The Hong Kong Polytechnic University

Institute of Textiles & Clothing

Prediction of Clothing Thermal Insulation and Moisture Vapour Resistance

A thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

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Under the Supervision of

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Certificate of originality

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

Qian Xiaoming

List of Publications from the Study

Refereed Journal Papers

Chen, Y. S., Fan J., Qian, X. and Zhang, W., 2004, Effect of garment fit on thermal insulation and evaporative resistance, Textile Research Journal, 74(8), 742-748 (2004).

Fan J. and Qian X., 2004, New functions and applications of Walter, the sweating fabric manikin, European Journal of Applied Physiology, V92, pp 641-644.

Qian X. and Fan J., Dynamic Surface resistance of Human Body to Heat and Mass transfer. Submitted to Applied Ergonomics.

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Qian X. and Fan J., Effects of textile physical properties on the heat and moisture transfer through clothing system. Submitted to Ergonomics.

Conference Papers

Qian X., Fan J., Newton E., 2003. A Physical Model for Predicting the Clothing Thermal Insulation under Body Movement and Windy conditions, Proceedings of the 2nd European Conference on Protective Clothing (ECPC), Montreux, Switzerland, May, 2003, pp47.

Fan J., Qian X., 2003, Recent Developments of Sweating Fabric Manikin-“Walter”, Proceedings of the 2nd European Conference on Protective Clothing (ECPC), Montreux, Switzerland, May, 2003, pp10.

Qian X. and Fan J., 2005. Surface Thermal Insulation and Moisture Vapour Resistance of Human Body under Varying Environmental Conditions and Walking Speeds, ICEE2005, 11th International Conference on Environmental Ergonomics. 22-26 May, 2005, Ystad, Sweden, pp 115-119.

Patent

Fan J. and Qian X., 2004. Walk-able sweating manikin with automated water supply and real-time water loss measurement system. Chinese patent, application No: 200410043339.6.May 2004.

Award

Fan J., Qian X. and Chen Y., 2004. Walter – Dummy for testing thermal insulation and moisture vapour resistance of clothing. Gold Medal, 32nd International Exhibition of Inventions, New Technology and Products in Geneva, 2 April 2004.

Abstract

Clothing thermal insulation and moisture vapor resistance are two most important clothing properties with respect to thermal comfort. The accurate determination of these two clothing properties is crucial to the selection of clothing for different end uses, functional clothing design and thermal environmental engineering. Although these two properties can be measured by tests on human subjects or by using sweating manikins, it is highly desirable to predict them not only because of the variability, cost and danger in using human subjects for measurements and the scarceness of sweating manikins, but also because of the fact that it is practically impossible to measure them for endless clothing ensembles under the different body motions and various environmental conditions.

For the establishment of prediction models for clothing thermal insulation and moisture vapour resistance, it is necessary to first acquire experimental data under various body motions and environmental conditions. With a newly constructed climate chamber of variable temperature, humidity and wind velocity and an improved sweating fabric manikin-Walter with patent pending innovations in terms of the simulation of "walking" motion and real-time water loss measurement, experiments were conducted for the nude manikin and for the manikin wearing 32 sets of different clothing ensembles under various "walking" speeds and environmental conditions.

With the data of surface thermal insulation and moisture vapour resistance of the nude manikin, simultaneously measured for the first time under various conditions, the present study showed that there is no significant difference between the surface thermal

insulation measured on the non-sweating manikin and those measured on the sweating manikin, indicating the moisture transfer having little effect on the direct heat transfer through the surface air layer; the surface moisture vapour resistances measured under isothermal conditions tend to be greater than those measured under non-isothermal conditions, likely due to the increase of surface air layer with the absence of the temperature gradients; Lewis relation holds under non-isothermal conditions.

The present experimental investigation further showed that the clothing moisture vapour resistance measured under the non-isothermal condition is about 17~32% smaller than that measured under the isothermal condition, possibly caused by the moisture absorption and condensation within clothing and the increased temperature gradients under the non-isothermal condition.

Based on improved understanding of the effects of wind and walking motion on the heat and moisture transfer through clothing, the present study proposed two new models, the direct regression model and the quasi-physical model, for the prediction of the dynamic clothing thermal insulation and moisture vapour resistance under windy conditions and walking motion from the static values when a clothed person is standing in “still” air. The models can take into account the effects of clothing characteristics through the model parameters. The direct regression model is very simple and effective, but the quasi-physical model has the advantage of incorporating the fundamental mechanisms of heat and moisture transfer. Comparison of the two new models with the published existing models, by applying the models to fit experimental data from both the present investigation and published sources, showed that the prediction accuracy of the direct regression model is very high in most instances, but the quasi-physical model provided the best prediction accuracy.

The present study is significant in providing a novel instrumental technique for the measurement of thermal comfort properties of clothing under simulated “walking” motion; in providing an improved understanding of the effects of wind and body motion on clothing thermal comfort and in establishing accurate models for the prediction of clothing thermal insulation and moisture vapour resistance, which have important applications in thermal environmental engineering, functional clothing design and selection of clothing for different end uses.

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Nomenclatures

Φ = coefficient which can be determined from the calibration

ρ = density of air, kg/m^3

β = equivalent air velocity factor for "walking" motion on the thermal insulation and moisture vapour resistance of outer surface air layer of clothing.

