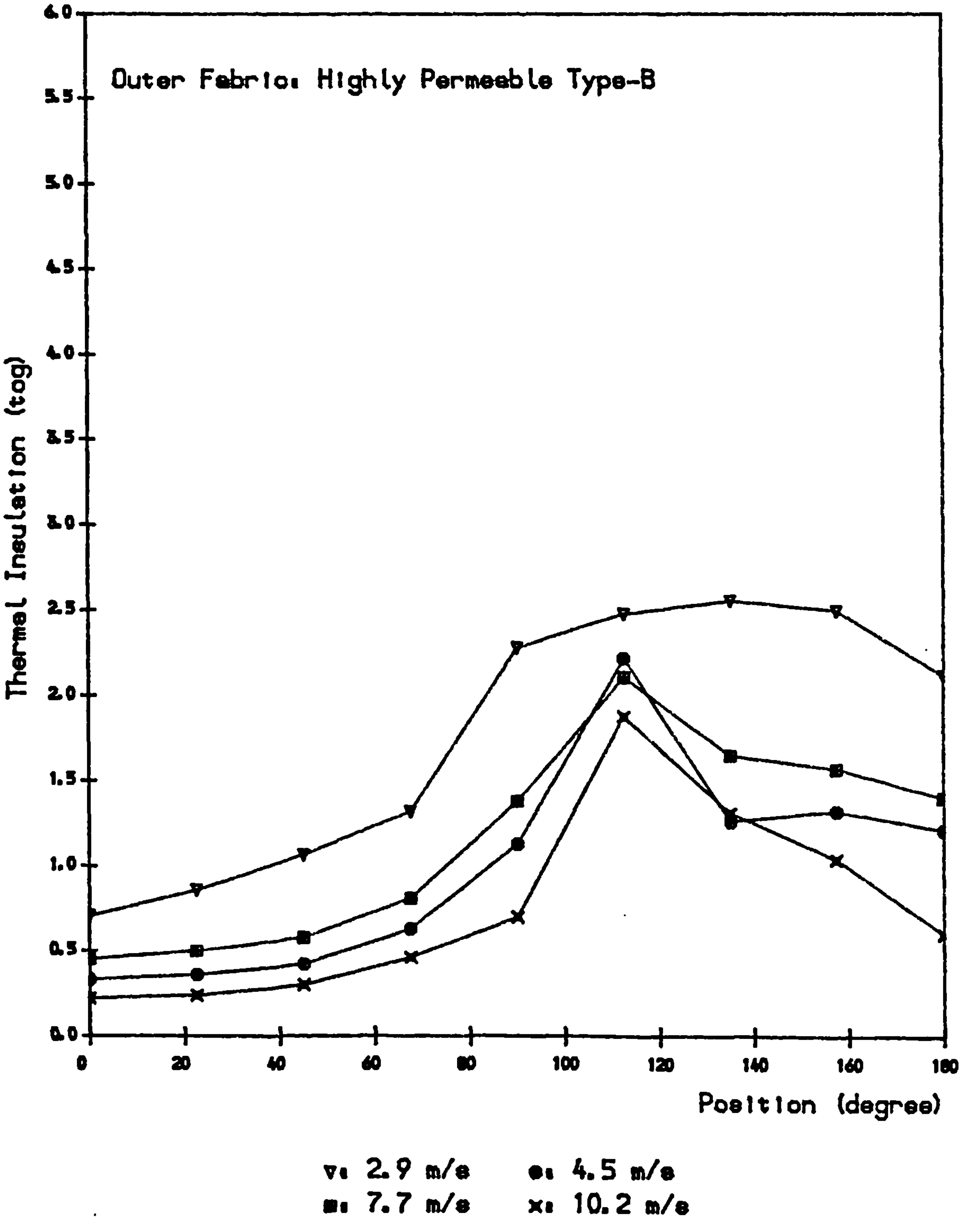


FIGURE 3.6 Thermal Insulation at Different wind velocities (type-B).

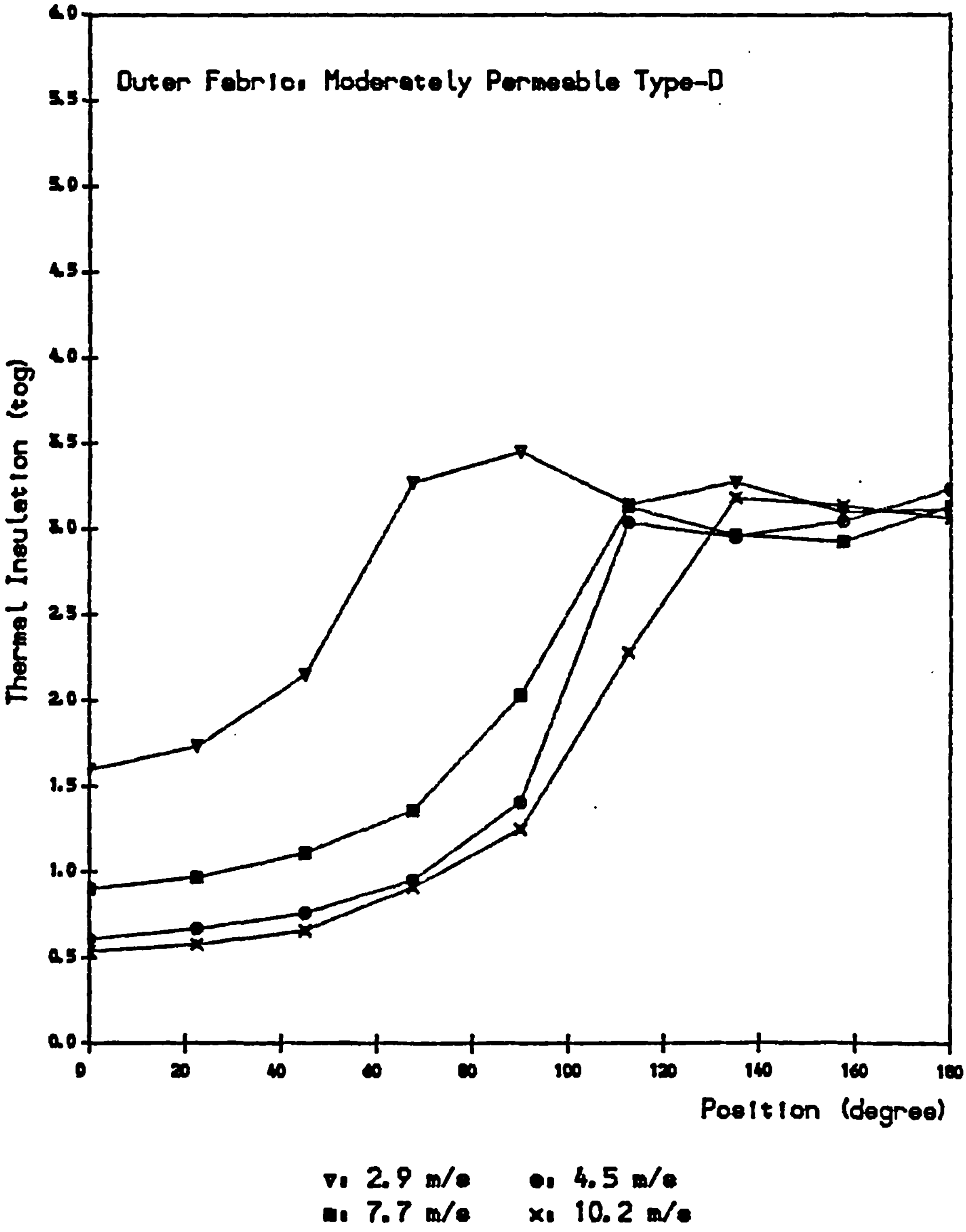


FIGURE 3.7 Thermal Insulation at Different wind Velocities (type-D).

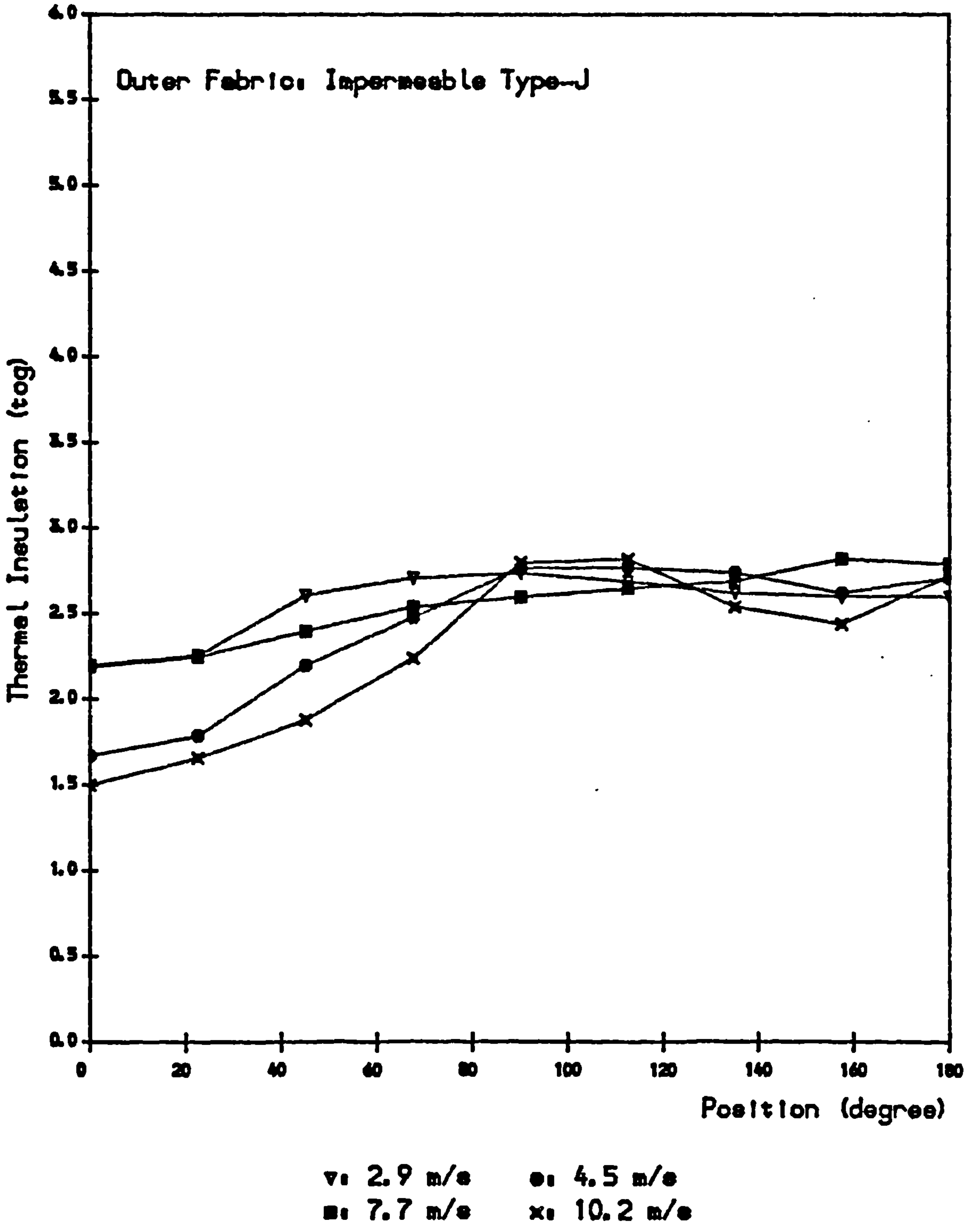


FIGURE 3.8 Thermal Insulation at Different Wind Velocities (type-J).

thermal insulation for all these assemblies reduces with increasing wind velocity because of increasing air penetration and compression of the assemblies. While, in the leeward areas, only the thermal insulation of the clothing assembly covered with highly permeable outer fabric reduces with increasing wind velocity. Such special behaviour of the highly permeable clothing assembly was later understood by the theoretical analyses to be presented in the next chapter.

3.6.3 Surface Insulation of Clothing in Windy Conditions

In contrast to the clothing thermal insulation, the surface thermal insulation measured under this testing condition was less accurate. This is because of the small temperature difference so that the measured temperature differences between the clothing surface and the environment could be more easily influenced by the slight changes of the room temperature and possible temperature shifts of the thermocouple ice water junction. However, from the results shown in Fig. 3.9 and Fig. 3.10, it is certain that the surface thermal insulation contributes only a small percentage to the total thermal insulation. This is especially the case for permeable clothing assemblies in the windward areas because of air penetration. In fact, little temperature difference could be detected between the clothing surface and the environment for permeable clothing assemblies in the windward areas in these experiments. In the leeward areas, the surface temperature of the clothing assemblies were higher due to hot air passing into the environment, and therefore, the apparent surface insulation was

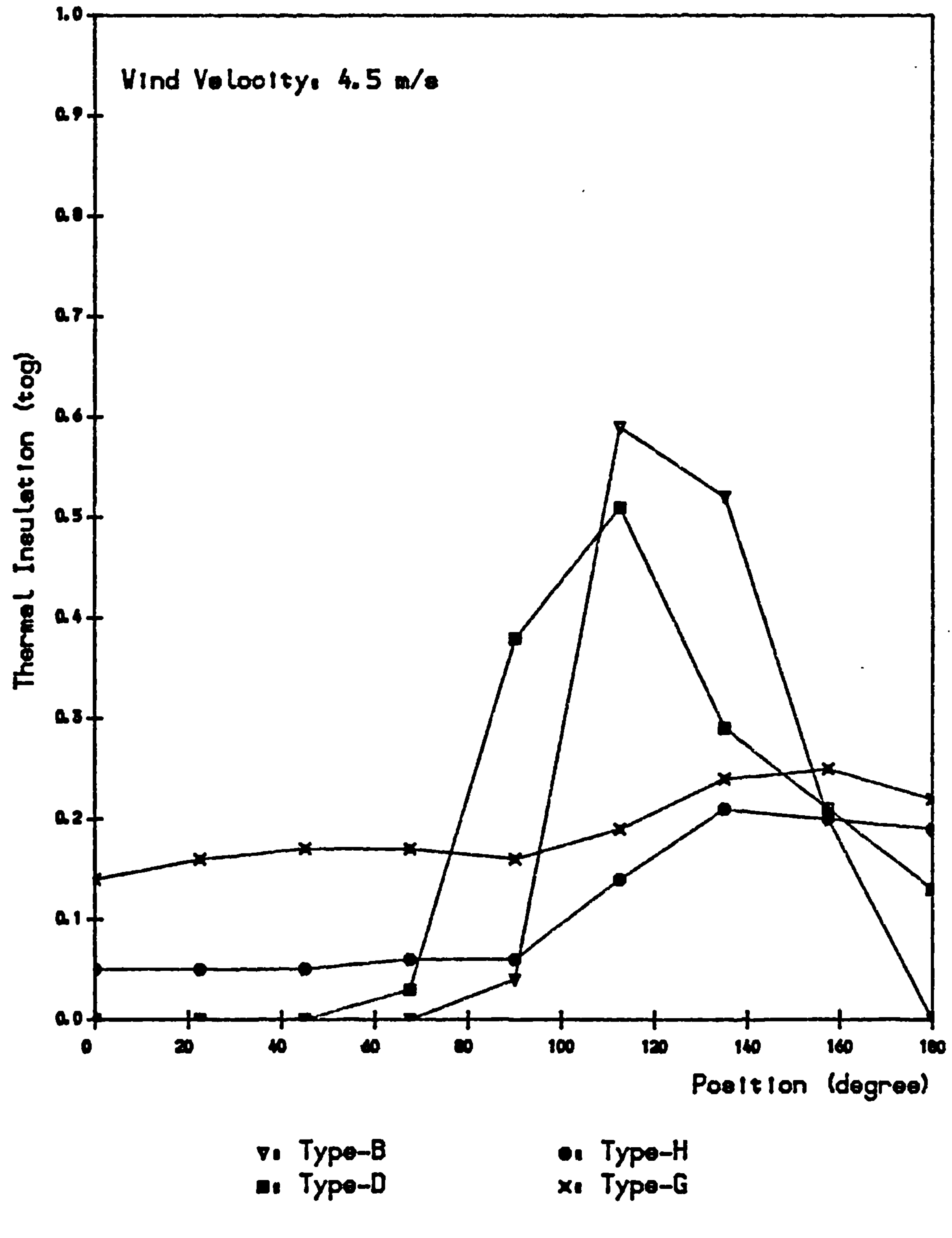


FIGURE 3.9 Surface Thermal Insulation Distribution for clothing Assemblies with Different Outer Fabrics.

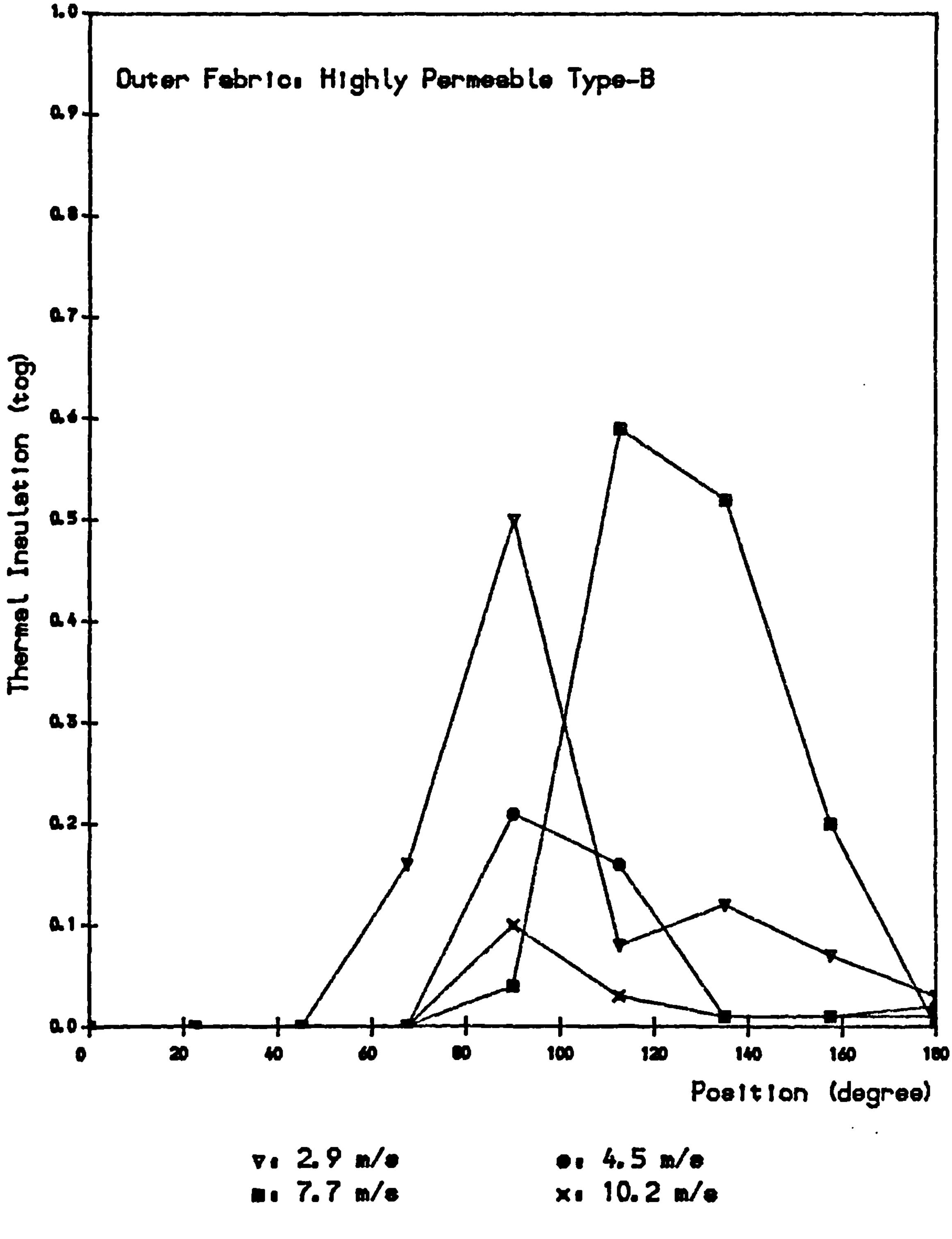


FIGURE 3.10 Surface Thermal Insulation at Different Wind Velocities.

higher.

3.7 Concluding Remarks

With the newly developed cylindrical togmeter, experimental investigations in a wind tunnel indicated that air penetration and changes in clothing geometry due to compression and expansion of the assemblies which arises from the air movement are two mechanisms involved in the reduction of clothing insulation in windy conditions. As far as the surface thermal insulation is concerned, possible mechanisms involved are air penetration, changes in clothing geometry and the removal of boundary still air layer. Since the problem under investigation involves several mechanisms, further work needs to be done to clarify the individual effects of these mechanisms.

Chapter 4

Theoretical Analyses and Results Comparison with Experimental Ones

4.1 Introduction

In the last chapter, it has been shown that, for permeable clothing assemblies, air penetration into the clothing assemblies and changes in clothing geometry due to compression or expansion of the assemblies which arises from the air movement are two possible mechanisms involved in the reduction of clothing thermal insulation. Our understanding of these phenomena was still limited if based on these experimental investigations.

In order to further understand these phenomena, theoretical analyses were carried out. In this theoretical model, no changes in clothing geometry were assumed. With this assumption, by comparing theoretical and experimental results, the two mechanisms involved were better clarified and understood. This chapter is devoted to give a detailed report of this theoretical study.

4.2 Basic Equations

4.2.1 General Considerations

The system we are considering operates in a free air stream. In steady state conditions, the air penetrates into the clothing assembly in places where the air pressure outside the clothing surface is higher than inside. At the same time, such air filters back from the clothing into the environment in those places where the air pressure inside is higher than on the outside. The air which penetrates within the inner porous fibrous material forms a slow air flow which exchanges hot and cold air within the system.

The theoretical analysis starts with the air movement and heat transfer within the clothing assembly. Because outer fabrics are much thinner than the porous materials, which is polyester batting in this work, their contribution to the overall thermal insulation is small enough to be ignored.

4.2.2 Air Movement Within the Clothing Assembly

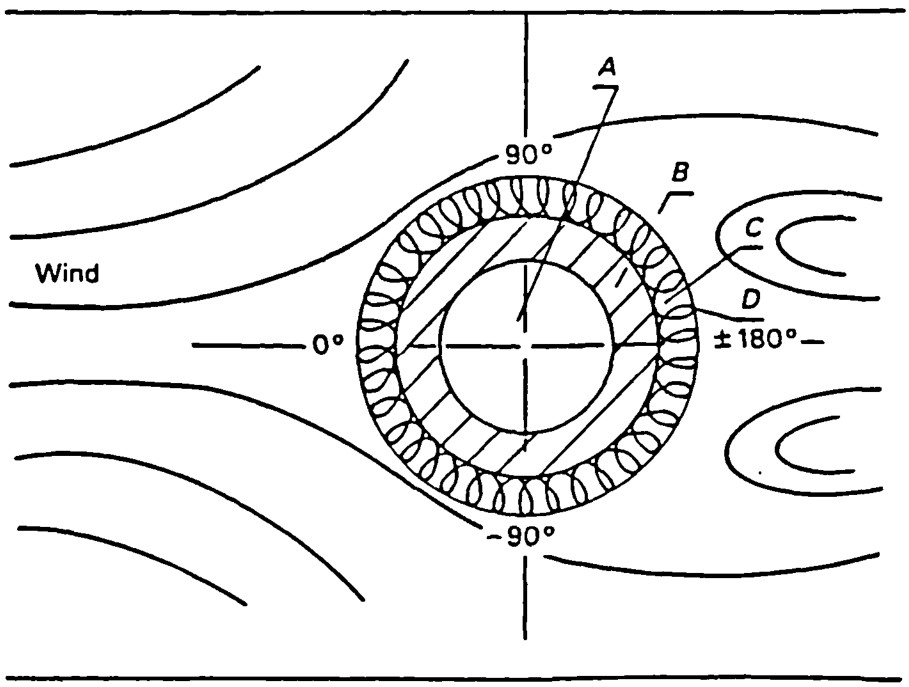
The air movement within the inner porous material must obey the principle of mass conservation. In the case of constant fluid density, air flow into and out of a control volume should be equal, or the net amount of flow into and out of the control volume in r and θ directions should be zero.

Considering the control volume sketched in Fig. 4.1, the net amount of air flow into the control volume in θ direction is

$$\left[\upsilon + \frac{\partial \upsilon}{\partial \theta}\cdot d\theta\right]\cdot dr - \upsilon\cdot dr = \frac{\partial \upsilon}{\partial \theta}\cdot d\theta\cdot dr \quad ,$$

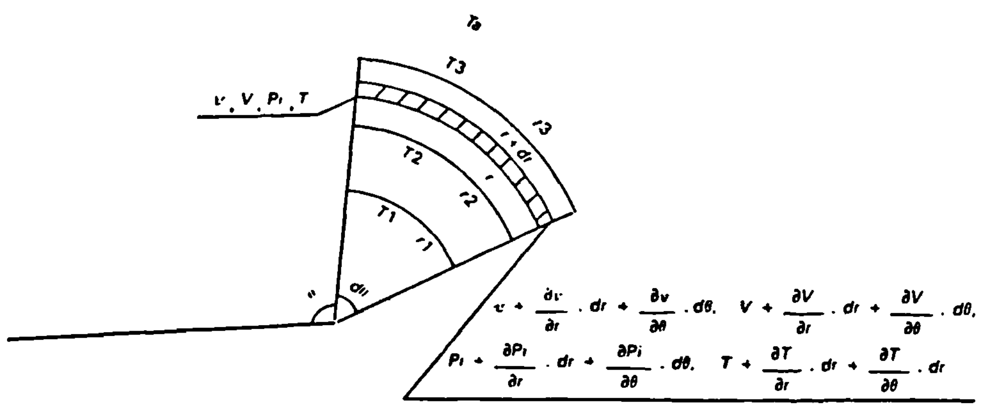
where, θ is angle, r radius, υ circular air flow rate per unit time and per unit area. The net amount of air flow into the control volume in r direction is

$$\left[V + \frac{\partial V}{\partial r}\cdot dr\right]\cdot(r+dr)\cdot d\theta - V\cdot r\cdot d\theta = \frac{\partial V}{\partial r}\cdot dr\cdot r\cdot d\theta + V\cdot dr\cdot d\theta ,$$



A: Internally temperature controlled area, B: hollow cylinder, C: porous fibrous material, D: outer fabric

Theoretical Model



v: circular air flow rate per unit time per unit area. V: radial air flow rate per unit time per unit area, P_t: air pressure inside the porous fibrous material, T_1: internally controlled temperature. T_2: inner surface temperature of the clothing assembly. T_3: outer surface temperature of the clothing assembly. T_a: ambient temperature.

Control Volume

FIGURE 4.1 Theoretical Model and its Control Volume.

where V is the radial air flow rate in r direction per unit time per unit area.

According to the principle of mass conservation, therefore, we have the equation which is refered to as the equation of continuity,

$$\text{i.e.}\quad \frac{\partial \upsilon}{\partial \theta} + r\cdot\frac{\partial V}{\partial r} + V = 0 \quad , \qquad (4.1)$$

Furthermore, the air flow within the porous media can also be described by Darcy's Law (Bejan 1984), so that we have

in the r direction,

$$V = -K_r\cdot\frac{\partial P_i}{\partial r} \quad , \qquad (4.2)$$

and in the θ direction,

$$\upsilon = -K_\theta\cdot\frac{1}{r}\cdot\frac{\partial P_i}{\partial \theta} \quad , \qquad (4.3)$$

where P_i is the air pressure within the fibrous material, K_r is the air permeability per unit thickness of the fibrous material in r direction and K_θ is the air permeability per unit thickness of the fibrous material in θ direction.

4.2.3 Heat Transfer Within the Clothing Assembly

As far as the heat transfer in the clothing assembly is concerned, according to the First Law of Thermodynamics in the steady state condition (Bird et al. 1960),

$$\begin{bmatrix}\text{the rate of energy}\\ \text{accumulation in the}\\ \text{control volume}\end{bmatrix}_1 = \begin{bmatrix}\text{The net transfer}\\ \text{of energy by}\\ \text{air flow}\end{bmatrix}_2 + \begin{bmatrix}\text{the net heat}\\ \text{transfer by}\\ \text{conduction}\end{bmatrix}_3 = 0.$$

$$[\quad]_2 = \left[V + \frac{\partial V}{\partial r}\cdot dr\right]\cdot(r+dr)\cdot d\theta\cdot Cv\cdot(T + \frac{\partial T}{\partial r}\cdot dr) - V\cdot r\cdot d\theta\cdot Cv\cdot T$$

$$+\left[\upsilon + \frac{\partial \upsilon}{\partial \theta}\cdot d\theta\right]\cdot\left[T + \frac{\partial T}{\partial \theta}\cdot d\theta\right]\cdot dr\cdot Cv - \upsilon\cdot dr\cdot Cv\cdot T$$

$$= Cv\cdot\left[V\cdot T + \frac{\partial V}{\partial r}\cdot r\cdot T + V\cdot r\cdot\frac{\partial T}{\partial r} + \upsilon\cdot\frac{\partial T}{\partial \theta} + \frac{\partial \upsilon}{\partial \theta}\cdot T\right]\cdot dr\cdot d\theta$$

$$= Cv\cdot\left[V\cdot r\cdot\frac{\partial T}{\partial r} + \upsilon\cdot\frac{\partial T}{\partial \theta}\right]\cdot dr\cdot d\theta \quad ,$$

$$[\quad]_3 = -Kcr\cdot(r+dr)\cdot d\theta\cdot\frac{\partial}{\partial r}\left[T + \frac{\partial T}{\partial r}\cdot dr\right] + Kcr\cdot r\cdot d\theta\cdot\frac{\partial T}{\partial r}$$

$$-Kc\theta\cdot dr\cdot\frac{1}{r}\cdot\frac{\partial}{\partial \theta}\left[T + \frac{\partial T}{\partial \theta}\cdot d\theta\right] + Kc\theta\cdot dr\cdot\frac{1}{r}\cdot\frac{\partial T}{\partial \theta}$$

$$= -Kcr\cdot\left[r\cdot\frac{\partial^2 T}{\partial r^2} + \frac{\partial T}{\partial r}\right]\cdot dr\cdot d\theta - Kc\theta\cdot\frac{1}{r}\cdot\frac{\partial^2 T}{\partial \theta^2}\cdot dr\cdot d\theta \quad ,$$

where Kcr and Kcθ are the effective conductivities of the clothing assembly in r and θ directions respectively, Cv is the specific heat of air, and T is the temperature. In the steady state condition, $[\quad]_1$ is zero and we have the following equation;

$$Cv\cdot\left[V\cdot r\cdot\frac{\partial T}{\partial r} + \upsilon\cdot\frac{\partial T}{\partial \theta}\right] = Kcr\cdot\left[r\cdot\frac{\partial^2 T}{\partial r^2} + \frac{\partial T}{\partial r}\right] + Kc\theta\cdot\frac{1}{r}\cdot\frac{\partial^2 T}{\partial \theta^2} \quad . \quad (4.4)$$

4.2.4 Heat Transfer within the Vicuclad Cylinder

Considering the Vicuclad hollow cylinder, which is made of homogeneous material, the steady state heat transfer in a two dimensional cylindrical coordinate system must obeys Laplace Equation (Eckert et al. 1972), i.e.

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T}{\partial r} + \frac{1}{r^2} \cdot \frac{\partial^2 T}{\partial \theta^2} = 0 \quad . \qquad (4.5)$$

4.3 Boundary Conditions

The boundary conditions which apply to the above equations are as follows.

(1). $v(r,0)=0$, $v(r,\pi)=0$. These two equations imply that at the 0° degree and 180° degree positions, no circular air flow exists. This is because upper half and lower half of the model are symmetrical.

(2). $V(r_2,\theta)=0$. This means that, at the outer surface of the Vicuclad hollow cylinder, the radial air flow rate is zero.

(3). $V(r_3,\theta) = -AP \cdot (P_o(\theta)-P_i(r_3,\theta))$,

where $V(r_3,\theta)$ is the radial air flow rate emerging from the clothing assembly, AP is the air permeability of the outer fabric, $P_i(r_3,\theta)$ is the air pressure adjacent to the inner surface of the outer fabric, $P_o(\theta)$ is the static air pressure imposed on the outer surface of the outer fabric.

An acceptable solution for $P_o(\theta)$ has not been previously proposed for an air permeable cylinder. An assumption was made by other workers [Yankelevich 1972, Stuart and Denby 1983] that, a cylindrical clothing system covered by a wind resistant outer fabric is equivalent to an air impermeable cylinder. In this work, $P_o(\theta)$ was measured for clothing assemblies covered by knitted fabrics of high air permeability and impermeable coated fabrics using an air flow meter (see Fig.4.2) on the cylindrical togmeter. The wind velocity used for the work ranged from 1m/s to 10m/s in a wind tunnel. The results shown in Fig.4.3 suggested that, within the range concerned, the pressure distribution Po(θ) is very uniform and can be expressed in an analytical form as follows;

$$Po(\theta) = \begin{cases} p_b+p_d \cdot (\frac{4}{3} \cdot \cos(2 \cdot \theta) - \frac{1}{3}) & (0 \le \theta \le \frac{3\pi}{8}) \\ Pb+Pd \cdot (1.644 \cdot (\sin(\frac{1}{2} \cdot \theta)-2.190) & (\frac{3\pi}{8} < \theta \le \pi) \end{cases},$$

where Pb is environmental pressure which is set to be zero in this work as we are only interested in pressure differences, Pd is the dynamic air pressure, $Pd = \frac{1}{2} \cdot \rho \cdot W^2$, ρ is the air density, W is the wind velocity.

(4) Since the upper half and lower half of the model are symmetrical, no circular heat flow exists at the 0°degree and the 180°degree positions. The mathematical form of this condition is

$$\frac{\partial T}{\partial \theta}\Big|_{\theta=0} = 0 \quad \text{and} \quad \frac{\partial T}{\partial \theta}\Big|_{\theta=\pi} = 0 .$$

(5) Because the radial heat transfer is continuous at the outer surface of the hollow cylinder, we also have $Kcr \cdot \frac{\partial T^c}{\partial r}\Big|_{r=r2} = Kv \cdot \frac{\partial T^s}{\partial r}\Big|_{r=r2}$,

where T^c and T^s are the temperatures in the clothing assembly and hollow cylinder respectively, Kv is the conductivity of the hollow cylinder, r2 is the outer radius of the hollow cylinder.

(6) At the outer surface of the clothing assembly, the heat

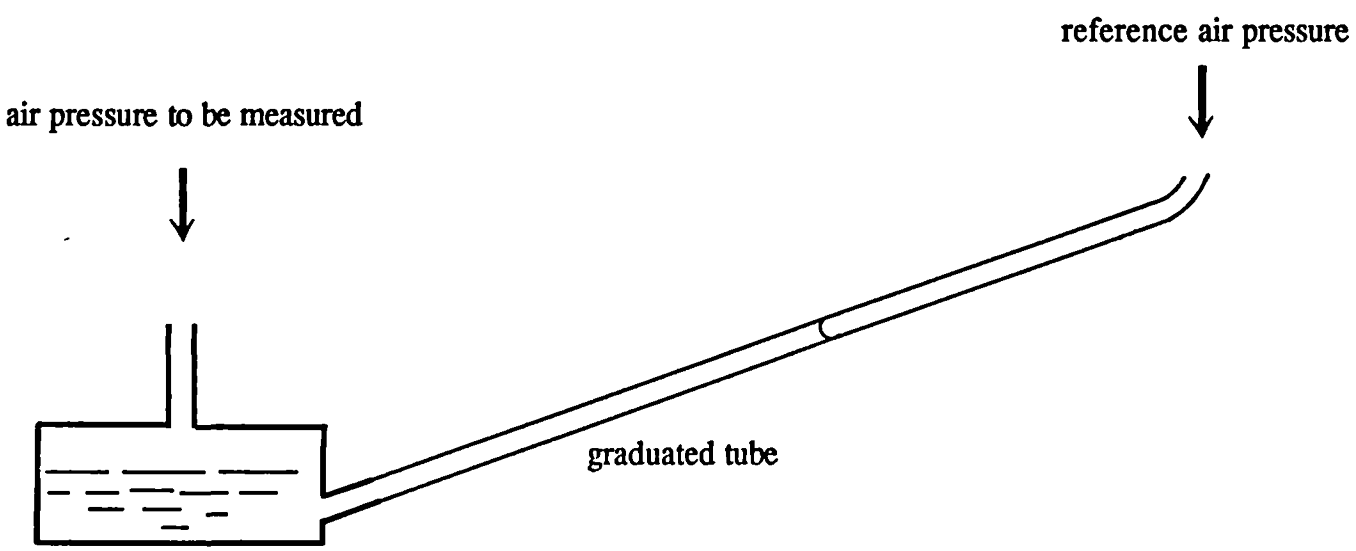


FIGURE 4.2 Diagram of the Air Flow Meter for the Measurement of Air Pressure.

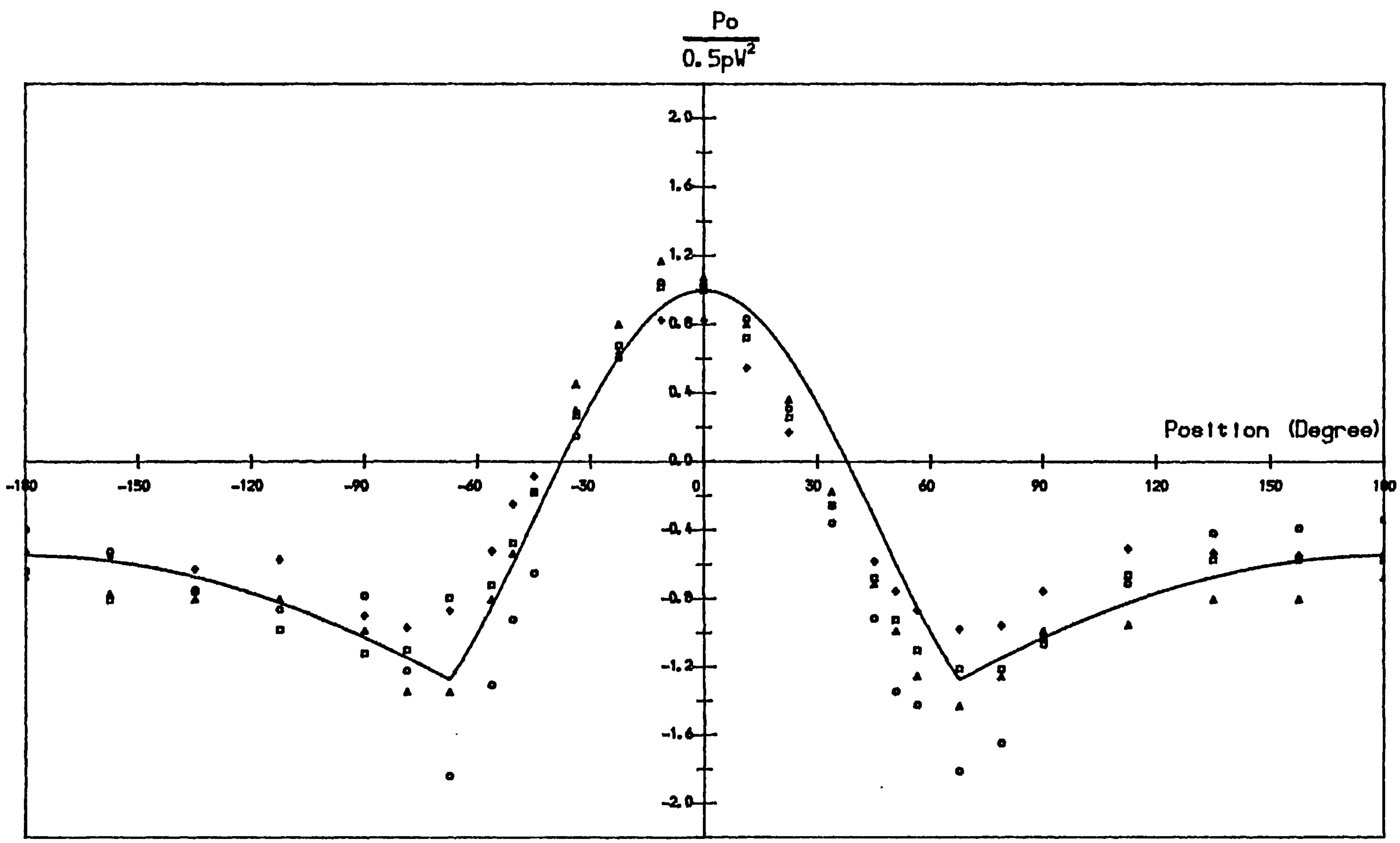


FIGURE 4.3 Air Pressure Distribution Around the Outer Surface of a Clothed Cylinder.

conducted from its inner layer is lost by surface convection, i.e.

$$-Kcr \cdot \left.\frac{\partial T}{\partial r}\right|_{r=r3} = h(\theta) \cdot (T3(\theta) - T_a) \quad ,$$

where, $T_3(\theta)$ is the surface temperature of the clothing assembly, T_a is the ambient temperature, r_3 is the outer radius of the clothing assembly, $h(\theta)$ is the convective heat transfer coefficient which was determined by the following experimental method. Using the cylindrical togmeter and covering the clothing assemblies with impermeable outer fabrics through which heat loses are almost radial, the conductive heat lost per unit area at a given angular position from the clothing surface is given by $Kv \cdot \frac{T2(\theta)-T1}{r3 \cdot \ln(r2/r1)}$. It can be deduced, therefore, that

$$h(\theta) = \frac{T2(\theta)-T1}{T3(\theta)-Ta} \cdot \frac{1}{r3 \cdot \ln(r2/r1)} \cdot Kv,$$

where $T_2(\theta)$ and T_1 are the outer and inner temperatures of the hollow cylinder, r_1 is the inner radius of the hollow cylinder. Since T_1, $T_2(\theta)$ and $T_3(\theta)$ have been measured, $h(\theta)$ can be calculated. From the data recorded at wind velocity 1.5m/s, 2.9m/s, 7.7m/s and 9.1m/s, an empirical formula was obtained by curve fitting to Fig.4.4 viz.

$$\frac{h(\theta)}{19.3 \cdot W^{0.6}} = 0.32 \cdot \cos\theta - 0.10 \cdot \cos3\theta + 1 \quad .$$

The average convective coefficient in relation to the wind velocity predicted by this empirical formula is similar to that for a solid cylinder, suggested by Douglas and Churchill (Eckert et al. 1972) except that a larger constant applies here. This may be due to the surface roughness of clothing assemblies. In addition, the variation of $h(\theta)$ over the whole circumference of

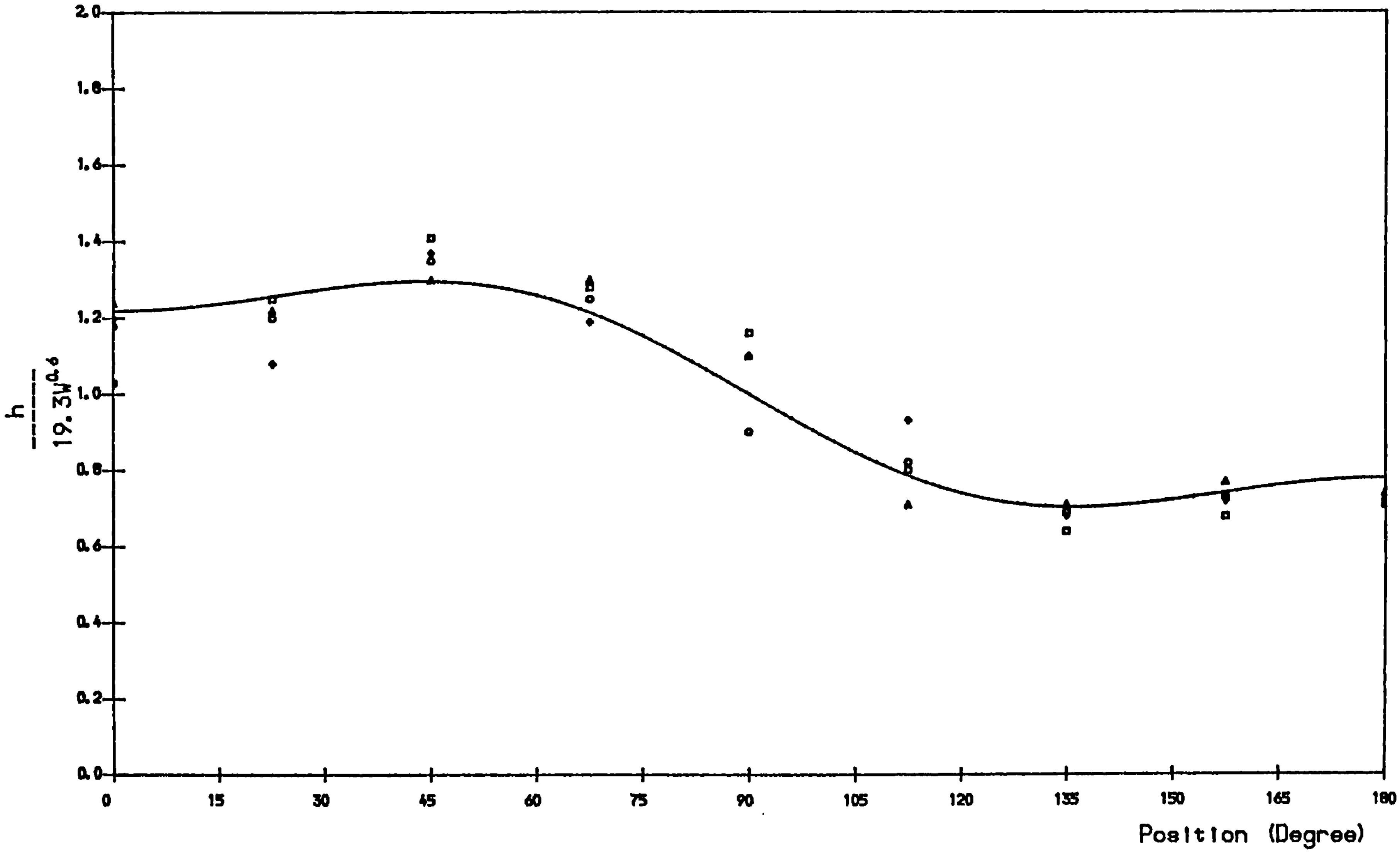


FIGURE 4.4 Surface Convective Coefficient Around a Clothed Cylinder.

the cylinder predicted by the above equation is less than that obtained by Kerslake (1963) on a solid cylinder. This may be partly due to the approximation of radial heat transfer through the clothing assemblies in the above calculation of $h(\theta)$. This approximation must be subject to some error due to the compression and expansion of these clothing assemblies which arised from the air pressure imposed on the clothing surface. Although the empirical formula is obtained from clothing assemblies of impermeable outer fabrics, it can probably be used for those of permeable outer fabrics, since the surface heat transfer coefficient is determined mainly by the air flow pattern around the surface and this air flow pattern remains almost unchanged regardless of the permeability of outer fabrics as can been seen in Fig. 4.3.