λ = evaporative heat of water at the skin temperature, λ =0.67 W.hr/g

$\Re$ = moisture vapor constant ($\Re$=0.4615 j/gK)

ψ = percent of body surface area covered by garment (%)

α = thermal diffusivity of the air, $\alpha=2.18\times10^{-5}$m^2/s

η = volumetric latent heat capacity of moisture vapor, at normal thermal conditions, η is 17.5 J/m^3pa

ΔC = concentration difference in g/m^3 across the thermal boundary layer and the concentration boundary layer

ρC_p = volumetric heat capacity of air (1.005kj/kg =1.18×10^3J/m^3 at normal temperature

β_F = an equivalent air velocity factor for walking motion on the reduction ratio of total thermal insulation and moisture vapour resistance of clothing.

ΔT = temperature difference in °C or K across the thermal boundary layer and the concentration boundary layer

Δt = time interval, s

β_V = an equivalent air velocity factor for walking motion on the heat and mass transfer induced by air ventilation

A_c = surface area of a clothed

A_i =surface area of section *i* of the body in m^2,

ap = air permeability

A_s = body (manikin) surface area, m^2

C_{pa} = specific heat capacity of air, C_{pa} =1.005J/g^{o}C

C_{pw} = specific heat capacity of water, C_{pw} =4.1784J/g^{o}C

D = mass diffusivity of the water vapor in the air, m2/s

d = water vapour resistance expressed in air equivalent, mm

E_r = sum of the latent and sensible respiration heat loss

f_c = clothing area factor f_c.

f_i = area factor of section *i* of the clothing

FI = the reduction ratio for thermal insulation

Fit = value of fit index of clothing fitting for the body

F_{pc} = a reduction factor for evaporative heat loss with clothing, compared to the nude person

F_R = Fickian thermal constant

FR = reduction ratio for moisture vapour resistance

H_a = Energy required to heat the water supplement to manikin's body temperature, W

h_b = body height (m).

h_c = convective heat transfer coefficient, W/m^{2o}C

H_c = rates of convective heat transfer

H_d = dry heat loss from the manikin, W

H_e = evaporative heat loss from skin to the environment, W

h_e = evaporative heat transfer coefficient, W/m^{2o}C

h_{edv} = effective dry heat transfer coefficient induced by air ventilation and/or wind penetration,

h_{eev} = effective latent heat transfer coefficient by air ventilation and/or wind penetration

h_m = mass transfer coefficient, m/s

H_p =heat generated from the pumps and He is the evaporative heat loss, W

h_r = radiative heat transfer coefficient, W/m^{2o}C

H_s = heat generated from the heating elements in the manikin, W

H_t = total heating power supplied to the body in W.

H_{ti} = local heating power supplied to section *i* of the body in W,

I_{ci} = thermal insulation of garment *i* in the clothing ensembles

I_{cldyn} = intrinsic thermal insulation of garment in the case of walking in windy conditions.

I_{cls} = intrinsic thermal insulation of garment standing in still air

I_{ct} = total insulation of clothing ensembles,

i_m = moisture vapour permeability index

I_{oa} = thermal insulation of air layer, m^{2o}C/W

I_{st} = total thermal insulation when standing in still

I_t = total thermal insulation of the clothing system

I_{tdyn} = dynamic thermal insulation of clothing system under body motion in windy condition

I_{wind} = actual thermal insulation with wind penetration

K = still air conductivity (k=0.026 W/m^{o}C at 20^{o}C)

KI = thermal insulation prediction which depend on garment(s) fitting, styles of design and construction of the clothing ensembles

KR = moisture vapour resistance prediction parameter, which depend on garment(s) fitting, styles of design and construction of the clothing ensembles

KV = air ventilation coefficient of clothing system

KVI = thermal insulation prediction which depend on garment(s) fitting, styles of design and construction of the clothing ensembles

KVR = moisture vapour resistance prediction parameter, which depend on garment(s) fitting, styles of design and construction of the clothing ensembles

Lc_{cl}, Lw_{cl}, $Llap_{cl}$, Lsu_{cl} and Lsl_{cl} = girth of clothing at chest, waist, lap, armhole and wristband, respectively;

Lc_{nu}, Lw_{nu}, $Lhip_{nu}$, Lsu_{nu} and Lsl_{nu}= girth of nude manikin at chest, waist, lap, armhole and wristband, respectively;

L_e = Lewis number

L_H = Lewis heat constant.

L_M = Lewis mass constant.

L_R = Lewis resistance constant

m = fraction of the intrinsic thermal insulation of the inner garment(s) from that of the total clothing system

M = metabolic rate, i.e. internal heat production of the body

M_a = percentage of moisture accumulation within clothing

n = fraction of the intrinsic moisture vapor resistance of inner garment(s) from that of the total clothing system

p_a = water vapor pressure at environment, p_a

p_{as} =saturated moisture vapour pressure at environment temperature, p_a

p_c = mean water vapor pressure at the surface of clothing.

p_s = water vapor pressure at skin, p_a

p_{ss} = saturated moisture vapour pressure at skin temperature, p_a

Q = water loss (or "perspiration rate) from the manikin, g/h

Q_i = sweating rate of a segment in g/m^2h,

R = moisture vapour resistance, P_am^2/W

R_Ω = electric resistance of the heaters, Ω

R_{es} = moisture vapour resistance of the skin, p_am^2/W

RH_a = relative humidity of the environment, %

R_{oa} = moisture vapour resistance of air layer, p_sm^2/W

R_{st} = total moisture vapor resistance due to convection and conduction in still air

R_t = total water vapor resistance of the clothing system

R_t = total moisture vapour resistance of skin and air layer, P_am^2/W

R_{tdyn} = dynamic moisture vapour resistance of clothing system under body motion in windy condition

R_{tdyn} = total moisture vapour resistance of clothing system in the case of walking in windy conditions

R_{wind} = actual moisture vapour resistance with wind penetration

R_{wind} = actual moisture vapour resistance with wind penetration

S = rate of body heat storage (under thermal equilibrium, $S=0$)

T_1~T_{15} = local skin temperature of heat, chest, back, tummy, hip, right and lift upper arm, right and lift forearm, front of right and lift thigh, back of right and lift thigh, right and lift calf, respectively

T_a = mean environmental temperature, ^oC

T_c = core temperature of the manikin, ^oC

Th = fabric thickness

t_{on}, t_{off} = "on" and "off" time of the electric heaters, s

T_s =the area weighted mean skin temperature, ^oC

T_{si} = local surface temperature of section ith of the body

U_{vent} = air ventilation index

U_{vent}' = volume of air ventilation from clothing system.

V_0 = a lower limit related to natural convection, m/s

V_{act} =equivalent wind speed induced by body activity depending on the rate of motion, for a clothed person with treadmill walking, its value is 0.67 times of walking speed

V_{eff} = an equivalent air velocity for surface air layer, m/s

v_F = an equivalent wind velocity for reduction ratio of thermal insulation and moisture vapour resistance.

$Volt$ = electricity voltage supplied, V

v_V = an equivalent wind velocity for the thermal insulation and moisture vapour resistance induced by wind and walking motion

V_{walk} = walking speed, m/s

V_{wind} = wind velocity, m/s

w_b = body weight (Kg)

W_k = external work

Chapter 1

General Introduction

1.1 Man and his thermal environment

The human body, considered as a thermal dynamic system, produces mechanical work and low temperature heat, using food and oxygen as input. The heat which is generated and which must be dissipated by the body varies from a minimum of about 30 watt per square meter when lying at rest to a maximum of about 600 watt per square meter or more during extreme physical activity. The body has a human thermoregulation system to control its loss of heat partly by varying the flow of blood to the blood vessels near the skin and so varying the skin temperature within limits and partly by varying the amount of perspiration which can produce evaporative cooling (about one-third of the heat loss from a resting person is due to evaporation). The cooling by the evaporation of perspiration is the most important means of dissipating the body heat in hot conditions and it is therefore important that the cooling should allow this function to operate.

Butera (1998) states that the human thermoregulation system requires, in healthy conditions, to maintain a constant internal temperature around 37±0.5°C, otherwise the functionality of important organs like liver and spleen, may be severely damaged. It has been reported that:

(1) Body temperature above 40°C maintained for many hours lead to a breakdown of the thermoregulatory system.

(2) Body temperature below 36°C for a duration leads to a weakness of muscle.

If the body core temperature keeps a constant around 37±0.5°C, the person will be in thermal comfort. In agreement with ASHRAE standard 55-66, thermal comfort for a person is defined as “that condition of mind which expresses satisfaction with the thermal environment”. Thus the thermal comfort environment is a condition in which the subject would prefer neither warmer nor cooler surroundings. That is to say, in thermal comfort environmental condition, the rate of heat energy generation of the body must be equal to the rate of heat energy loss from it. Fanger (1970) described the energy balance between man and environment in per unit body surface area as follows:

$$S = M - W_k - H_d - H_e - E_r \quad (W/m^2) \qquad (1\text{-}1)$$

Where S is the rate of body heat storage (under thermal equilibrium, $S=0$); M is the metabolic rate, i.e. internal heat production of the body; W_k is the external work; H_d is dry heat loss from the skin induced by conduction, convection and radiation. H_e is evaporative heat loss from the skin; E_r is the sum of the latent and sensible respiration heat loss.

For a clothed person, H_d and H_e may be determined by:

$$H_d = \frac{A_s \cdot (T_s - T_a)}{I_t} \qquad W \qquad (1\text{-}2)$$

$$H_e = \frac{A_s \cdot (p_s - p_a)}{R_t} \qquad W \qquad (1\text{-}3)$$

where, $(T_s\text{-}T_a)$ and $(p_s\text{-}p_a)$ are the temperature difference and difference of water vapor pressure between the skin and environment, respectively; I_t and R_t are total thermal insulation and total water vapor resistance of the clothing system, respectively.

The combined equations (1-1), (1-2) and (1-3) are used to determine the heat stress of a clothed man in terms of the required evaporation for thermal equilibrium, required sweat rate, and skin wetted-ness (ISO7933, Parsons 1995). They were used to determine the cold stress in terms of the required insulation for thermal comfort (Holmer 1984), and evaluate the functional design and suitability of clothing systems (Mecheels and Umbach 1977).

The successful application of Equations (1-1), (1-2) and (1-3), however, very much depends on how accurately I_t and R_t can be determined, which is not a simple task. The total thermal insulation I_t and vapor resistance R_t of a clothing system are the complex integration of the thermal insulation and vapor resistance of constituent garments and trapped air layers. I_t and R_t are also not constants. They vary depending on the way the garments are worn, body posture, body movement, and environmental conditions such as wind, rain and radiant heat.