(7) $T(r_1,\theta)=T_1$. This implies that the inner surface temperature of the hollow cylinder is controlled to be constant and equal to T1.

4.4 Analytical Solutions to the Equations of Air Movement

From the equations of (1), (2) and (3), we have

$$\frac{K\theta}{r}\cdot\frac{\partial^2 P_i}{\partial\theta^2} + r\cdot K_r\cdot\frac{\partial^2 P_i}{\partial r^2} + K_r\cdot\frac{\partial P_i}{\partial r} = 0 \quad . \qquad (4.6)$$

Let $P_i = g(r)\cdot f(\theta) + C$, (C is an arbitray constant) and substitute it into Eq.(4.6), we have

$$\frac{K\theta}{r}\cdot g(r)\cdot f''(\theta) + r\cdot K_r\cdot g''(r)\cdot f(\theta) + K_r\cdot g'(r)\cdot f(\theta) = 0 \ . \qquad (4.7)$$

Let $f''(\theta)=\lambda\cdot f(\theta)$, where λ is an arbitrary constant, then Eq.(4.7) becomes

$$\begin{cases} f''(\theta) = \lambda\cdot f(\theta) & (4.8) \\ g''(r) + \frac{1}{r}\cdot g'(r) + \frac{1}{r^2}\cdot\frac{\lambda\cdot K\theta}{Kr}\cdot g(r) = 0 & (4.9) \end{cases}$$

Eq.(4.8) is a Cauchy-Euler Equation, its solution depends on λ. If $\lambda > 0$, the solution is

$$f(\theta) = C_1\cdot e^{\sqrt{\lambda}\cdot\theta} + C_2\cdot e^{-\sqrt{\lambda}\cdot\theta} \quad (4.10)$$

If $\lambda \le 0$, the solution is

$$f(\theta) = C_1'\cdot\cos(\sqrt{-\lambda}\cdot\theta) + C_2'\cdot\sin(\sqrt{-\lambda}\cdot\theta) \quad . \quad (4.11)$$

In Eq.(4.10) and Eq.(4.11), C_1, C_2, C_1' and C_2' are constants.

Considering Eq.(4.9) which is also a Cauchy-Euler Equation, if $\lambda > 0$, its general solution is

$$g(r) = C_3\cdot\cos\left(\sqrt{\frac{\lambda\cdot K\theta}{Kr}}\cdot Ln(r)\right) + C_4\cdot\sin\left(\sqrt{\frac{\lambda\cdot K\theta}{Kr}}\cdot Ln(r)\right) \quad ; \quad (4.12)$$

if $\lambda \le 0$, its general solution is

$$g(r) = C_3'\cdot r^{\sqrt{-\lambda\cdot K\theta/Kr}} + C_4'\cdot r^{-\sqrt{-\lambda\cdot K\theta/Kr}} \quad . \quad (4.13)$$

In Eq.(4.12) and Eq.(4.13), C_3, C_4, C_3', and C_4' are constants.

Therefore, the general solution of Eq.(4.6) is

$$P_i=\left[C_1 \cdot e^{\sqrt{\lambda}\cdot\theta} + C_2 \cdot e^{-\sqrt{\lambda}\cdot\theta}\right] \cdot \left[C_3 \cdot \cos\left(\sqrt{\frac{\lambda\cdot K\theta}{Kr}}\cdot Ln(r)\right)+C_4\cdot \sin\left(\sqrt{\frac{\lambda\cdot K\theta}{Kr}}\cdot Ln(r)\right)\right] + C \quad (\lambda > 0) \qquad (4.14)$$

or

$$P_i=\left[C_1' \cdot \cos(\sqrt{-\lambda}\cdot\theta)+C_2'\cdot\sin(\sqrt{-\lambda}\cdot\theta)\right] \cdot \left[C_3'\cdot r^{\sqrt{-\frac{\lambda\cdot K\theta}{Kr}}} + C_4'\cdot r^{-\sqrt{-\frac{\lambda\cdot K\theta}{Kr}}}\right] + C \qquad (\lambda \le 0) \qquad (4.15)$$

According to Boundary Condition (1), the general solution of $\lambda > 0$ cannot be the solution of this problem, in other words, Eq.(4.15) is a solution of this problem. Now let $n^2=-\lambda$, (n is another constant, $n \ge 0$) and $\varepsilon = \sqrt{K\theta/Kr}$, Eq.(4.15) becomes

$$P_i=[C_1'\cdot\cos(n\cdot\theta)+C_2'\cdot\sin(n\cdot\theta)]\cdot[C_3'\cdot r^{\varepsilon\cdot n}+C_4'\cdot r^{-\varepsilon\cdot n}]+C \quad . \qquad (4.16)$$

From Boundary Condition (1) and Eq.(4.2) and Eq.(4.3), we have

$$\left.\frac{\partial P_i}{\partial\theta}\right|_{\theta=0} = 0 \qquad (a)$$

and

$$\left.\frac{\partial P_i}{\partial\theta}\right|_{\theta=\pi} = 0 \quad . \qquad (b)$$

Can Eq.(4.16) satisfy Condition (a), only if $C_2'= 0$. Thus, Eq.(4.16) becomes

$$P_i= (C_{11}\cdot r^{\varepsilon\cdot n}+ C_{22}\cdot r^{-\varepsilon\cdot n})\cdot\cos(n\cdot\theta) + C , \qquad (4.17)$$

where, C_{11} and C_{22} are constants. Also, to satisfy condition (b), $\sin(n\pi) = 0$, or n must be an integer. Thus, the solution of this problem is a sum of any number of solutions described in Eq.(4.17), i.e.

$$P_i = \sum_{n=1}^{\infty} (C_n^1 \cdot r^{\varepsilon \cdot n} + C_n^2 \cdot r^{-\varepsilon \cdot n}) \cdot \cos(n \cdot \theta) + C \quad , \qquad (4.18)$$

where, C_n^1, and C_n^2 are the n-th constants of the series. By applying Boundary Condition (2), we have

$$\left.\frac{\partial P_i}{\partial r}\right|_{r=r_2} = 0 \quad . \qquad (c)$$

Substituting Boundary Condition (c) into Eq.(4.18), we get

$$C_n^2 = C_n^1 \cdot r_2^{2 \cdot \varepsilon \cdot n} \quad ,$$

and Eq.(4.18) can be written as

$$P_i = \sum_{n=1}^{\infty} C_n \cdot (r^{\varepsilon \cdot n} + r_2^{2 \cdot \varepsilon \cdot n} \cdot r^{-\varepsilon \cdot n}) \cdot \cos(n\theta) + C \quad , \qquad (4.19)$$

where C_n is the n-th constant of the series. With Boundary Condition (3), i.e.

$$-K_r \left.\frac{\partial P_i}{\partial r}\right|_{r=r_3} = -AP \cdot (P_o(\theta) - P_i(r_3, \theta)) \quad , \qquad (d)$$

we get

$$\sum_{n=1}^{\infty} \cos(n \cdot \theta) \cdot [C_n \cdot \varepsilon \cdot n \cdot r_3^{\varepsilon \cdot n - 1} - C_n \cdot \varepsilon \cdot n \cdot r_2^{2 \cdot \varepsilon \cdot n} \cdot r_3^{-\varepsilon \cdot n - 1}]$$

$$= \frac{AP}{K_r} \cdot [P_o(\theta) - P_i(r_3, \theta)] \quad . \qquad (4.20)$$

Multiplying Eq.(4.20) by $\cos(m \cdot \theta)$ (m is an interger) and integrating from 0 to π, we get

$$\int_0^{\pi} \sum_{n=1}^{\infty} \cos(n \cdot \theta) \cdot C_n \cdot \varepsilon \cdot n \cdot (r_3^{\varepsilon \cdot n - 1} - r_3^{-\varepsilon \cdot n - 1} \cdot r_2^{2 \cdot \varepsilon \cdot n}) \cdot \cos(m \cdot \theta) \cdot d\theta$$

$$= \int_0^{\pi} \frac{AP}{K_r} \cdot \left[P_o(\theta) - \sum_{n=1}^{\infty} C_n \cdot \cos(n \cdot \theta) \cdot (r_3^{\varepsilon \cdot n} + r_2^{2 \cdot \varepsilon \cdot n} \cdot r_3^{-\varepsilon \cdot n}) - C \right] \cdot \cos(m \cdot \theta) \cdot d\theta \quad .$$

therefore,

$$Cn = \frac{\int_0^{\pi} \frac{AP}{Kr} \cdot Po(\theta) \cdot \cos(n \cdot \theta) \cdot d\theta}{\frac{\pi}{2} \cdot [\varepsilon \cdot n \cdot (r3^{\varepsilon \cdot n-1} - r2^{2 \cdot \varepsilon \cdot n} \cdot r3^{-\varepsilon \cdot n-1}) + \frac{AP}{Kr} \cdot (r3^{\varepsilon \cdot n} + r2^{2 \cdot \varepsilon \cdot n} \cdot r3^{-\varepsilon \cdot n})} \quad .$$

(4.21)

Again from Boundary Condition (3), at the position $r = r3$, $\theta = 0^\circ$, we have

$$[Po(0) - Pi(r3, 0)] \cdot AP = Kr \cdot \left. \frac{\partial Pi}{\partial r} \right|_{\theta=0,\ r=r3} ,$$

or

$$Po(0) - \sum_{n=1}^{\infty} Cn \cdot (r3^{\varepsilon \cdot n} + r2^{2 \cdot \varepsilon \cdot n} \cdot r3^{-\varepsilon \cdot n}) - C$$

$$= \frac{Kr}{AP} \cdot \sum_{n=1}^{\infty} Cn \cdot \varepsilon \cdot n \cdot (r3^{\varepsilon \cdot n-1} - r3^{-\varepsilon \cdot n-1} \cdot r2^{2 \cdot \varepsilon \cdot n}) \quad .$$

Therefore,

$$C = -\sum_{n=1}^{\infty} Cn \cdot \left[(r3^{\varepsilon \cdot n} + r2^{2 \cdot \varepsilon \cdot n} \cdot r3^{-\varepsilon \cdot n}) + \frac{Kr}{AP} \cdot \varepsilon \cdot n \cdot (r3^{\varepsilon \cdot n-1} - r3^{-\varepsilon \cdot n-1} \cdot r2^{2 \cdot \varepsilon \cdot n}) \right] + Po(0) \quad . \qquad (4.22)$$

With a known air pressure inside the clothing assembly, the air flow rate can be calculated from Eq.(4.2) and (4.3), viz.

$$V = -Kr \cdot \frac{\partial Pi}{\partial r} = \sum_{n=1}^{\infty} -Kr \cdot Cn \cdot \varepsilon \cdot n \cdot (r^{\varepsilon \cdot n-1} - r2^{2 \cdot \varepsilon \cdot n} \cdot r^{-\varepsilon \cdot n-1}) \cdot \cos(n \cdot \theta), \quad (4.23)$$

and

$$\upsilon = -K\theta \cdot \frac{1}{r} \cdot \frac{\partial P_i}{\partial \theta} = \sum_{n=1}^{\infty} K\theta \cdot \frac{1}{r} \cdot C_n \cdot n \cdot (r^{\varepsilon \cdot n} + r_2^{2 \cdot \varepsilon \cdot n} \cdot r^{-\varepsilon \cdot n}) \cdot \sin(n \cdot \theta). \quad (4.24)$$

4.5 Numerical Solutions to the Equations of Heat Transfer

4.5.1 Finite Difference Approximation

The equations of heat transfer within the system, i.e. Eq.(4.4) and (4.5), were solved by using the Finite Difference method. The main idea behind the method is to approximate the derivatives appearing in the equations by a set of values of the function at a selected number of points called nodes. Fig.4.5 shows the mesh used for the finite difference approximation in a cylindrical coordinate system. The region considered ($0 \le \theta \le \pi$, $r_1 \le r \le r_2$, $r_2 < r \le r_3$) were discretized with constant step sizes; $\Delta\theta$, Δr_1, $0 \le i \le n_1$, $1 \le j \le n_3$ in the Vicuclad cylinder and $\Delta\theta$, Δr_2, $n_1 \le i \le n_2$, $1 \le j \le n_3$ in the clothing assembly.

According to the five-point finite difference scheme, the approximations of the derivatives are as follows.

For Eq.(4.5) in the Vicuclad cylinder,

$$\frac{\partial^2 T_{i,j}}{\partial r^2} = \frac{T_{i+1,j} + T_{i-1,j} - 2 \cdot T_{i,j}}{\Delta r_1^2},$$

$$\frac{\partial^2 T_{i,j}}{\partial \theta^2} = \frac{T_{i,j+1} + T_{i,j-1} - 2 \cdot T_{i,j}}{\Delta \theta^2},$$

$$\frac{\partial T_{i,j}}{\partial r} = \frac{T_{i+1,j} - T_{i-1,j}}{2 \cdot \Delta r_1}.$$

For Eq.(4.4) in the clothing assembly,

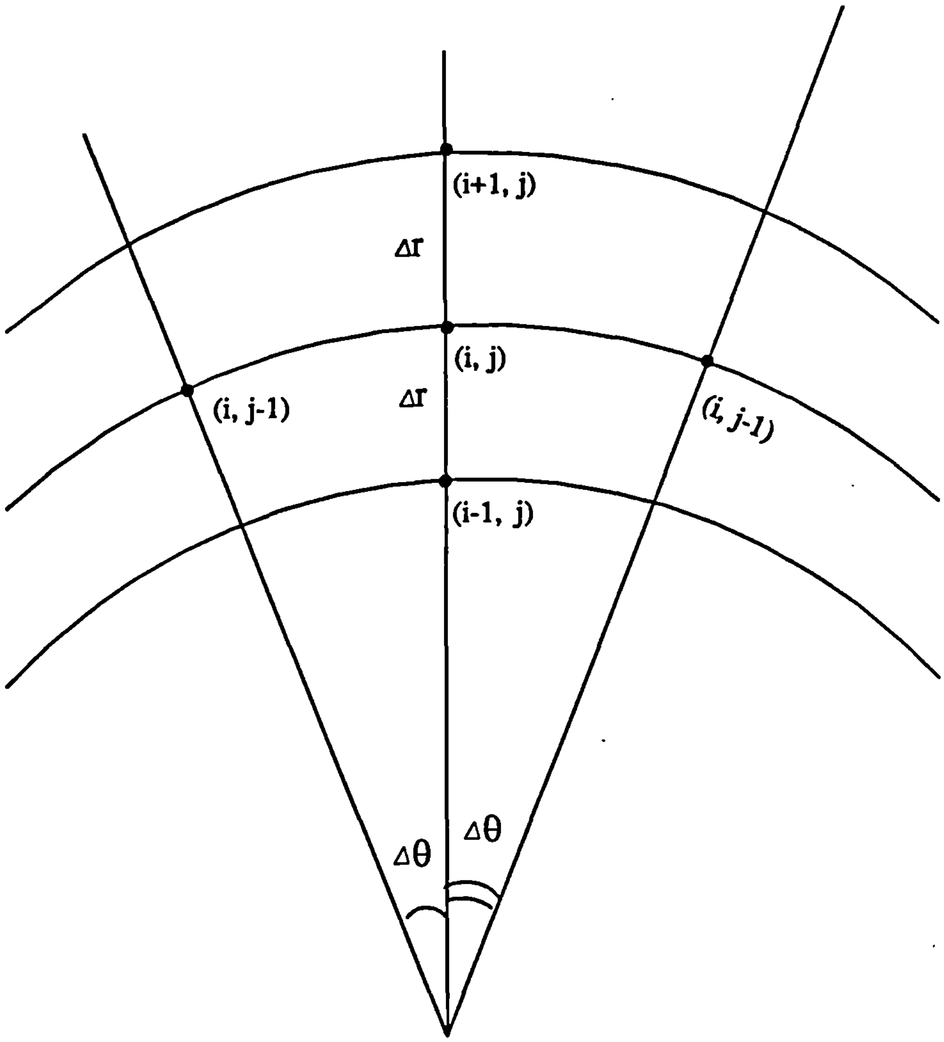


FIGURE 4.5 Mesh Used for the Five Point Finite Difference Approximation.

$$\frac{\partial^2 T_{i,j}}{\partial r^2} = \frac{T_{i+1,j} + T_{i-1,j} - 2\cdot T_{i,j}}{\Delta r2^2} ,$$

$$\frac{\partial^2 T_{i,j}}{\partial \theta^2} = \frac{T_{i,j+1} + T_{i,j-1} - 2\cdot T_{i,j}}{\Delta \theta^2} ,$$

$$\frac{\partial T_{i,j}}{\partial r} = \frac{T_{i+1,j} - T_{i-1,j}}{2\cdot \Delta r2} ,$$

$$\frac{\partial T_{i,j}}{\partial \theta} = \frac{T_{i,j+1} - T_{i,j-1}}{2\cdot \Delta \theta} .$$

By applying these derivativtes to Eq.(4.5), Eq.(4.4), Boundary Condition (5) and Boundary Condition (6), we get the following approximations.

In the Vicuclad cylinder,

$$T_{i,j} = \frac{B_i}{A_i}\cdot T_{i+1,j} + \frac{C_i}{A_i}\cdot T_{i-1,j} + \frac{D_i}{A_i}\cdot T_{i,j+1} + \frac{D_i}{A_i}\cdot T_{i,j-1} , \quad (4.25)$$

where,

$$A_i = \frac{1}{\Delta r1^2} + \frac{2}{(r1+i\cdot \Delta r1)^2 \cdot \Delta \theta^2} ,$$

$$B_i = \frac{1}{\Delta r1^2} + \frac{1}{2\cdot (r1+i\cdot \Delta r1)\cdot \Delta r1} ,$$

$$C_i = \frac{1}{\Delta r1^2} - \frac{1}{2\cdot (r1+i\cdot \Delta r1)\cdot \Delta r1} ,$$

$$D_i = \frac{1}{(r1+i\cdot \Delta r1)^2 \cdot \Delta \theta^2} .$$

In the clothing assembly,

$$T_{i,j} = Q_{i,j}\cdot T_{i+1} + R_{i,j}\cdot T_{i-1,j} + S_{i,j}\cdot T_{i,j+1} + U_{i,j}\cdot T_{i,j-1} ,$$

(4.26)

where,

$$Q_{i,j} = \frac{G_i + C_{o1} - E_{i,j}}{2\cdot(G_i + P_i)} ,$$

where, $$G_i = \frac{K_{cr}\cdot(r_2+(i-n_1)\cdot\Delta r_2)}{\Delta r_2^{\,2}} ,$$

$$C_{o1} = \frac{K_{cr}}{2\cdot\Delta r_2} ,$$

$$E_{i,j} = \frac{C_v\cdot V_{i,j}\cdot(r_2+(i-n_1)\cdot\Delta r_2)}{2\cdot\Delta r_2} ,$$

$$P_i = \frac{K_{c\theta}}{(r_2+(i-n_1)\cdot\Delta r_2)\cdot\Delta\theta^{\;2}} ,$$

$$R_{i,j} = \frac{G_i - C_{o1} + E_{i,j}}{2\cdot(G_i + P_i)} ,$$

$$S_{i,j} = \frac{P_i - F_{i,j}}{2\cdot(G_i + P_i)} ,$$

where,

$$F_{i,j} = \frac{C_v\cdot \upsilon_{i,j}}{2\cdot\Delta\theta} ,$$

$$U_{i,j} = \frac{P_i + F_{i,j}}{2\cdot(G_i + P_i)} .$$

At the common boundary of Eq.(4.5) and Eq. (4.4), ie, the outer surface the Vicuclad cylinder or the inner surface of the clothing assembly, ($r = r_2$, $i = n_1$) according to Boundary Condition (5), we have

$$T_{n1,j} = \frac{1}{C_{o2}+1}\cdot T_{n1+1,j} + \frac{C_{o2}}{C_{o2}+1}\cdot T_{n1-1,j} , \qquad (4.27)$$

where,

$$C_{o2} = \frac{K_v\cdot\Delta r_2}{K_{cr}\cdot\Delta r_1} .$$

From Boundary Condition (4) we have

$$T_{i,2} = T_{i,1} , \qquad (4.28)$$

and

$$T_{i,n3-1} = T_{i,n3} \quad . \tag{4.29}$$

At the outer surface of the clothing assembly, from Boundary Condition (6), we have

$$T_{n2,j} = C_{o3} \cdot T_{n2-1,j} + C_{o4} \cdot T_a \quad , \tag{4.30}$$

where,

$$C_{o3} = \frac{K_{cr}}{K_{cr} + \Delta r_2 \cdot h_j} \quad ,$$

$$C_{o4} = \frac{\Delta r_2 \cdot h_j}{K_{cr} + \Delta r_2 \cdot h_j} \quad .$$

At the inner surface of the Vicuclad cylinder, from Boundary Condition (7), we have

$$T_{0,j} = T_1 \quad . \tag{4.31}$$

4.5.2 Linear Equations

The application of Eq.(4.25), Eq.(4.26), Eq.(4.27), Eq.(4.28), Eq.(4.29), Eq.(4.30) and Eq.(4.31) at the $(n_2+1) \cdot n_3$ points (r_i, θ_j) within the domain $(0 \le i \le n_2,\ 1 \le j \le n_3$ or $r_1 \le r \le r_3,\ 0 \le \theta \le \pi)$ yields a set of $(n_2+1) \cdot n_3$ linear equations. The solution of the equations of heat transfer thus becomes the solution of these linear equations.

An iterative method was used for solving these linear equations. This method improves the solution from an initially guessed solution iteratively by means of computer. The iteration process will continue until the difference between the former and later solution (iterative error) is small enough and so finally obtain a converged solution.

4.5.3 Computation

The solution of the theoretical model was computed with a fortran 77 program on the university's Amdahl computer. The program is listed in the Appendix. The computational flow chart is shown in Fig.4.6. The computation starts by calculating the air pressure distribution $P_i(r,\theta)$ and the air flow distributions $V(r,\theta)$, $\upsilon(r,\theta)$ within the clothing assembly by using Eq.(4.19), Eq.(4.21), Eq.(4.22), Eq.(4.23) and Eq.(4.24). By applying $V_{i,j}$ and $\upsilon_{i,j}$, i.e. $V(r,\theta)$ and $\upsilon(r,\theta)$ in the mesh used for finite difference approximation, into the series of linear equations discussed in the last section, the temperature distribution and effective thermal insulation around the circumference of the cylindrical body were computed by iteration. The iterative error was defined as

$$\mathrm{Max}\left|T_{i,j}^{(\lambda+1)} - T_{i,j}^{(\lambda)}\right| \quad ,$$

where, λ indicates the λ-th iteration. Computational experiments showed that the numerical results were well converged if the iterative error was smaller than 0.001. In addition, n_1, n_2 and n_3 were set to be 15, 25 and 181 respectively. Good balance in the accuracy and computing time by using this step size of the mesh was judged from the preliminary computational experiments.

Whenever the results were used for comparing with the experimental ones, all constants, such as K_r, K_θ, K_{cr}, $K_{c\theta}$, K_v, r_1, r_2 and r_3 were set at the same values as those in the experiments. K_r and K_θ were assumed to be the same, so were K_{cr} and $K_{c\theta}$. K_{cr} and $K_{c\theta}$ were converted from the measured tog value in still air, viz.

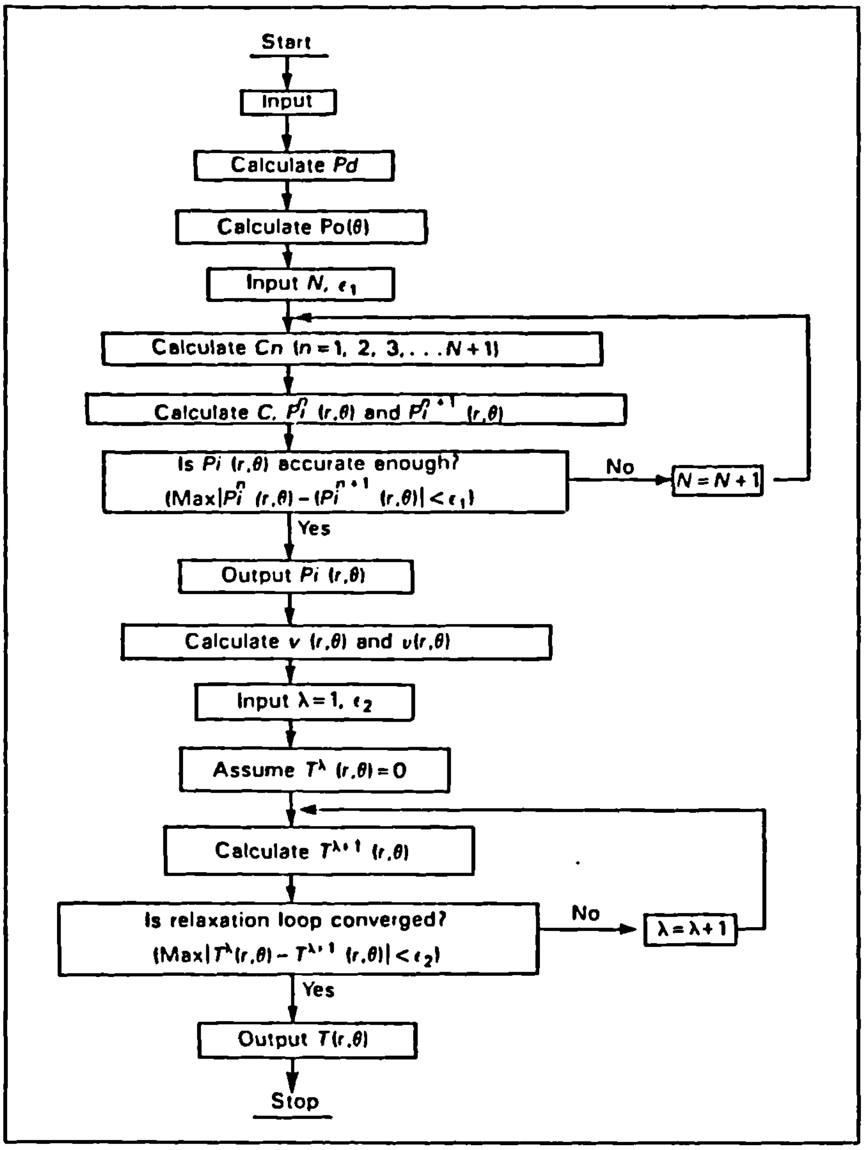


FIGURE 4.6 Computational Flow Chart.

$$Kcr = Kc\theta = \frac{10}{Rc} \cdot r2 \cdot \ln(\frac{r3}{r2}) = 0.072\ W/^{o}C\ M.$$

4.6 Results and Discussion

4.6.1 Mechanisms of Wind Induced Reduction in Thermal Insulation

THERMAL INSULATION OF CLOTHING

It has already been shown in the last chapter that air penetration and changes in clothing geometry are two essential mechanisms involved in the reduction of the thermal insulation of clothing. These two mechanisms can now be clearly identified by comparison of the theoretical and experimental results. In Fig.4.9, the thermal insulation distribution of a clothing assembly covered with moderately permeable outer fabric (type-D) is shown. As the theoretical results were obtained without the consideration of changes in clothing geometry, the discrepancy between the theoretical and experimental lines can reasonably be regarded as the result of the compression in the windward areas and expansion in the leeward areas due to the air pressure distribution outside the assembly.

Furthermore, the mechanism of air penetration, which causes the reduction in the thermal insulation in the windward areas and increase in the leeward areas, can now be better understood by considering the air pressure distribution outside and inside the clothing assembly, air flow within the clothing assembly and temperature distribution of the clothed cylindrical body, which are shown in Fig.4.7. From 0^{o}positon to about 45^{o}position, the

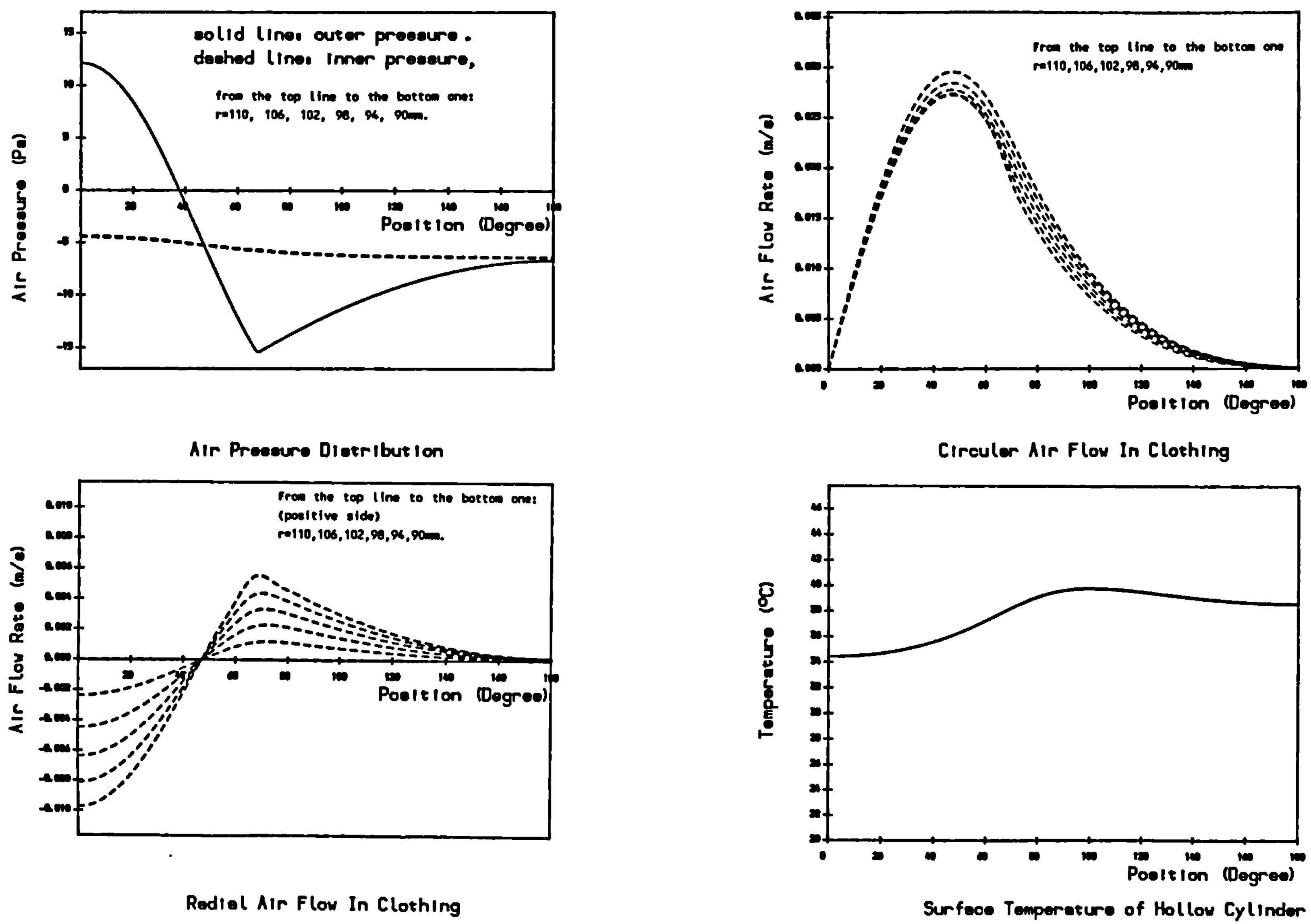


FIGURE 4.7 The Distribution of Air Pressure inside and outside a Clothing Assembly, Air Flow Rate within the Clothing, and the Outer Surface Temperature of the Vicuclad Hollow Cylinder (Outer Fabric: Type-D).

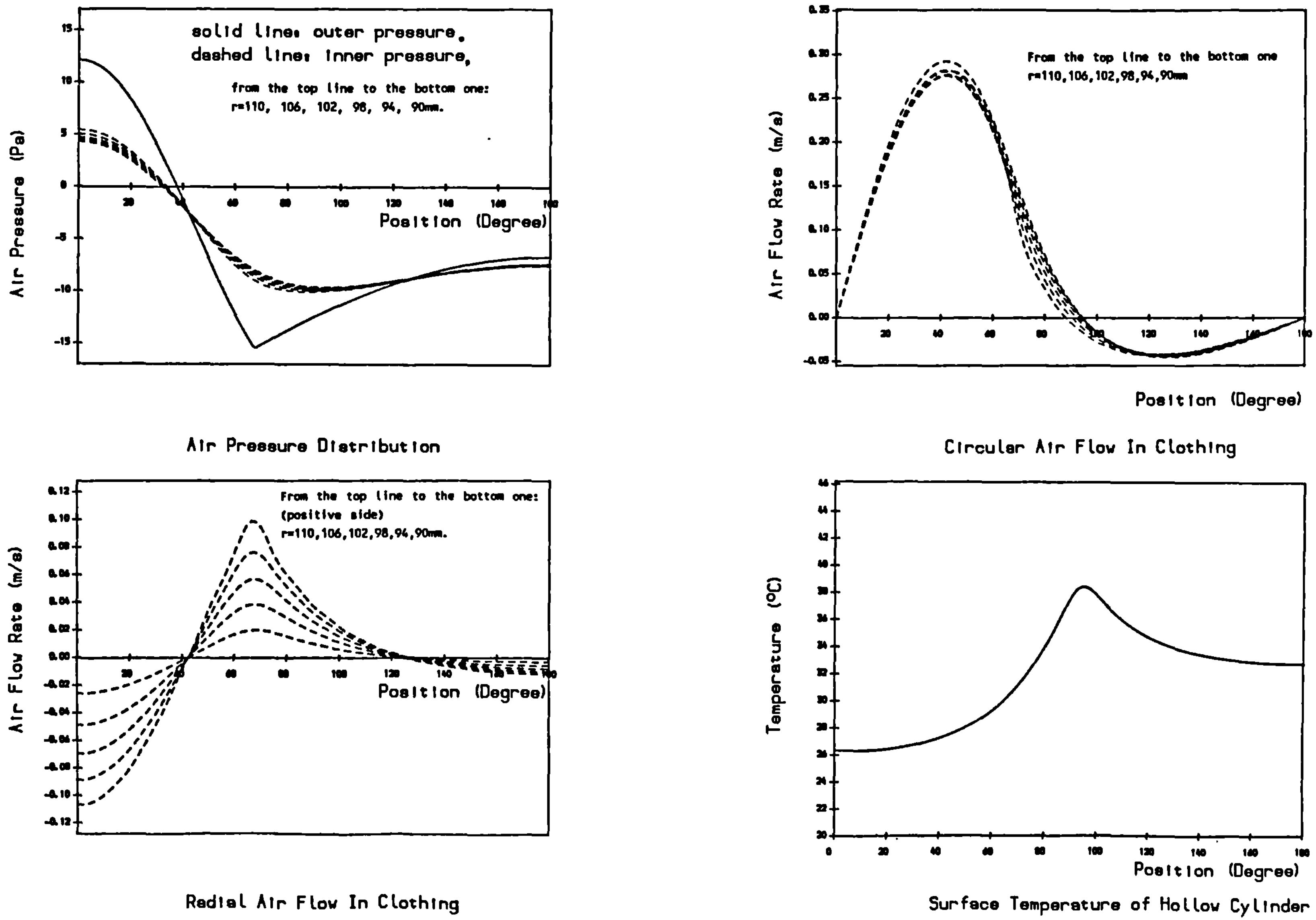


FIGURE 4.8 The Distribution of Air Pressure inside and outside a Clothing Assembly, Air Flow Rate within the Clothing, and the Outer Surface Temperature of the Vicuclad Hollow Cylinder (Outer Fabric: Type-B).

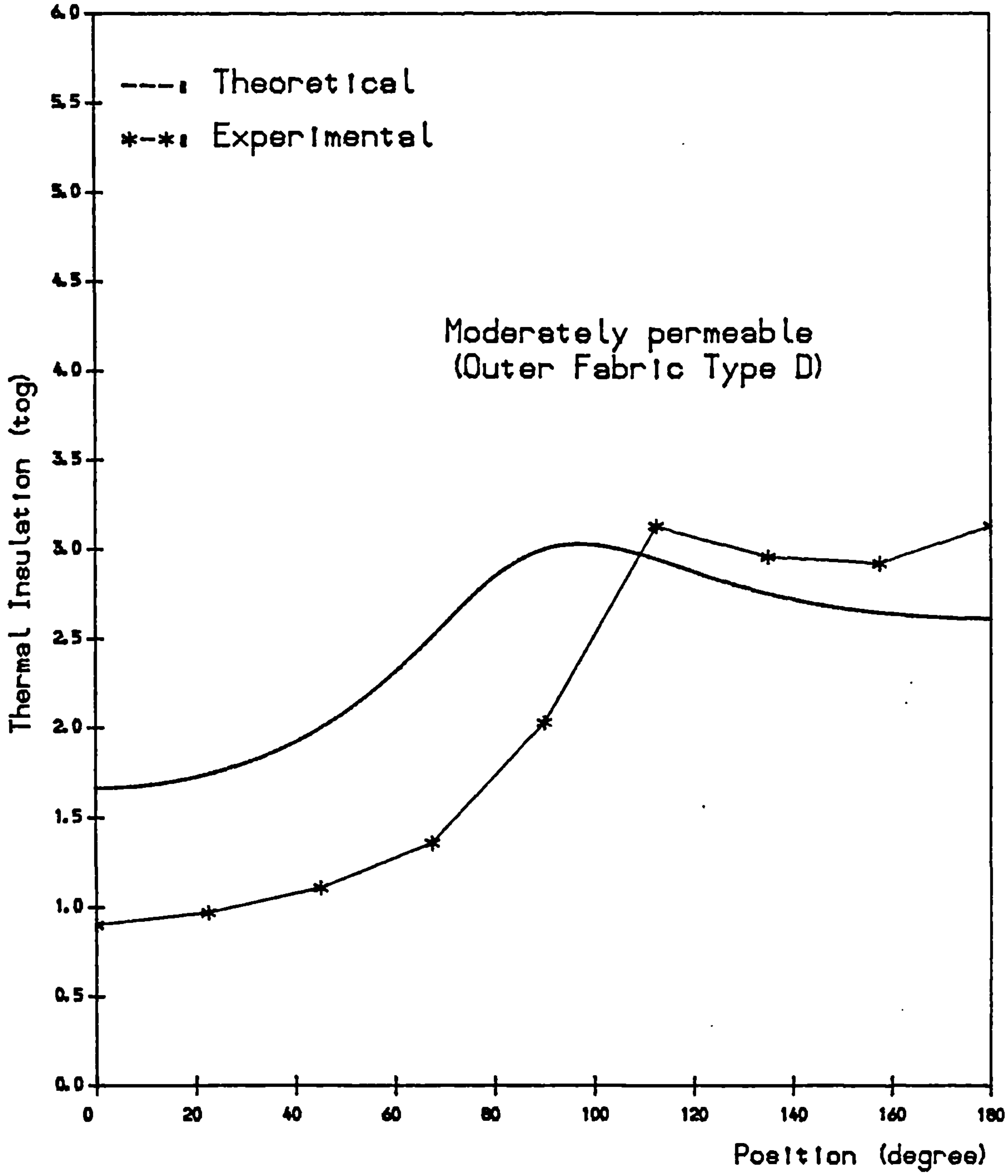


FIGURE 4.9 Clothing Thermal Insulation Distribution.

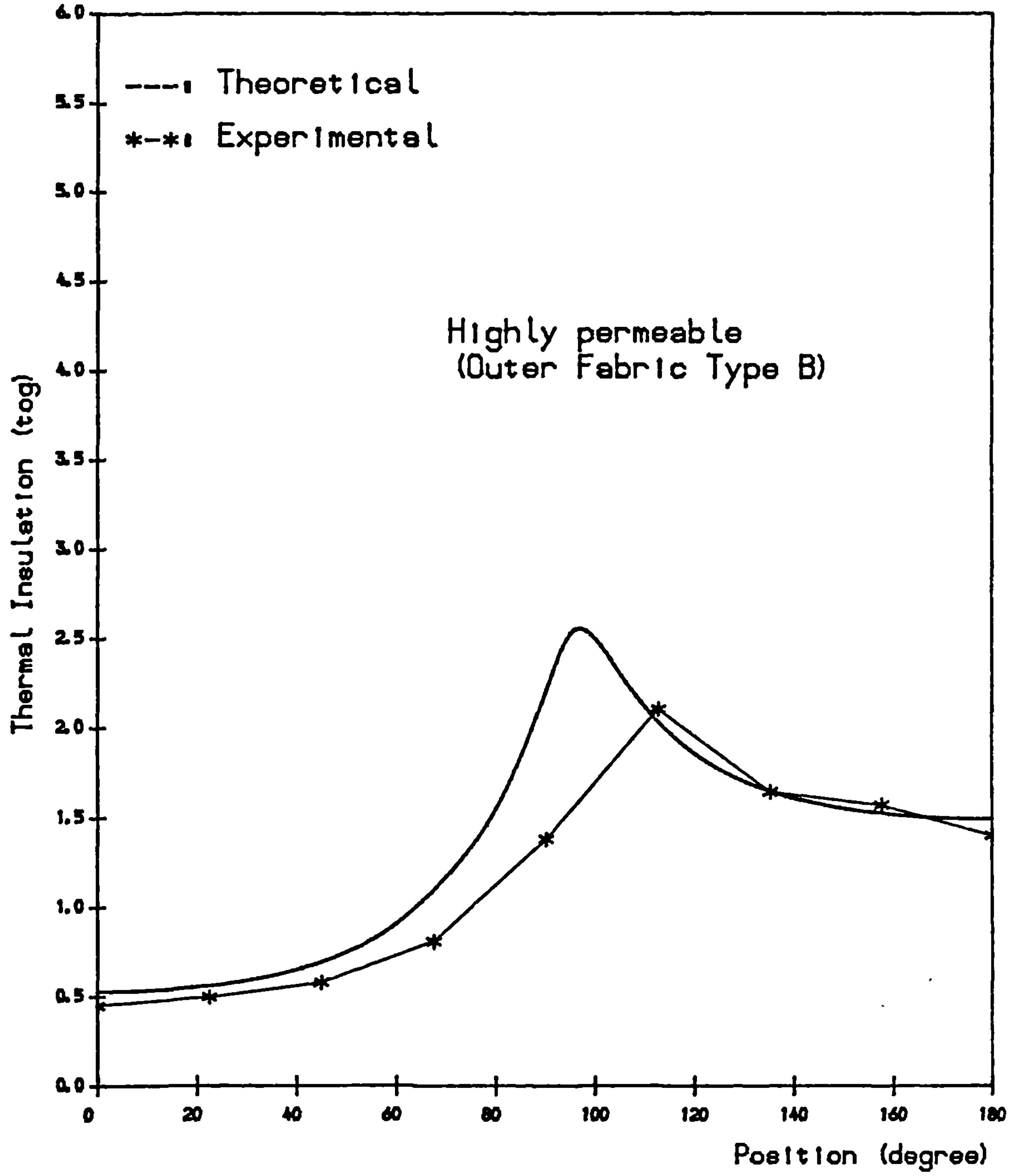


FIGURE 4.10 Clothing Thermal Insulation Distribution.

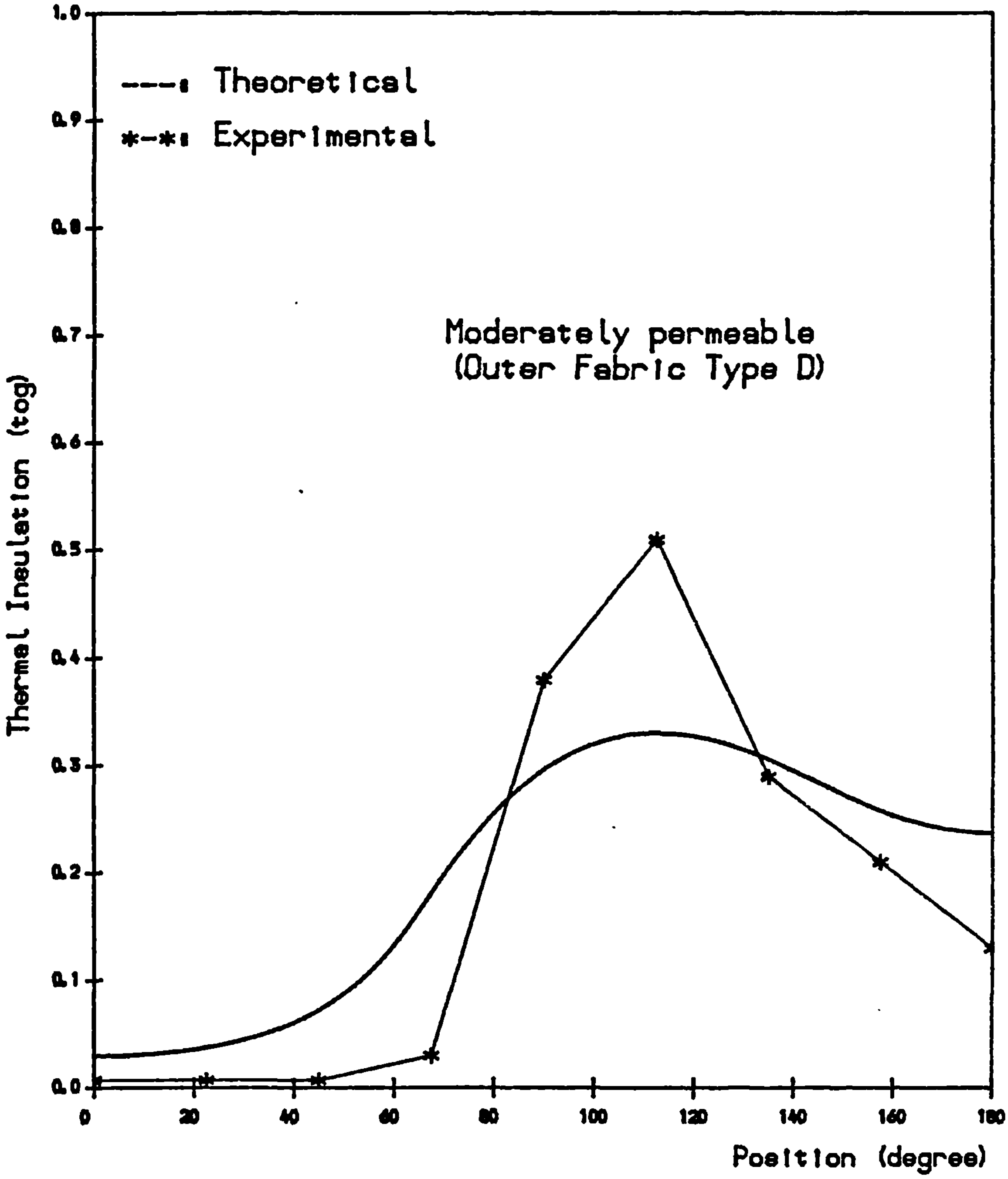


FIGURE 4.11 Surface Thermal Insulation Distribution.

outer air pressure is higher than the inner one, and cold air penetrates inwards. The air which penetrates absorbs conductive heat from the inner layer and therefore reduces the thermal insulation. Because most of the conductive heat is absorbed by penetrative air but lost into the environment, the effective thermal insulation calculated from temperature differences appears very low in that area. Due to inner air pressures, air within the insulating materials moves in a leeward direction. In the area, where the inner air pressure is higher than the outer one, heated air passes back into the environment through the outer fabric and heat is lost from within the insulation. This is why the apparent effective thermal insulation increases in the leeward area.