1.2 Importance of the clothing thermal comfort

As we know, the human thermal regulation system is able to adjust the rate of energy exchange from his body to the thermal environment, but this ability is limited only while the environmental condition varies within a small limited range. If the environmental condition is extreme, such as too hot or too cold thermal conditions, the regulation ability of body is insufficient to keep the energy balance with the environment. In such situations, the body suffers from discomfort and health problem (Haymes and Wells 1986). Thus, as a natural physiological response, human wants to put something on his body to assist his body in resisting those environments. At most situations, that "something" is clothing. When the appropriate clothing was put on the body, human body gets additional ability to regulate the thermal balance with the environment. The clothing acts as buffers or barriers to the free exchange of heat and moisture between the wearer and the environment.

On the other hand, thermal comfort is by definition a subjective sensation. It is a psychological phenomenon and not a physiological state. It will be therefore influenced by individual differences in mood, personality, culture background and other individual, organizational and social factors. Because different clothing ensembles have different abilities to assist the human body adjusting the rate of energy exchanges, clothing can meet the individual demands for thermal comfort. Watkins (1995) described clothing as a portable environment.

It is our most intimate environment, which can be carried everywhere, creating its own room within a room and its own climate within the larger climate of our surroundings.

The ability of clothing in assisting the human body to adjust the rate of energy exchanges is related to the values of clothing thermal insulation and moisture vapour resistance which are affected by many factors, such as materials, designs and construction. An ideal clothing for thermal comfort is such that allows the wearer to feel comfortable in as a wide range of environments and physical activity as possible. The term “comfort” here means the clothing thermal comfort which distinguishes the other comfort of garment such as freedom comfort of body movement, tactile comfort and so on.

Under the conditions where the thermal comfort cannot be achieved by the human body’s own regulation ability, clothing must be worn to support its temperature regulation by resisting or facilitating the heat exchange between the human body and the environment. It is therefore important to know what kind of clothing ensembles can make our body thermally comfortable. Today, more and more people are involved in various activities in extremes of temperature and other hazardous environments, such as the pole lands, offshore, high mountains, deep caves, even outer space, where the function of clothing can be a matter of life or death. For indoor conditions, clothing may have no survival value, but still contributes to the body comfort. Therefore, clothing thermal comfort is increasingly concerned by both clothing consumers and manufacturers.

1.3 Objectives and scopes of this study

Obviously clothing thermal comfort is much dependent on the heat and mass transfer through garments. The two key parameters of clothing related to thermal comfort are thermal insulation and moisture vapor resistance. These two parameters are very important in thermal environmental engineering, functional clothing design and end use of clothing ensembles. A full understanding of the phenomenon of the heat transfer through clothing requires the knowledge of the thermal behavior of the clothing materials and clothing systems as a whole. Many researchers have carried out a lot of works since from 1930s on this academic area and considerable literature is available.

The thermal insulation and moisture vapor resistance can be measured by taking measurements on human subjects. This method gives realistic results, but requires sophisticated equipment and is time consuming, and the measured values may also have large variability. Thermal manikins have therefore been developed for the purpose. Measurements on thermal manikins are more reproducible, but they are generally very expensive and very few can simulate perspiration effectively. So it is desirable to predict the clothing thermal insulation I_t and moisture vapor resistance R_t, not only because of the limitations of measuring these parameters on human subjects and thermal manikins, but also because of the fact that it is practically impossible to measure I_t and R_t for endless clothing ensembles under the different body motions and various environmental conditions.

In order to predict the clothing thermal insulation and water vapor resistance under various circumstances accurately, the effects of body activities, garment design, garment fit and environmental conditions should be quantified. To achieve this objective, the present study includes:

(1) Improving the existing sweating manikin -“Walter” in terms of the simulation of “walking” motion and measurement systems.

(2) Investigating the effects of “walking” motion and environmental conditions on the clothing thermal insulation and moisture vapour resistance.

(3) Developing models for predicting the clothing thermal insulation and water vapor resistance, taking into account of clothing characteristics, body motion and environmental conditions.

1.4 Significances of this study

The study is significant in the following aspects:

(1) Improved prediction of clothing thermal insulation and water vapor resistance under various walking speeds and environmental conditions has am important application in environmental engineering.

Thermal stress of a clothed man should be accurately determined in environmental engineering. The latest ISO standard (IS0 7933) specifies the heat stress in terms of required evaporation for thermal equilibrium, required sweat rate and skin wetted-ness, etc. The cold stress may be expressed by the required thermal insulation. The improved prediction in clothing thermal insulation and water vapor resistance under various body movement and environmental conditions will result in more accurate determination of the thermal stress of a clothed man using the energy balance equation.

(2) Knowledge and guidelines for functional clothing design and product development.

The quantification of the effects of clothing parameters, such as garment design and fit, on ventilative heat and moisture transfer will provide us knowledge on how to optimize clothing design for different end uses, for example, how to maximize protection and minimize water vapor resistance for specialist work-wear, and how to minimize thermal insulation and water vapor resistance for summer wear. Such expertise is very much needed by the apparel industry.

(3) An enhanced walk-able sweating manikin will be a useful tool for practical applications:

It will be very useful for the measurement of the thermal insulation and moisture vapor resistance of clothing. Although there are in principle three movable and perspiring manikins in the world, viz. “Coppelius” in Finland (Meinander 1992), “SAM” in Switzerland (Mattle 1999) and “Walter” in Hong Kong (Fan and Chen 2002), few experimental results have been reported so far. Thus the experiments on the enhanced movable sweating manikin - “Walter” should improve the understanding of dynamic heat and moisture transfer through clothing.

(4) The prediction model to be developed is a useful tool for practical applications

It will be useful to environmental engineers in calculating the thermal stress of a clothed man under different circumstances, to clothing designers in assessing the effectiveness of clothing design for different end uses; and to explorers or field workers in choosing adequate clothing to wear in extreme conditions.

1.5 Outlines of the thesis

A general introduction including the background, objectives and significance of the present study is provided in Chapter 1. Chapter 2 reviews the relevant fundamental theories as well as past researches with regard to clothing thermal comfort. Chapter 3 describes the design and construction of the improved walk-able sweating fabric manikin-Walter, particularly on the enhancement of the simulation of “walking” motion and on the development of the novel automated water supply and real-time water loss measurement system. The calibration and performance evaluation of the improved walk-able sweating fabric manikin are the newly constructed climate chamber are reported in Chapter 4. Chapter 5 reports on the experimental investigation of the surface thermal insulation and moisture vapour resistance of the nude manikin under various conditions. Two new prediction models, the direct regression model and the quasi-physical model are presented in Chapter 6 and Chapter 7, respectively. Chapter 8 compares the new models with existing models in terms of prediction accuracy. Chapter 9 is the last chapter providing a general conclusion and suggestions for further work.

Chapter 2

Literature Review

2.1 Fundamentals of heat and mass transfer through clothing

2.1.1 Simple clothing system and definition of thermal insulation and moisture vapor resistance

Consider a clothed person standing in still air; the thermal system can be described by the simple figure as below:

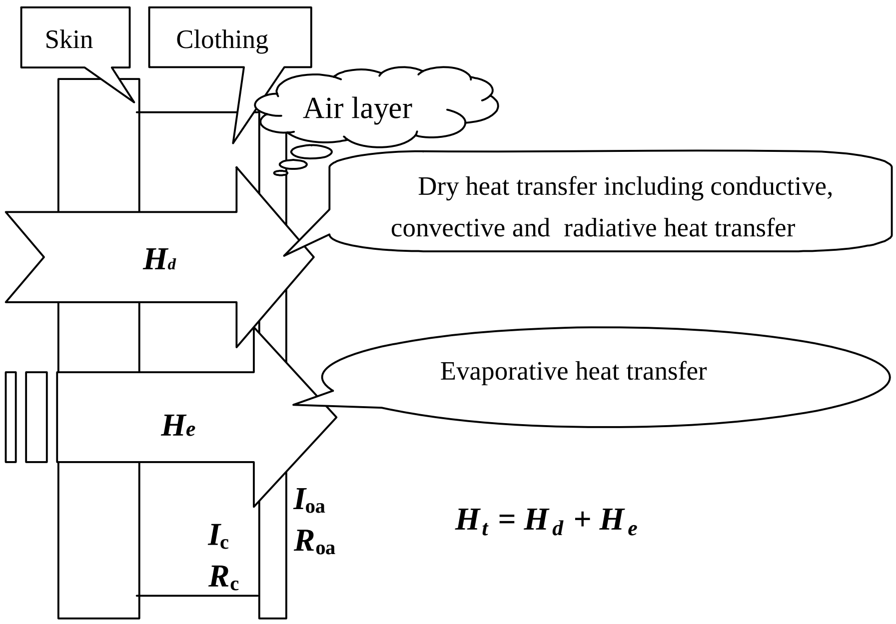


Figure 2-1 A simple clothing system for heat and mass transfer

The heat generated by body metabolic system can be transferred through clothing by conduction, radiation, convection and latent heat transfer by moisture transmission. Conduction, convection and radiation are dominated by the temperature difference between the skin surface and the environment, and are therefore grouped as dry heat transfer or direct heat loss H_d (W/m^2). On the other hand, the evaporative heat transfer or latent heat loss H_e (W/m^2) is achieved by moisture transmission which is driven by the difference in partial water vapor pressure between the skin surface and the environment.

Under the heat equilibrium, Woodcock (1962) had assumed that the direct heat loss H_d and the evaporative heat loss H_e are independent of each other and can be measured independently, therefore the total rate of heat transfer through the clothing H_t (W/m^2) then can be expressed as:

$$H_t = H_d + H_e \qquad (2\text{-}1)$$

Then, the total thermal insulation I_t and the total moisture vapor resistance R_e of the clothing system can be expressed by equations (2-2) and (2-3):

$$I_t = \frac{A_s(T_s - T_e)}{H_d} \qquad m^{2o}C/W \qquad (2\text{-}2)$$

$$R_t = \frac{A_s \cdot (p_s - p_e)}{H_e} \qquad p_a m^2/W \qquad (2\text{-}3)$$

where, (T_s-T_a) and (p_s-p_a) are the temperature difference and difference of water vapor pressure between the skin and environment, respectively; I_t and R_t are total thermal insulation and total water vapor resistance of the clothing system, respectively.

According to the energy conservation law, the dry heat and the latent heat passing through the skin, clothing and the air layer next to the outer surface of clothing must be equal to the total dry heat and the total latent heat, respectively. Then the intrinsic resistance of clothing can be calculated by:

$$I_c = \frac{A_s \cdot (T_s - T_c)}{H_d} \qquad m^{2o}C/W \tag{2-4}$$

$$R_c = \frac{A_s \cdot (p_s - p_c)}{H_e} \qquad p_a m^2 /W \tag{2-5}$$

where, T_c and p_c are the mean surface temperature and the mean water vapor pressure at the surface of clothing, A_s is the Dubois area in m^2.

Allowing for people of different sizes and shapes, a good estimate of the body surface area is given by Dubois (1916) in the following expression:

$$A_s = 0.202 w_b^{0.425} h_b^{0.725} \qquad m^2 \tag{2-6}$$

Where, w_b is the body weight (Kg) and h_b is the body height (m).