From the experimental observations, it had been found that clothing assemblies with highly permeable outer fabrics perform very differently in the leeward areas. As Fig. 4.10 shows, for such assemblies, not only the thermal insulation in the windward area is reduced but in the leeward area as well. The reason, however, was not understood until the air pressure and air movement within the porous material were examined with the help of the theoretical model. As can been seen from Fig.4.8, for clothing assemblies with highly permeable outer fabrics, not only can air penetrate into clothing in the windward areas but pass into the leeward areas as well.

SURFACE THERMAL INSULATION

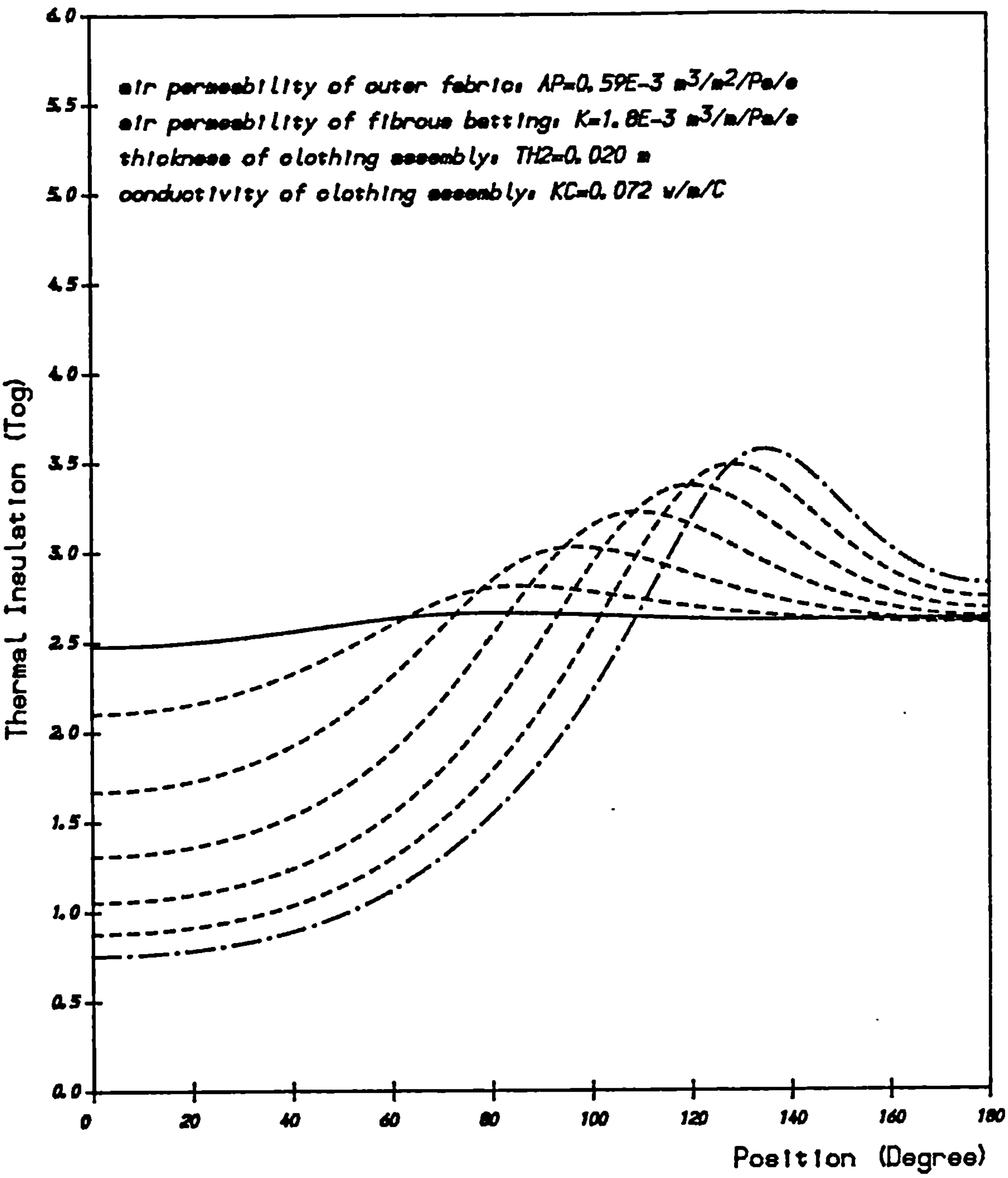
Typical theoretical and experimental results of surface thermal insulation in windy conditions are compared in Fig.4.11.

The absolute values of the theoretical results are subject to the accurancy of surface convective heat transfer coeffient converted from the surface thermal insulation of impermeable clothing assemblies. However, the comparison in Fig.4.11 certainly provides evidence to explain how air penetration affects the surface thermal insulation. In the windward areas, the absorption of conductive heat by the penetrative air reduces the surface thermal insulation dramatically, while in the leeward areas, the surface thermal insulation is increased because hot air passes into the cold environment.

4.6.2 Effects of Wind Velocity

The theoretical results of the thermal insulation distribution of clothing under a range of wind velocities for a moderately permeable assembly are shown in Fig.4.12. If this is compared with the experimental results shown in Fig.3.7, their behaviours are in good agreement. As far as this sample is concerned, in the windward areas, thermal insulation reduces with increasing wind velocity. The rate of reduction reaches its maximum at the wind velocity of about 3.0 m/s, then slows down as the wind velocity increases. While, in the leeward areas, the thermal insulation increases, but the change is small.

As far as the surface thermal insulation is concerned, the results in Fig.4.13 showed a rather complicated, but interesting phenomenon. One point, which can be raised from the theoretical solution, is that the maximum surface insulation changes its angular position with increasing wind velocity. This confirms the

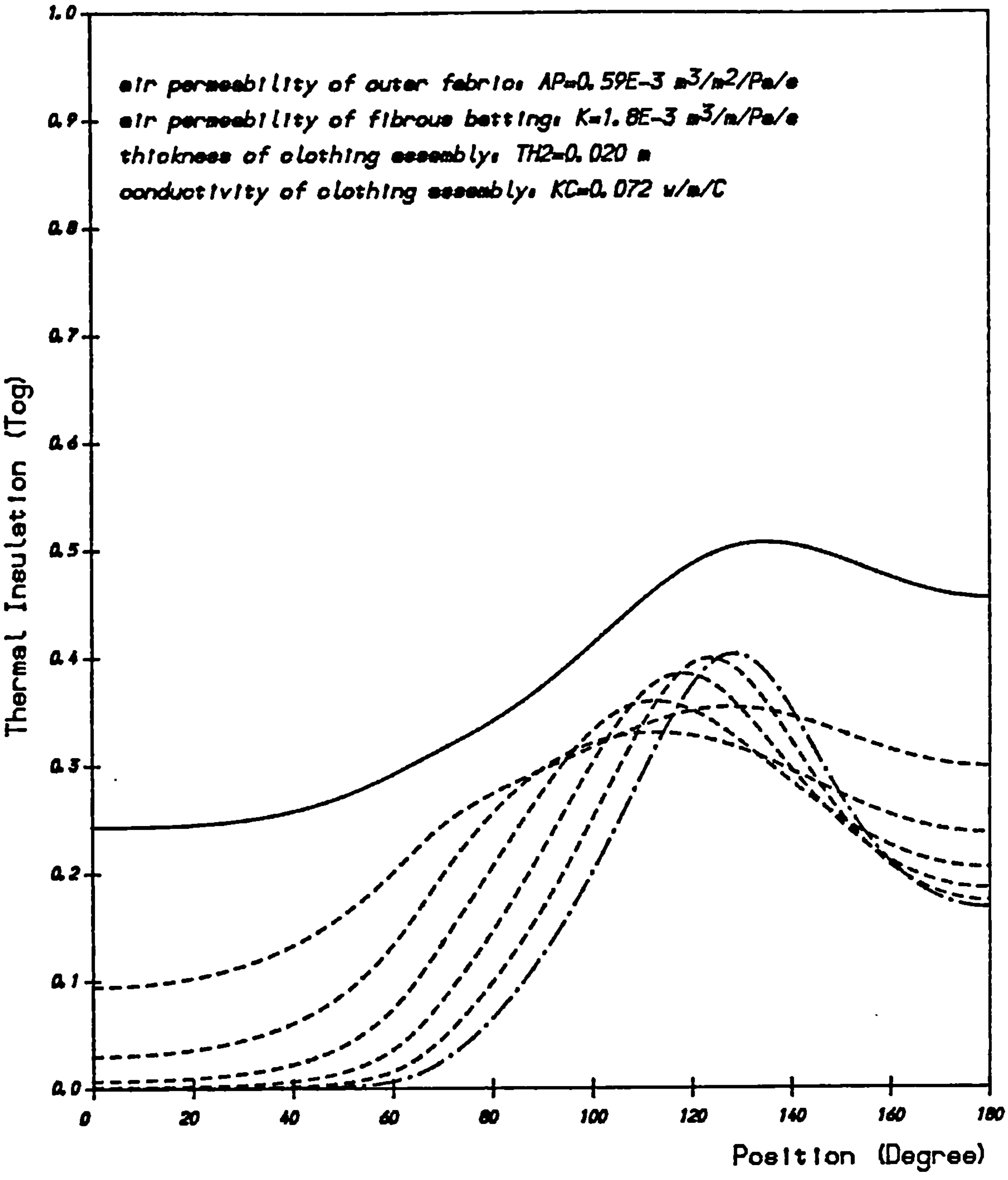


Corresponding Wind Veltcity of Each Curve:

solid curve to dashed curve: 1.5 to 10.5 (step: 1.5)
units: m/s

Clothing Thermal Insulation Under Different wind Velocities

FIGURE 4.12.



Corresponding Wind Velicity of Each Curve:

solid curve to dashed curve: 1.5 to 10.5(step: 1.5)
unit: m/s

Surface Thermal Insulation Under Different wind Velocities

FIGURE 4.13.

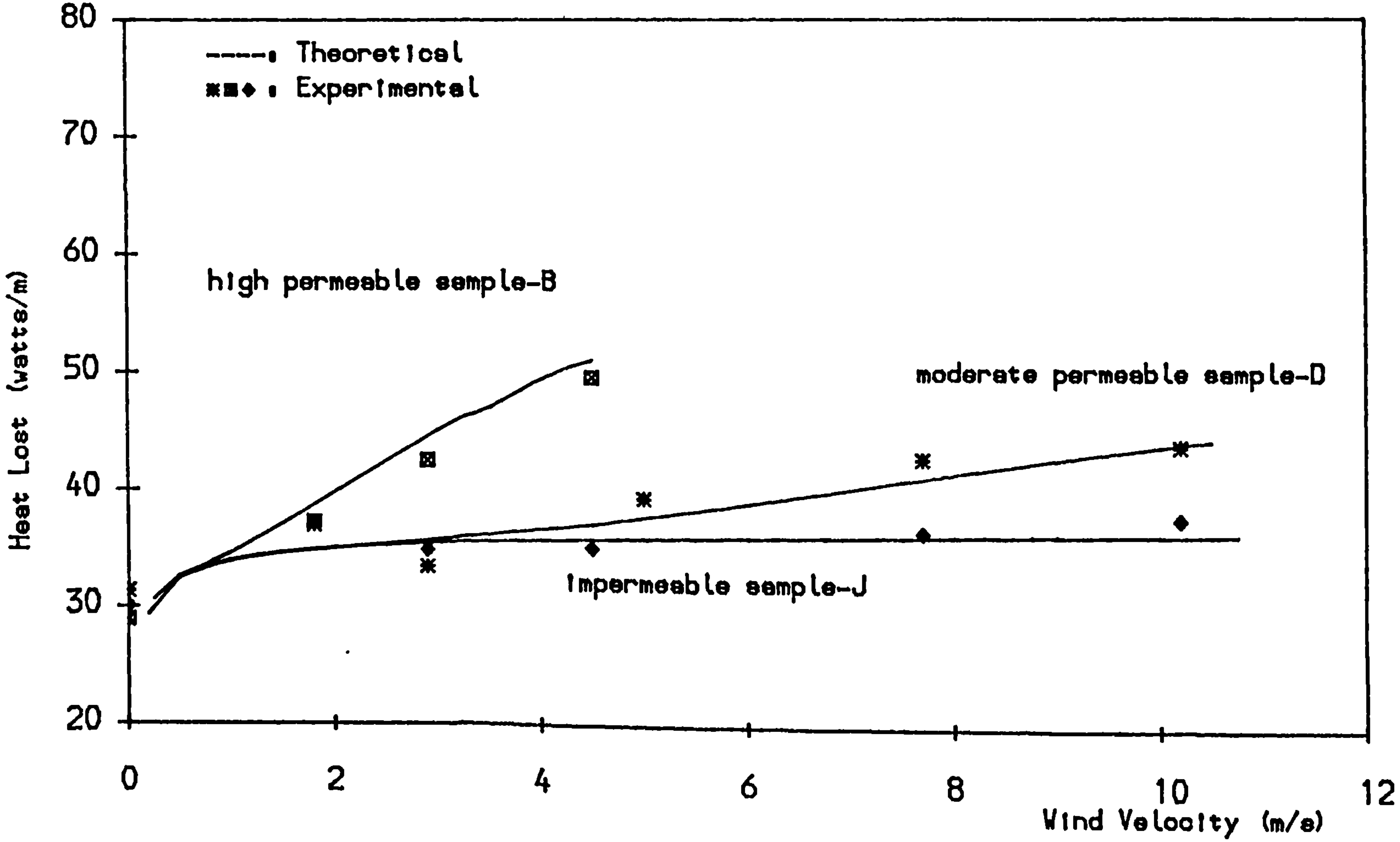


FIGURE 4.14 Heat Lost Under Different Wind Velocities.

findings from the experimental results.

The effect of wind on the total heat lost from the clothed cylindrical system is perhaps more important. With the experimentally measured temperatures over the circumference, the total heat lost from the system was computed as follow,

$$H = \sum_{i=1}^{n} \frac{1}{n} \cdot 2\pi r2 \cdot \frac{0.5[T2(i)+T2(i+1)]-T1}{Rs} \quad ,$$

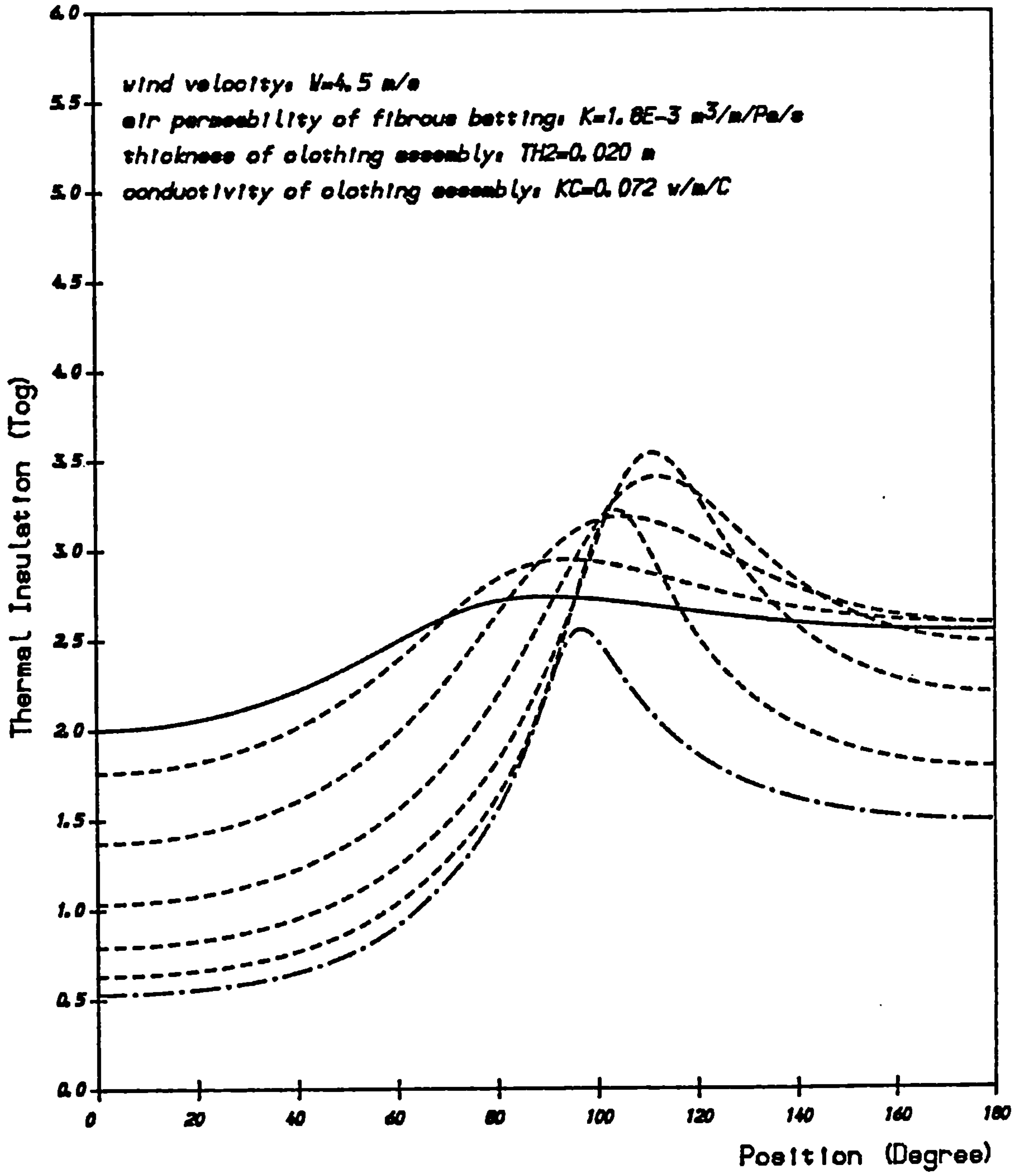
where, T2 is the outer surface temperture of the viculcad cylinder, Rs is the thermal resistance of the vicuclad cylinder, $Rs=\frac{10}{Kv} \cdot r2 \cdot Ln\frac{r2}{r1}$, n is the number of evenly spread positions where temperatures were measured. While, from the theoretical model, the total heat lost can be calculated by using the following equation.

$$H = 2 \cdot \int_0^{\pi} Kv \cdot \frac{\partial T}{\partial r}\bigg|_{r=r2} \cdot r2 \cdot d\theta \quad .$$

The total heat lost from the system for clothing assemblies of three typical outer fabrics under different wind velocities is shown in Fig.14. The difference between theoretical and experimental results is less than that of thermal insulation distribution. This is because the effect of the compression and expansion of the essemblies on the experimental results of the overall heat lost is partly self cancelling. As can been seen, for clothing assemblies with all kinds of outer fabrics, heat lost increases with increasing wind velocity, but the rate of increase reduces gradually. At low wind velocities, heat lost from the system can be the same for clothing assemblies which use different permeable outer fabrics. And interestingly, it seems that there is a critical value of wind velocity for a clothing assembly with a given kind of permeable outer fabric. When the wind velocity is lower than this critical value of wind velocity, the total heat lost from the permeable system is the same as that from an impermeable one. This is because the reduction of thermal insulation in the windward area is compensated by the increase in the leeward area. It can be seen, that when the wind velocity is lower than 3m/s, a clothing assembly of a moderately permeable outer fabric (type-D) behaves equally well to that of an impermeable outer fabric in terms of overall thermal insulation. However, the thermal insulation of a clothing assembly of a knitted outer fabric is much lower unless the wind velocity is below 0.8m/s.

4.6.3 Effects of the Air Permeability of Outer Fabrics

The theoretical results of thermal insulation of clothing for assemblies with different permeable outer fabrics are plotted in Fig.4.15. It shows that thermal insulation in the leeward areas increases slightly with increasing air permeability of outer fabrics until the air permeability gets higher than $2.0\times10^{-3}m^3/m^2/Pa/sec$, after which the thermal insulation declines. This reveals why only clothing assemblies with highly permeable outer fabrics has its thermal insulation reduced in the leeward areas, a fact which was first noted from the experimental results. The theoretical results of the surface thermal insulation shown in Fig.4.16 has a similar trend to that of experimental results shown in Fig.3.9. In both windward and leeward areas, surface thermal



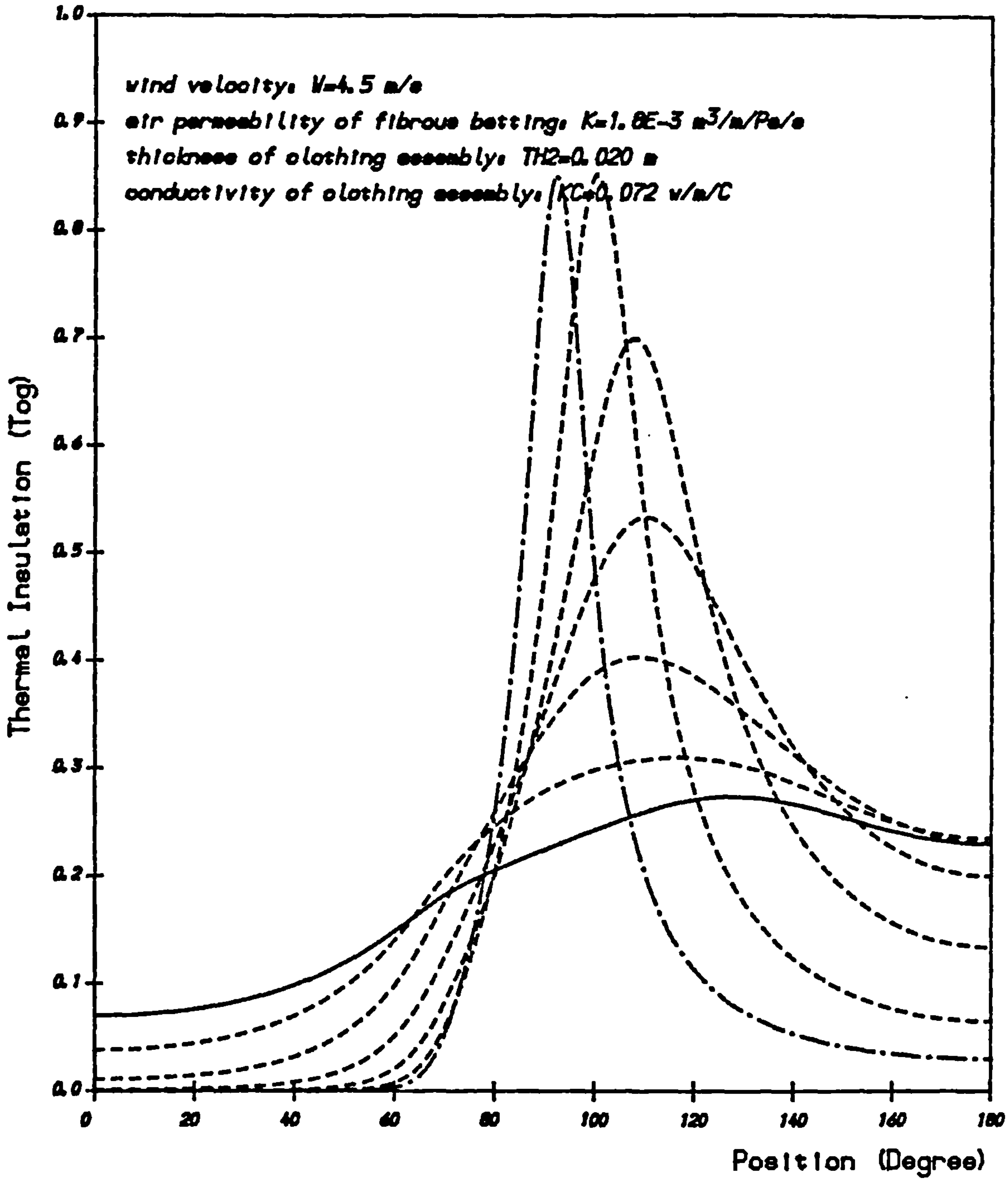
Corresponding Air Permeability of Each Curve:

solid curve to dashed curve: 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, 16.0

unit: $10^{-3} m^3/m^2/Pa/sec$

Clothing Insulation for Clothing Assemblies of Different Air Permeable Outer Fabrics

FIGURE 4.15.



Corresponding Air Permeability of Each Curve:

solid curve to dashed curve: 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, 16.0

unit: $10^{-3}m^3/m^2/Pa/sec$

Surface Insulation for Clothing Assemblies
of Different Air Permeable Outer Fabrics

FIGURE 4.16.

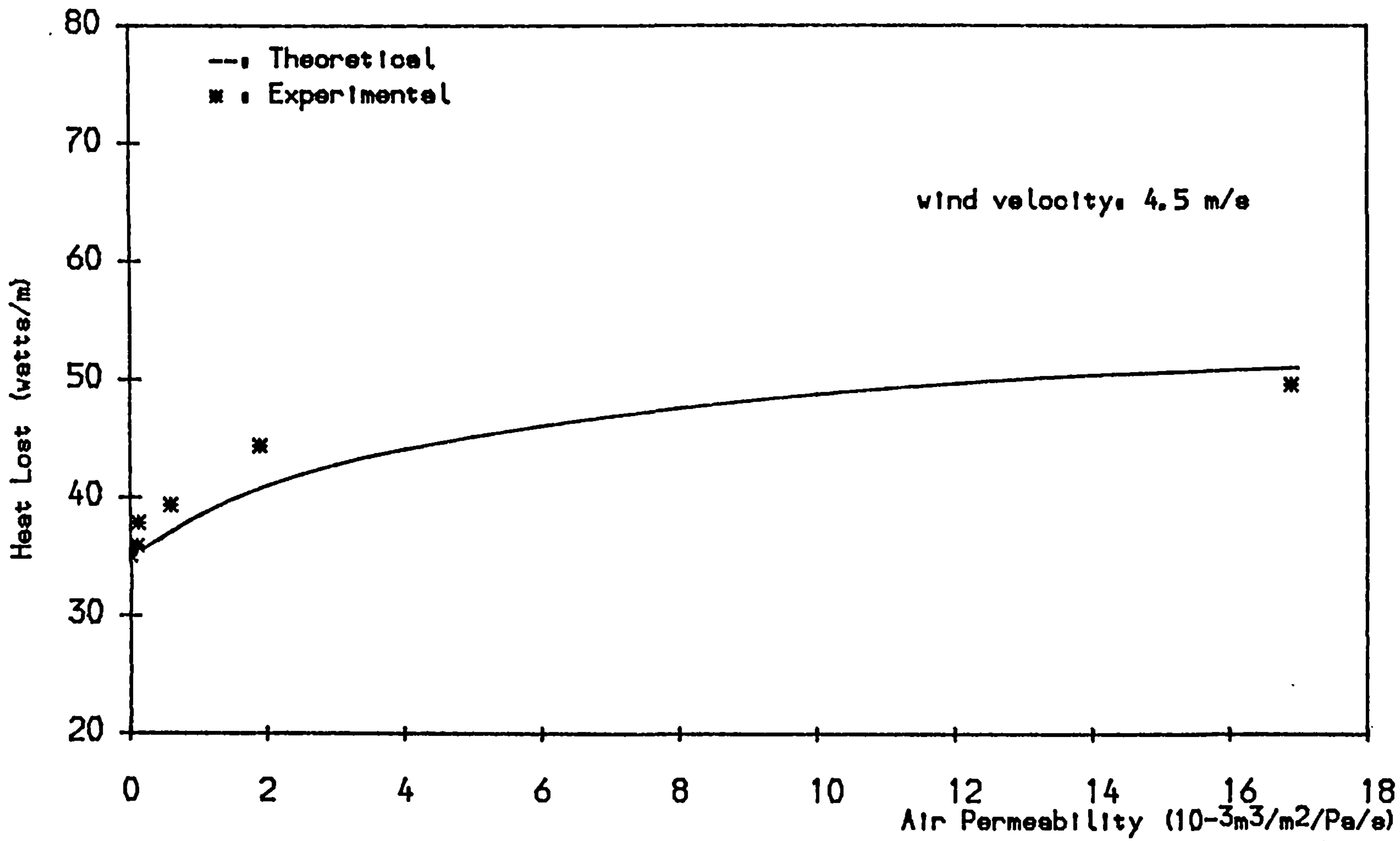


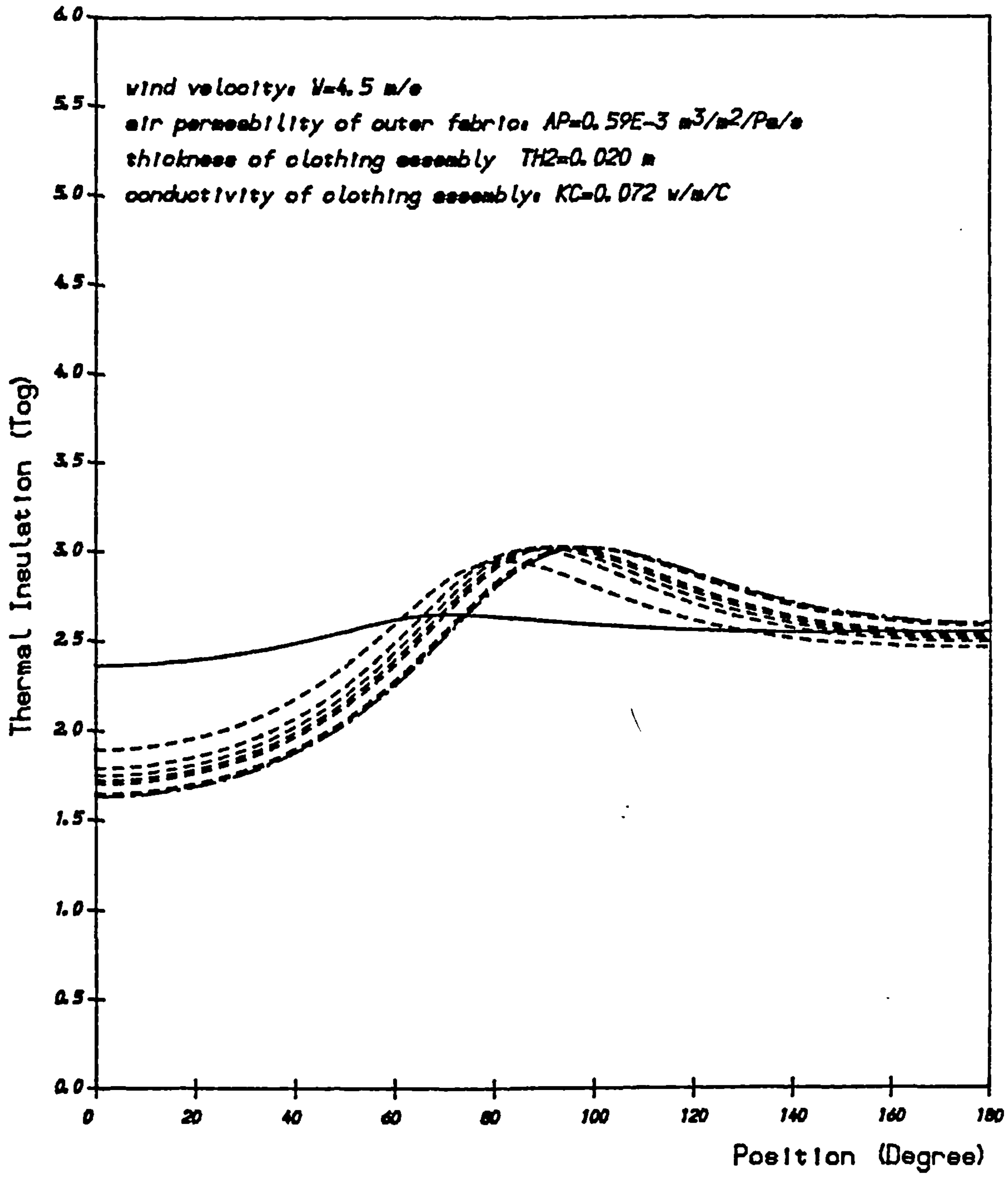
FIGURE 4.17 Heat Lost through Assemblies of Different Permeable Outer Fabrics.

insulation reduces with increasing air permeability, but at around 90° position, the surface thermal insulation increases.

Heat lost from the system plotted against air permeability of the outer fabric is shown in Fig.17. As can be seen, if the thermal insulation of clothing assemblies using different air permeable outer fabrics are to be compared, the differences will be large for low fabric permeability and small if they are all highly permeable.

4.6.4 Effects of the Air Permeability of Fibrous Battings

It was claimed that fibrous battings with large specific surfaces such as "thinsulate" are of considerable significance in connection with the thermal insulation properties [Rees, 1971], because convection is minimised as still air is retained near fibre surfaces due to frictional effects. Hence fibrous battings with a low permeability but with the same packing density would be better insulators. This has been demonstrated in still air conditions. It is interesting to see if this still applies at high air velocities. For clothing assemblies covered with moderately permeable outer fabrics, the results shown in Fig.4.20 suggest that little difference exists for different air permeabilities in terms of overall heat lost. The reason can been found from the results shown in Fig.4.18, for more permeable clothing assemblies, a higher increase in thermal insulation in the leeward area compensates for the higher reduction in the windward area. If local thermal insulation is not important, one would speculate that fibrous battings of large specific surfaces, in order words,

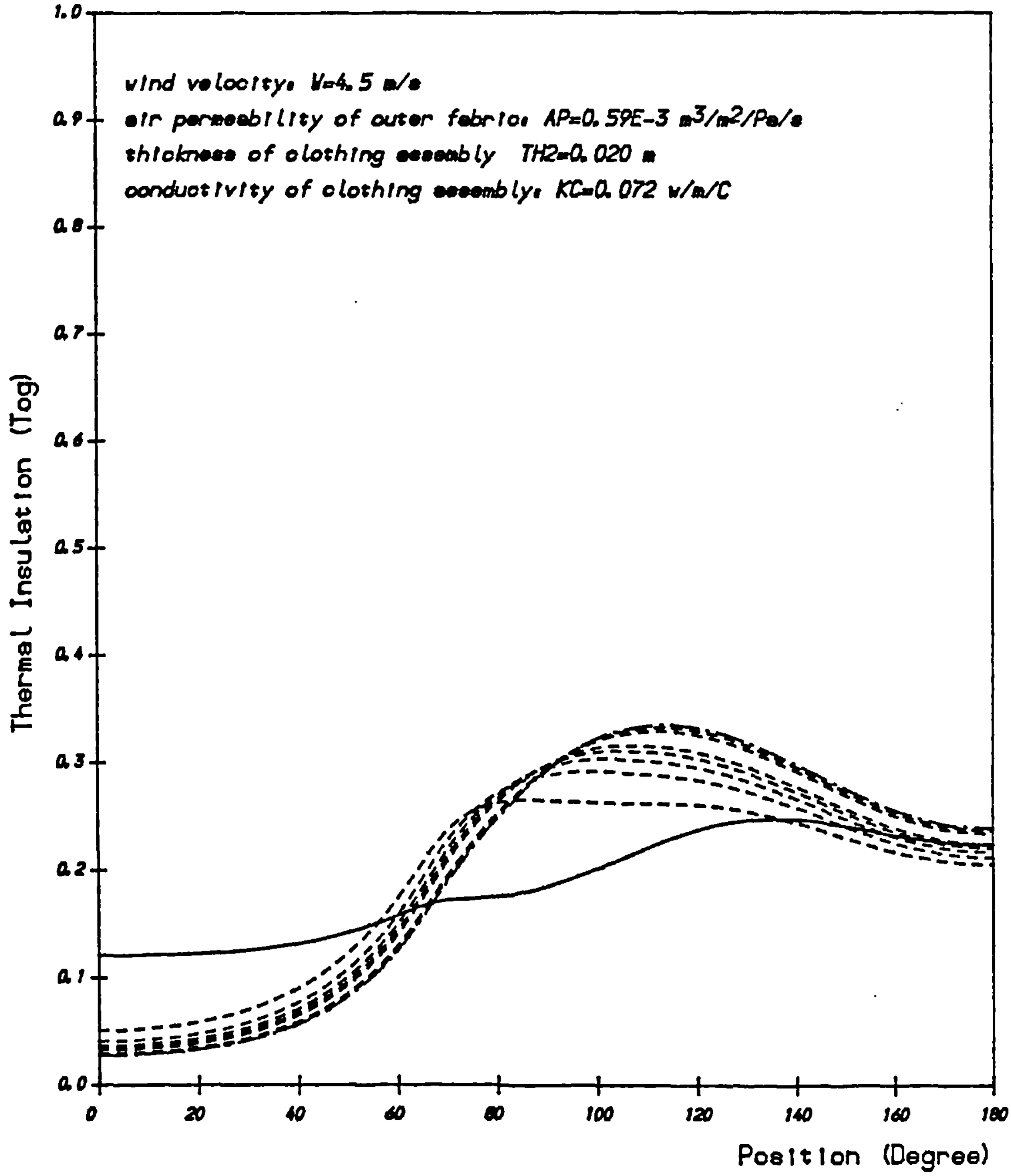


Corresponding Air Permeability of Each Curve:

solid curve to dashed curve: 0.01, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 3.0, 4.0
unit: $10^{-3} m^3/m/Pa/sec$

Clothing Insulation Distribution
For Assemblies of different permeable Fibrous Battings

FIGURE 4.18.



Corresponding Air Permeability of Each Curve:

solid curve to dashed curve: 0.01, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 3.0, 4.0
units: $10^{-3} m^3/m/Pa/sec$

Surface Insulation Distribution
For Assemblies of different permeable Fibrous Battings

FIGURE 4.19.

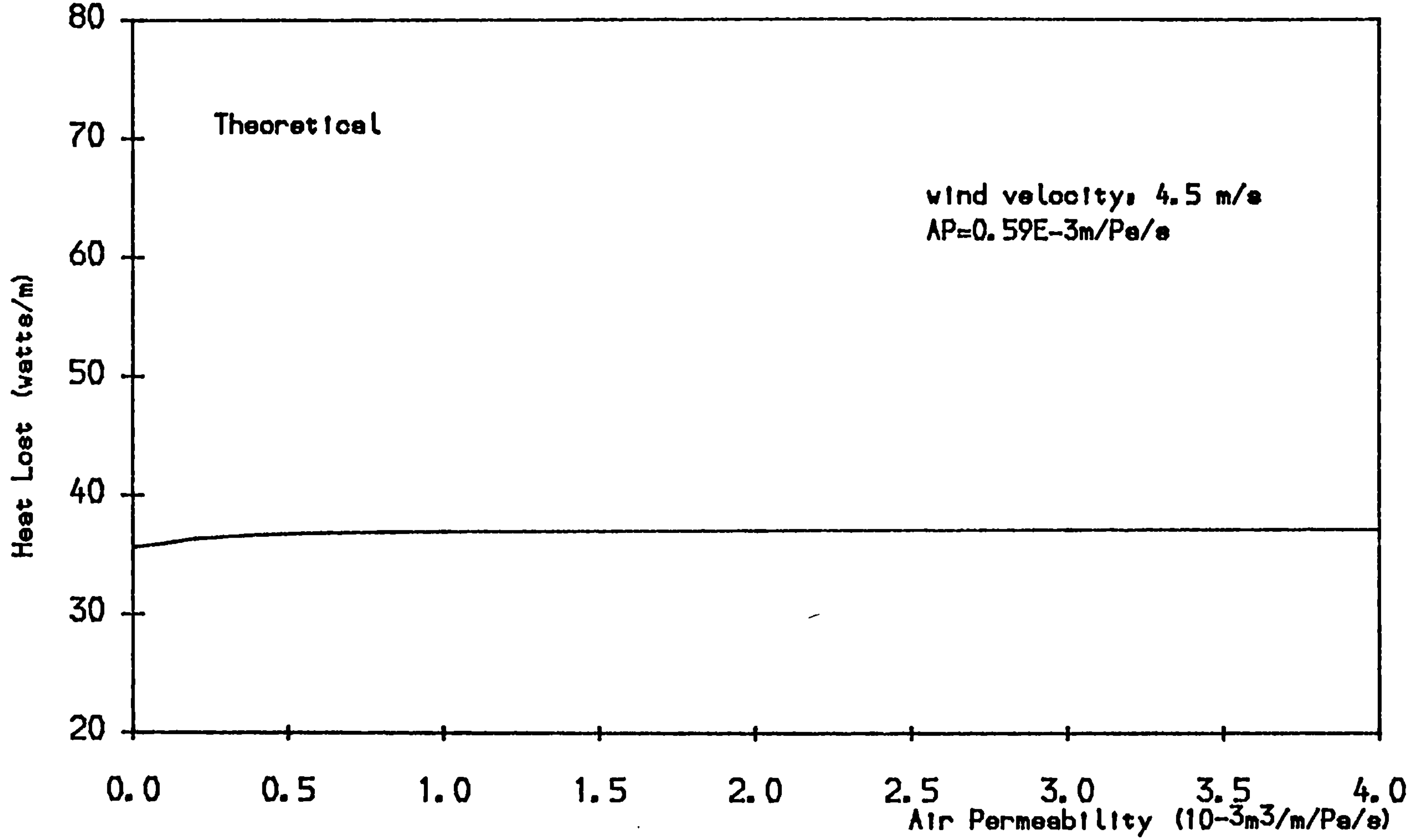


FIGURE 4.20 Heat Lost through Assemblies of different permeable fibrous battings.

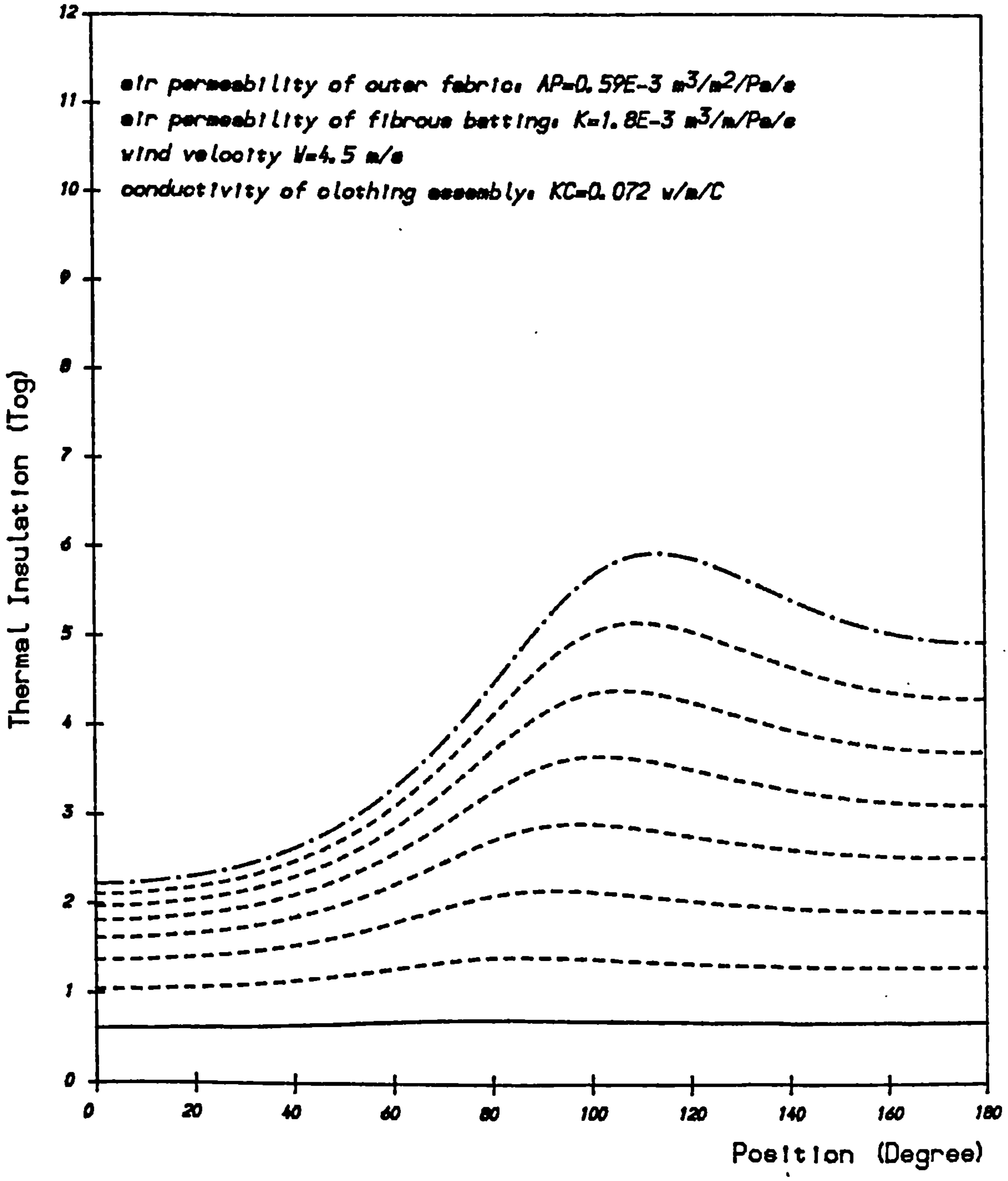
low air permeabilities, are of little better than those of low specific surfaces in windy conditions, if the outer fabric is not too permeable. The surface insulation distribution for fibrous battings of different permeabilities is shown in Fig. 4.19.

4.6.5 Effects of the Thickness of Fibrous Battings

The thermal insulation of textile materials is almost proportional to their thickness. One would expect that clothing thermal insulation is proportionally related to the thickness variations over the circumference of a clothed cylindrical body. However, in strong windy conditions, Fig.4.21 shows that the thermal insulation increases less with thickness in the windward area than in the leeward area. The heat lost from the system is not proportional to the thickness variation as shown in Fig.4.23. The surface thermal insulation distribution of clothing assemblies with different thickness of fibrous battings is shown in Fig.4.22.

4.6.6 Effects of Body Dimensions

The dimension of the Vicuclad cylinder in the model is similar to the dimensions of the human trunk or limbs. Results shown in Fig.4.24, Fig.4.25 and Fig.4.26 were computed for clothing assemblies covered on Vicuclad hollow cylinders of different outer radii. These results showed that the dimensions of the human trunk or limbs affect the thermal insulation such that the bigger the dimension, the higher the thermal insulation of clothing. This comforms to common experience that the trunk is easier to keep warm than the arms, legs or hands.

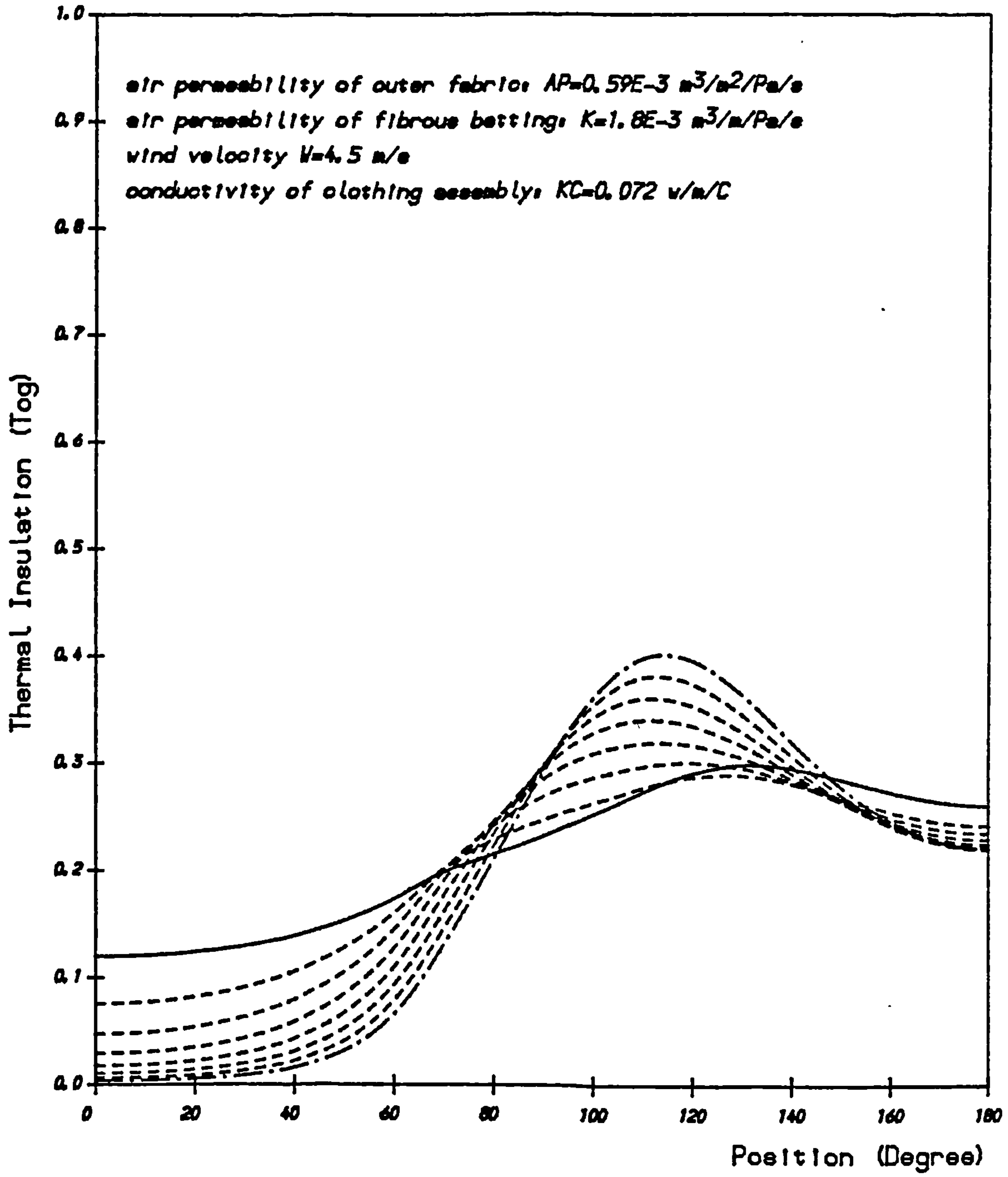


Corresponding Thickness of Each Curve:

solid curve to dashed curve: 0.5 TO 4.0 (step: 0.5)
unit: cm

Clothing Insulation Distribution
For Assemblies of Fibrous Battings of Different Thickness

FIGURE 4.21.



Corresponding Thickness of Each Curve:

solid curve to dashed curve: 0.5 TO 4.0 (step: 0.5)
unit: cm

Surface Insulation Distribution
For Assemblies of Fibrous Battings of Different Thickness

FIGURE 4.22.

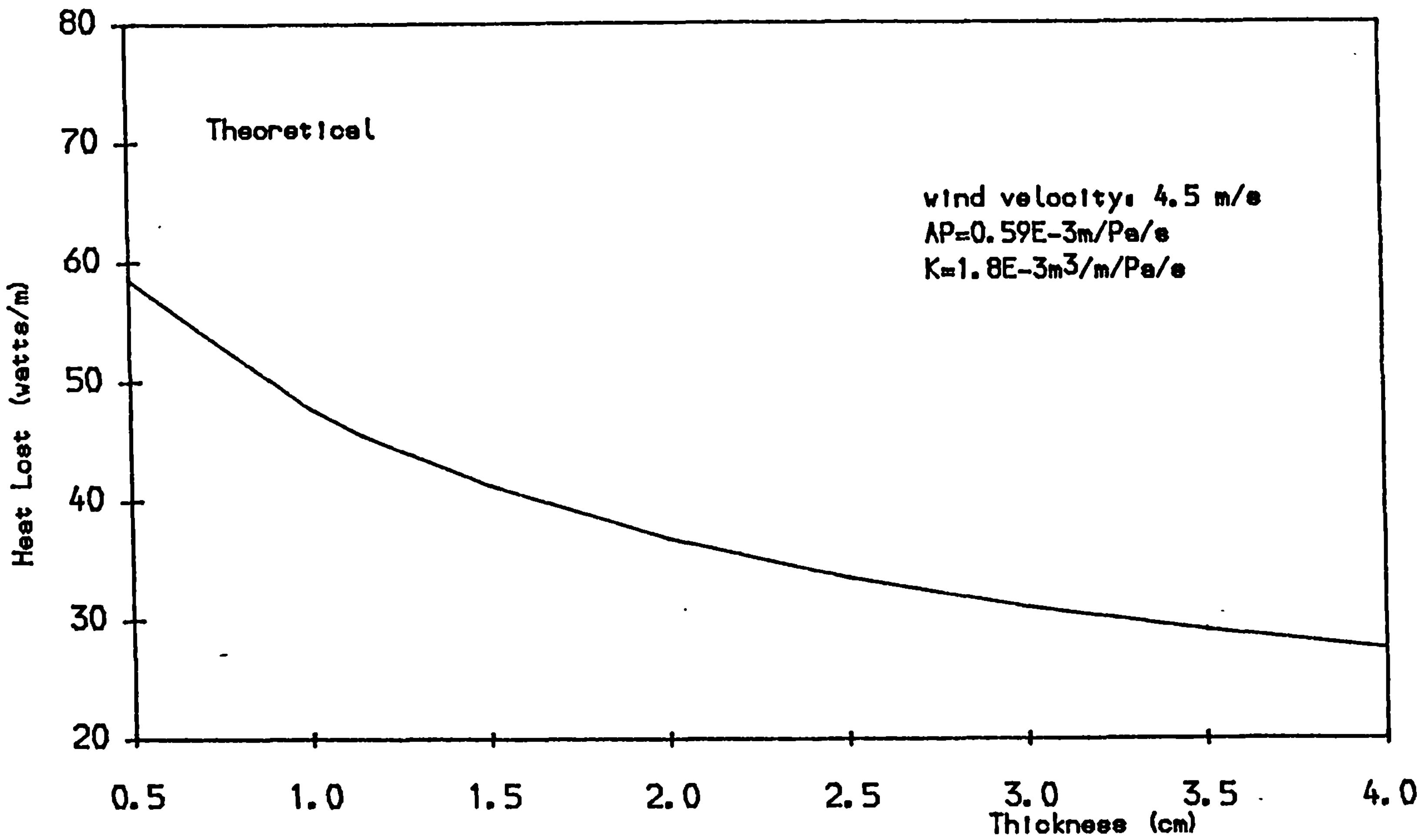
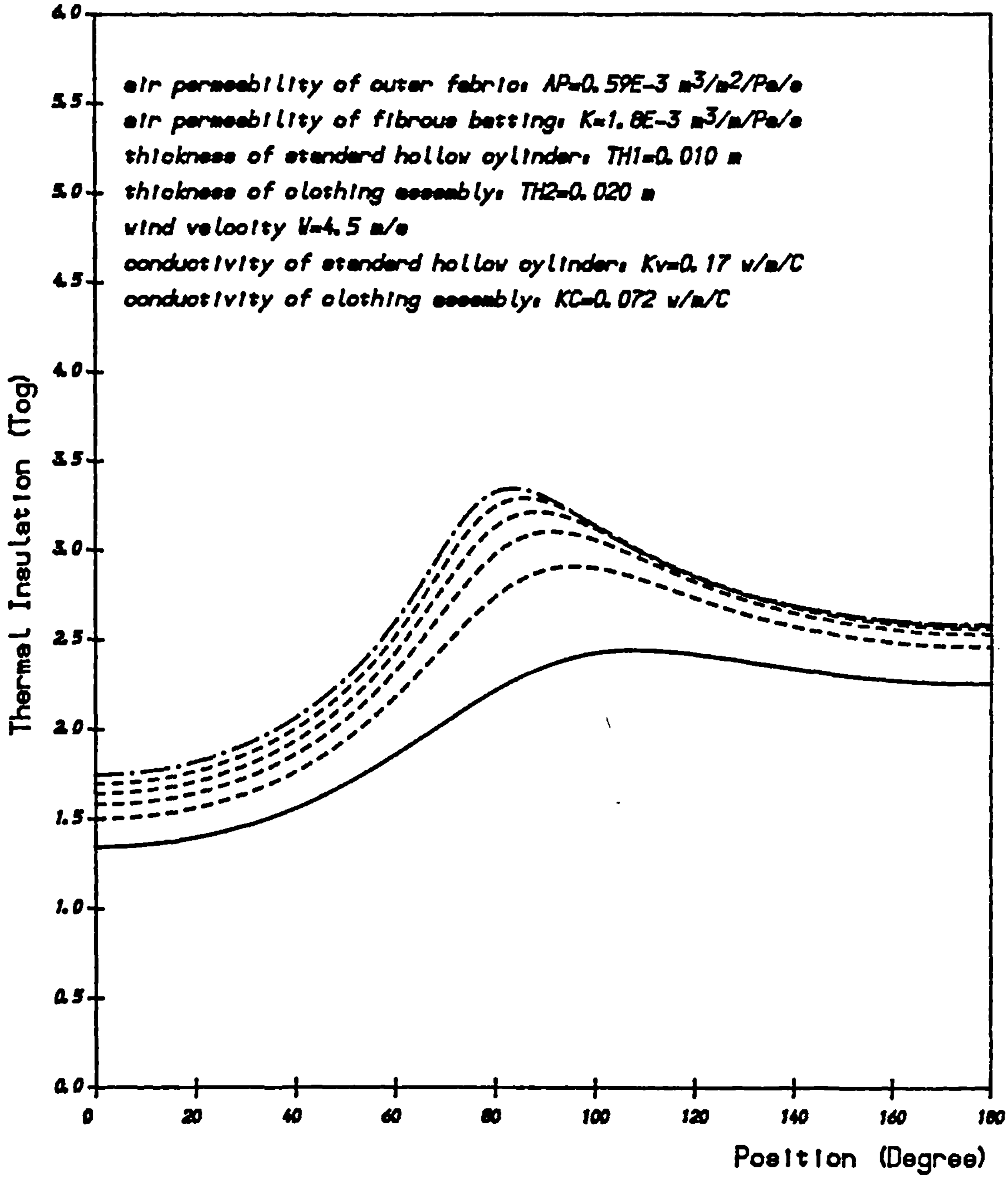


FIGURE 4.23 Heat lost through Assemblies of Different Thickness.

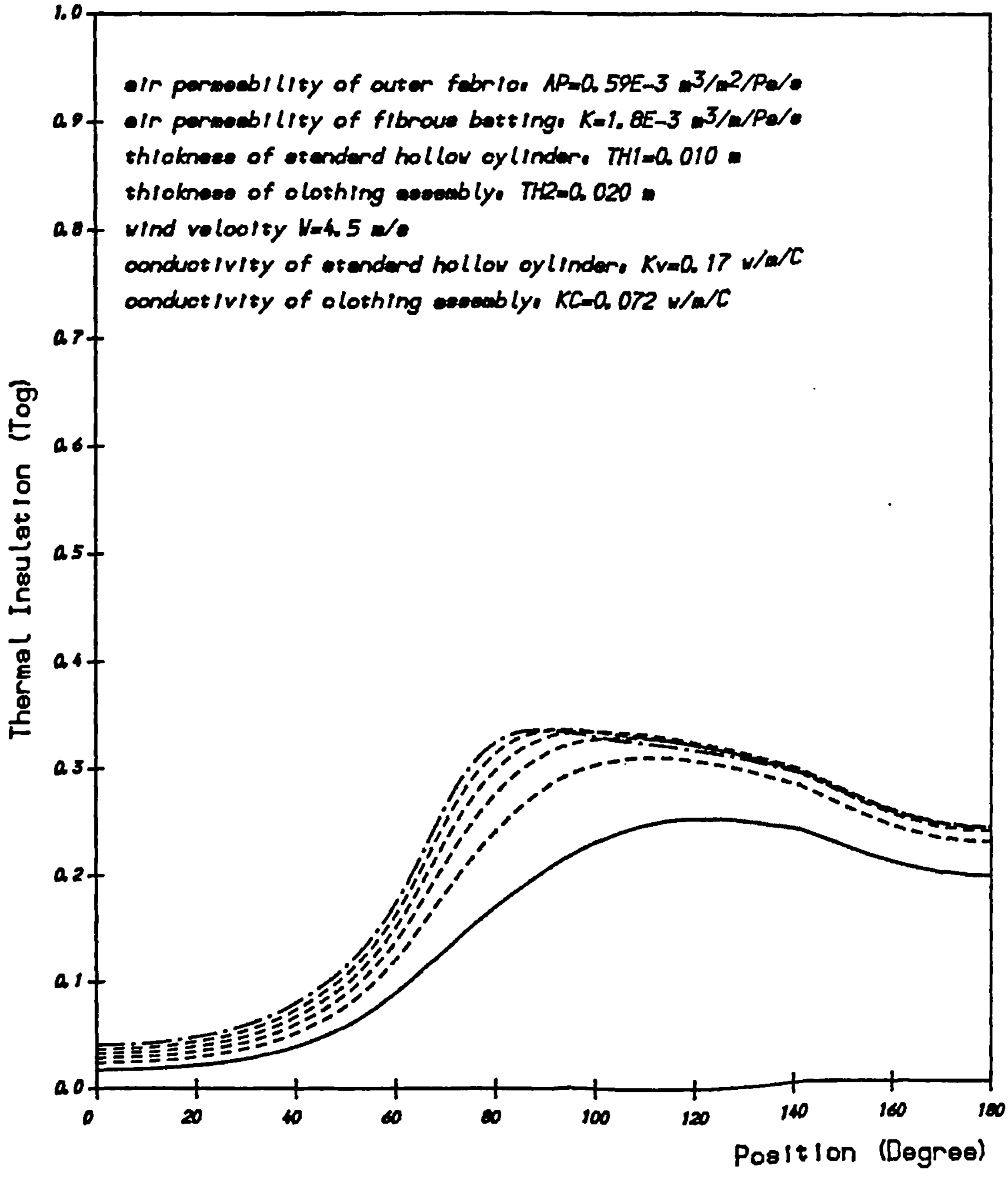


Corresponding Outer Radius of Standard Hollow Cylinder of Each Curve:

solid curve to dashed curve: 3.0 to 18.0 (step: 3.0)
unit: cm

Clothing Insulation Distribution
For Assemblies Covered on Hollow Cylinders of Different Sizes

FIGURE 4.24.



Corresponding Outer Radius of Standard Hollow Cylinder of Each Curve:

solid curve to dashed curve: 3.0 to 18.0 (step: 3.0)
units: cm

Surface Insulation Distribution
For Assemblies Covered On Hollow Cylinders of Different Sizes

FIGURE 4.25.

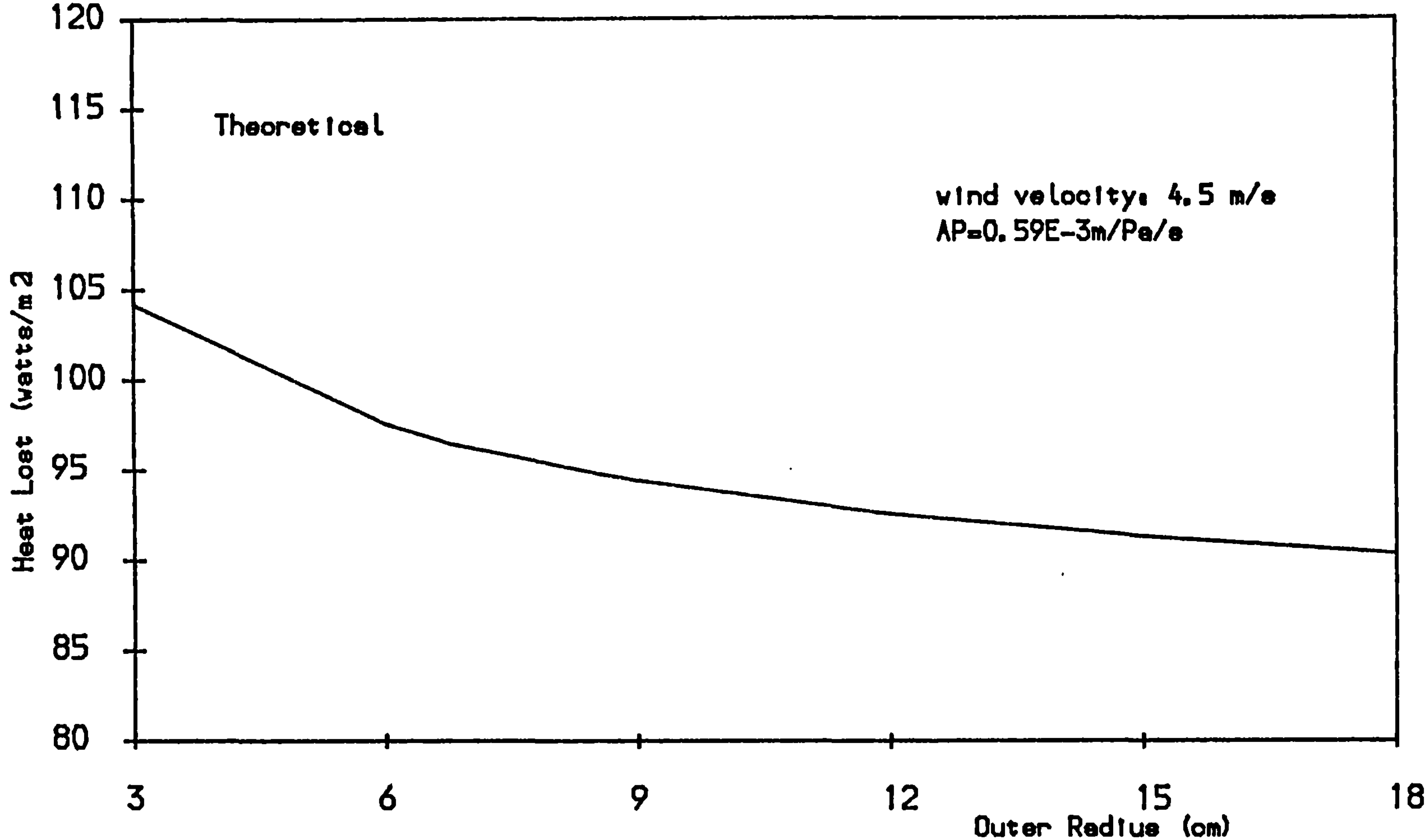


FIGURE 4.26 Heat Lost through Assemblies Covered on Hollow Cylinders of Different Outer Radii.

4.7 Concluding Remarks

The clothing thermal insulation in actual windy conditions is very complex. Wind, clothing system and human body can never be described in simple terms. However, considering the basic mechanisms, which are air penetration and changes in clothing geometry, the model presented here is representative, especially for a person wearing an anorak. The heat lost from each of the limbs of a sedentary man wearing a close-fitting anorak in a strong windy condition can be essentially predicted from the model.

As regards clothing manufacture, the work demonstates that, (1), there is an optimal selection of outer fabrics as a cover of a clothing system used for windy conditions in respect of air permeability. At low wind velocities, a moderately permeable outer fabric should be selected rather than an impermeable one which is expensive and impermeable to moisture transfer. (2), in contrast to the behaviour in still air conditions, fibrous battings of large specific surfaces are of little significance in thermal insulation in windy conditions. (3), because the thermal insulation of clothing reduces in the windward areas and increases in the leeward areas, a proper clothing design should have more textile materials in the windward area than in the leeward area if these are predictable in use. (4), to prevent the reduction caused by compression, rigid fibrous battings may be perferable within the limit of body movement.

Chapter 5

The Design of Effective Clothing for Use in Windy Conditions

5.1 Introduction

As a result of the experimental and theoretical investigations into clothing assemblies in windy conditions, the mechanisms involved are illucidated in this work. We now turn to the problem how to apply these findings to the design and construction of effective clothing for use in windy conditions.

In the last chapter, some design methods of optimal selection and use of outer fabrics and inner fibrous battings were suggested. However, these methods still failed to eliminate the reduction in thermal insulation by air penetration when air permeable outer fabrics are used in the construction of clothing systems for use in windy conditions. If impermeable outer fabrics are used to prevent air penetration, as they are traditionally, sensations of discomfort can arise due to the restriction of moisture vapour lost from inner body of the wearer. In this chapter, we consider the design methods by which air penetration is prevented even though the outer fabrics of clothing systems are air permeable, and therefore design clothing systems which are both wind resistant protective and moisture vapour permeable. These design methods were evaluated on a cylindrical togmeter located in a wind tunnel.

5.2 Design Methods

The traditional way to prevent air penetration, as already mentioned, is to cover clothing systems with impermeable or wind proof fabrics all over the surfaces of the systems. However, research has shown that the air pressure on the outer surfaces of the clothing systems only changes notably in the windward areas and remains almost constant in the leeward areas (see Fig.4.3), and therefore the air penetration can be eliminated if only the windward areas are covered with impermeable fabrics.

The air penetration can also be eliminated if the air movement within a clothing system can be minimised. In this case, penetration of air will increase the air pressure inside the clothing system and this will continue until the inside and outside pressures are in balance. In addition, because the air penetration is produced by the variation of the air pressure all over the outer surface of a clothing system, if the air pressure can be modified to give an even pressure distribution, no air penetration will occur.

The above ideas highlight three methods in which wind resistant protective and moisture vapour permeable clothing systems can be constructed. These three methods are (1), to cover the windward areas of clothing systems with impermeable fabrics and the leeward areas with permeable fabrics; (2), to block the air movement within the insulating materials of clothing systems; (3), to have even air pressure distributions over the outer surfaces of clothing systems.

5.3 Experimental Evaluation

To test the above three methods, cylindrical clothing assemblies of such designs were constructed to represent the clothing systems in use. They are shown diagramatically in Fig. 5.1. Assembly (a) and (l) were covered with impermeable coated fabrics all over the outer surfaces. Assembly (b) and (k) were covered with permeable fabrics of different permeabilities. (a), (b), (k), and (l) acted as references to other assemblies which were designed to test the above three methods. Assembly (c), (d) and (e) were designed based on the first method with the variation of the percentage of the areas which were covered with impermeable or permeable outer fabrics. Assembly (f), (g), (h), (i) and (j) were designed according to the second method with the variation of the permeabilities of the inner and outer fabrics, the arrangement and permeabilities of the baffles which resist or block the air movement within the polyester battings. Assembly (m) was designed according to the third method by using a front shield to modify the air pressure distribution around the clothing assembly.

In these clothing assemblies, the air permeability of the highly permeable woven fabric was $1.9\times10^{-3}m^3/m^2/Pa/sec$, that of the lowly permeable woven fabric $1.0\times10^{-4}m^3/m^2/Pa/sec$, that of the highly permeable knitted fabric $1.7\times10^{-2}m^3/m^2/Pa/sec$. The air permeability per unit thickness of the polyester batting was $1.8\times10^{-3}m^3/m/Pa/sec$.

These clothing assemblies were closely fitted to a cylindrical togmeter in a wind tunnel (see Fig. 3.1). Wind was

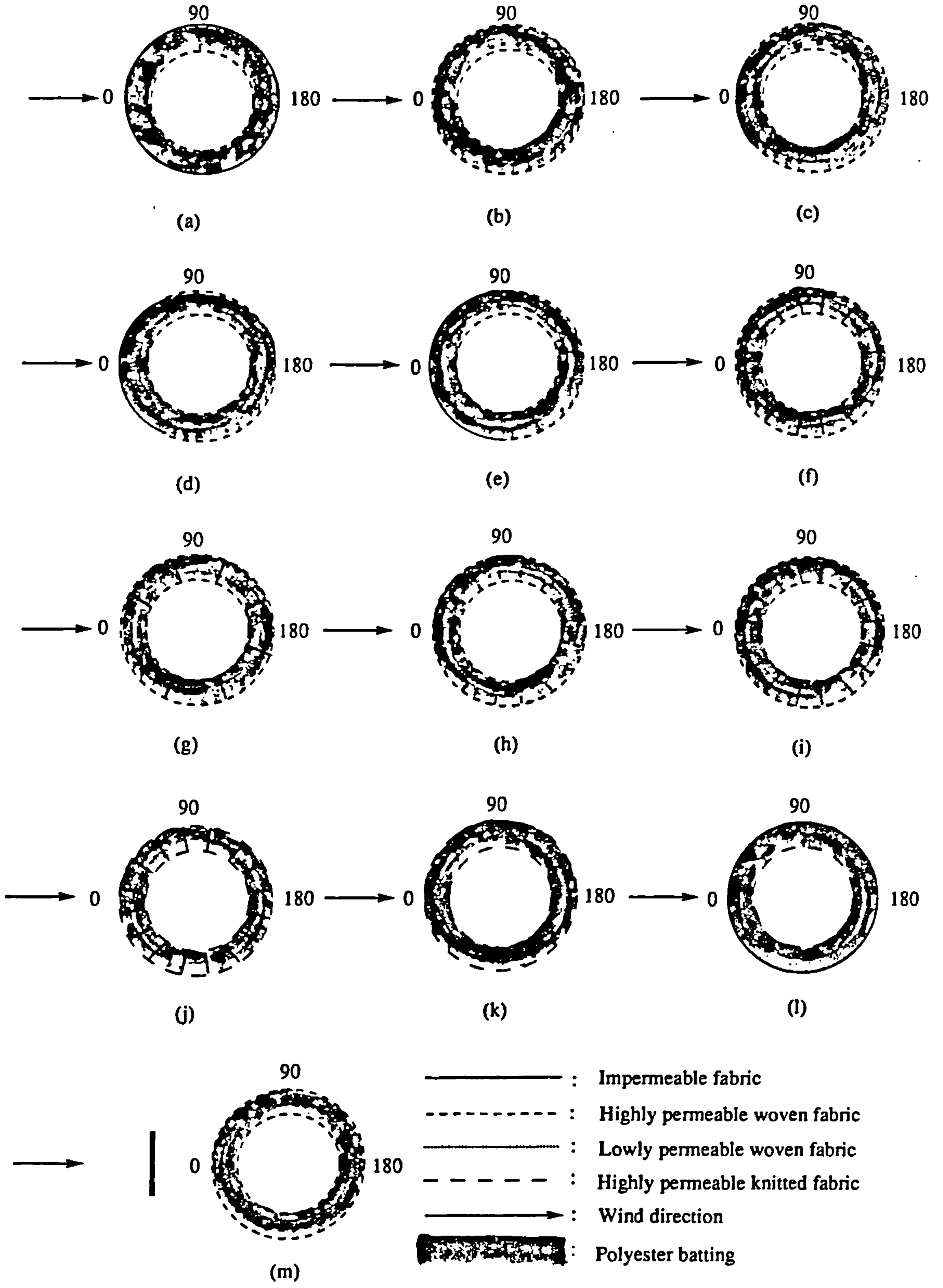


FIGURE 5.1 Diagram of the Clothing Assemblies Tested.

prevailing toward the clothing assemblies in the directions as indicated in Fig. 5.1. By measuring the temperatures at corresponding positions K1, K2, and K3, effective thermal insulation at different angular positions relative to the wind direction were calculated for each sample. All experiments were conducted in a standard atmosphere.

5.4 Results and Discussion

The thermal insulation distributions around the circumferences of assemblies (a), (b), (c), (d) and (e) are compared, as shown in Fig. 5.2. It can be seen that all clothing assemblies which are partly covered with impermeable fabrics and partly permeable fabrics have considerably higher thermal insulation than assembly (b), which is totally covered with a permeable fabric. If half of the clothing assembly is covered with an impermeable fabric (assembly (e)), the thermal insulation will be as high as that of the clothing assembly which is totally covered with the impermeable fabric when the wind is prevailing against the impermeable side. Such behaviour of a clothing assembly which is partly covered with impermeable fabrics and partly permeable fabrics is very useful in the design of clothing used in the conditions when the wind direction is not changing, such as the case in motor-cycling. In other windy conditions however, the wearer can always turn the impermeable side of his clothing against the wind to keep himself warm.

Comparisons between permeable clothing assemblies which are

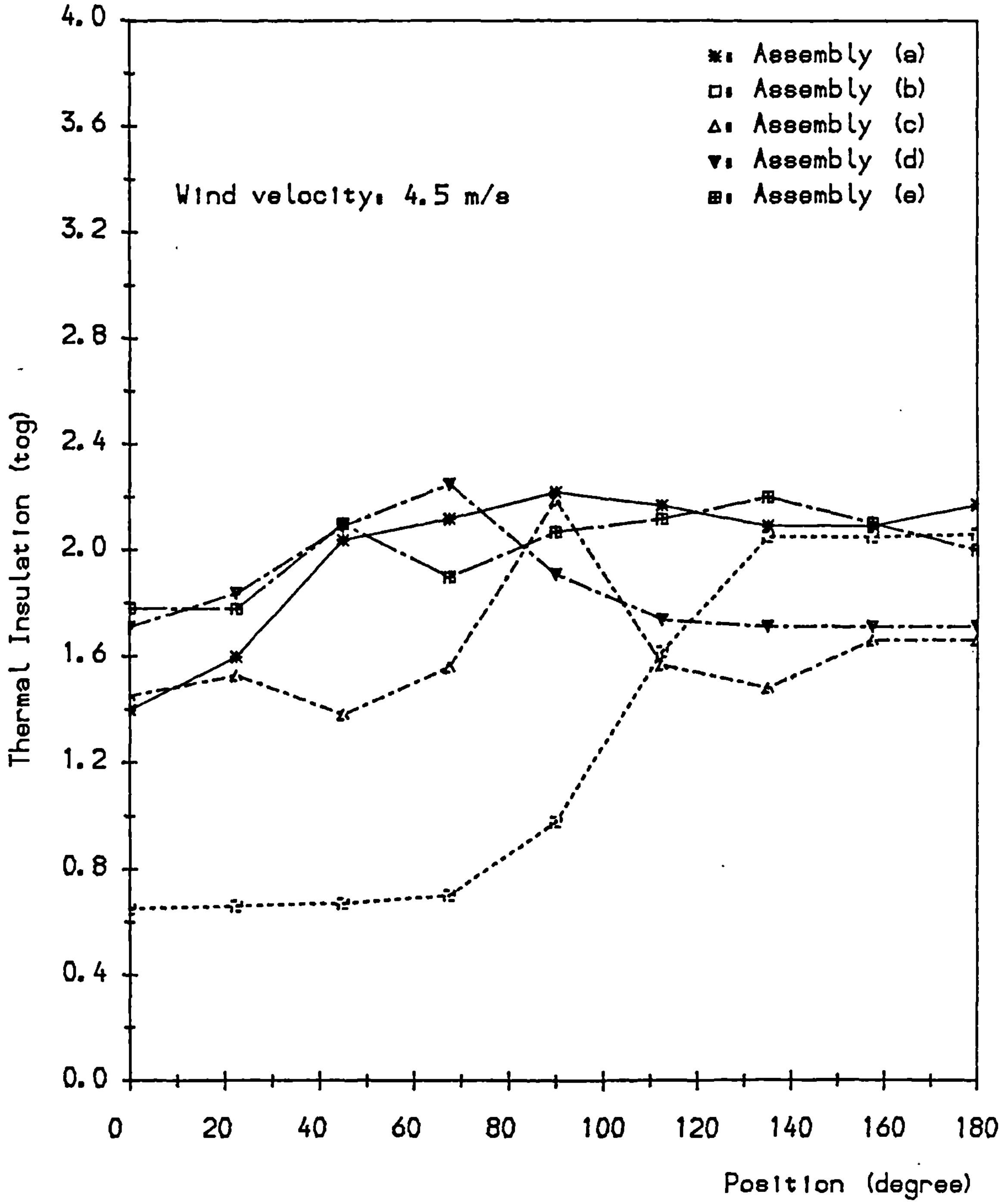


FIGURE 5.2 The Effect of Covering Impermeable Fabrics in the Windward Areas.

sectionally designed with baffles ((f), (g), (h), (i), (j)), and permeable clothing assemblies which are not sectionally designed ((b), (k)) and impermeable clothing assemblies ((a), (l)) are given in Fig.5.3, Fig.5.4 and Fig.5.5. As can be seen, to the different extents, all sectionally designed permeable clothing assemblies have higher thermal insulation than the non-sectionally designed permeable clothing assemblies. This is because the amount of air penetration into and out of the sectionally designed assemblies is reduced by the restriction of the air movement within the polyester battings due to the effects of baffles. The extent to which the thermal insulation of a permeable clothing assembly is increased by such a design is the function of the distance between each of the baffles and their permeabilities. As Fig. 5.3 and Fig. 5.4 show, the more closely the baffles are arranged and the lower the air permeability, the higher the increased thermal insulation of the assembly. Furthermore, the increased thermal insulation is also related to the air permeability of the outer fabric. Considering the sectionally designed assembly (k), its outer fabric is knitted and has an air permeability 10 times as high as the highly permeable woven fabric used for other sectionally designed permeable clothing assemblies. The effect of such a design on the thermal insulation is not very significant, as shown in Fig.5.5. The explanation for this is that, the baffles are not close enough to make any significant reduction in the air penetration into and out of this extremely permeable clothing assembly.

Among these permeable clothing assemblies which are

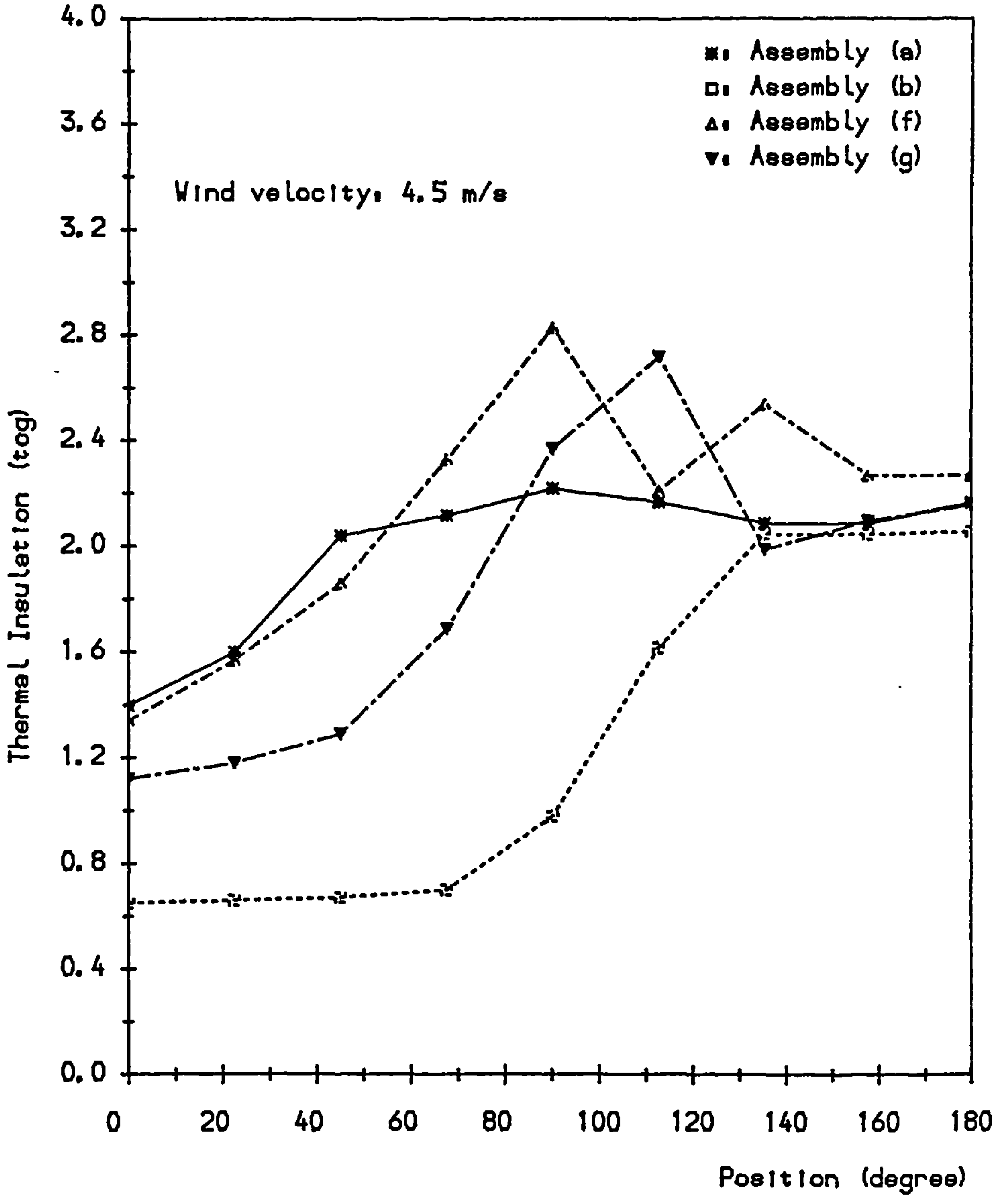


FIGURE 5.3 The Effect of the Angle of the Baffles in the Sectional Design.

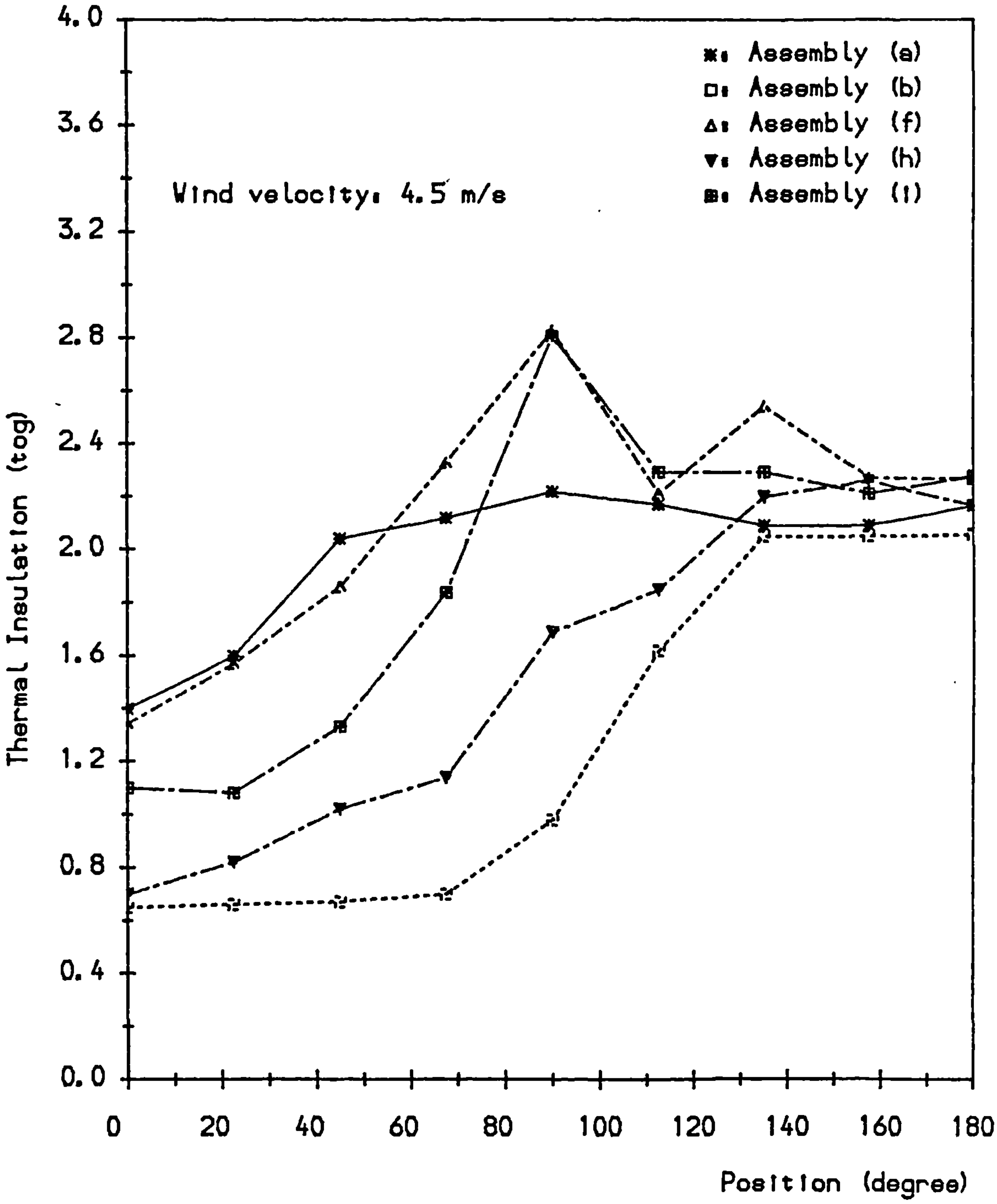


FIGURE 5.4 The Effect of the Air Permeability of the Baffles in the Sectional Design.