The surface area of a clothed person A_c is greater than the surface area of nude body A_s, the ratio is called clothing area factor f_c.

$$f_c = A_c / A_s \tag{2-7}$$

f_c can be obtained by using the photographic method described by Olesen et al. (1982). It is dependent upon many parameters including garment design, fabric stiffness or drape, and support materials used in garment construction. Measuring f_c with a photographic method is time-consuming and expensive, and the resulting measurement is not very precise. Slight differences in the drape of the clothing on the body can change the f_c significantly. The looseness or tightness of fit and body position also affect the f_c. Because of difficulties associated with the measurement of f_c, researchers have tried to estimate f_c values for use in calculating the clothing resistance from the total resistance for garments and ensembles (Fanger 1970; Hollies and Goldman 1977; McCullough et al 1983; Olesen et al 1983), ISO 7933 and ISO 9920 gave a relationship between the value of f_c and the value of the clothing thermal insulation as below:

$$f_c = 1 + 1.97\, I_c \tag{2-8}$$

where, I_c is expressed in $m^{2o}C/W$.

The resistance of the air layer next to the outer surface of the clothing can then be calculated by:

$$I_{oa} = \frac{A_c \cdot (T_c - T_a)}{H_{oa}} = \frac{A_s f_c (T_c - T_a)}{H_d} \tag{2-9}$$

$$R_{oa} = \frac{A_c \cdot (p_c - p_a)}{H_{ec}} = \frac{A_s f_c (p_c - p_a)}{H_e} \tag{2-10}$$

The intrinsic resistance of clothing can also be determined by subtracting the resistance of the air layer next to the outer surface of the clothing from the total resistance of clothing as follows:

$$I_c = I_t - I_{oa}/f_c \tag{2-11}$$

$$R_c = R_t - R_{oa}/f_c \tag{2-12}$$

In 1941, Gagge et al (1941) introduced the *Clo* value as a readily recognizable "human scale" unit to express the total clothing thermal insulation. One *Clo* means that the thermal insulation value of an assembly in which a man wears and feels comfort when sitting in an environment at 20-21°C, less 50%RH, and with wind speed no more than 0.1m/s with the body metabolic rate of around 58W/m^2. By physical measurements, it was determined:

$$1\ Clo = 0.155\ m^2\ °C/W \tag{2-13}$$

2.1.2 Interaction between heat and mass transfer in clothing systems

In 1962, Woodcock (1962) introduced i_m (permeability index) as a dimensionless parameter to denote the vapor permeability of clothing. i_m is defined as:

$$i_m = \frac{I_t / R_t}{I_a / R_a} \qquad (2\text{-}14)$$

The ratio I_a/R_a, is assumed as a constant. It can be measured by using a wet-bulb column in strong wind, I_a/R_a =2.2°C/mmHg = 0.0165°C/Pa. Therefore, if I_t and R_t are in ISO standard units, i_m can be calculated by:

$$i_m = \frac{I_t}{0.0165 \times R_t} = 60.6 \times \frac{I_t}{R_t} \qquad (2\text{-}15)$$

Equation 2-15 is used to predict the moisture vapour resistance by ISO 9920 in the case of the thermal insulation is known.

The permeability index i_m takes the form of an efficiency factor. Since the ratio I_t/R_t is always less than the ratio I_a/R_a. It has a theoretical range from one (for the ideally permeable clothing system) to zero (for the completely impermeable one).

Although i_m could give a quantitative measure for the Man-clothing-environment complex, as Woodcock pointed, it is only valid under the equilibrium, i.e. a constant distribution of moisture in the system has been achieved.

After testing 22 clothing ensembles, the average i_m value for the conventional indoor ensembles was found to be 0.4, (McCllough 1989). In summary, for many types of one- or two-layer, permeable clothing, the permeability index may be set to 0.38 (Havenith 1999; ISO 9920), equation 2-15 simplifies to:

$$R_t = 160 I_t \qquad (2\text{-}16)$$

Using this equation, we can therefore roughly estimate the moisture vapour resistance of clothing (ISO 9920), but it is not suitable for non- or low-permeable clothing.

Whelan (1955) introduced a term "air equivalent (m)" to express vapor resistance as it represents the thickness of an air layer with equivalent resistance. For the wet air, according to the Flick's law of diffusion, the evaporative heat transport is given by:

$$H_e = \lambda \times \frac{D\Delta C}{d} \qquad (W/m^2) \qquad (2\text{-}17)$$

Where, λ is the heat of evaporation for water (λ=2419 j/g or 0.67 Whr/g at 35^{o}C), D is the diffusion coefficient for water vapor in air (D=2.68×10^{-5} m^2/s), ΔC is the vapor concentration difference in g/m^3, d is the air equivalent in m.

For still air layer, the air equivalent is by definition equal to the actual thickness of the air layer, viz. the same air layer which forms the conductive heat resistance.

$$d = k/h_c = 0.026/h_c \qquad (m) \tag{2-18}$$

where, k is the air conductivity (k= 0.026 W/mK at 20°C), h_c is the convective heat transfer coefficient in W/m^2K.

On the other hand, according the analogy theory between heat and mass transfer (Cengel 2003), the rate of mass convection can be expressed as the form of Newton’s law of cooling:

$$M = h_m \Delta C \qquad g/m^2s \tag{2-19}$$

where, M is the rates of mass convective transfer, h_m in m/s is the mass convective transfer coefficient, ΔC in g/m^3 is the concentration difference across the thermal boundary layer and the concentration boundary layer.