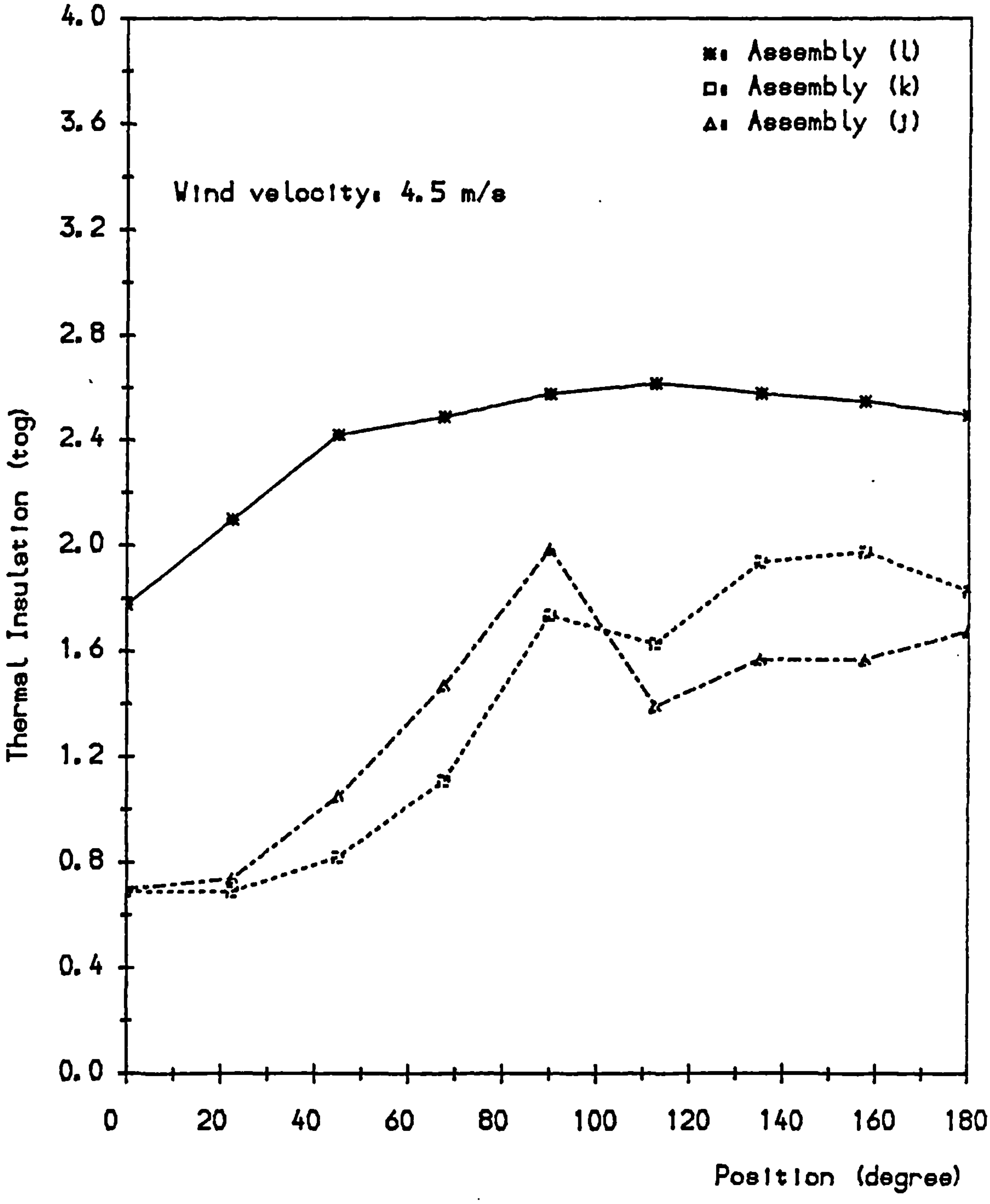


FIGURE 5.5 The Effect of Sectional Design in Assemblies of Knitted Outer Fabrics.

sectionally designed with baffles, it is interesting to see that assembly (f) behaves almost equally well to the one which is totally covered with an impermeable fabric in terms of thermal insulation properties. From this sample and the discussion above, it can be deduced that permeable clothing systems of such design can be constructed and that these will be as warm as impermeable clothing systems in windy conditions. In reality, however, most clothing systems do not fit as tightly to the body surface as those used in these experiments for covering the cylindrical togmeter. Since air can penetrate into the spaces between the body surfaces and inner surfaces of loose-fitting clothing, the effectiveness of such sectional design in thermal insulation can therefore only be achieved either if the inner fabrics of the loose-fitting clothing systems are of low permeability or if the clothing system is a good fit to the body. Although the use of the low permeability inner fabrics for loose-fitting clothing systems lowers the overall moisture vapour permeability, such design can help eliminate condensation within clothing, which is a serious problem in cold and windy conditions, by preventing moisture concentration in the outer layers of clothing.

Fig. 5.7 shows the modified air pressure distribution around the outer surface of assembly (m). The increased thermal insulation by using a front shield is very significant as can be seen from Fig. 5.6. This finding can be applicable in some circumstances by fixing a piece of thin and light plastic in front of the clothing.

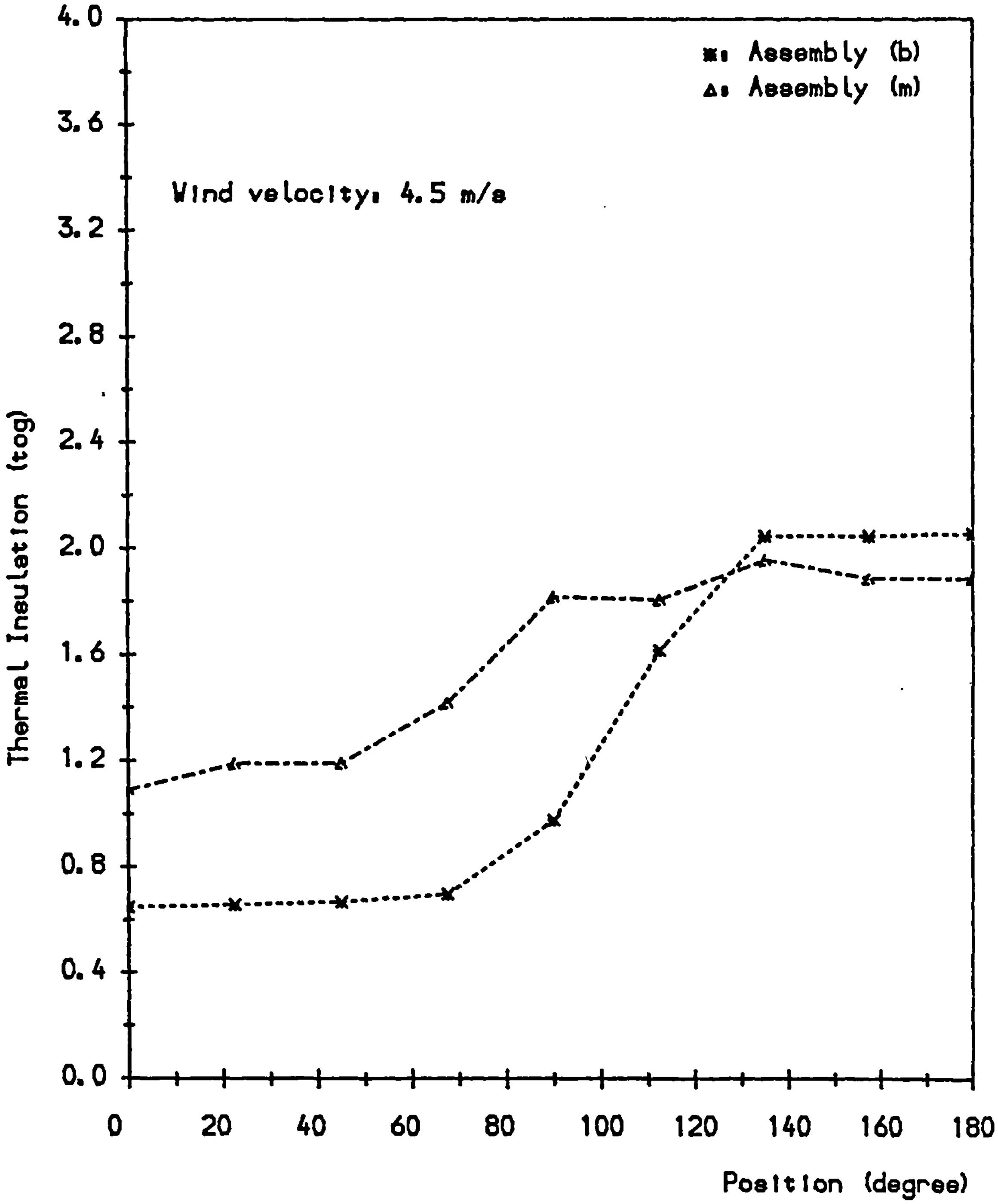


FIGURE 5.6 The Effect of Changing Air Pressure Outside a Clothing Assembly.

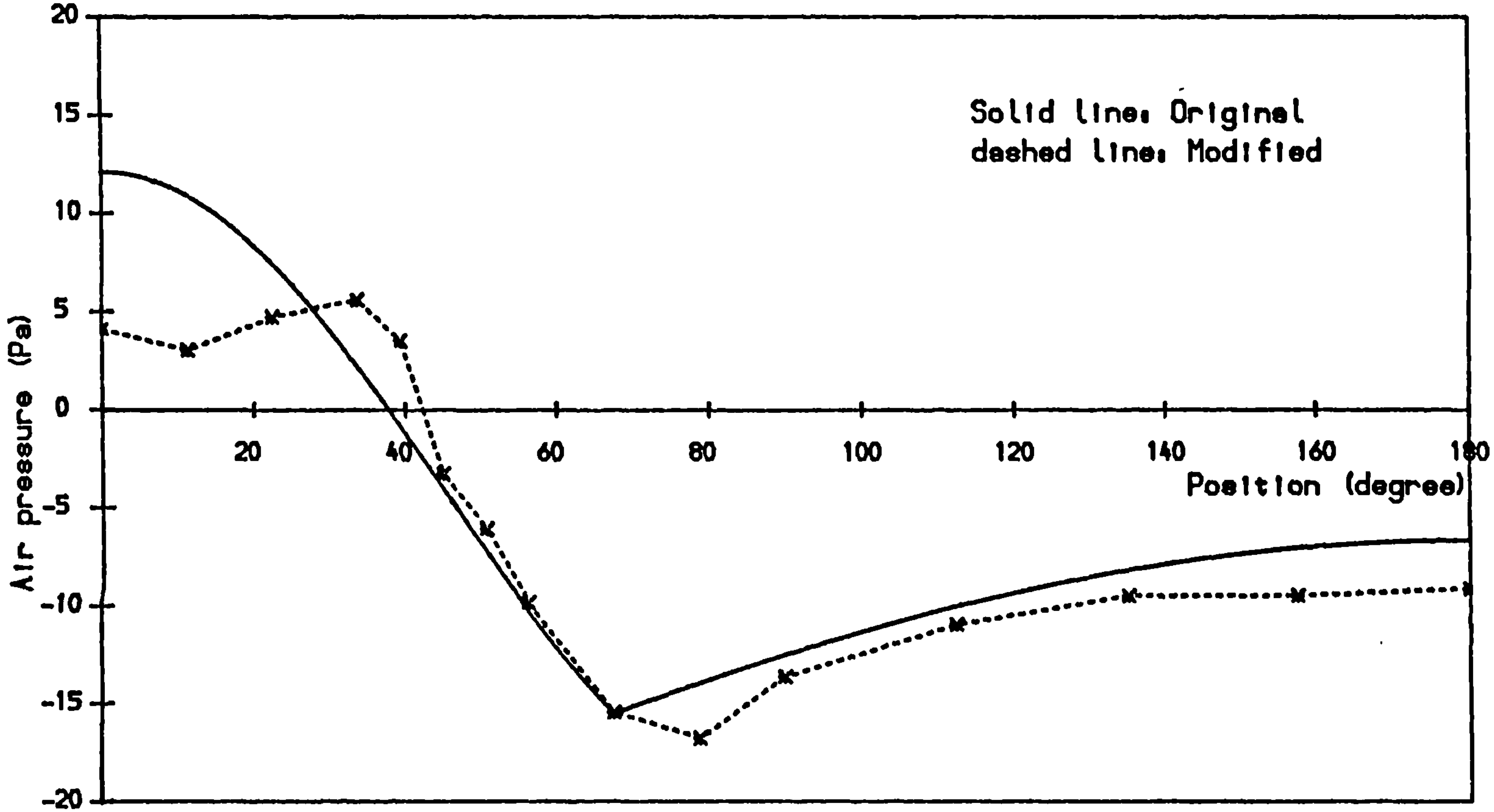


FIGURE 5.7 The Comparison between the Modified and orginal Air Pressure Distribution.

5.5 Concluding Remarks

In cold and windy conditions, wind resistant protective and moisture vapour permeable clothing systems are highly desirable to prevent condensation within clothing and associated discomfort. On this account, a wide range of breathable fabrics have been introduced during recent years. However, the breathabilities of such fabrics are insufficient to avoid the condensation without due regard to the functional garment design (Keighley 1985). This study highlighted three methods by which wind resistant protective and moisture vapour permeable clothing systems can be designed and constructed in which the problem of condensation can be eliminated. Among these three methods, the second one viz the fitting of internal baffles is especially useful, since it is not restricted to the condition that wind should be prevailing towards specific side of clothing system.

PART-III

THE DEVELOPMENT AND LABORATORY USE OF A FABRIC MANIKIN

Chapter 6

The Design and Construction of a Fabric Manikin

6.1 Introduction

Flat plate methods and cylindrical methods are useful for the study of heat transfer through clothing. However, results from these methods can not be directly applied to predict the environmental stress and tolerance for clothed men in thermal environments and applied to the analysis of the effect of body motion and posture on the heat transfer through clothing. This is extremely important for the design and construction of effective clothing in use. The above problem can only be solved by using either wearer trials or manikins. Wearer trials are not usually used in view of inconsistancy, inaccuracy, high cost and danger to human subjects under extreme testing conditions. Therefore, the introduction of manikins for this purpose has been regarded as the most significant development in this area in recent years.

The existing manikins are very expensive. A recently developed manikin in USA cost 2 million dollars according to the report in New Scientist (Anon, 3rd, Dec. 1988). Obviously, there are financial problems in widely applying such expensive manikins.

The present project, therefore, was aimed to develop a cheap, walking manikin utilizing new and cheaper techniques. The "skin" of the manikin was to be made of a coated fabric instead of a copper skin of which most of the existing manikins were made. The manikin was to be shaped by holding water inside the body. So that the breathability of the coated fabric corresponded to the rate of the "perspiration" of the "skin". The distribution of the "skin" temperature was to be controlled by adjusting the rate of flow of warm water around the inner body.

Manikins for simulating human bodies at low activity lavels in a cold environment are not usually required to simulate "sweating". Since most of this work is cold protection, the present project was therefore limited to develop a non-sweating, but walking manikin by using non-breathable coated fabrics. In the following sections of this chapter, detailed considerations of the design and constrution of the manikin, and the general performance are reported. The success of this non-sweating manikin provided a sound basis for the further development of a sweating manikin.

6.2 General Features of the Fabric Manikin

The fabric manikin and its accessaries, shown in Fig. 6.1, Plate 6.1 and Plate 6.2, has the following features.

(1). Similar to a real man in size and configuration.

(2). Simulated skin made of coated fabrics.

(3). A water circulation system to simulate human body's blood circulation in order to reproduce the skin temperature distribution.

(4). A body temperature control and heat supply system to control the core temperature of the manikin at about 37°C; together with a method of measuring the amount of heat supplied to

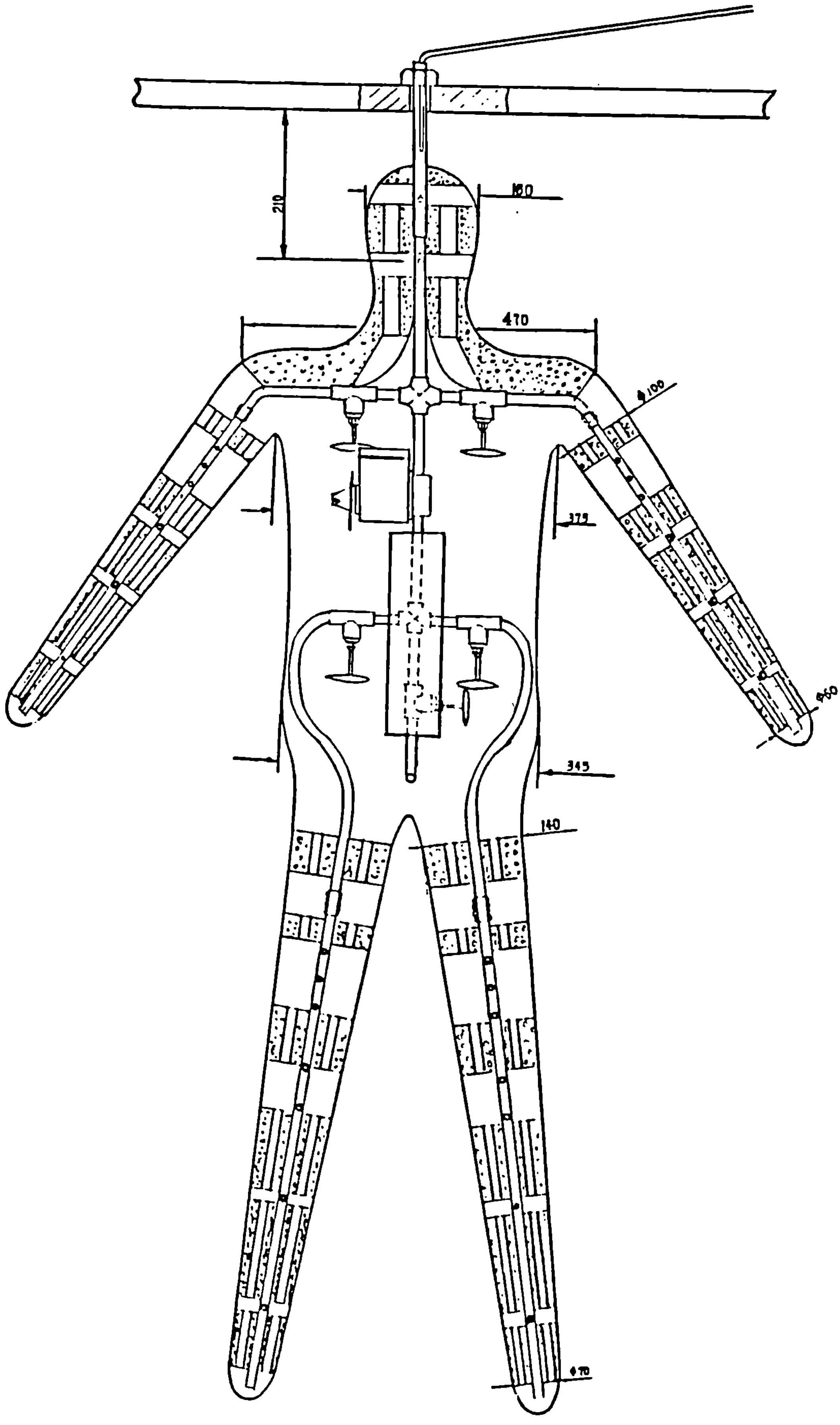


Figure 6.1 Design Diagram of the Fabric Manikin.

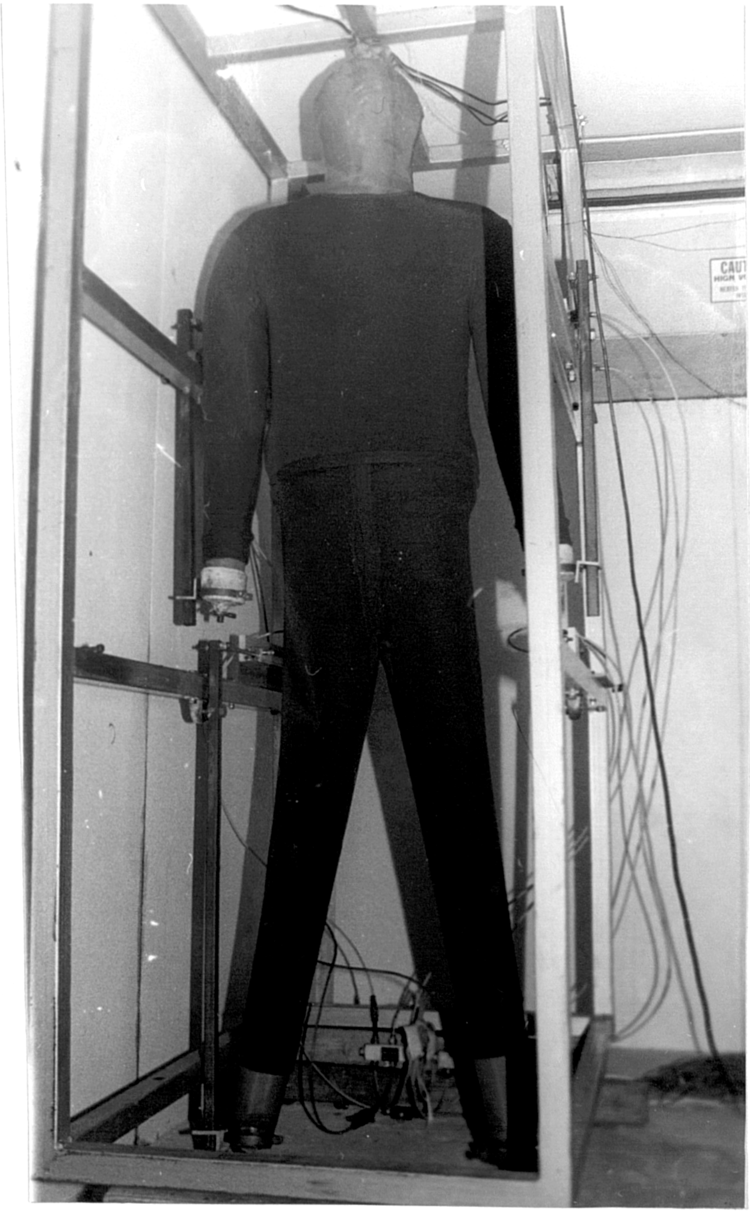


Plate 6.1 View of the Developed Fabric Manikin

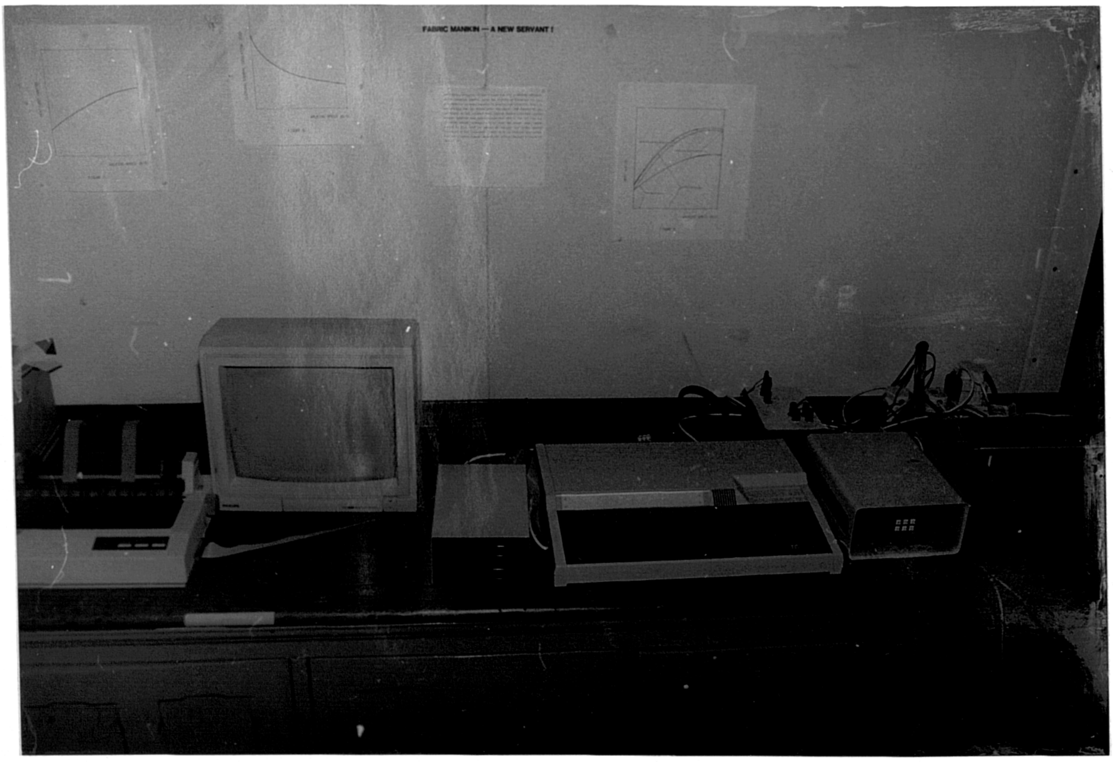


Plate 6.2 View of the Operational Equipment of the Manikin

or lost from the manikin.

(5). A suface temperature acquisition system to measure the temperature of the "skin" and the clothing surface all over the body.

(6). A body motion system to push and pull the arms and legs forward and backward to simulate walking.

(7) A tube projecting from the head of the manikin to supply water into the manikin. (The tube can aslo be used to measure the amount of "perspiration" when such a sweating manikin is developed.)

6.3 The Making Up of the "Skin"

The "skin" of the manikin is very crucial to the success of this design. It should be able to shape the body into human form by holding as much as 80Kg of water inside the body and allow flexing induced by the body movement. To achieve these requirements, the strength, flexibility, stiffness of the coated fabric, of which the "skin" is made, should be examined before making up the "skin".

6.3.1 The Selection of Coated Fabrics

THE STRENGTH OF THE COATED FABRIC

The manikin was required to be similar in size to that of an ordinary man, i.e. its chest measurement should be around 100cm, its waist measurement 80cm and its height 175 cm. Within such a body volume, the water will weigh about 80 Kg. Because all this water was to be contained inside the "skin" and hung on a shoulder model which was made of polystyrene foam, the deformation force on the fabric would be given approximately by the following;

$$\text{Deformation force} = \frac{\text{water weight}}{\text{waist measurement}} = \frac{80\text{Kg}}{80\text{cm}} = 1\text{Kg/cm.}$$

A fabric, which have a strengh of more than 1Kg/cm, is readily available. However, in order to minimize the stretch of the fabric when water was held inside the manikin, which was important practically for a well shaped manikin to be constructed and to ensure a long service life of the manikin, the strengh of the selected coated fabric was chosen to be much higher than the calculated deformation force. A coated fabric of breaking strength of about 100Kg/5cm was considered to be suitable.

THE FLEXIBILITY OF THE COATED FABRIC

Coated fabrics may breakdown in use particularly after an extensified period of flexing. Since the arms and legs were to be pushed and pulled forward and backward to simulate walking, the selected fabric must not fail in both strengh and water proofness. A neoprene coated fabric was chosen as suitable for the purpose and flexing tests were carried out before the fabric was used in construction of the manikin.

THE STIFFNESS OF THE COATED FABRIC

In the construction of the "skin" by sewing and taping, soft fabrics could be handled more easily. The selected fabric should be as soft as possible.

Based on the above considerations, by examining commercially available coated fabrics, the selected fabric was a non-breathable neoprene coated fabric with the properties listed in Table 6.1.

Table 6.1 Physical Properties of the Selected Coated Fabrics

weight	thickness	breaking strengh	flexibility at 20°C	bending length
240g/m^2	1.38mm	warp:130kg/5cm weft: 90kg/5cm	no breakdown after 1 million flexes	warp:3.8cm weft:3.6cm

6.3.2 Technique and Procedure in Making up the "Skin"

Having selected the coated fabric, the next thing to be considered was the technique and procedure in making up the "skin" from the fabric. In this consideration, water proofness and strengh of the seams were the most important elements.

There are two choices of technique for making water proof seams in coated fabrics; (1), welding and (2), taping. The former is only suitable for fabrics of thermo-plastic coatings. The later, which was applied in this work, means making up the "skin" from fabric patterns by sewing, and taping all the stitches to make them water proof. This technique requires an adequate type of adhesive, which should be highly water resistant and strong enough to avoid any breakage at the seams. Dunlop S2000 High Performance Bonding System was selected for this purpose. Its water proofing performance was demonstrated by a simple test, in which water was poured into a long cylindrical bag sewn with the selected fabric and taped with the adhesive to see if leaking was apparent through the seams. The strengh of the taped seams were tested using an Instron tensil testing machine. No breakage was found at the seams but the fabric itself failed at the certain sites.

Besides, the patterns of the "skin" should be designed to avoid cross seams at which leaking is most likely to occur due to the difficulty in taping at such places. Plate 6.3 shows the final design of the patterns which circumvented the above problem.

6.4 Water Circulation System

The water circulation system simulates the human body's blood circulation to carry heat to the extremities and produce a temperature distribution similar to that of the human body. In this system, water was pumped firstly through a heat exchanger and then through copper tubes into the extremities of the manikin and return flow into the central part of the body through the grooves in the polystyrene blocks underneath the "skin" allowed a continuous flow of water (see Fig. 6.1). The use of polystyrene was to reduce the weight of the manikin and help shape the body.

The pump was supplied by Rolf Hagan Ltd. It was originally made for water circulation inside fish tanks. Such a pump was regarded as suitable for this purpose, since (1), the pump could be mounted inside the body because of its small size; (2), the pump was immersible in water; (3), the pump output was sufficiently high.

Temperatures at extremities depend on the water flow rates into them. The water flow rates were adjustable with five valves

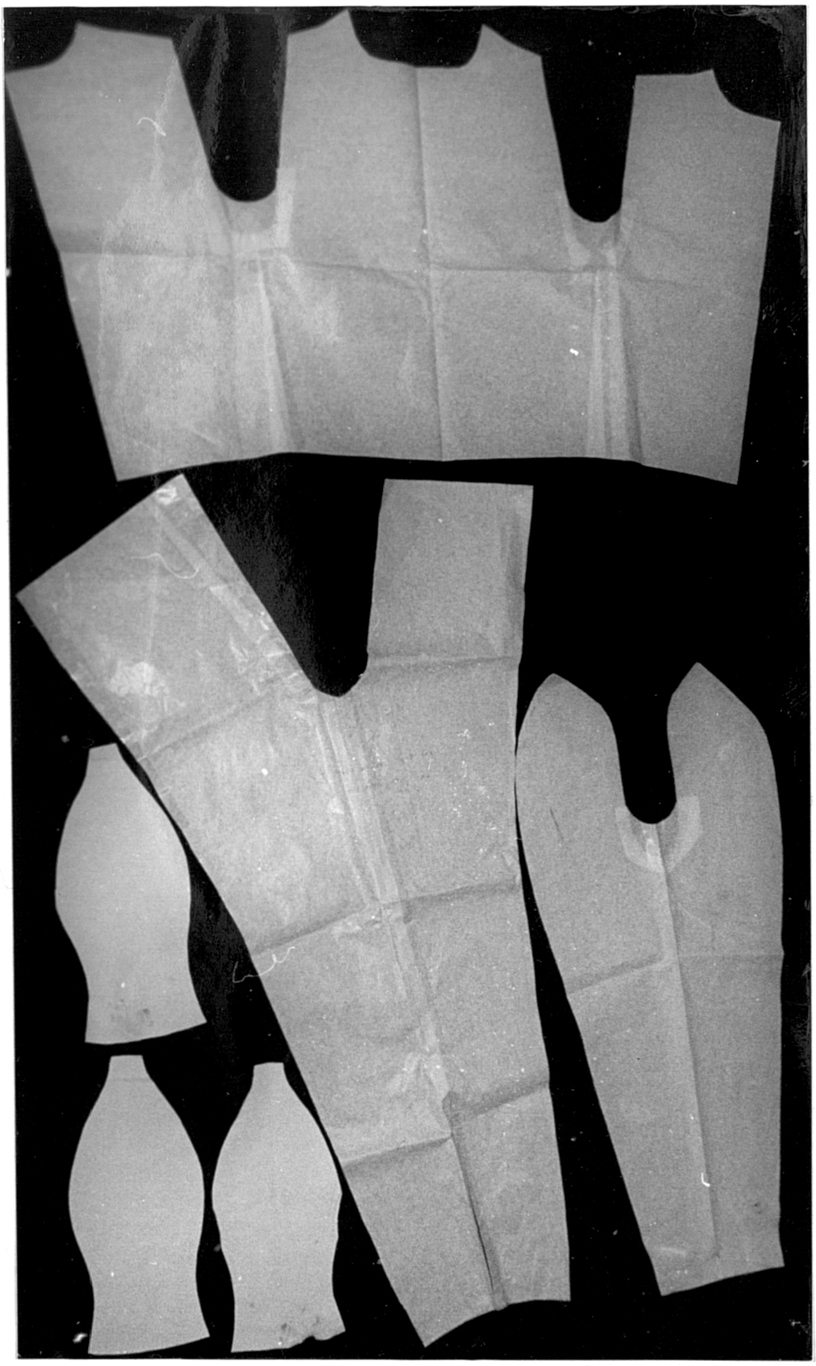


Plate 6.3 View of the Pattern of the "Skin"

within the body to achieve the best simulation in temperature distribution.

In order to produce a temperature gradient in each of the arms and legs similar to that in a real human, a series of small holes were drilled on the pipes buried in the centre of the extremities. The size and arrangement of these holes were simply determined by experience. Although this was not designed by strict scientific criteria, it was later proved to give reasonable approximation to the skin temperature distribution of a human body.

6.5 Body Temperature Control and Heat Supply System

This system is to control the core temperature of the manikin at a constant level of 37°C, and measure the amount of heat lost from the manikin.

Two types of temperature control modes are common, i.e. ON/OFF mode and proportional mode. The former is simpler and cheaper, but less precise. It is especially not recommended when the heat supplied is measured by taking the "ON" time of the heaters. Therefore, a proportional temperature controller (CAL 9000 Series PID Temperature Controller supplied by RS) was used. The principle of this controller is to change the "on" time within a proportional time according to the error temperature from the setpoint.

According to this principle, the heat supplied to or lost from the manikin can be calculated from the measured "ON" time, i.e. $\text{Heat} = \frac{\text{"ON" Time}}{\text{Proportional Time}} \times \text{Power of Heaters} + \text{Pump Power}$.

The measurement of "ON" time was carried out by a BBC microcomputer through a interfacing circuit, which is shown in Fig. 6.2. The heat supplied into the manikin was calculated and shown on the screen with a software.

6.6 Surface Temperature Acquisition System

In order to assess the clothing thermal insulation, the temperature of the "skin" and the clothing surface should be measured at different points all over the body. The temperature acquisition system used here was developed by Nasser-Moghaddassi (1986). It has the following main features.

(1). There were 15 sensors, which could be used to record temperatures at 15 different points simultaneously.

(2). The accurancy of the measurement was within ± 0.1°C.

(3). Temperature data recorded was stored in the memory of the instrument during tests.

(4). The instrument could be interfaced with a computer or a chart recorder to retrieve the data stored.

The mean temperatures of the "skin" and the clothing surface were calculated as an area weighted average of measurements at five different places around the body as suggested by Houdas, et al. (1982) (see Fig. 6.3). That is

$\bar{T}_s = 0.07T_{head} + 0.175(T_{chest} + T_{back}) + 0.19T_{arm} + 0.39T_{leg}$.

An example of the measured surface temperature distributions and calculated mean values are shown in Table 6.2.

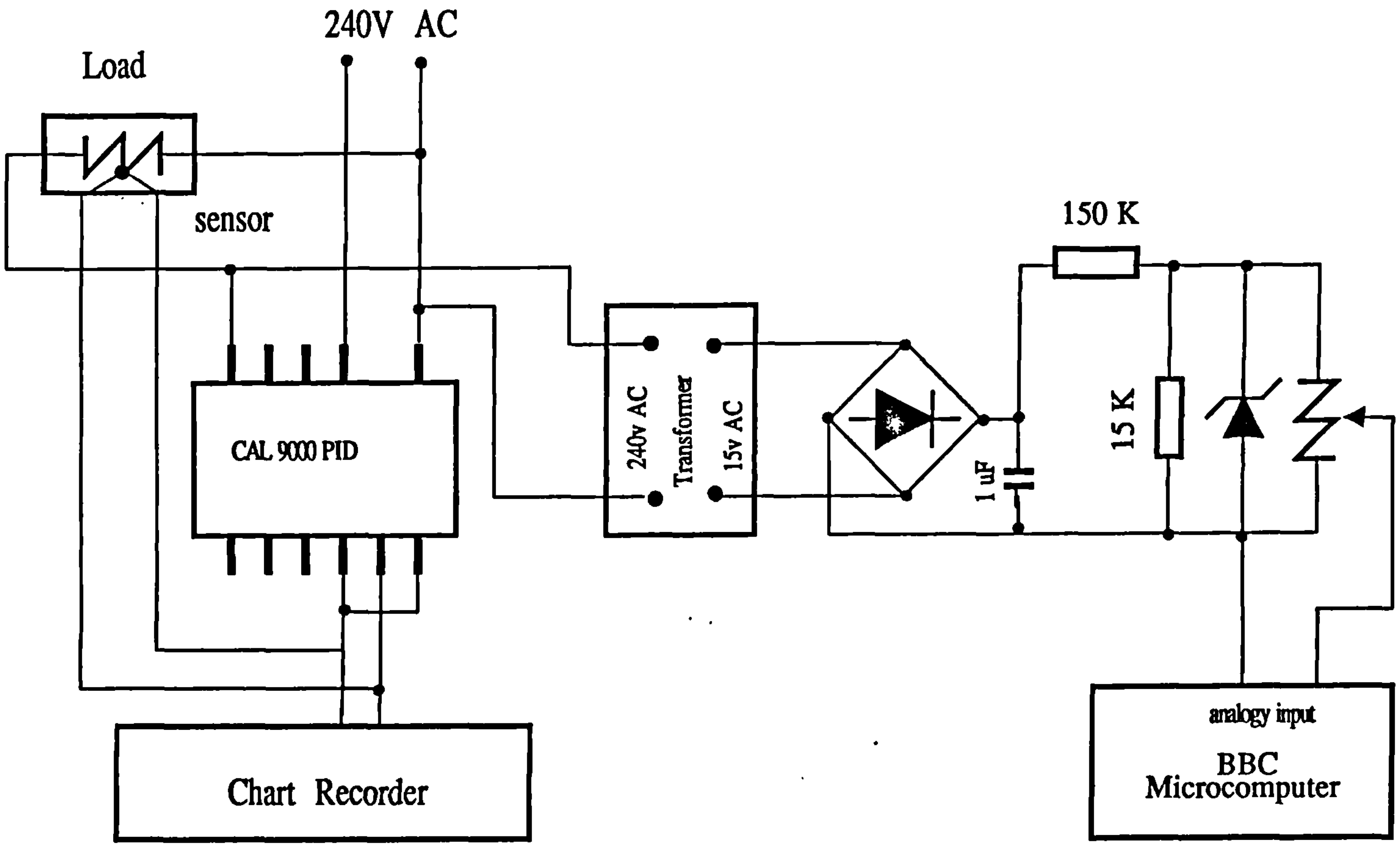


FIGURE 6.2 Temperature Control and Heat Input Measurement System .

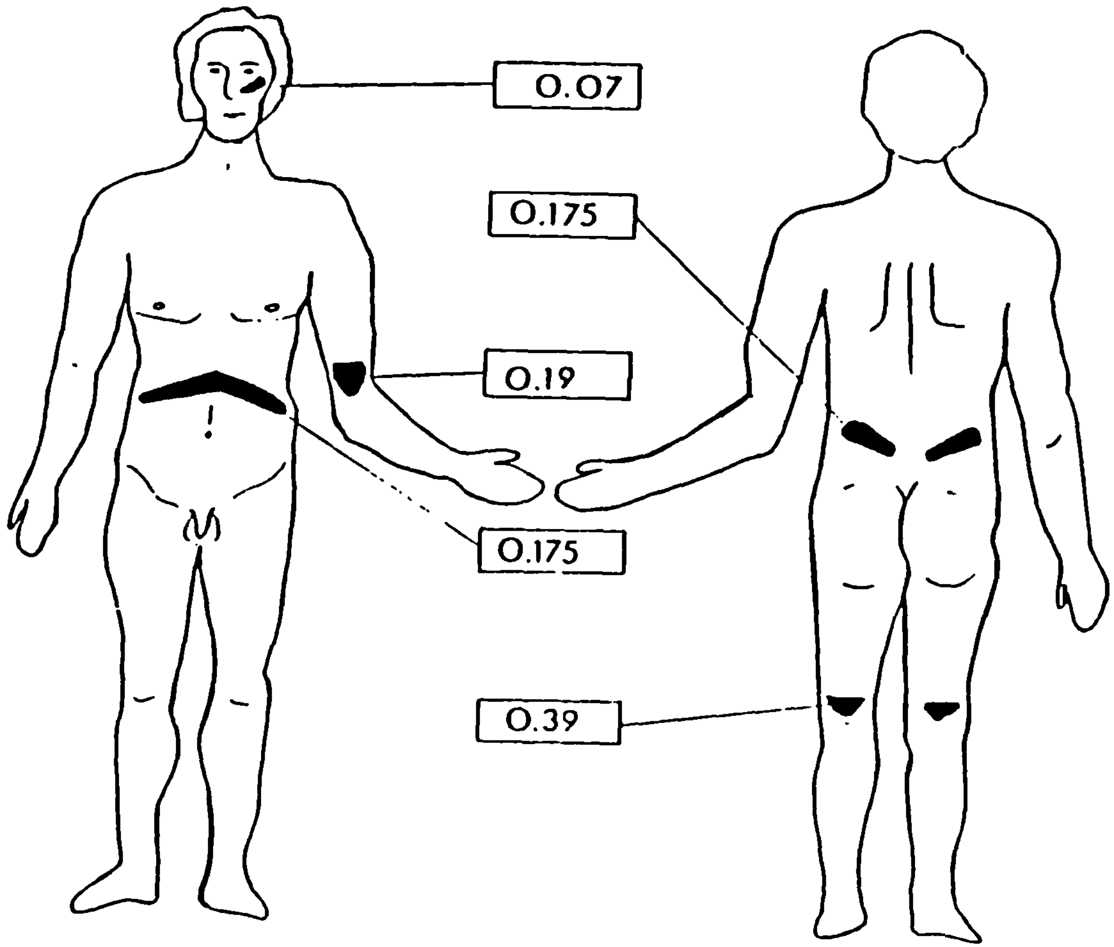


Figure 6.3 Sites for Calculating Mean Skin and Mean Clothing Surface Temperature with Weighting Coefficients.

Table 6.2 Surface Temperature Distributions of Skin and Clothing when the manikin is covered with clothing system A* and standing still at 20°C.

	T_{head}	T_{chest}	T_{back}	T_{arm}	T_{leg}	mean
skin surface	31.8	34.6	34.3	33.5	32.9	33.5
clothing surface	31.8	23.5	24.1	28.3	26.1	26.1

* Clothing system A is described in Chapter 7.

Table 6.3 Experimental Results Obtained from the Fabric Manikin.*

sample	condition			$\bar{T}_s$	$\bar{T}_{cl}$	H		Ic		Is		It	
	T_a	V	W			m	CV	m	CV	m	CV	m	CV
A	20.6	0	0	33.3±0.1	25.2±0.3	94.2	5	1.64	10	1.06	10	2.70	10
A	3.7	0	0	32.1±0.3	14.0±0.3	202.	2	1.77	9	1.01	5	2.77	3
A	-21.1	0	0	28.4±0.7	-8.9±2.5	345.	1	2.14	6	0.70	18	2.80	6
A	19.3	0	2.2	32.2±0.2	22.3±0.6	163.	1	1.18	6	0.38	13	1.56	2
A	20.2	1.2	2.2	31.9±0.2	21.0±0.8	281.	9	0.77	11	0.11	17	0.88	8
B	20.1	0	2.2	32.2±0.2	21.6±0.2	162.	1	1.28	5	0.18	11	1.47	4
C	21.1	0	0	32.8±0.2	27.6±0.1	143.	1	0.71	3	1.05	3	1.77	3
C	19.7	0	2.2	30.6±0.2	23.5±0.4	270.	1	0.52	8	0.28	9	0.80	6
C	-0.3	0	2.2	24.5±0.4	7.7±0.5	564.	8	0.59	7	0.28	18	0.87	5
C	19.4	1.2	2.2	30.0±0.3	21.9±0.6	402.	6	0.40	9	0.12	22	0.52	8
D	21.1	0	0	31.0±0.2	25.3±0.3	100.	1	1.12	3	0.83	4	1.96	2
D	19.6	1.2	2.2	30.5±0.4	21.8±0.9	407.	8	0.42	14	0.11	28	0.53	10
nude	20.0	0	0	29.9±0.8	—	215	1	—	—	0.91	9	0.91	9
nude	19.8	0	2.2	30.0±0.1	—	490.	7	—	—	0.42	7	0.42	7

* In this table, H is the heat lost from the manikin in watts, $\bar{T}_s$ is the mean skin temperature in °C, $\bar{T}_{cl}$ is the mean surface temperature of clothing in °C, I_c is the effective clothing insulation in tog units, I_s is surface insulation in tog units, I_t is the total insulation in tog units, T_a is the ambient temperature in °C, V is the walking velocity in km/hr, and W is the wind velocity in m/s. "m" indicates the mean value, and "CV" is the coefficient of variation. The definition of I_c, I_s and I_t and the experimental procedure are discussed in Chapter 7. The description of clothing systems A, B, C and D are shown in Plate 7.1.

6.7 Body Motion System

The body motion system is to push and pull the arms and legs forward and backward to simulate walking. Since pneumatic systems are the simplist in accomodating reciprocating operations, it was decided to design such a system for this purpose.

In pneumatic systems, mechanical movements are produced by compressed air operating through actuators. Such actuators are usually not longer than 30cm, since, if they are too long, air leakage can easily occur at the seals. The actuators which were used in this work were 25cm in length. As the movement of the hands and feet of an ordinary man marching on the street is about 50-70cm, levers were designed for each arm and leg to exaggerate the reciprocating movement produced by the actuators, and to push and pull the bottoms of the arms and legs of the manikin.

The designed body motion system consisted of a portable air compresser, a switching manifold, a timer, an air distributor, four actuators, and four levers. Compressed air of controlled air pressure was supplied by the portable air compressor. The arms and legs were moved by changing the passage of the compressed air into the actuators by using the switching manifold, which was controlled by a timer. By changing the setting of the timer, different "walking" velocities could be simulated.

6.8 The Performance of the Fabric Manikin

When the fabric manikin was filled up with water, the dimension of the body was slightly bigger than it was expected because of fabric stretching. Its hight was 190 cm, head circumference 60 cm, neck circumference 47 cm, shoulder width 44 cm, arm length 74 cm, upper arm circumference 38 cm, lower arm circumference 20 cm, chest circumference 106 cm, waist circumference 91 cm, leg length 106 cm, upper leg circumference 56 cm, low leg circumference 23 cm, and hip measurement 90 cm. The surface area of the body was 1.98 m^2. It was measured by discretizing the body surface into several parts, which were of simple geometries, and adding the areas of these parts together.

The body temperature distribution was first set up by adjusting five valves inside the manikin to get the best simulation (see Fig. 6.1). However, when the environmental condition and clothing thermal insulation changed, the temperature distribution changed. During the experiments for steady state heat transfer, the recorded temperatures must be stabilized. The time taken for stablizing the temperatures depended on the changes in the environmental conditions, clothing thermal insulation and walking velocities. It was usually not more than 1.5 hrs.

The reproducibility of the resuls from the fabric manikin was assessed by conducting repeated experiments when the manikin was naked, covered with different clothing systems, standing or walking. It was found that the heat lost from the manikin was very reproducible, the variation coefficient (CV) of the heat lost was below 10% (see Table 6.3). When the thermal insulation of the clothing and clothing surface were calculated, however, the CV values were higher. Most of these errors came from the measurements of surface temperatures. To get the best results, the sites where temperatures were recorded must be fixed.

After several months' service of the manikin, fabric damage occured where the "skin" was flexed when the manikin was walking. This was not expected to happen so soon because the flexibility of the fabric was good when it was tested on a Schildknecht flex tester. The explanation of this problem might be that the flexibility of a fabric becomes lower when it is streched. Because of this problem, the fabric manikin needed repair after several months' walking. In developments to be made in the future, joints should be used at connections of arms and the shoulder, and the connections of the hip and the legs.

Generally speaking, the fabric manikin performed well and provided a sound basis for further development. In the later version of such a fabric manikin, better simulated temperature regulation system could be achieved by controlling the water flow rate into the extremities with a computer based pneumatic or hydraulic system; the human body's perspiration could be simulated by using breathable coated fabrics.

Chapter 7

The Effects of Body Motion, Clothing Design and Environmental Conditions on the Clothing Thermal Insulation

7.1 Introduction

In order to evaluate the heat transfer through clothing worn on human bodies, knowledge of the thermal insulation of clothing materials and simple clothing assemblies is essential but not sufficient. Understandings about the effects of body motion, clothing design and environmental parameters on the thermal insulation of actual clothing systems must be added.

Many workers have studied the effect of clothing design and fit (McCullogh et al. 1983), the effect of body motion (Gagge et al. 1941, Belding et al. 1947, Nishi et al. 1975, Olesen et al. 1982, Nielsen 1985) and the effect of wind velocity (Winslow et al. 1939, Belding et al. 1947, Burton and Edholm 1955, Fonseca 1975, Breckenridge and Goldman 1977, Nielsen 1985) on the thermal insulation of actual clothing systems by means of wearer trials or manikins. However, few of these investigations considered more than one or two levels of body motion, and took into account the effects of environmental temperature. Information about the effects of these factors and their interactions is still limited.

In the present study, therefore, the newly developed fabric manikin was covered with four typical clothing systems, and the thermal insulation of these clothing systems and the heat lost from the clothed manikin were investigated under various walking speeds, wind velocities and room temperatures inside a cold chamber. In this chapter, the results of this investigation and their implications are presented.

7.2 Sample Description

The four clothing systems under investigation are listed as follows (see Plate 7.1):

A: Polypropylene underwear, thermal vest made of polyester batting and Aluminium foil, water-proof jacket, ordinary trousers.

B: Polypropylene underwear, thermal vest made of polyester batting only, water-proof jacket, ordinary trousers.

C: Polypropylene underwear.

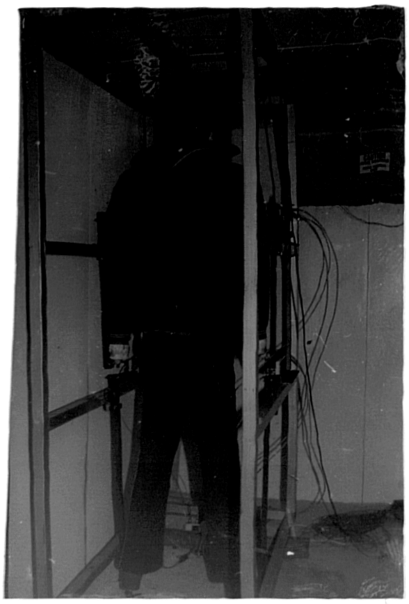
D: Shirt and ordinary trousers.

Clothing system A and B were identical in design, weight and fit except that system A contained Aluminum foil, while system B didn't. There were to be compared to see the advantage of the use of Aluminum foil in preventing the radiative heat transfer through clothing. System A and B were heavy weight in comparison with system C and D, among which system C was close-fitting and system D was loose-fitting.

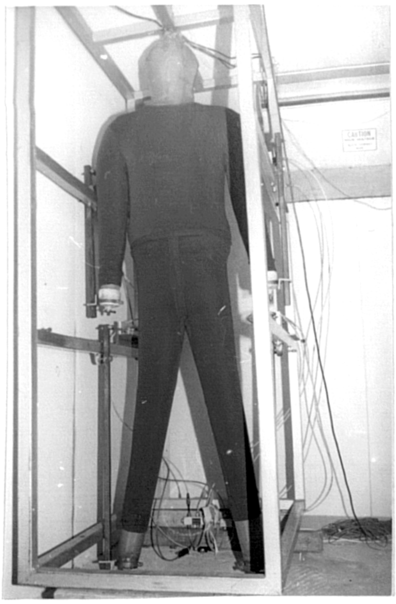
7.3 Experimental Conditions and Testing Procedure

All experiments were conducted in a cold chamber where the temperature could be lowered to -29 ^{o}C when there was no heating

A



B



C

D

Plate 7.1 View of the Clothing Systems under Tests

elements in side the chamber. When the fabric manikin and a fan were moved into the chamber for these experiments, the lowest temperature, which could be reached, was about -20 °C.

Wind inside the chamber was generated by a propeller fan. Since the air movement was not linear, a mean wind velocity was calculated from the measurements at the cross-section which was about 50cm in front of the manikin for each level of wind. In addition, it must be noted that, when there was no apparent wind inside the chamber, the air was not absolutely still due to the effect of the cooling system of the chamber.

The testing procedure for a certain sample under a certain experimental condition was as follows.

(1). Set the temperature of the cold chamber.

(2). Put the clothing items on the fabric manikin.

(3). Calibrate the temperature aquisition system.

(4). Locate the temperature sensors at the right positions (head, chest, back, arm, legs).

(5). Turn on the fan if wind is to be simulated.

(6). Turn on the body motion system if walking is to be simulated.

(7). Wait until the heat lost from the system is stablized. The time taken for stablizing the system was estimated from preliminary experiments. Usually, it was less than 30 mins if the manikin was standing and less than 1.5 hrs if the manikin was moving to simulate walking.

(8). Run computer software to register the heat lost from the manikin by using a BBC Micro-computer.

(9). At the same time, register the temperature of the "skin" and the clothing surface all over the body by using the temperature aquisition system.

(10). Calculate the mean "skin" temperature and the mean temperature of the clothing surface.

(11). Calculate the surface insulation, the effective clothing insulation and total insulation of the clothing system.

7.4 The Expression of Results

The surface insulation, the effective clothing insulation and the total insulation of a clothing system were defined as follows.

$$I_s = \frac{10 \cdot (\bar{T}_{cl} - T_a) \cdot A}{H} \quad , \qquad (7.1)$$

$$I_t = \frac{10 \cdot (\bar{T}_s - T_a) \cdot A}{H} \quad , \qquad (7.2)$$

$$I_c = I_t - I_s \quad , \qquad (7.3)$$

where, I_s was the surface insulation in tog unit, I_c was the effective clothing insulation in tog unit, I_t was the total insulation of the clothing system in tog unit, $\bar{T}_s$ was the mean "skin" temperature, $\bar{T}_{cl}$ was the mean temperature of the clothing surface, T_a was the environmental temperature, A was the surface area of the fabric manikin in m^2, and H was the heat lost from the manikin in Watts.

Here, the defination of the surface insulation and the effective clothing insulation was different from those suggested by Olesen et al. (1982). They defined the surface insulation as the resistance to the heat flow rate from the outer surface of a clothed body. While, here, the surface insulation meant the contribution of the surface air layer in resisting the heat flow rate from the inner body. The difference between these two definations is a clothing area factor f_{cl}, which is the ratio of the surface area of the clothed body to the nude body. We prefer our defination because the effective clothing insulation deduced from the total insulation and the surface insulation has a clearer physical meaning.

7.5 Results and Discussion

7.5.1 Effects of Environmental Temperature

Clothing system A and B were put on the manikin and tested at the ambient temperatures of about -20°C, -3°C and 20°C. Results were plotted in Fig. 7.1 and Fig. 7.2. As can be seen, the effective clothing insulation for each sample increased with reducing room temperature. This was understandable with a radiative conductivity model, which was regarded as suitable for heavy weight clothing (Farnwarth 1983). According to such a model, the effective clothing insulation increases when reducing the mean temperature of the clothing materials (reduced by lowering the room temperature in these experiments). The amount of increase in the effective clothing insulation is related to the emissivity of the clothing materials, the lower the emissivity, the more the increase. In these experiments, the effective clothing insulation of clothing system A, which contained Aluminum foil of low emissivity, increased by 26% when the room temperature was lowered

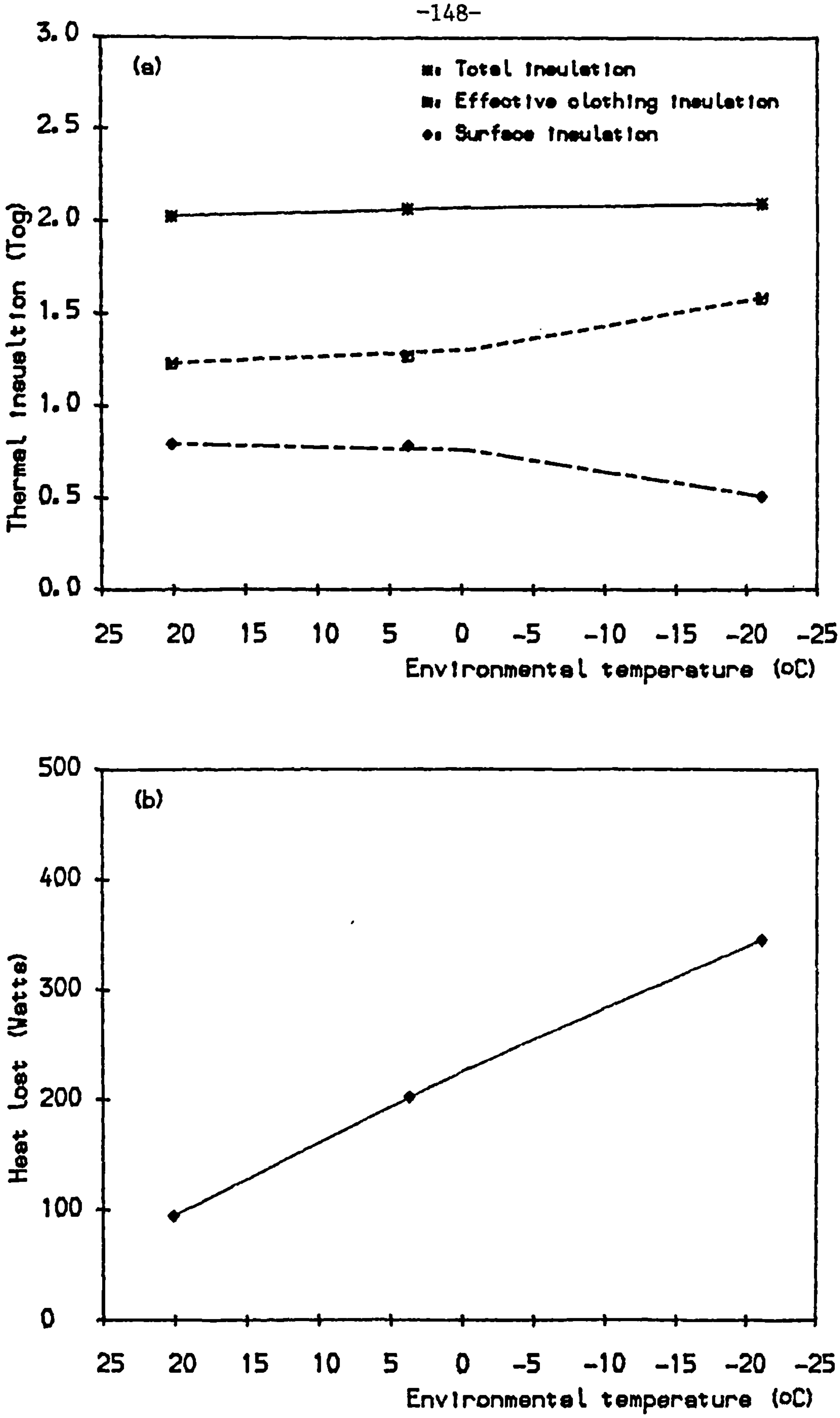
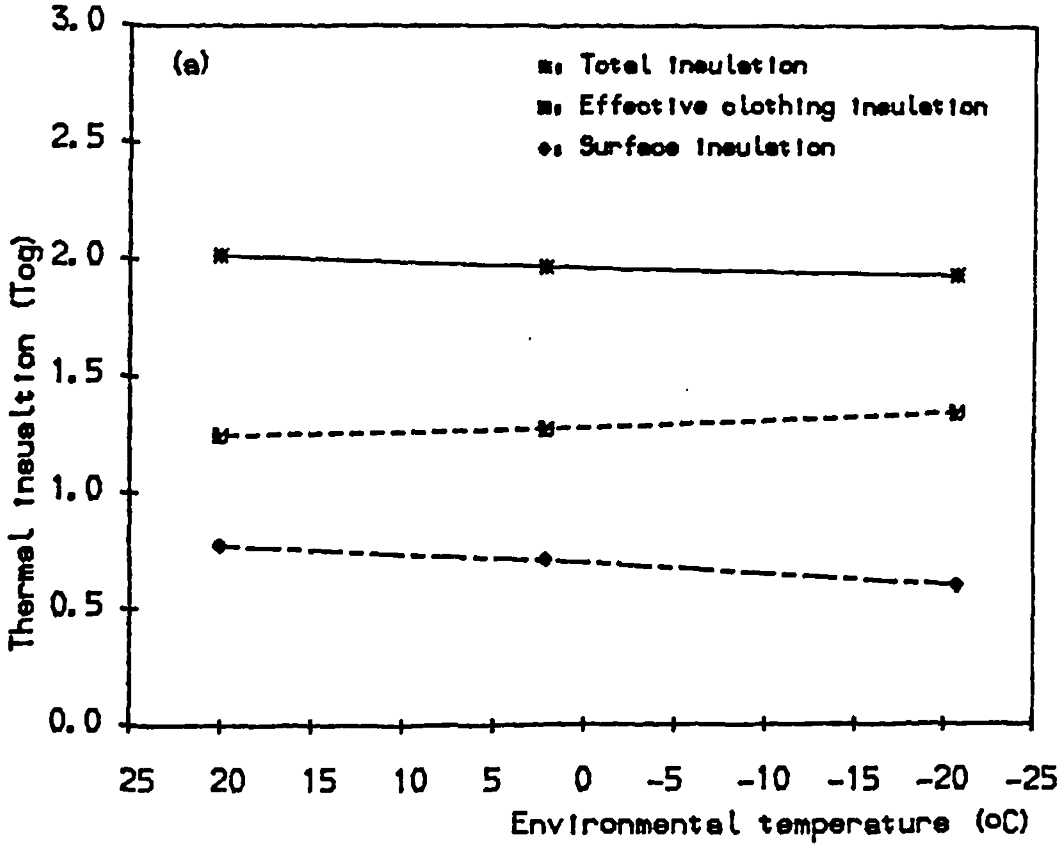


FIGURE 7.1 Effect of environmental temperature on the thermal insulation of and heat lost through clothing system A (no wind, standing still).



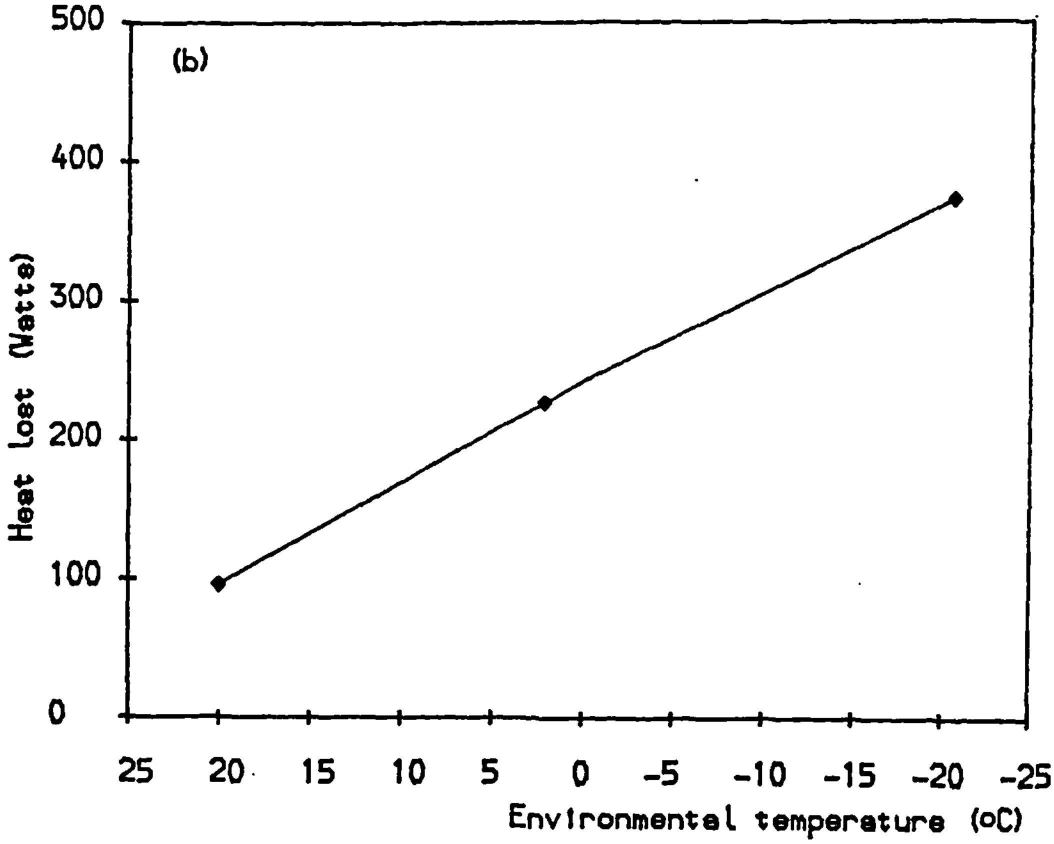


FIGURE 7.2 Effect of environmental temperature on the thermal insulation of and heat lost through clothing system B (no wind, standing still).

from 20°C to -20°C, while that of clothing system B increased by only 7%. This finding showed the advantage of the use of Aluminum foil in very cold environmental conditions.

Heat lost from the outer surface of clothing is through convection and radiation. The surface insulation of clothing decreases with reducing the environmental temperature due to increased natural convection. The results shown in Fig. 7.1 and Fig. 7.2 indicated a 25% reduction in the surface insulation at -20°C compared to 20°C.

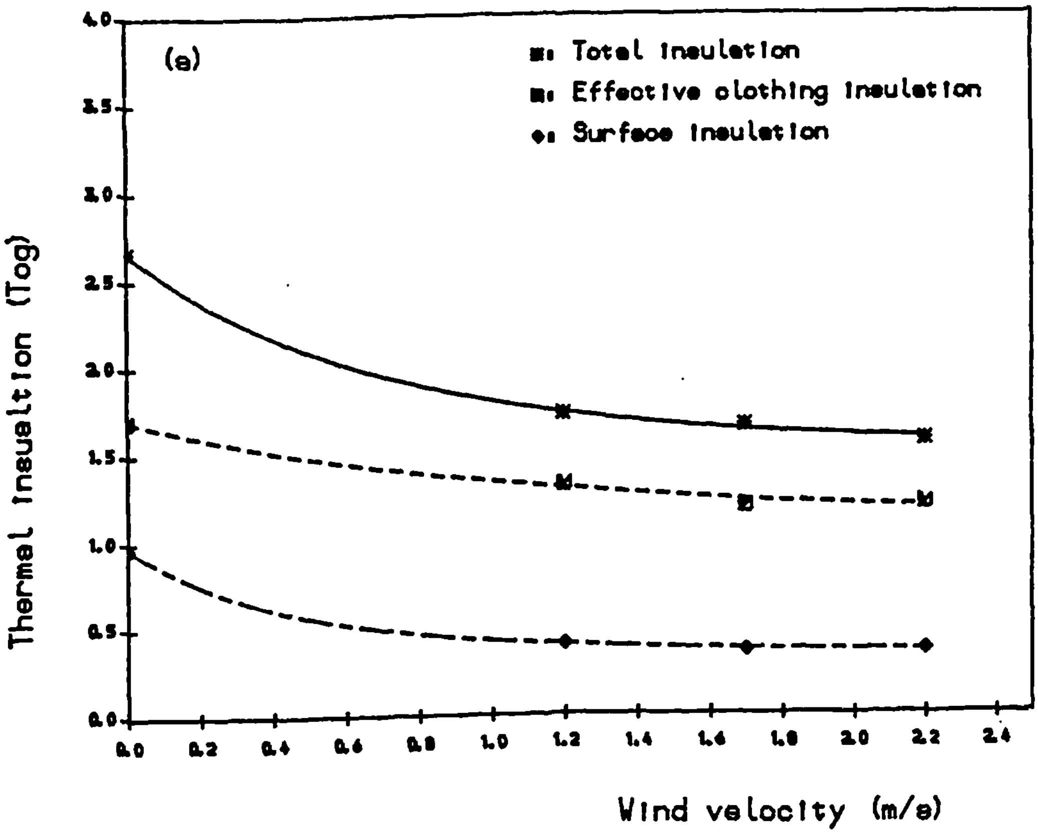
As far as the total insulation of the clothing systems is concerned, it increased slightly for clothing system A and reduced slightly for clothing system B with reduction in room temperature due to the combined effect of the effective clothing insulation and the surface insulation.

7.5.2 Effects of Wind Velocity

Results for the manikin covered with different clothing systems and the uncovered manikin under different wind velocities are shown in Fig. 7.3-Fig. 7.11.

SURFACE INSULATION

As far as the surface insulation I_s is concerned, I_s was found to be lowest for the manikin covered with loose-fitting clothing system D (0.16 tog at the wind velocity 2.2 m/s) and highest for the uncovered manikin (0.42 tog at the wind velocity of 2.2 m/s). It seemed that the fluctuation of clothing, which was induced by wind, reduced the surface insulation. From the results



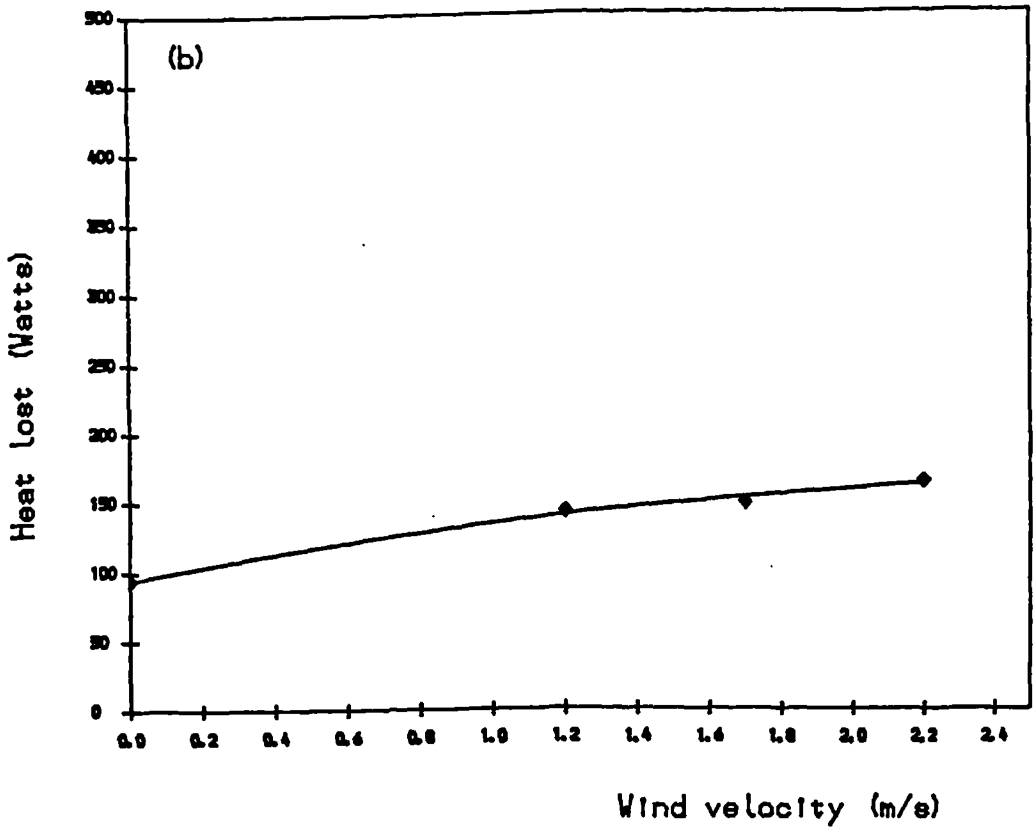


FIGURE 7.3 Effect of wind velocity on the thermal insulation of and heat lost through clothing system A (environmental temperature: 20oC, standing still).

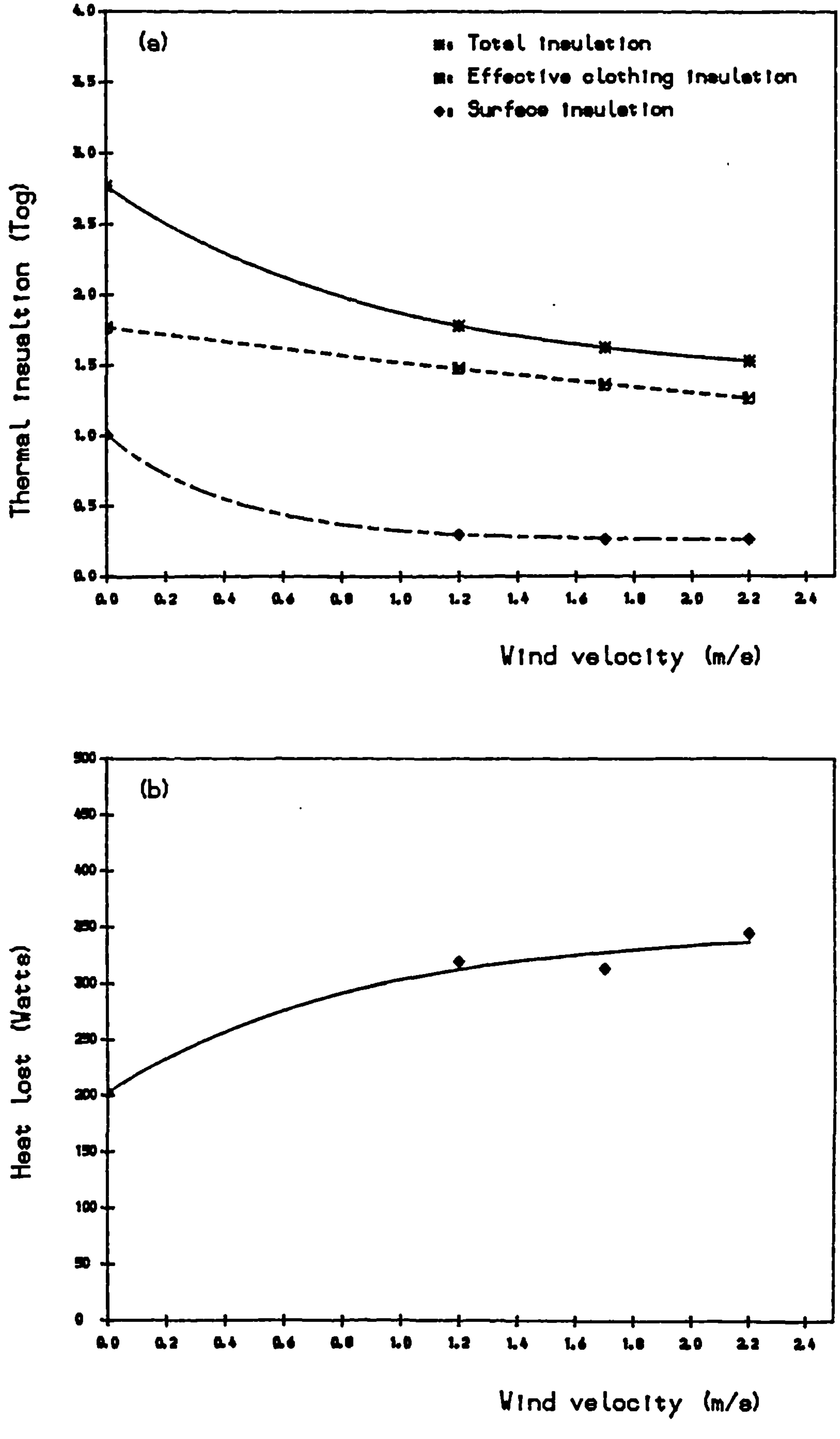
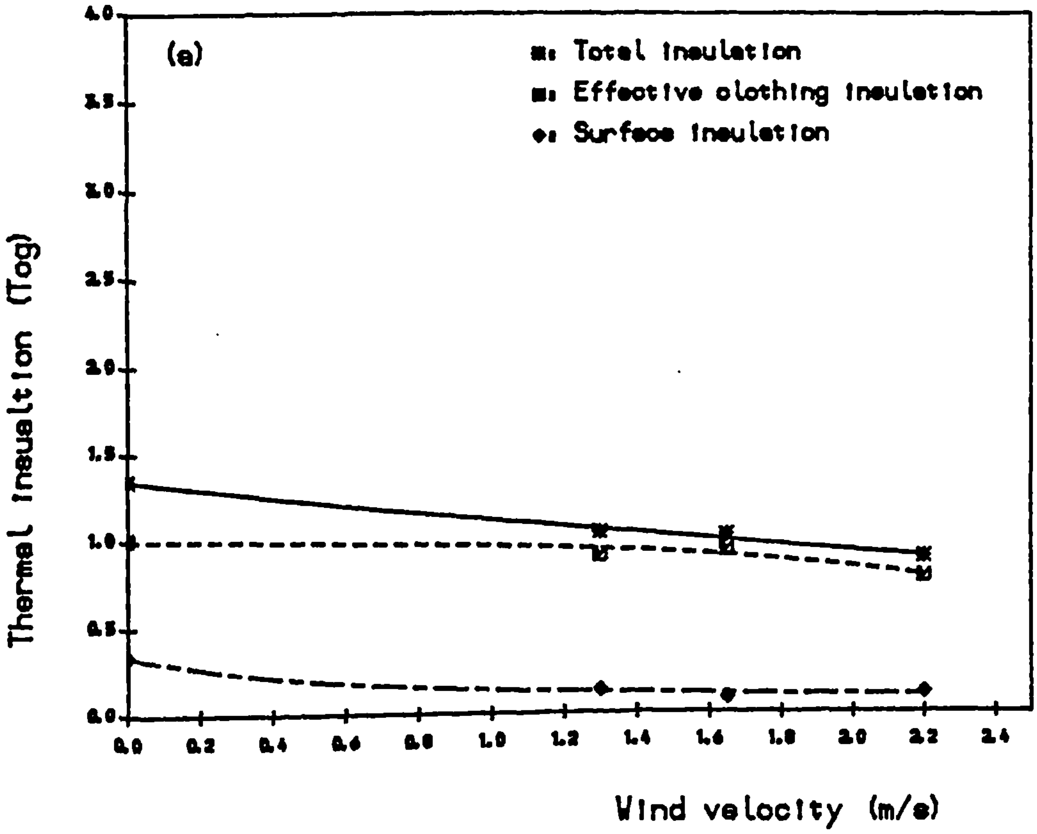


FIGURE 7.4 Effect of wind velocity on the thermal insulation of and heat lost through clothing system A (environmental temperature: 0°C, standing still)



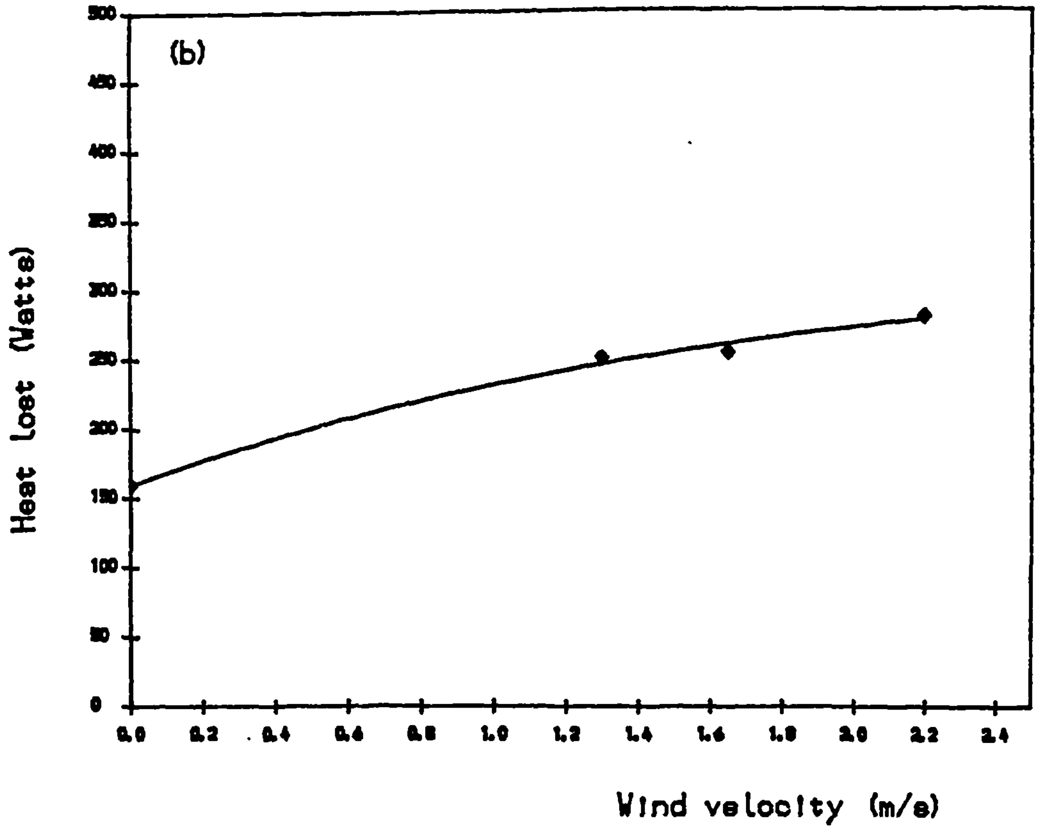
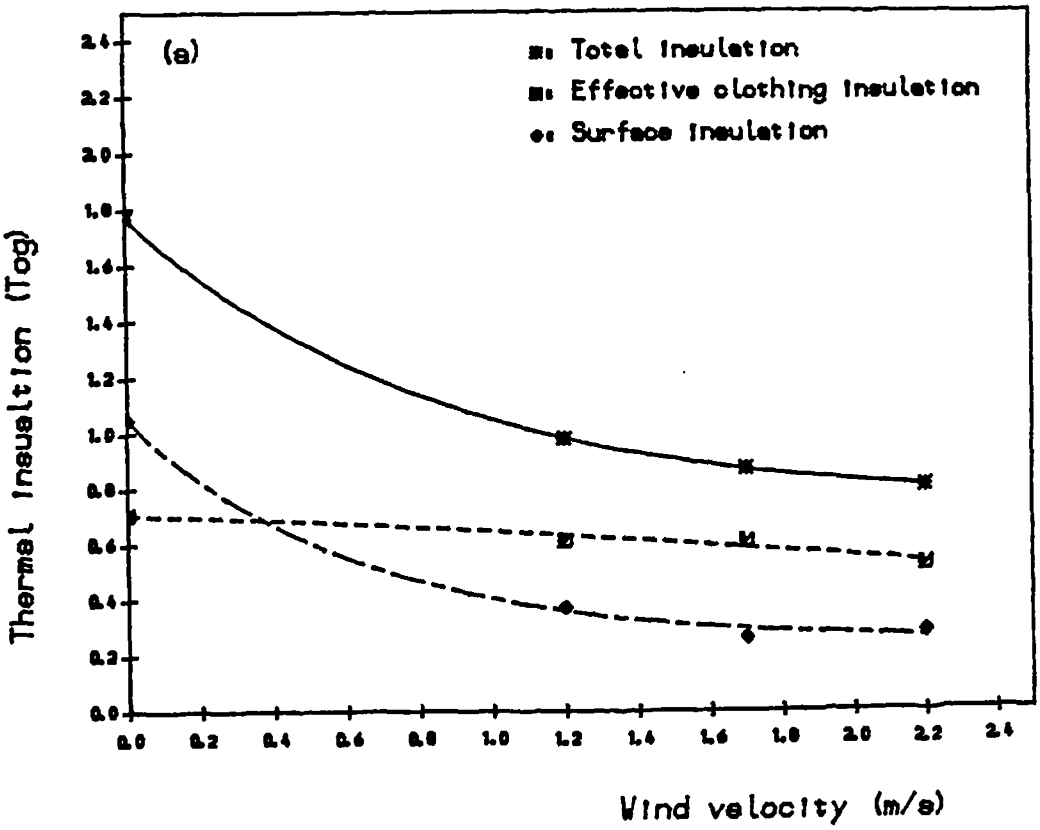


FIGURE 7.5 Effect of wind velocity on the thermal insulation of and heat lost through clothing system A (environmental temperature: 20oC, walking speed: 1.2km/hr)



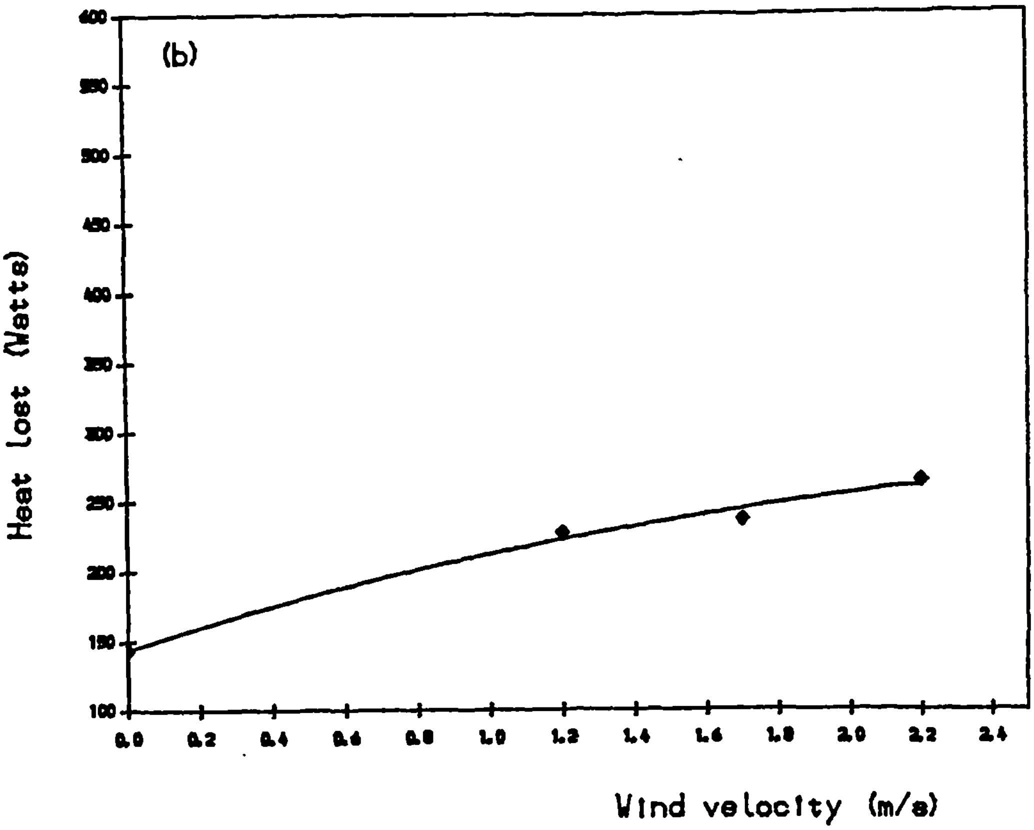
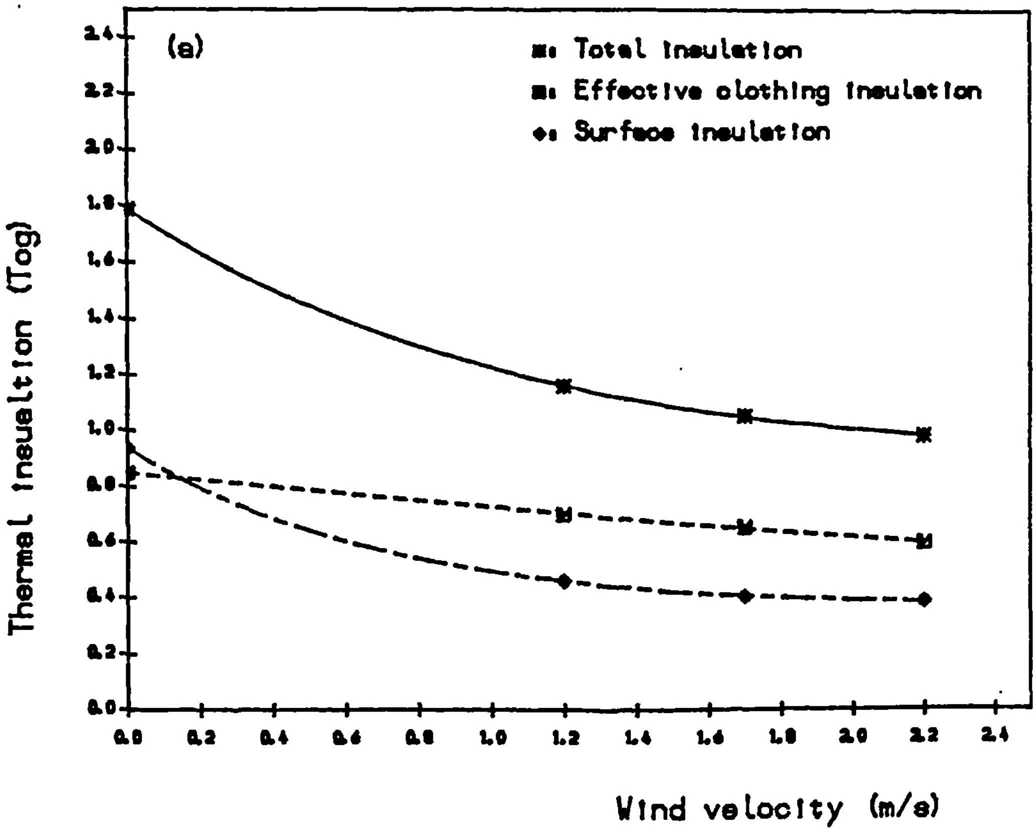


FIGURE 7.6 Effect of wind velocity on the thermal insulation of and heat lost through clothing system C (environmental temperature: 20oC, standing still).



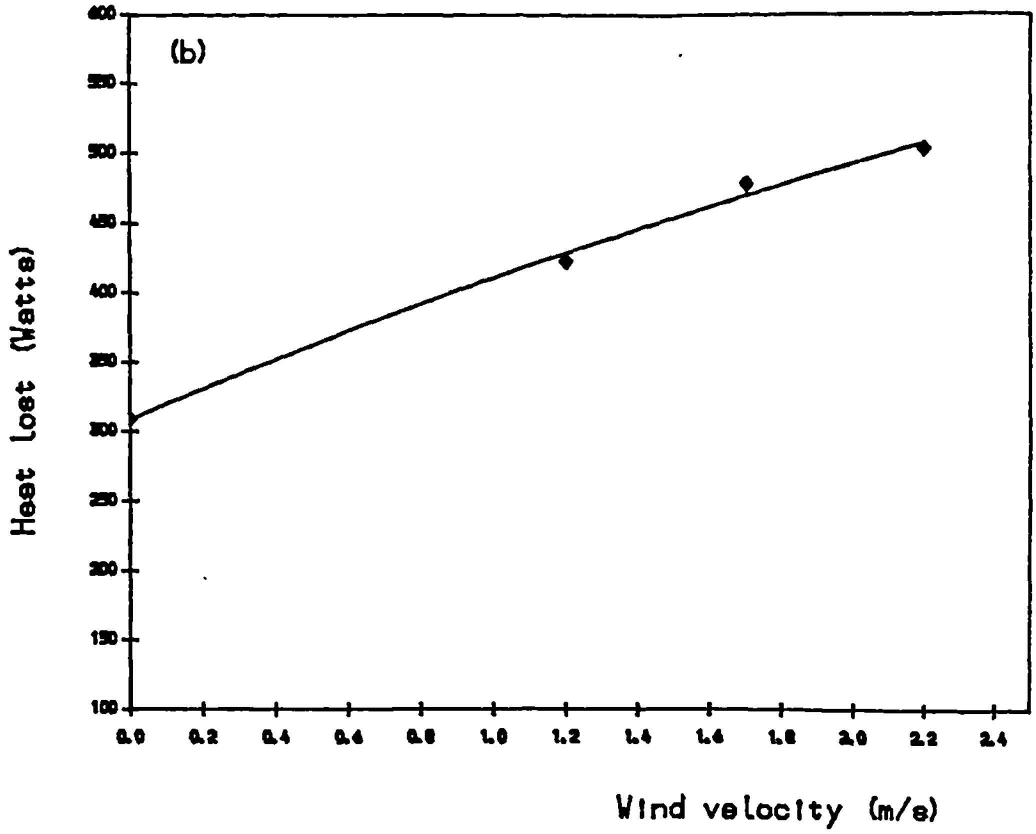


FIGURE 7.7 Effect of wind velocity on the thermal insulation of and heat lost through clothing system C (environmental temperature: 0°C, standing still).