By using the definition of heat and mass Stanton numbers, the analogy between heat and mass transfer can be expressed more conveniently as:

$$\frac{h_c}{h_m} = \rho C_p (\frac{\alpha}{D})^{2/3} = \rho C_p Le^{2/3} \tag{2-20}$$

where, α is the air thermal diffusivity, D is mass diffusivity of the water vapor into air, ρ and C_p are the density and specific heat of air at mean conditions (or ρC_p is the specific heat of air per unit volume in kj/m^{3}K), L_e is the Lewis number which is relatively insensitive to variations in temperature.

For air-water vapor mixtures at 298K, the mass and thermal diffusivities are D=2.5×10^{-5} m^2/s and α=2.18×10^{-5} m^2/s, and thus the Lewis number is (we simply use the α value of dry air instead of the moist air since the fraction of vapor in the air at atmospheric conditions is low):

$$Le = \frac{\alpha}{D} = 0.872$$

Therefore, for moisture vapour in air, the relation between heat and mass transfer coefficients can be expressed with a good accuracy as:

$$h_c = 0.913 \rho C_p h_m \qquad (2\text{-}21)$$

This equation is known as the Lewis relation that establishes a "bridge" between the heat and mass transfer. Generally, at the normal conditions, we assumed:

$$L_M = \frac{1}{0.913 \rho C_p} = \frac{1}{0.913 \times 1.184 \times 1007} = 9.2 \times 10^{-4} \qquad m^3\, K/J$$

L_M can be given a name as Lewis mass constant.

Thus, we have:

$$h_m = L_M h_c \qquad (2\text{-}22)$$

$$H_e = \lambda h_m \Delta C = \lambda L_M h_c \Delta C = L_H h_c \Delta C = h_e^{'} \Delta C \qquad W/m^2 \qquad (2\text{-}23)$$

where $L_H = \lambda L_M = 2420 \times 9.2 \times 10^{-4} = 2.23 m^3 / g$ L_H can be given a name as Lewis heat constant.

According to the basic principle of thermodynamics, and assume the air-water vapor mixtures obeys the ideal-gas relation, we can have:

$$p_s = \rho_s \Re (273.15 + T_s) \approx \rho_s \Re \overline{T} \qquad p_a \qquad (2\text{-}24)$$

$$p_e = \rho_e \Re (273.15 + T_e) \approx \rho_e \Re \overline{T} \qquad p_a \qquad (2\text{-}25)$$

where, $\Re$ is the moisture vapor constant ($\Re$=0.4615 j/gK). $\overline{T} = 273.15 + (T_s + T_e)/2$, In most situations, $\overline{T}$ is about 300K (for example, $T_s = 35^oC$, $T_e = 20^oC$), thus we have:

$$\Delta p = \Re \overline{T} \Delta C \qquad (2\text{-}26)$$

Substituting equations (2-26) into (2-23), we have:

$$H_e = \frac{L_H}{\Re \overline{T}} h_c \Delta p = L_R h_c \Delta p = h_e \Delta p \tag{2-27}$$

where, $L_R = \frac{L_H}{\Re \overline{T}} \approx 0.0165 \quad {m^3K}/{J} \quad or \quad {K}/{p_a}$

L_R may be defined as the Lewis resistance constant to differentiate with the Lewis constant L_M, and L_H.

For the clothing system, according to Fickian law of diffusion, we have:

$$\frac{A_s \Delta p}{R_t} = \lambda M = \frac{A_s L_H \Delta C}{d} \tag{2-28}$$

Substituting equations (2-21) into (2-28), we have:

$$R_t = \frac{\Re \overline{T}}{\lambda D} \times d = F_R d \tag{2-29}$$

where,

$$F_R = \frac{\Re \overline{T}}{\lambda D} = \frac{0.4615 \, {J}/{gK} \times 300K}{2419 \, {J}/{g} \times 2.5 \times 10^{-5} \, {m^2}/{s}} = 2.3 \times 10^3 \, \frac{p_a m}{W}$$

F_R could be given a name as Fickian thermal constant of air layer.

In fact, at the normal conditions, $F_R = \frac{R_t}{d}$ implies the moisture vapour resistance per unit thickness of the still air layer, thus we can obtain the following equation directly:

$$F_R = \frac{1}{h_e} = \frac{1}{L_R h_c} = \frac{1}{0.0165 \times 0.026} \approx 2.3 \times 10^3 \qquad \frac{p_a m}{W}$$

ISO 7933 refer to another method for determination of evaporative resistance of clothing ensembles: the use of F_{pc}, a reduction factor for evaporative heat loss with clothing, compared to the nude person.

$$R_t = \frac{1}{h_e F_{pc}} \tag{2-30}$$

where, h_e is the evaporative heat transfer coefficient in W/m^{2}pa. And

$$F_{pc} = \frac{R_a}{R_t} = \frac{1}{1 + 2.22 h_c \left(I_c - \frac{1 - \frac{1}{f_c}}{h_c + h_r}\right)} \tag{2-31}$$

where, R_a and R_t is the moisture vapour resistance of outer surface air layer of clothing and total clothing moisture vapour resistance, respectively.