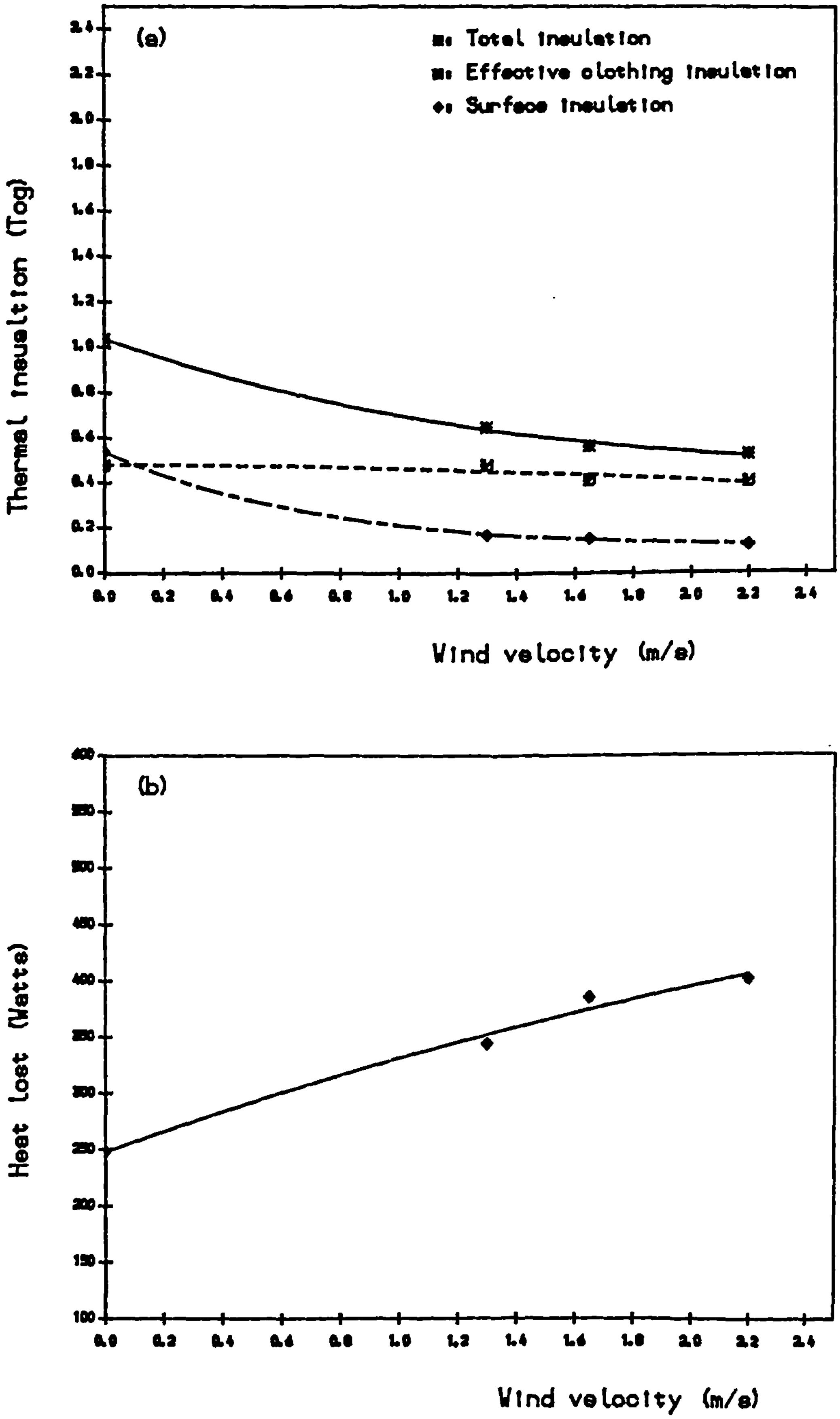
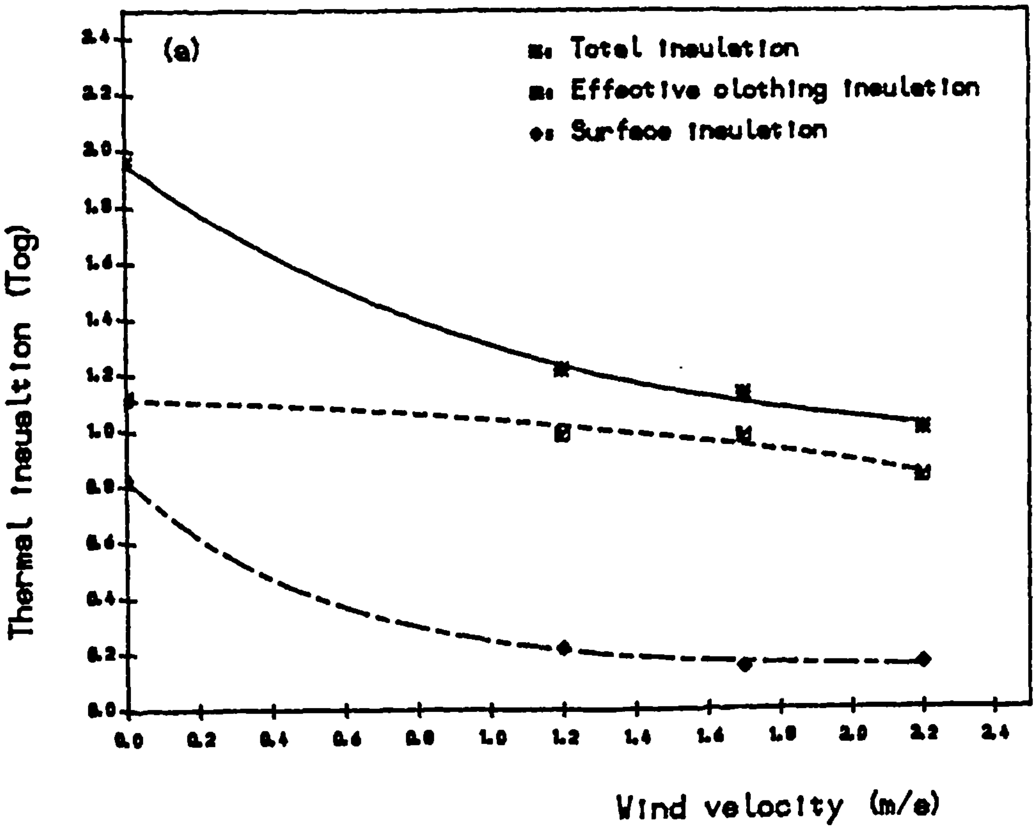


FIGURE 7.8 Effect of wind velocity on the thermal insulation of and heat lost through clothing system C (environmental temperature: 20oC, walking speed: 1.2km/hr).



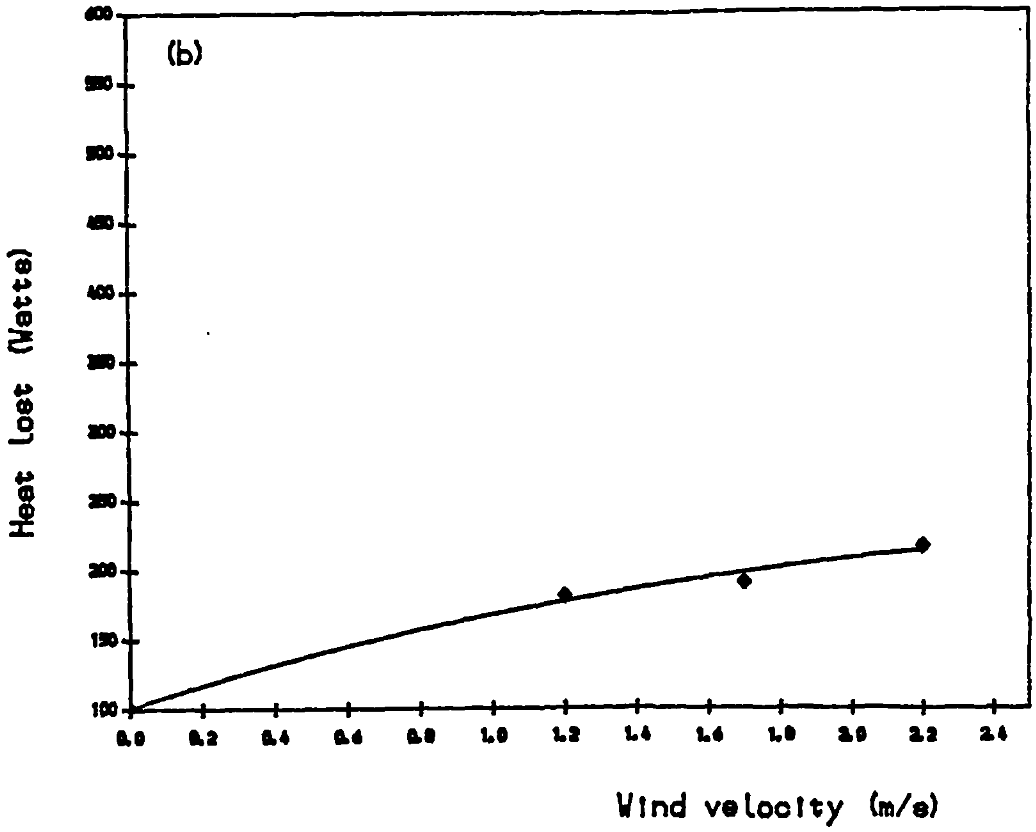
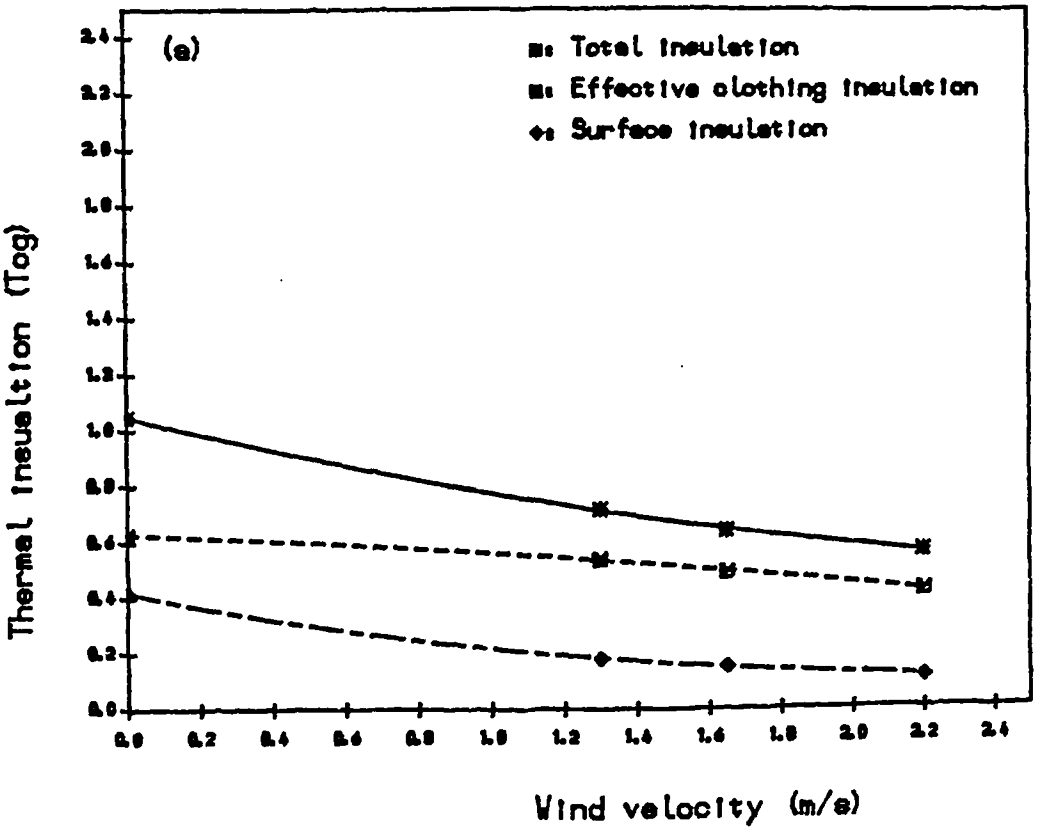


FIGURE 7.9 Effect of wind velocity on the thermal insulation of and heat lost through clothing system D (environmental temperature: 20oC, standing still).



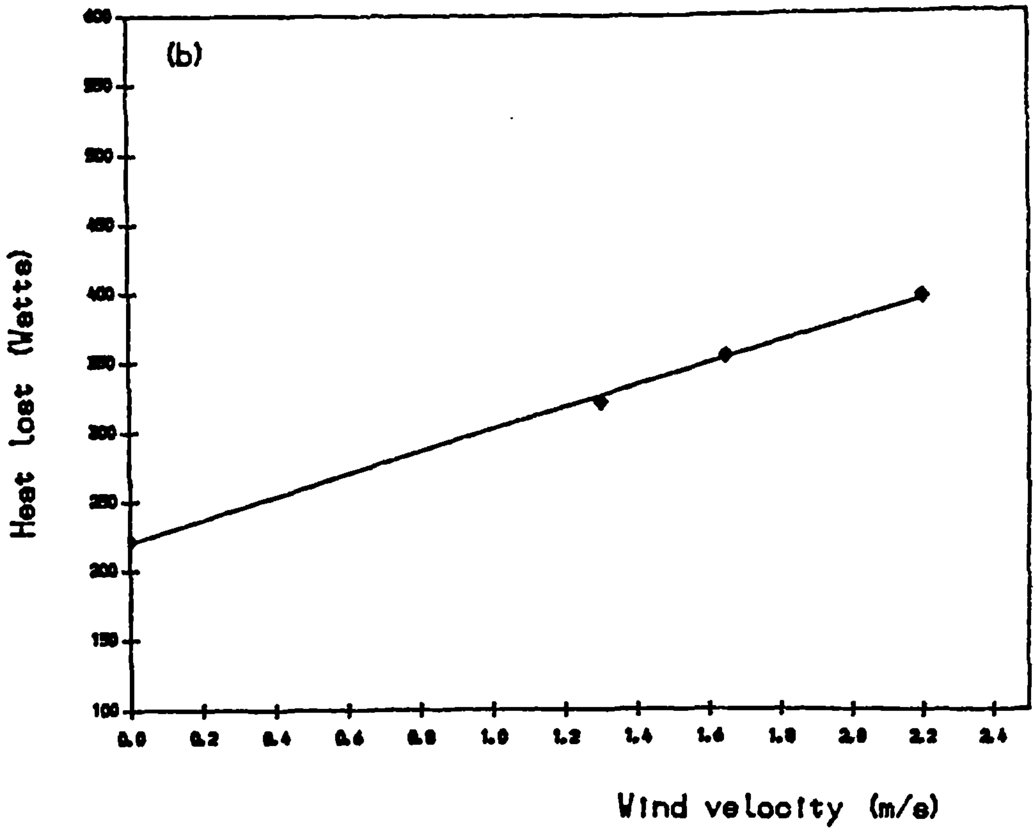


FIGURE 7.10 Effect of wind velocity on the thermal insulation of and heat lost through clothing system D (environmental temperature: 20oC, walking speed: 1.2km/hr).

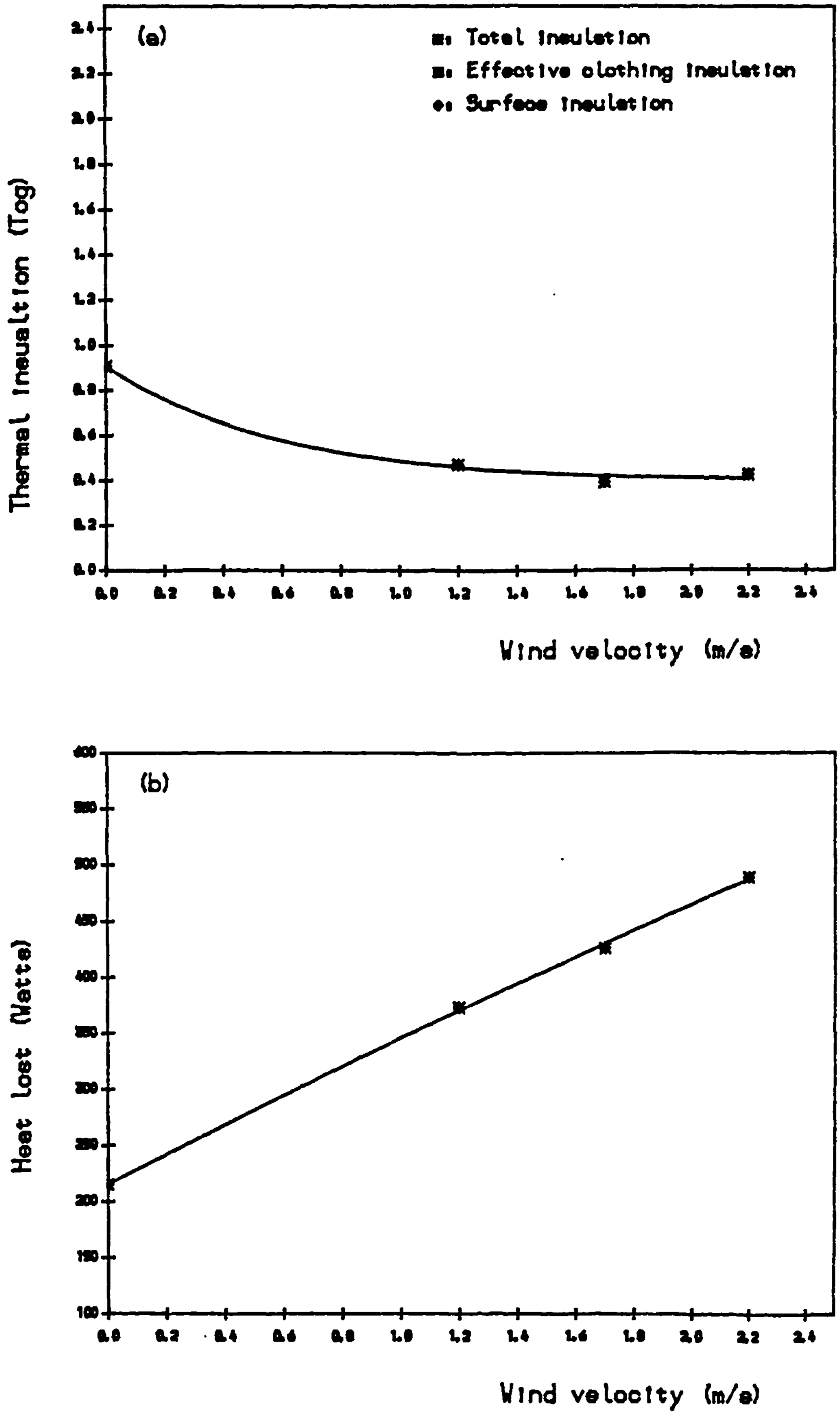


FIGURE 7.11 Effect of wind velocity on the ambient insulation and heat lost from the manikin when no clothing is covered (environmental temperature: 20oC, standing still).

obtained in this work, it can also be seen that most reduction in surface insulation due to wind is induced under the wind velocity lower than 1.2 m/s. When the wind velocity is higher than 1.2 m/s, the surface insulation remains almost constant. The reduction at the wind velocity of 1.2 m/s when the manikin was standing in an environment of indoor temperature (20°C) was found to be within 50-70% compared to still air. This finding was in general agreement with that registered by other workers (Burton and Edholm 1955, Nielsen et al. 1985).

While the reduction of the room temperature can reduce the surface insulation in still air, the results showed that the effect of room temperature on the surface insulation in windy conditions was not evident. This is because, natural convection is no more effective in windy conditions due to forced convection.

The effect of wind velocity on the surface insulation when the manikin was walking was found to be similar to the one when the manikin was standing except that it was smaller in magnitude at all wind velocities. This finding was in support to the finding obtained by Nielsen et al. (1985).

EFFECTIVE CLOTHING INSULATION

Compared to the surface insulation, the reduction in the effective clothing insulation induced by wind was much smaller within the limit of the wind velocity investigated. A trend of a bigger reduction was found at the wind velocity of 2.2 m/s for permeable clothing systems (C and D, A was covered with impermeable jacket). To see the wind effect on the effective clothing insulation, experiments should be conducted at wind velocities higher than 2.2 m/s. This is in agreement with the findings presented in Part-II of this thesis.

The effects of room temperature on the effective clothing insulation was found to be still effective in windy conditions. Higher effective clothing insulation was found at a lower room temperature at different wind velocities.

To see the combined effects of walking and wind, experiments were conducted under different wind velocities when the manikin was walking. The effective clothing insulation obtained at different wind velocities were found to be little different. This could be because body movements have a larger effect than wind has (Nielsen et al. 1985), or because the range of the wind velocities investigated was too small to see any effects of wind velocity.

TOTAL INSULATION

The total insulation is a combined result of the surface insulation and the effective clothing insulation. Because the effect of wind on the effective clothing insulation was small within the range of the wind velocities considered in this work, the reduction in total insulation with increasing wind velocities was similar to that of the surface insulation except for a small percentage. At the wind velocity of 1.2 m/s, under which most reduction was induced, the total insulation was about 25-45% lower than in still air. The percentage of reduction was slightly higher when the manikin was standing than walking.

7.5.3 Effects of Walking Speed

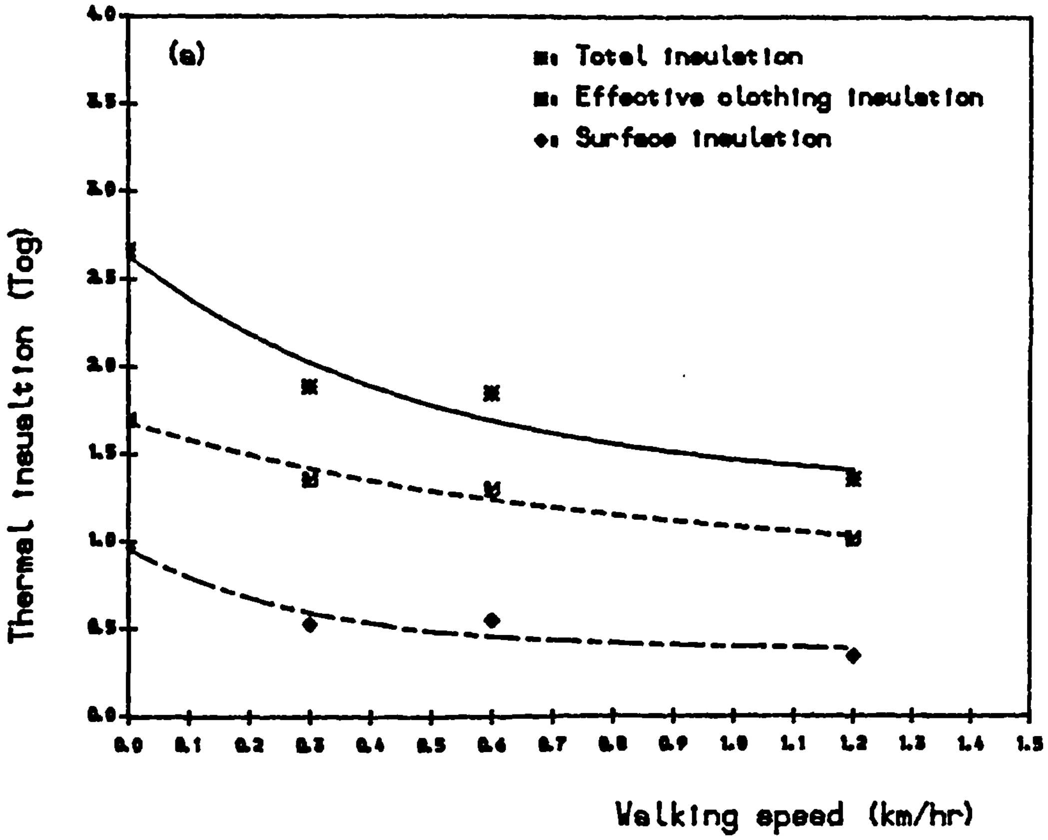
Results for the manikin covered with different clothing systems and walking at different speeds are shown in Fig. 12 - Fig. 17.

SURFACE INSULATION

The surface insulation could be reduced by the erosion of the surface air layer due to walking. As the results show, most reduction was induced when the walking speed was lower than 0.3 km/hr. At this walking speed, in still air, the surface insulation was only 55-70% of the value when the manikin was standing. When walking speed increased from 0.3 to 1.2 m/s, no further significant reduction could be found. This could explain why the amount of reduction registered here was similar to that observed by others (Olesen et al. 1982, Nielson et al. 1985) at much higher walking or cycling speeds. In contrast to that in still air, at a wind velocity 2.2 m/s, a further reduction in surface insulation with increasing walking speed could still be seen for each sample, but the rate of reduction was much smaller than in still air.

EFFECTIVE CLOTHING INSULATION

The effects of body motion on the effective clothing insulation was very significant. Similar to the surface insulation, the largest reduction in the effective clothing insulation was also under the walking speed lower than 0.3 km/hr. In still air, the amount of reduction, when walking at a speed higher than 0.3 km/hr, was found to be within 25-40% compared to



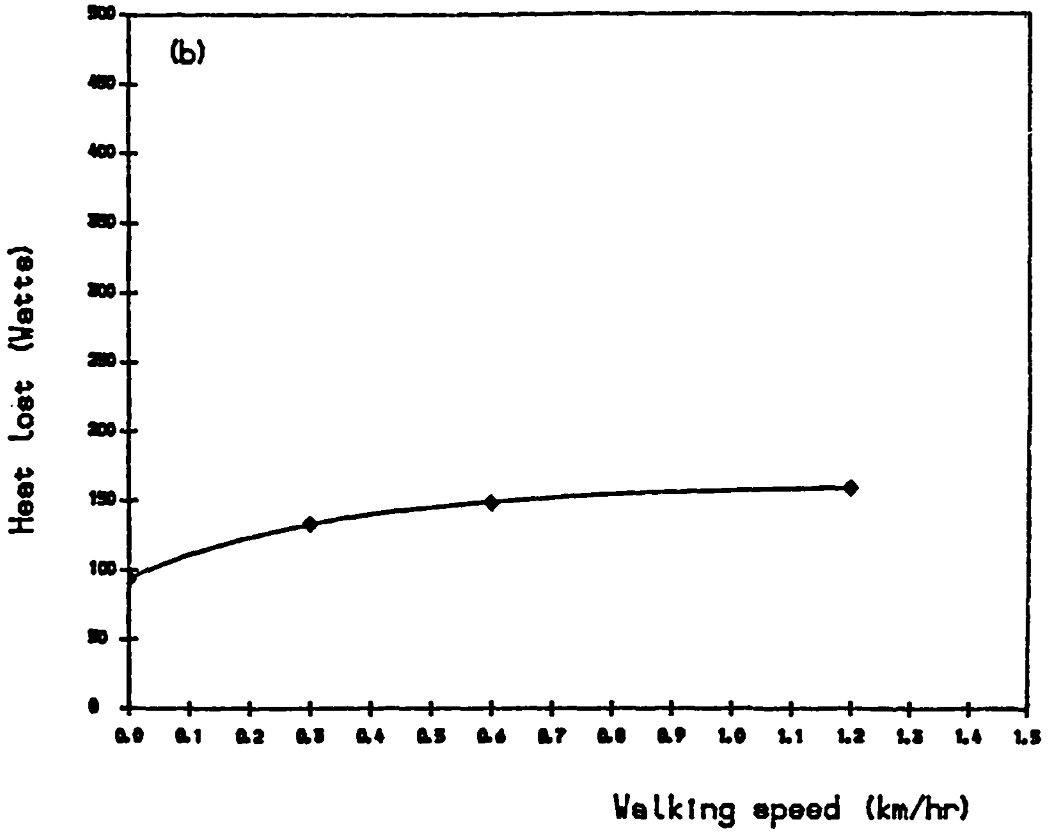
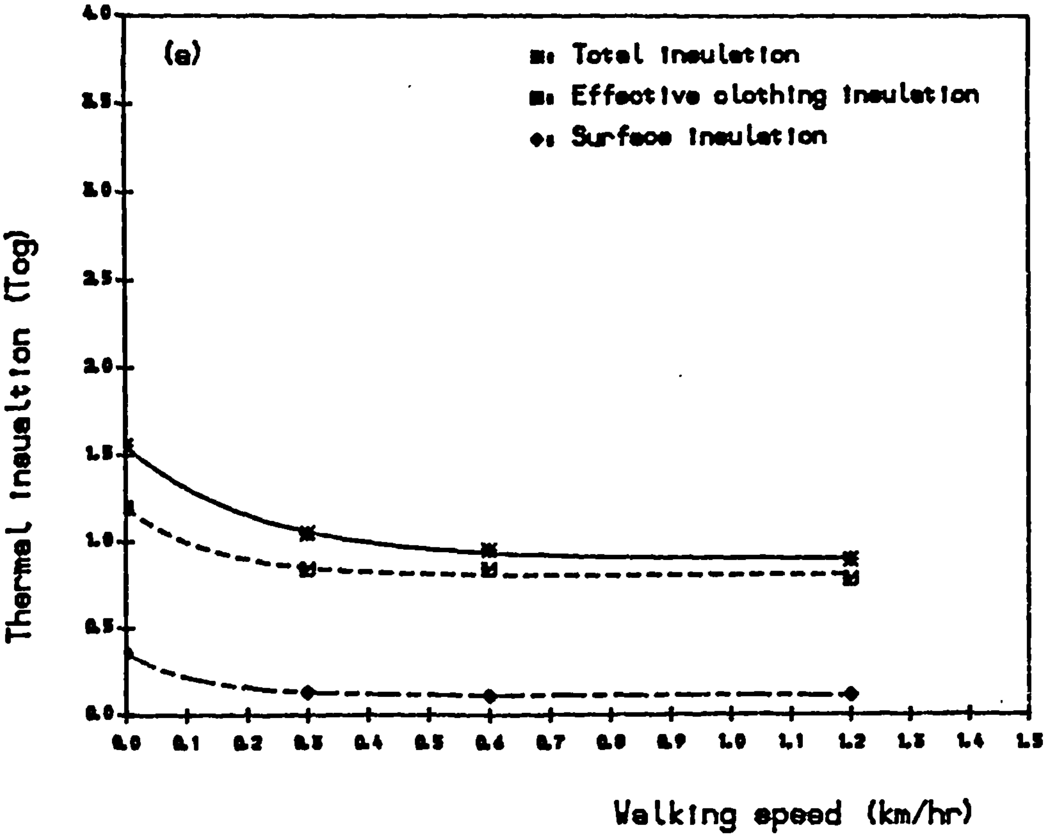


FIGURE 7.12 Effect of walking speed on the thermal insulation of and heat lost through clothing system A (environmental temperature: 20oC, no wind).



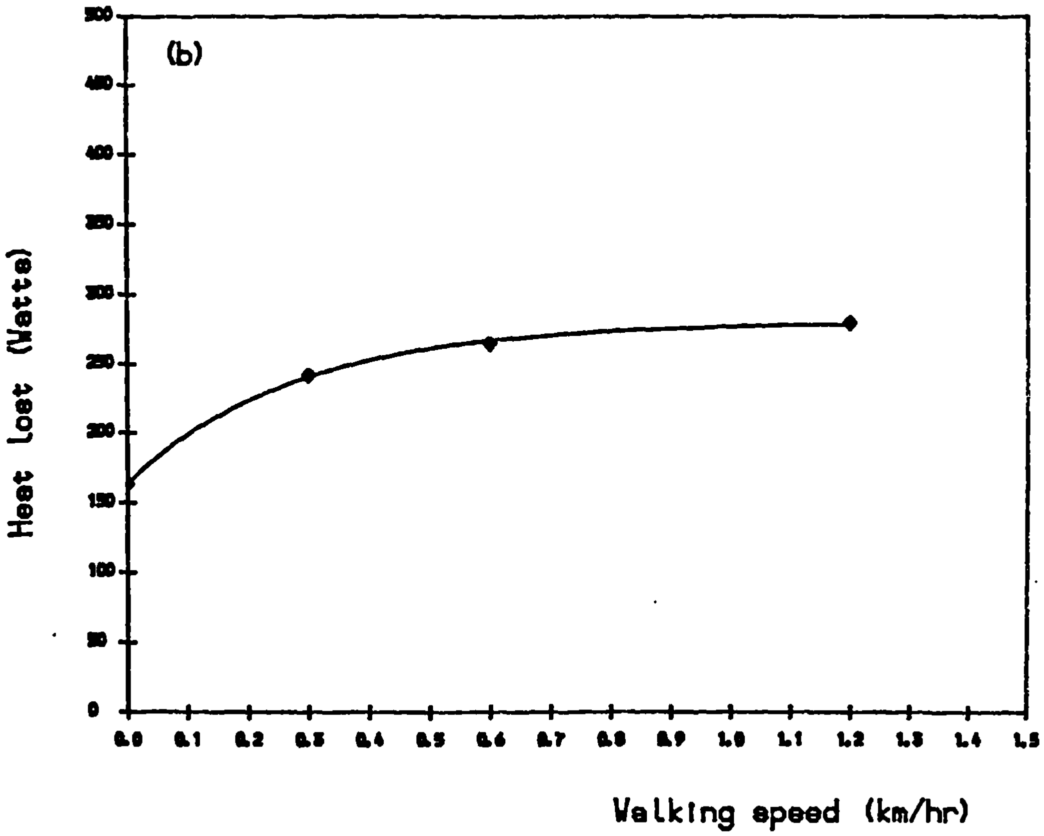
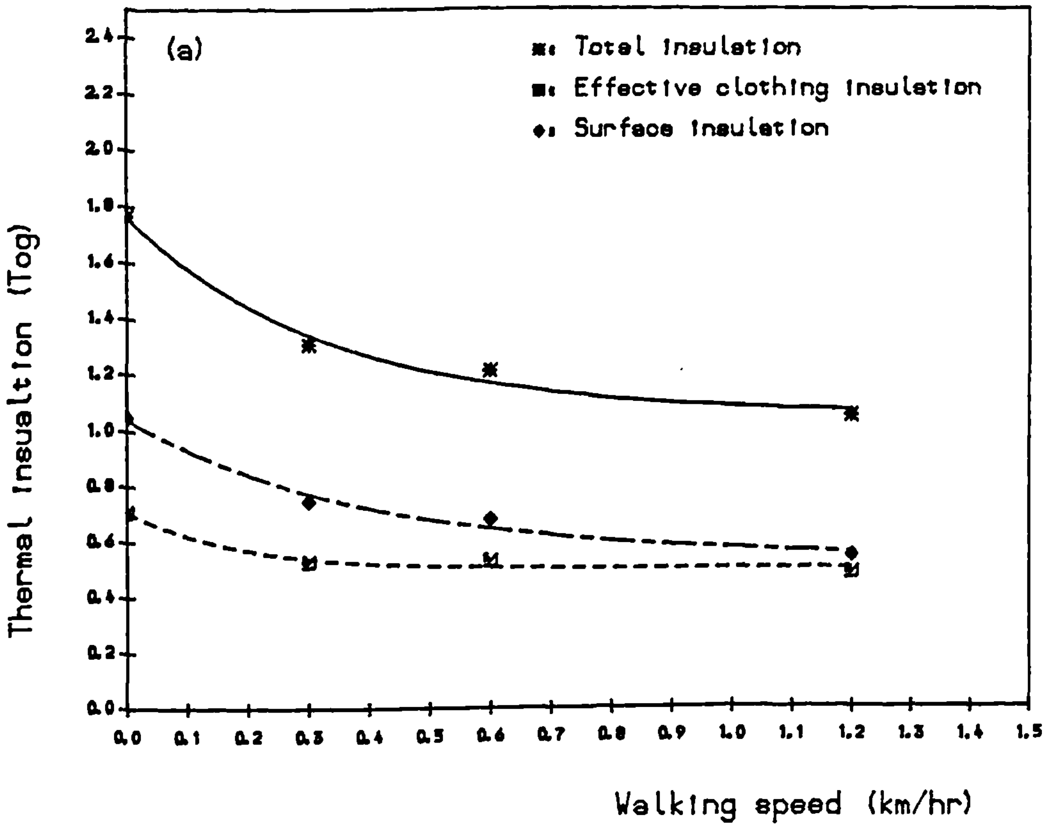


FIGURE 7.13 Effect of walking speed on the thermal insulation of and heat lost through clothing system A (environmental temperature: 20oC, wind velocity: 2.2m/s).



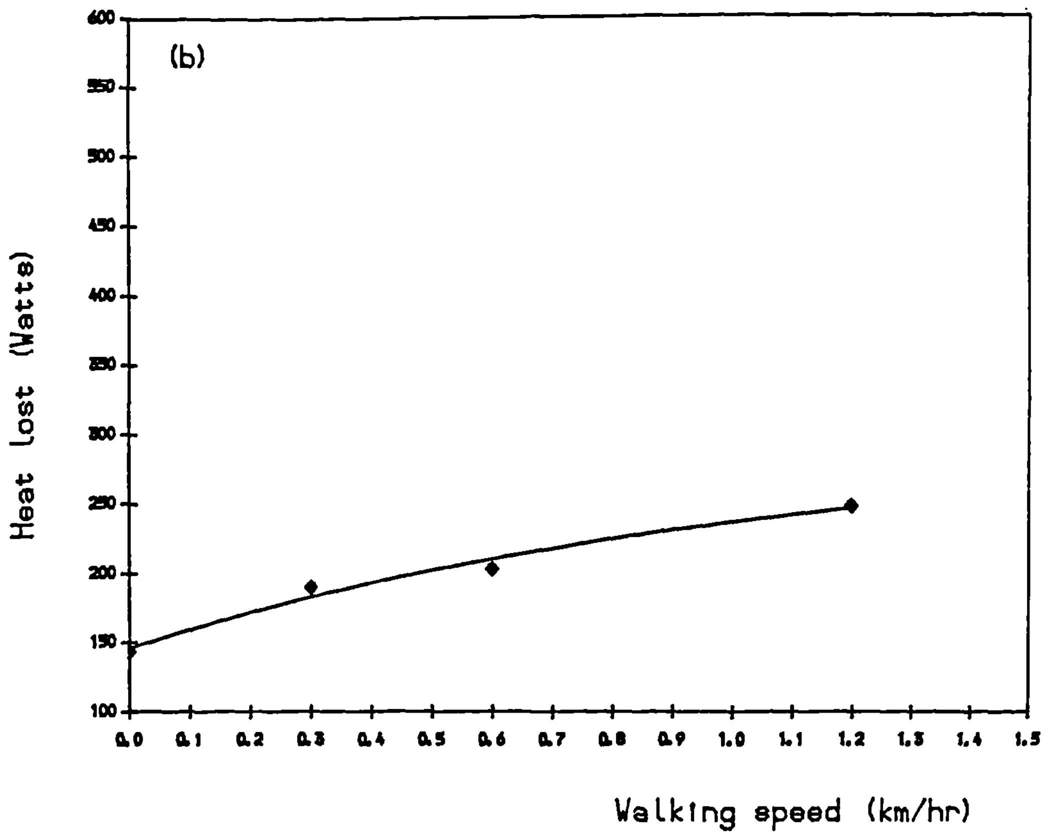
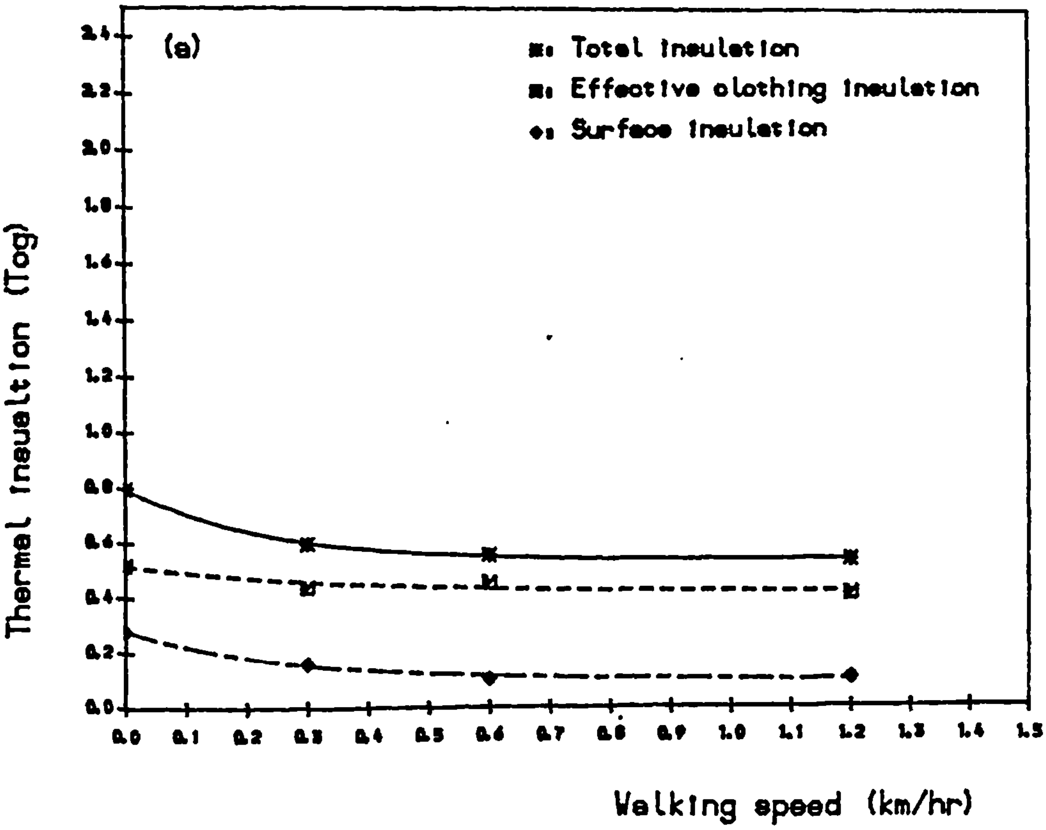


FIGURE 7.14 Effect of walking speed on the thermal insulation of and heat lost through clothing system C (environmental temperature: 20oC, no wind)



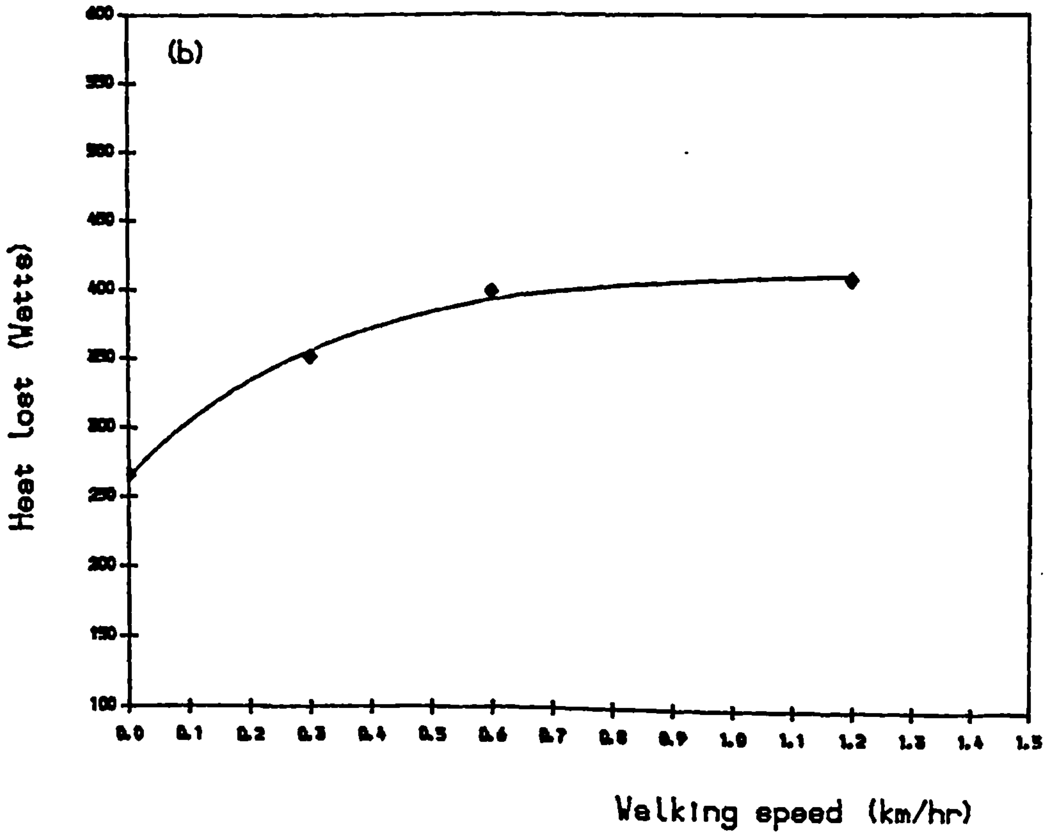


FIGURE 7.15 Effect of walking speed on the thermal insulation of and heat lost through clothing system C (environmental temperature: 20oC, wind velocity: 2.2m/s).

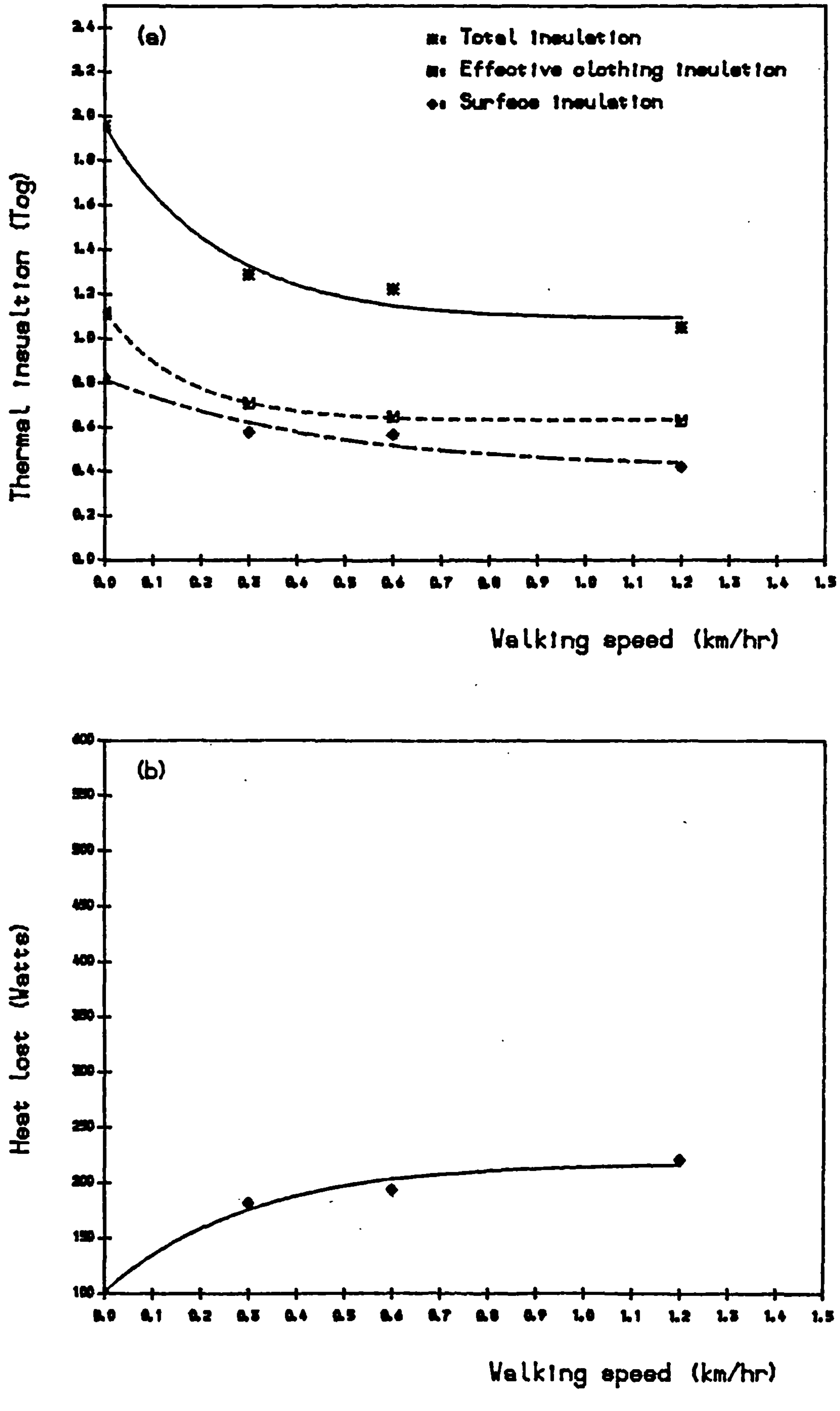


FIGURE 7.16 Effect of walking speed on the thermal insulation of and heat lost through clothing system D (environmental temperature: 20 C, no wind)

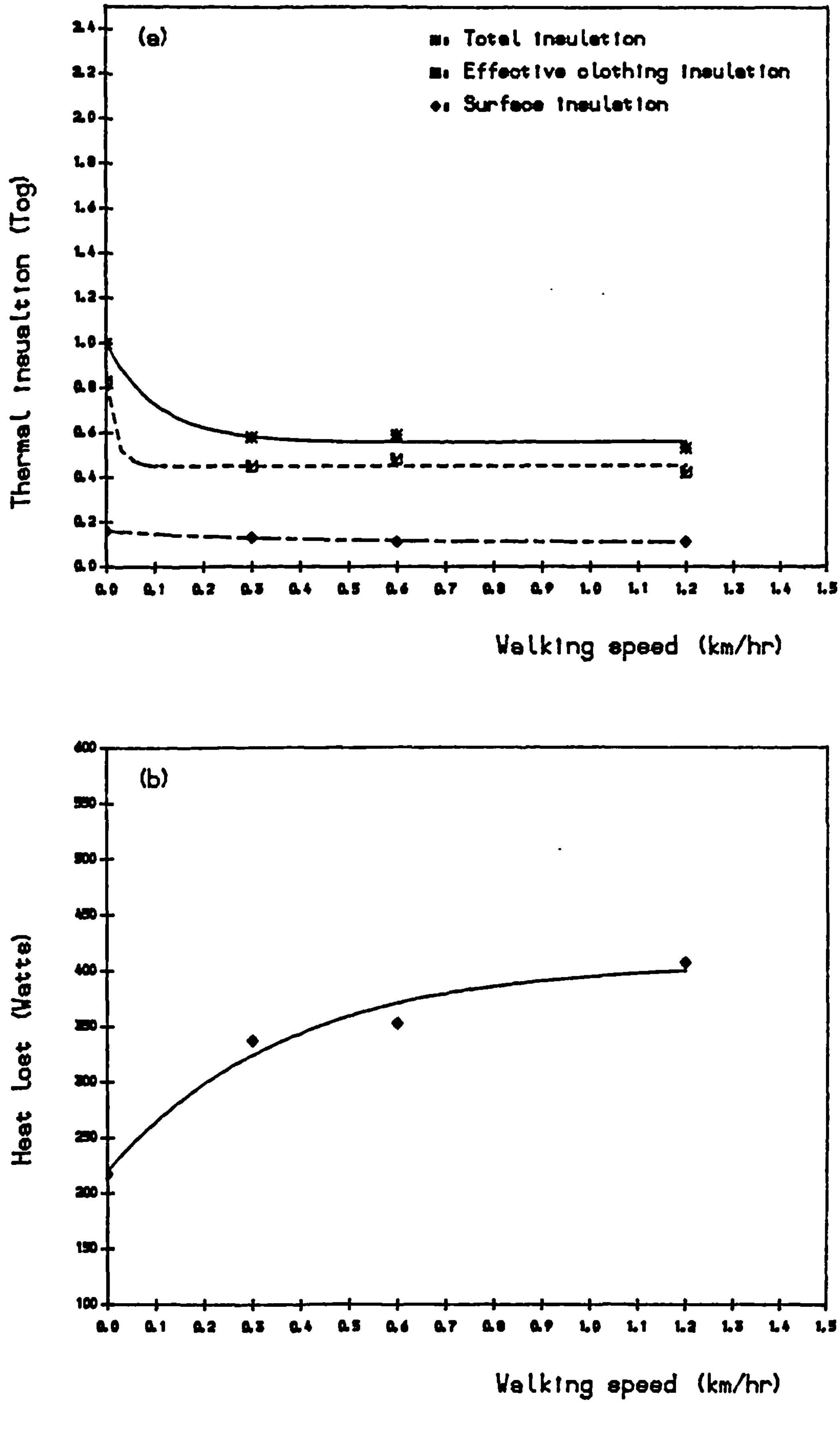


FIGURE 7.17 Effect of walking speed on the thermal insulation of and heat lost through clothing system D (environmental temperature: 20oC, wind velocity: 2.2m/s).

standing. In windy conditions (2.2 m/s), the effects of walking was smaller, the amount of reduction was found to be within 15-30% compared to standing.

In addition, the comparison between the results of clothing system C and D revealed that body movements have much more effects on loose-fitting clothing systems than close-fitting clothing systems. Loose-fitting clothing system D had initially higher effective clothing insulation, but with increasing walking speed, the difference became smaller and smaller.

TOTAL INSULATION

As a combined result of the effective clothing insulation and the surface insulation, the total insulation of the clothing systems was reduced by 30-45% during walking compared to standing. The reduction was higher for loose-fitting clothing systems than for close-fitting clothing systems.

7.6 Concluding Remarks

The effects of wind, temperature and body motion on the thermal insulation of clothing systems and the interactions between these factors are very complex. The work presented here is still a limited investigation. However, it does provide some useful information, which can be summarized as follows.

1. The effective clothing insulation is increased at a lower environmental temperature. The amount of increase is related to the emissivity of the clothing materials. The use of Aluminum foil

can have very significant advantages in the construction of clothing for use in cold environments.

2. In still air, the surface insulation reduces with lowering environmental temperature. At -20°C, it is approximately 25% lower than that at 20°C. In windy conditions, the temperature effect is no more significant.

3. The surface insulation, the effective clothing insulation and the total insulation of a clothing system are maximum when the body is standing in still air.

4. Wind induced reduction in the surface insulation is very pronounced even through the wind velocity is low. Under the wind velocity of 1.2 m/s, the reduction is about 30-50% compared to standing in still air. Similarly, the surface insulation can be greatly reduced by a slow body motion. At a walking speed of 0.3 km/hr, the reduction is about 30-45% compared to standing in still air.

5. The effects of wind and body motion on the effective clothing insulation is less significant than that on the surface insulation under low wind velocities and walking speeds. The insulation of loose-fitting clothing systems can be more easily influenced by body motion and wind than close-fitting clothing systems.

6. The interaction between body motion and wind seems to work in such a way that once the microclimate and surface air layer have been disturbed, a further influence may have only a reduced effect.

7. As a combined result of the surface insulation and the

effective clothing insulation, the total insulation reduces with increasing wind velocity and walking speed. At the wind velocity of 1.2 m/s, the total insulation is about 25-45% lower than that in still air. The total insulation is reduced by 30-45% during walking compared to standing.

8. It is interesting to note from this work that body motion can have a very signficant effect on the clothing thermal insulation even though the body activity is low. This could be the reason why people, when they feel cold, would like to increase the activity level to increase the heat production instead of reducing the activity level to reduce the heat lost.

In addition, the heat lost from the manikin measured under different circumstances in this work provided useful data for predicting the thermal stress of a person wearing a clothing system in different environmental conditions. By comparing the heat lost from the manikin and heat production of a clothed person in the identical conditions, the thermal stress of the person can be predicted.

PART-IV

General Summary and Suggestions for Future Work

Chapter 8

General Summary and Suggestions for Future Work

The work presented in this thesis is devoted to the study of heat transfer through clothing under different circumstances, in order to provide guidelines for the design and construction of clothing with regard to thermal comfort.

In one part of this work, studies were concentrated on the thermal insulation in windy conditions. Although much work has been done in this field, this project was initiated to improve our understanding of this phenomenon by the use of better performing experimental devices and theoretical modelling. In this study, a cylindrical togmeter was developed based on the lines of Mak's version. As the size of the body can affect the final results, the diameter of the newly developed cylindrical togmeter was designed as the area weighted average diameter of different parts of an average human body to ensure that the results from the cylindrical togmeter were representative of that obtained from a human body. In addition, insulation was used to cover the ends of the cylindrical togmeter to make sure that the heat lost from there was negligible. The cylindrical togmeter was placed in a wind tunnel where the air movement was essentially linear. The outer surface temperature was controlled within 30-35°C, which was similar to that of skin.

With this newly developed cylindrical togmeter, a series of experiments were conducted in the standard atmosphere (20±1°C, RH.65±2%) for different clothing assemblies which consisted of a layer of polyester batting and a wind resistant outer fabric. The wind velocity studied ranged from 0 to 10.2 m/s. Comparison between results for clothing assemblies of different permeable outer fabrics revealed that air penetration was the main mechanism involved in the wind induced reduction in clothing insulation for permeable clothing assemblies. The thermal insulation of clothing was found to be uneven around the cylindrical body, being the lowest in the windward areas and the highest in the leeward areas. The thermal insulation of impermeable clothing assemblies was found to be also reduced by wind. This is caused by the compression of the clothing materials which arised from the air pressure imposed on the clothing surface. By comparing the results for clothing assemblies covered with different impermeable outer fabrics, it was found that the thermal insulation was highly related to the stiffness of the outer fabric. This was explained as being due to the fact that assemblies of stiffer outer fabrics were more resistant to changes in their geometry due to compression.

In order to further understand the mechanism of air penetration, a theoretical model was developed. This model applied fundamental physical principles and worked out the air pressure distribution, air movement and temperature distribution within a clothing assembly, and the clothing and surface insulation. In this model, changes in clothing geometry due to compression or expansion were not considered. However, by comparing the theoretical and experimental results, the mechanism of changes in clothing geometry was clearly identified. With the help of this theoretical model, the effects of wind velocity, body dimensions, air permeability of outer fabrics, thickness and air permeability of inner fibrous battings were examined. The heat lost from each of the limbs of a sedentary man wearing a close-fitting anorak in a windy condition can be essentially estimated. An interesting discovery, which was confirmed by the theoretical and experimental study, was that, for clothing assemblies of highly permeable outer fabrics, unlike those of moderately permeable outer fabrics, not only air can penetrate into clothing in the windward area but into the leeward area as well.

The present study provided design guidelines for clothing manufacture. It demonstrated that there is an optimal selection of outer fabrics as a cover of a clothing system for use in windy conditions in respect of air permeability. At low wind velocities, a moderately permeable outer fabric should be selected rather than an impermeable one which is expensive and impermeable to moisture vapour transfer. Also, it showed that fibrous battings of large specific surfaces, such as "thinsulate", which was regarded as better insulators in still air than those of low specific surfaces, are of little better in windy conditions if they are covered with moderately permeable outer fabrics. In addition, if wind is prevailing in a fixed direction, such as the case in motor-cycling, more insulating materials should be used in the windward area than in the leeward area to prevent local wind chill. Besides, to prevent the reduction in thermal insulation caused by compression, rigid fibrous battings may be perferable within the limit of body movement.

Having understood the mechanism of air penetration, one interesting point to arise was that if a wind resistant protective clothing system can be made with air permeable outer fabrics, it would be an advantage, since although clothing systems covered with impermeable outer fabrics are wind resistant protective, moisture vapour transfer is restricted. Three possible solutions to this problem were proposed. They are (1), to cover the windward areas of clothing systems with impermeable fabrics and the leeward areas with permeable fabrics; (2), to block the air movement within the insulating materials of clothing systems by sectional design with baffles; (3), to modify the air movement to achieve even air pressure distributions over the outer surfaces of clothing systems. These three methods were tested by experiments on the cylindrical togmeter. Practically speaking, method (1) and (3) are only applicable when wind is prevailing in a fixed direction; while method (2) has no such limitation. If clothing systems are closely fitted to the body, which is usually required for clothing used in cold weather, no impermeable fabrics, apart from those used for making baffles are needed, and moisture transfer from the inner body is essentially free. For loose-fitting clothing systems, this method requires the use of low permeable fabrics in the inner layer of the clothing systems. This does restrict the moisture transfer as in ordinary design, but has the advantage of avoiding condensation within the clothing.

Future work in the area of the wind effect on the heat transfer through clothing is needed to develop suitable methodologies to consider the difficult geometry of the human body and to study the simultaneous dry and latent heat transfer. In the present studies, the geometry of the human body was considered as similar to a hollow cylinder, it can be replaced by an elliptic cylinder in future. Knowledge of the simultaneous dry and latent heat transfer in windy conditions is still very limited, and study of this aspect should be interesting.

The other part of the present work was focused on the development and laboratory use of a fabric manikin. The skin of the manikin was made of water-proof coated fabric. The manikin was shaped by holding water inside the body. Its central body temperature was controlled at 37°C, and temperature distribution around the body was set to be similar to an ordinary man by adjusting the water flow rate into the extremeties. The arms and legs of the manikin could be moved to simulate walking. With this fabric manikin, a series of experiments were conducted to investigate the effects of body motion, clothing design and environmental conditions on the thermal insulation of clothing systems. Some useful information for the design of functional clothing and for the prediction of the thermal stress of a clothed person in different environmental conditions has been obtained from this investigation. The interesting finding was that the effective clothing insulation increases with reducing environmental temperature, and the amount of increase is related to the emissivity of the clothing materials. The study demonstrated the advantage of the use of Aluminum foil in the construction of clothing for use in cold environments. This study also showed that the clothing insulation can be reduced significantly by body motion even though the body activity is low. This explained why people, when they feel cold, would like to increase their activity level to increase the heat production instead of reducing the activity level to reduce the heat lost.

The fabric manikin developed in this project generally performed well and was very cheap compared with a copper manikin. It can be widely applied for routine tests for outdoor and military garments subject to some modifications in the design. Further development of the fabric manikin with better simulation in the temperature regulation, body motion and perspiration would be a fruitful project.

In this work, it has been observed that dry heat lost from a clothed body increases dramatically with increasing body activity. Further understanding of this phenomenon would enable us to design clothing systems which ensure that the dry heat lost from a human body is close to the heat production inside the human body under wide range of body activities. Such a clothing system is ideal, since sweating can be eliminated even at a high level of body activity, and the wearer can experience no wet discomfort sensation.

APPENDIX

```
C
C    PROGRAM FOR CLOTHING THERMAL INSULATION IN WINDY CONDITIONS
C                        ( J. FAN )
C                     14TH, APRIL, 1988
C
C
C                          PART-1
C
C            AIR PRESSURE AND VELOCITY DISTRIBUTION
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION AI(200,40),BI(40),CC(40),AA(200,40),RR(30),TT(200)
      DIMENSION PO(200),PI(30,200),PP(30,200),UI(30,200),VI(30,200)
      DIMENSION T(30,200),TEM(30,200),TO(200)
      DIMENSION AT(30),BT(30),CT(30),DT(30),GT(30),PT(30),OT(30)
      DIMENSION ET(30,200),FT(30,200),QT(30,200),RT(30,200),ST(30,200)
      DIMENSION UT(30,200),SH(200)
      REAL P2PLOT(200),P3PLOT(200),P4PLOT(200),P5PLOT(200),TTPLOT(200)
      REAL P6PLOT(200),V1PLOT(200),V2PLOT(200),V3PLOT(200),POPLOT(200)
      REAL V4PLOT(200),V5PLOT(200),V6PLOT(200),U1PLOT(200),P1PLOT(200)
      REAL U2PLOT(200),U3PLOT(200),U4PLOT(200),U5PLOT(200)
      REAL U6PLOT(200),TWPLOT(200)
      REAL*8 AP,H,E,R2,R3,ZHE,KT,KR,PD,P,CD,KSR,KCR,R1,TC,KCT,HH
      REAL VMAX,UMAX,TWMAX,TTMAPL,TTMAPH,PPMAPL,PPMAPH,VVMAPL
      REAL VVMAPH,UUMAPL,UUMAPH,TWMAPL,TWMAPH,VE,UE,TE
      READ(1,*) AP,W,R2,TH,KT,KR,NT,NR,NN
      READ(1,*) KSR,KCR,TC,R1,N1,N2,CV,KCT
C
C DEFINE CONSTANCES
C
      H=3.1415927D0
      E=DSQRT(KT/KR)
      P=1.2D0
      PD=0.5D0*P*W*W
      R3=R2+TH
      NO=(NT-1)/3+1
```

```
C
C OUTER PRESSURE DIETRIBUTION
C
      DO 100 I = 1,NT
      TT(I)=1.0D0*(I-1)*180.0D0/(NT-1)
100   CONTINUE
      DO 102 I = 1,68
      PO(I)=(4.0D0*DCOS(2.0D0*H/180.0D0*TT(I))-1)*PD/3.0D0
102   CONTINUE
      DO 104 I = 69,NT
      PO(I)=PD*(1.644D0*DSIN(0.5D0*TT(I)*H/180.D0)-2.19D0)
104   CONTINUE
C
C INNER PRESSURE DISTRIBUTION
C
      DO 106 I = 1,NT
      DO 106 J = 1,NN
      DUM1=(DEXP(E*DFLOAT(J)-1.0D0))**DLOG(R3)
      DUM2=(DEXP(2.0D0*E*DFLOAT(J)))**DLOG(R2)
      DUM3=(DEXP(-E*DFLOAT(J)-1.0D0))**DLOG(R3)
      DUM4=(DEXP(E*DFLOAT(J)))**DLOG(R3)
      DUM5=(DEXP(-E*DFLOAT(J)))**DLOG(R3)
      AI(I,J)=AP/KR*PO(I)*DCOS(DFLOAT(J*(I-1))*H/DFLOAT(NT-1))
      BI(J)=H*(DFLOAT(J)*E*(DUM1-DUM2*DUM3)+AP/KR*
     +(DUM4+DUM2*DUM5))*0.5D0
      AA(I,J)=AI(I,J)/BI(J)
106   CONTINUE
      DO 108 J= 1,NN
      CALL FANJ(AA,NT,J,ZHE,H)
      CC(J)=ZHE
108   CONTINUE
      DO 110 I= 1,NR
      RR(I)=TH/(NR-1)*(I-1)+R2
      DO 112 J= 1,NT
      PP(I,J)=0.0D0
      VI(I,J)=0.0D0
      UI(I,J)=0.0D0
```

```
      KK=1
1988  DUM1=(DEXP(-E*DFLOAT(KK)))**DLOG(RR(I))
      DUM2=(DEXP(E*DFLOAT(KK)))**DLOG(RR(I))
      DUM3=(DEXP(2.0D0*E*DFLOAT(KK)))**DLOG(R2)
      DUM4=(DEXP(E*DFLOAT(KK)-1.0D0))**DLOG(RR(I))
      DUM5=(DEXP(-E*DFLOAT(KK)-1.0D0))**DLOG(RR(I))
      SDUM1=DFLOAT(KK)*DFLOAT(J-1)*H
      SDUM=SDUM1/DFLOAT(NT-1)
      PP(I,J)=PP(I,J)+CC(KK)*(DUM2+DUM3*DUM1)
     +*DCOS(SDUM)
      VI(I,J)=VI(I,J)-KR*CC(KK)*E*KK*(DUM4-DUM3*DUM5
     +)*DCOS(SDUM)*100.0D0
      UI(I,J)=UI(I,J)+KT*CC(KK)*KK/RR(I)*(DUM2+DUM3*
     +DUM1)*DSIN(SDUM)*100.0D0
      KK=KK+1
      IF(KK.LE.NN) GOTO 1988
112   CONTINUE
110   CONTINUE
      CD=PO(1)
      KL=1
1989  DUM6=(DEXP((E*KL)))**DLOG(R3)
      DUM7=(DEXP((2*E*KL)))**DLOG(R2)
      DUM8=(DEXP((E*KL-1)))**DLOG(R3)
      DUM9=(DEXP((-E*KL-1)))**DLOG(R3)
      CD=CD-CC(KL)*((DUM6+DUM7/DUM6)+
     +KR/AP*E*KL*(DUM8-DUM9*DUM7))
      KL=KL+1
      IF(KL.LE.NN) GOTO 1989
      PRINT*, NN,NT,NR,AP
      DO 114 I=1,NR
      DO 114 J=1,NT
      PI(I,J)=PP(I,J)+CD
114   CONTINUE
C
C OUTPUT
C
      NF=(NR-1)/2+1
```

```
9000  FORMAT(2X,5(E9.3,2X))
C     WRITE(2,*)' POSITION  OUT-P  INNB-P  INNC-P  INNE-P'
C     DO 1000 I=1,NT,15
C     WRITE(2,9000) TT(I),PO(I),PI(1,I),PI(NF,I),PI(NR,I)
C1000  CONTINUE
9001  FORMAT(2X,4(E9.3,2X))
C     WRITE(2,*)' POSITION       INNB-V       INNC-V       INNE-V'
C     DO 1001 I=1,NT,15
C     WRITE(2,9001) TT(I),VI(1,I),VI(NF,I),VI(NR,I)
C1001  CONTINUE
C9002  FORMAT(2X,4(E9.3,2X))
C     WRITE(2,*)' POSITION       INNB-U       INNC-U       INNE-U'
C     DO 1002 I=1,NT,15
C     WRITE(2,9002) TT(I),UI(1,I),UI(NF,I),UI(NR,I)
C1002  CONTINUE
C
C                         PART2
C       COMPUTATION FOR HEAT TEANSFER EQUATIONS
C
C DEFINE CONSTANCES
C
      TA=20.D0
      R3=0.1D0*R3
      R2=0.1D0*R2
      R1=0.1D0*R1
      TH=R3-R2
      DR1=(R2-R1)/N1
      DR2=TH/(N2-N1)
      BTB=KSR*DR2/KCR/DR1
      DLT=H/DFLOAT(NT-1)
      DO 3000 I=1,181
      SH(I)=19.3D0*(W**0.6)*(0.32D0*DCOS(TT(I)*H/180.D0)-0.10D0*DCOS(
     +TT(I)*H/180.D0*3.D0)+1.0D0)
3000  CONTINUE
      HH=0.5D0*KCR/DR2
      DO 200 I=1,N1-1
      AT(I)=2.0D0/DR1**2.0D0+2.0D0/(R1+DFLOAT(I)*DR1)**2.0D0
```

```
     +/DLT**2.0D0
      BT(I)=1.0D0/DR1**2.0D0+0.5D0/(R1+DFLOAT(I)*DR1)/DR1
      CT(I)=1.0D0/DR1**2.0D0-0.5D0/(R1+DFLOAT(I)*DR1)/DR1
      DT(I)=1.0D0/(R1+DFLOAT(I)*DR1)**2.0D0/DLT**2.0D0
200   CONTINUE
      DO 202 I=N1+1,N2-1
      GT(I)=KCR*(R2+DFLOAT(I-N1)*DR2)/DR2**2.0D0
      PT(I)=KCT/(R2+DFLOAT(I-N1)*DR2)/DLT**2.0D0
      OT(I)=2.0D0*(GT(I)+PT(I))
      NC=I-N1+1
      DO 204 J=2,180
      ET(I,J)=CV*VI(NC,J)*(R2+DFLOAT(I-N1)*DR2)/DR2*0.5D0
      FT(I,J)=CV*UI(NC,J)/DLT*0.5D0
      QT(I,J)=(GT(I)+HH-ET(I,J))/OT(I)
      RT(I,J)=(GT(I)-HH+ET(I,J))/OT(I)
      ST(I,J)=(PT(I)-FT(I,J))/OT(I)
      UT(I,J)=(PT(I)+FT(I,J))/OT(I)
204   CONTINUE
202   CONTINUE
C
C ASSUMING INITIAL VALUE AND ITERATION CONSTANCES
C
      OMG=0.076D0
      EPSL=10.005D0
      DO 206 I=1,N2
      DO 208 J=2,180
      READ(3,*) T(I,J)
208   CONTINUE
206   CONTINUE
      DO 210 I=1,181
      TO(I)=50.0D0
210   CONTINUE
C
C ITERATION
C
      K=1
1992  TEM(1,2)=(BT(1)*T(2,2)+CT(1)*TO(2)+
```

```
     +DT(1)*T(1,3))/(AT(1)-DT(1))
      DO 212 J=3,179
      TEM(1,J)=BT(1)/AT(1)*T(2,J)+CT(1)/AT(1)*TO(J)+
     +DT(1)/AT(1)*T(1,J+1)+DT(1)/AT(1)*TEM(1,J-1)
212   CONTINUE
      TEM(1,180)=(BT(1)*T(2,180)+CT(1)*TO(180)+
     +DT(1)*TEM(1,179))/(AT(1)-DT(1))
      DO 214 I=2,N1-1
      TEM(I,2)=(BT(I)*T(I+1,2)+CT(I)*TEM(I-1,2)+
     +DT(I)*T(I,3))/(AT(I)-DT(I))
214   CONTINUE
      DO 216 I=2,N1-1
      DO 218 J=3,179
      TEM(I,J)=BT(I)/AT(I)*T(I+1,J)+CT(I)/AT(I)*TEM(I-1,J)+
     +DT(I)/AT(I)*T(I,J+1)+DT(I)/AT(I)*TEM(I,J-1)
218   CONTINUE
216   CONTINUE
      DO 220 I=2,N1-1
      TEM(I,180)=(BT(I)*T(I+1,180)+CT(I)*TEM(I-1,180)+
     +DT(I)*TEM(I,179))/(AT(I)-DT(I))
220   CONTINUE
      DO 222 J=2,180
      TEM(N1,J)=1.0D0/(BTB+1.0D0)*T(N1+1,J)+
     +BTB/(BTB+1.0D0)*TEM(N1-1,J)
222   CONTINUE
      DO 224 I=N1+1,N2-1
      TEM(I,2)=(QT(I,2)*T(I+1,2)+RT(I,2)*TEM(I-1,2)+
     +ST(I,2)*T(I,3))/(1.0D0-UT(I,2))
224   CONTINUE
      DO 226 I=N1+1,N2-1
      DO 228 J=3,179
      TEM(I,J)=QT(I,J)*T(I+1,J)+RT(I,J)*TEM(I-1,J)+
     +ST(I,J)*T(I,J+1)+UT(I,J)*TEM(I,J-1)
228   CONTINUE
226   CONTINUE
      DO 230 I=N1+1,N2-1
      TEM(I,180)=(QT(I,180)*T(I+1,180)+RT(I,180)*TEM(I-1,180)+
```

```
      +UT(I,180)*TEM(I,179))/(1.0D0-ST(I,180))
230   CONTINUE
      DO 231 J=2,180
      TEM(25,J)=(KCR/DR2*TEM(24,J)+SH(J)*TA)/(KCR/DR2+SH(J))
231   CONTINUE
      COMAX=0.0D0
      DO 232 I=1,N2
      DO 234 J=2,180
      CO=DABS(TEM(I,J)-T(I,J))
      IF (COMAX.LE.CO) COMAX=CO
234   CONTINUE
232   CONTINUE
C     WRITE(6,*) COMAX
      IF (COMAX.LT.EPSL) GOTO 1993
      DO 236 I=1,N2
      DO 238 J=2,180
      T(I,J)=TEM(I,J)*OMG+T(I,J)*(1.0D0-OMG)
238   CONTINUE
236   CONTINUE
      GOTO 1992
1993  DO 240 I=1,N2
      DO 242 J=2,180
      T(I,J)=TEM(I,J)
242   CONTINUE
240   CONTINUE
      DO 244 I=1,N2-1
      T(I,1)=T(I,2)
      T(I,181)=T(I,180)
244   CONTINUE
9004  FORMAT(I2,4(E9.3,2X))
      WRITE(2,*)' ANGLE POSITION   VIC-C    SURFACE   CLO-C'
      DO 246 J=1,181
      WRITE(2,9004)   J-1,TO(J), T(7,J),T(15,J),T(20,J),T(25,J)
246   CONTINUE
C
C
C
```

```
C                                 PART 3
C                             DRAW GRAPHICS
C
C  PLOTFILES
C
      VMAX=0.0
      UMAX=0.0
      UMIN=0.0
      TWMAX=0.0
      DO 300 I=1,181
      TTPLOT(I)=DFLOAT(I-1)
      POPLOT(I)=PO(I)
      P1PLOT(I)=PI(11,I)
      P2PLOT(I)=PI(9,I)
      P3PLOT(I)=PI(7,I)
      P4PLOT(I)=PI(5,I)
      P5PLOT(I)=PI(3,I)
      P6PLOT(I)=PI(1,I)
      V1PLOT(I)=VI(11,I)
      V2PLOT(I)=VI(9,I)
      V3PLOT(I)=VI(7,I)
      V4PLOT(I)=VI(5,I)
      V5PLOT(I)=VI(3,I)
      V6PLOT(I)=VI(1,I)
      U1PLOT(I)=UI(11,I)
      U2PLOT(I)=UI(9,I)
      U3PLOT(I)=UI(7,I)
      U4PLOT(I)=UI(5,I)
      U5PLOT(I)=UI(3,I)
      U6PLOT(I)=UI(1,I)
      TWPLOT(I)=T(15,I)
      VE=ABS(V1PLOT(I))
      IF(VMAX.LE.VE) VMAX=VE
      UE=U6PLOT(I)
      IF(UMIN.GE.UE) UMIN=UE
      IF(UMAX.LE.UE) UMAX=UE
      TE=TWPLOT(I)
```

```
      IF(TWMAX.LE.TE) TWMAX=TE
300   CONTINUE
C
C DEFINE MAP
C
      TTMAPL=0.0
      TTMAPH=180.0
      PPMAPL=-1.40*PD
      PPMAPH=1.40*PD
      VVMAPL=-1.20*VMAX
      VVMAPH=1.20*VMAX
      UUMAPL=1.2*UMIN
      UUMAPH=1.20*UMAX
      TWMAPL=20.0
      TWMAPH=1.20*TWMAX
C
C PLOTING
C
      CALL PAPER(1)
      CALL PSPACE(0.,1.,0.,1.)
      CALL MAP(0.,1.,0.,1.)
      CALL CTRORI(90.0)
      CALL PLOTCS(0.05,0.66,'Air Pressure (Pa)',17)
      CALL CTRORI(0.0)
      CALL PLOTCS(0.20,0.88,'solid line: outer pressure',26)
      CALL PLOTCS(0.20,0.86,'dashed line: inner pressure',27)
      CALL PLOTCS(0.20,0.82,'W=4.5m/s',8)
      CALL PLOTCS(0.36,0.72,'Position (Degree)',17)
      CALL PLOTCS(0.12,0.53,'FIG.9    Air Pressure Distribution',34)
      CALL PLOTCS(0.12,0.51,'      (Moderately Permeable Type-D)',34)
      CALL CTRORI(90.0)
      CALL PLOTCS(0.05,0.23,'Air Flow Rate (m/s)',19)
      CALL CTRORI(0.0)
      CALL PLOTCS(0.36,0.26,'Position (Degree)',17)
      CALL PLOTCS(0.12,0.08,'Fig.     Radial Air Flow In Clothing',36)
      CALL PLOTCS(0.92,0.53,'Fig.     Circular Air Flow In Clothing',38)
      CALL PLOTCS(1.16,0.57,'Position (Degree)',17)
```

```
      CALL CTRORI(90.0)
      CALL PLOTCS(0.85,0.66,'Air Flow Rate (m/s)',19)
      CALL PLOTCS(.845,0.23,'             o  ',16)
      CALL PLOTCS(0.85,0.23,'Temperature ( C)',16)
      CALL CTRORI(0.0)
      CALL PLOTCS(0.90,0.08,'Fig.      Surface Temperature of Hollow Cyl
     +inder',48)
      CALL PLOTCS(1.16,0.11,'Position (Degree)',17)
      CALL PSPACE(0.1,0.5,0.6,0.9)
      CALL MAP(TTMAPL,TTMAPH,PPMAPL,PPMAPH)
      CALL BORDER
      CALL AXES
      CALL PTJOIN(TTPLOT,POPLOT,1,181,1)
      CALL BROKEN(5,5,5,5)
      CALL PTJOIN(TTPLOT,P1PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,P2PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,P3PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,P4PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,P5PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,P6PLOT,1,181,1)
      CALL FULL
      CALL PSPACE(0.1,0.5,0.14,0.44)
      CALL MAP(TTMAPL,TTMAPH,VVMAPL,VVMAPH)
      CALL BORDER
      CALL AXES
      CALL BROKEN(5,5,5,5)
      CALL PTJOIN(TTPLOT,V1PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,V2PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,V3PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,V4PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,V5PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,V6PLOT,1,181,1)
      CALL FULL
      CALL PSPACE(0.9,1.3,0.6,0.9)
      CALL MAP(TTMAPL,TTMAPH,UUMAPL,UUMAPH)
      CALL BORDER
      CALL AXES
```

```
      CALL BROKEN(5,5,5,5)
      CALL PTJOIN(TTPLOT,U1PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,U2PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,U3PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,U4PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,U5PLOT,1,181,1)
      CALL PTJOIN(TTPLOT,U6PLOT,1,181,1)
      CALL FULL
      CALL PSPACE(0.90,1.30,0.14,0.44)
      CALL MAP(TTMAPL,TTMAPH,TWMAPL,TWMAPH)
      CALL BORDER
      CALL AXES
      CALL PTJOIN(TTPLOT,TWPLOT,1,181,1)
      CALL GREND
      STOP
      END
C
C INTERGRATING SUBROUTINE
C
      SUBROUTINE FANJ(AA,NT,J,ZHE,H)
      IMPLICIT REAL(A-H, O-Z)
      REAL*8 AA(200,200)
      ZHE=0.0D0
      DO 9000 I=1,NT-1
      ZHE=ZHE+H/(NT-1)*0.5D0*(AA(I,J)+AA(I+1,J))
9000  CONTINUE
      RETURN
      END
```

REFERENCES

Augus, T. C. (1935). The Heat Retaining Properties of Clothing Computed on a Physiological Basis, J. Text. Inst., Vol. 26, T83.

Bachmann, V. P. (1928). Ueber die Bestimmung des Warmehaltungsvermogens Von Bekleidungsstoffen mit Hilfe des Hillschen Katathermometers, Deut. Med. Woch., Vol.54, pp. 146-147.

Bejan, A. (1984). *Convective Heat Transfer*, John Wiley & Sons, New York.

Black, A. P. and **Matthew**, J. A. (1934). The Physical Properties of Fabrics in Relation to Clothing, J. Text. Inst., Vol. 25, T197, T225, T249.

Belding, H. S., **Russel**, H. D., **Darling**, R. C., and **Folk**, G. E. (1947). Analysis of Factors Concerned in Maintaining Energy Balance for Dressed Men in Extreme Cold; Effects of Activity on the Protective Value and Comfort of an Arctic Uniform, Am. J. Physiol. Vol. 147, pp. 223-239.

Bird, R. B., **Stewart**, W. E., and **Lightfoot**, E. N. (1960). *Transport Phenomena*, John Wiley & Sons, New York.

Blyth, G. (1984). Heat and Vapor Transfer Properties of Knitted Fabrics, Ph.D Thesis, The University of Leeds.

Bogaty, H., **Hollies**, N. R. S., and **Harris**, M. (1957). Some Thermal Properties of Fabrics, Part I: The Effect of Fibre Arrangement, Tex. Res. J., Vol. 27, pp. 445-449.

Breckenridge, J. R. and **Goldman**, R. F. (1977). Effects of Clothing on Bodily Resistance against Meteorological Stimuli, In *Progress in Human Biometeorology*, ed. Tramp, J. F., Sweits & Zeiltinger, Amsterdam, pp. 194-208.

Brook, D. B. and **Keighley**, J. H. (1980). The Application of Pile Fabrics in Outdoor Clothing, Clo. Res. J., Vol. 8, pp. 139-144.

Burton, A. C. and **Edholm**, O. G. (1955). *Man in a Cold Environment,* Edward Arnold Ltd, London.

Chrenko, F. A. and **Pugh**, L. G. C. (1961). The Contribution of Solar Radiation to the Thermal Environment of Man in Antarctica, Proc. Roy. Soc. B, Vol. 155, pp. 143-265.

Clulow, E. E. and **Rees**, W. H. (1968). The Transmission of Heat through Textile Fabrics, Part III, A New Thermal-Transmission Apparatus, J. Text. Inst., Vol. 59, T285.

Eckert, E. R. G. and **Drake**, R. M. (1972). Analysis of Heat and Mass Transfer, McGraw-Hill, New York.

Fanger, P. O. (1982). *Thermal Comfort*, Robert E. Krieger Publishing Company, Malabar Florida.

Farnworth, B. (1983). Mechanism of Heat Flow through Clothing Insulation, Tex. Res. J., Vol. 53, No. 12, pp. 717-725.

Farnworth, B. (1986). A Numerical Model of the Combined Diffussion of Heat and Water Vapor through Clothing, Tex. Res. J., Vol. 56, pp. 653-665.

Fonseca, C. F. and **Breckenridge**, J. R. (1965). Wind Penetration Through Fabric Systems, Tex. Res. J., Vol. 35, pp. 95-103, pp.221-227.

Fonseca, G. F. (1970). Heat Transfer Properties of Ten Underwear-Outerwear Ensembles, Tex. Res. J., Vol. 40, pp. 553-558.

Fonseca, G. F. (1975). Sectional Dry-Heat-Transfer Properties of Clothing in Wind, Tex. Res. J., Vol. 45, pp. 30-34.

Fourt, L. and **Horris**, M. (1947). Diffusion of Water Vapour through Textiles, Tex. Res. J., Vol. 17, pp. 256-263.

Gagge, A. P., **Burton**, A. C., and **Bazett**, H. C. (1941). A Practical System of Units for the Description of the Heat Exchange in Man with His Thermal Environment, Science, Vol. 94, pp. 428-430.

Hanada, K. (1979). Studies on the Regional Thermal Resistance of Clothing System, Part. I, J. of the Japan Research Association for Textile End-Uses, Vol. 20, No. 7.

Hensel, H. (1981). *Thermoreception and Temperature Regulation*, Academic Press, London.

Hoge, H. J. and **Fonseca**, G. F. (1964). The Thermal Conductivity of a Multilayer Sample of Underwear Material under a Variety of Experimental Conditions, Tex. Res. J., Vol. 34, pp. 401-410.

Holmer, I. (1985). Heat Exchange and Thermal Insulation Compared in Woolen and Nylon Garments During Wear Trials, Tex. Res. J., Vol. 55, pp. 511-518.

Houdas, Y. and **Ring**, E. F. J. (1982). *Human Body Temperature: its Measurement and Regulation*, Plenum Press, New York.

Imre, L., **Bitai**, A., **Horvath**, C. D., and **Banhidi**, L. (1987). Thermal Analysis of Human Body-Clothing-Environment System, Numerical Methods in Thermal Problems, Vol. 5, pp. 657-668.

Imre, L., **Bitai**, A., **Horvath**, C. D., **Banhidi**, L., and **Pammer**, Z. (1988). Thermal Analysis of Human Body-Clothing-Environment System, Int. Journal for Numerical Methods in Engineering, Vol. 25, pp. 357-371.

Keighley, J. H. (1985). Breathable Fabrics and Comfort in Clothing, J. Coated Fabrics, Vol. 15.

Kerslake, D. Mck. (1963). A Heated Manikin for Studies of Ventilated Clothing, FPRC Memo NO. 214, M.O.D. London.

Kerslake, D. Mck. (1963). Errors Arising from the Use of Mean Heat Exchange Coefficients in the Calculation of the Heat Exchanges of a Cylindrical body in a Transverse Wind, In *Temperature: its Measurement and Control in Science and Industry*, Vol. 3, Part 3, ed. Hardy, J. D., Reinhold, New York, pp. 183-190.

Kerslake, D. Mck. (1972). *The Stress of Hot Environment*, University Press Cambridge, Cambridge.

Larose, P. (1947). The Effect of Wind on the Thermal Resistance of Clothing with Special Reference to the Protection Given by Coveral Fabrics of Various Permeabilities, Canad. J. Res., Vol. 25A, No.4, pp. 169-190.

Lees, C. H. (1898). On the Thermal Conductivity of Single and Mixed Solid and Liquid and Their Variation with Temperature, Phil. Trans. Vol. A191, pp. 399-440.

Lees, C. H. and **Chorlton**, J. D. (1896). On a Simple Apparatus for Determining the Thermal Conductivity of Cements and Other Substances Used in Arts, Phil. Mag., Vol. 41, pp. 495-503.

Mak, K. H. (1980). A Study of Thermal Properties of Some Textile Fabrics, Ph.D Thesis, The University of Leeds.

Marsh, M. C. (1931). The Thermal Insulation Properties of Fabrics, J. Text. Inst., Vol. 22, T245.

Martin, P. (1987). Heat Transfer Through Low Density Fibrous Assemblies, Ph.D Thesis, The University of Leeds.

McCullough, E. A., **Jones**, B. W. and **Zbikowski**, P. J. (1983). The Effect of Garment Design on the Thermal Insulation Values of Clothing, ASHRAE Transactions, Vol. 89, pp. 327-352.

Mecheels, J. (1971). Concomitant Heat and Moisture Transmission Properties of Clothing, in "Textile for Comfort", Third Shirley International Seminar.

Mecheels, J. (1977). Body-Climate-Clothing-Textiles, Melliand Textilberichte, Vol. 58, pp. 773-776, pp. 857-860, pp. 942-946.

Mecheels, J. and **Umbach**, K. H. (1977). Thermo-physiological Properties of Clothing System, Melliand Textilberichte, Vol. 57, pp. 1029-1032, 1977, Vol. 58, pp. 73-81, 1978.

Morris, G. J. (1953). Thermal Properties of Textile Materials, J.Text. Inst., Vol. 44, T449.

Nasser-Moghaddassi, M. (1986). Design of a Microprocessor Based Portable Temperature Data Acquisition System, M.Phil Thesis, The University of Leeds.

Nielsen, R., **Olesen**, B. W., and **Fanger**, P. O. (1985). Effect of Physical Activity and Air Velocity on the Thermal Insulation of Clothing, Ergonomics, Vol. 28, No. 12, pp. 1617-1631.

Nishi, Y., **Gonzales**, R. R. and **Gagge**, A. P. (1975). Direct Measurement of Clothing Heat Transfer Properties during Sensible and Insensible Heat Exchange with Thermal Environment, ASHRAE Transactions, Vol. 81, pp. 183-199.

Niven, C. D. (1962). A Simplified Hot Plate Apparatus, Tex. Res. J., Vol. 32, pp. 890-897.

Niven, C. D. and **Babbitt**, J. D. (1938). On the Heat Transmission of Textile Fabrics, J. Text. Inst., Vol. 29, T161.

Olesen, B. W., **Sliwinska**, E., **Madsen**, T. L. and **Fanger**, P. O. (1982). Effect of Body Posture and Activity on the Insulation of Clothing, ASHRAE Transactions, Vol. 32, pp. 791-805.

Priestman, H. (1921). The Heat Retaining Properties of Woollen and Worsted Clothes, J. Leeds University Text. Assc., Vol. 7, pp. 35-39.

Rees, W. H. (1941). The Transmission of Heat through Textile Fabrics, J. Text. Inst., Vol. 32, T149.

Rees, W. H. (1971). Physical Factors Determining the Comfort Performance of Textiles, in "Textiles for Comfort", third Shirley International Seminar.

Rood, E. S. (1921). Thermal Conductivity of Some Wearing Materials, Phy. Rev., Vol. 18, pp. 356-361.

Slater, K. (1986). The Assessment of Comfort, J. Text. Inst., Vol.

77, No. 6, pp. 157-171.

Speakman, J. B. and **Chamberlain**, N. H. (1930). The Thermal Conductivity of Textile Materials and Fabrics, J. Text. Inst., Vol. 21, T29.

Spencer-Smith, J. L. (1976). Physical Theory of Thermal Comfort, Part 1, Clo. Res. J., Vol. 4, pp. 126-138.

Spencer-Smith, J. L. (1977). The Physical Basis of Clothing Comfort, Part 2, Clo. Res. J., Vol. 5, pp. 3-17.

Stuart, I. M. and **Denby**, E. F. (1983). Wind Induced Transfer of Water Vapour and Heat Through Clothing, Tex. Res. J., Vol. 53, No. 10, pp. 655-660.

Vogt, J. J., **Meyer**, J. P. **Candas**, V., **Libert**, J. P. and **Sagot**, J. C. (1983). Pumping Effects on the Thermal Insulation of Clothing Worn by Human Subjects, Ergonomics, Vol. 26, No. 10, pp. 963-974.

Weiner, L. I. (1970). The Relationship of Moisture Vapour Transmission to the Structure of Textile Fabrics, J. Textile Chemist and Colorist Assc., Vol. 2, pp. 378-385.

Whelen, M. E., **MacHatties**, L. E., and **Goodings**, A. C. (1955). The Diffusion of Water Vapour Through Laminae with Particular Reference to Textile Fabrics, Tex. Res. J., Vol. 25, pp. 197-205.

Winslow, C. E. A., **Gagge**, A. P. and **Herrington**, L. P. (1939). The Influence of Air Movement upon Heat Losses from the Clothed Human Body, Am. J. Physio., Vol. 127, pp. 505-518.

Woodcock, A. H. (1962). Moisture Transfer in Textile Systems, Part-I, Tex. Res. J., Vol. 32, pp. 628-633.

Woodcock, A. H. (1962). Moisture Transfer in Clothing Systems, Part-II, Tex. Res. J., Vol. 32, pp. 719-727.

Yankilovich, V. I. (1972). Assessment of the Thermal Insulation Properties of Clothing (Russian), Tekhnol. Legkoi. Prom., 1, 88092(1972), DRIC Translation No. 2921, Nov. 1972.