2.1.3 Measurements of the thermal comfort properties of clothing

In addition to the thermal insulation, moisture vapour resistance and the moisture permeability index i_m, Fan and Chen (2002) proposed to use the percentage of moisture accumulation within clothing as an additional parameter for measuring the thermal comfort properties of clothing. It can be measured by weighing the garments before putting on manikin and after taking off from manikin after 24 hours or a specified period not less than 12 hours, and calculated by the following formula:

$$M_a = \frac{W_b - W_a}{W_a} \times 100\% \qquad (2\text{-}32)$$

where, M_a is the percentage of moisture accumulation in clothing during the test periods, W_a and W_b are original and final weight of clothing in gram, respectively.

Generally, according to the theory of heat and mass transfer, the thermal insulation (I_t) should be as small as possible for summer clothing to keep cool and it should be as high as possible for winter clothing to keep warm; The moisture vapor resistance (R_t) of clothing should be as low as possible for any type of clothing to make the clothing permeable; The moisture permeability index i_m should be as high as possible for any type of clothing to make the clothing permeable; and the moisture accumulation M_a should be as low as possible for any type of clothing to keep the skin and clothing dry.

2.1.4 Geometric model for calculation of thermal insulation and moisture vapor resistance

For the calculation of the thermal insulation, most researchers who studied the heat and mass transfer through a clothed body tend to consider the human body as a number of cylindrical elements with characteristic curvature and surface area for the various body parts (Lotens and Havenith 1991, Zhi 2001). Based on these body segments models, two principles can be used to calculate the thermal insulation (Nilsson 1997), one is based on the measurement of total heat loss by summation of local heat losses (serial model); the other method determines the local insulation values, which are summarized after area weighting (parallel method). The equations for the calculation of the two alternatives are:

Parallel method (ENV 342-1997):

$$I_{t,ser} = \sum_i f_i \left[\frac{A_i (T_{si} - T_a)}{H_{ti}} \right] = \sum_i f_i I_{ti} \qquad m^2 K / W \tag{2-33}$$

Serial method (PrEN342:1995):

$$I_{t,par} = \frac{\sum A_{si} \times \left[(\sum_i f_i T_{si}) - T_a \right]}{\sum_i H_{ti}} \qquad m^2 K/W \tag{2-34}$$

$$\overline{T_s} = \sum_i f_i T_{si} \tag{2-35}$$

where: f_i is the area factor of section i of the body, T_{si} is the local surface temperature of section I of the body, T_a is the air temperature in environmental chamber in m^2, A_i is the surface area of section i of the body in m^2, H_{ti} is the local heating power fed to section i of the body in W, T_s is the mean surface temperature of the body in K, A_s is the total body surface area of the body in m^2, H_t is the total heating power fed to the body in W.

The thermal insulation calculated by serial method was always higher than that calculated by parallel model (Meinander et al 2003).

For standing manikin:

$$I_{t,serial} = 1.2 I_{t,parallel} - 0.02 \qquad m^2 K/W \qquad R^2 = 0.99 \tag{2-36}$$

For walking manikin (walking speed ≈ 3.4 km/h)

$$I_{t,serial} = 1.27 I_{t,parallel} - 0.03 \qquad m^2 K/W \qquad R^2 = 0.98 \tag{2-37}$$

The serial calculation model is not based on the heat and mass transfer theory. It has been shown that the difference in the results meight be as high as 30%, particularly if the insulation is unevenly distributed on the body (Nillson, 1977).

2.2 Evaluation methods for the thermal comfort of clothing system

2.2.1 Evaluation methods

The thermal comfort of clothing systems may be evaluated by subjective wearer trials (Vogt et al 1983, Nielsen et al 1985, Bakkevig and Nielsen 1995) or objective simulation tests.

Subjective wearer trials can relate the results directly to the clothing in actual use but tend to be inconsistent and costly and can sometimes expose the subjects to danger when testing under extreme conditions.

Objective simulation tests include *flat plate methods* (e.g. guarded hot-plates), *cylindrical methods* (e.g. guarded hot cylinders) and *thermal manikins*. These instruments measure the clothing thermal insulation and vapor resistance (or permeability), which can then be used to predict the thermal comfort of the clothing system. Flat plate and cylindrical methods are useful for evaluating the thermal properties of clothing materials and simple clothing assemblies, but have difficulties in applying the results to the actual clothing systems in use. Thermal manikins have therefore been considered as the most useful tools for evaluating thermal comfort of overall clothing systems. A human-shaped thermal manikin measures heat and mass transfer in all directions over the whole surface or a defined, local surface area; it can also be placed in an extreme environment which would be dangers to human beings. A thermal manikin measures heat and mass losses in a relevant, reliable and accurate way. The method is quick, easily standardized and repeatable. There are two major areas of application for thermal manikin (Holmer 2004): (1) Determination of clothing heat and mass transfer characteristics and (2) assessment of the impact of thermal environments on the human body.

2.2.2 Development of thermal manikins around the world

The earliest manikin found in the literature (Holmer 1999) was made by the US Army in the early 1940s. After summarizing the history of thermal manikins development in the world, Fan and Chen (2002) pointed out that thermal manikin can be grouped into three generations.

The first generation were standing (not walk-able) and non-perspiring ones (Kerslake 1963, Fonseca 1975, McCullough et al 1989).

The second were movable (walk-able), but non-perspiring ones such as the copper manikin ‘Charlie’ in Germany (Mecheels and Umbach 1977) and those in Denmark (Olesen et al 1982) and Japan (Hanada 1979).

To simulate sweating on non-perspiring manikins, many workers put underwear made of highly absorbent fabrics on the manikin, and supplied water to the underwear by sprinkling or water pipes, so two steps of measurement were necessary as Woodcock and other workers suggested by using these kinds of manikins. The first Step was to measure the dry clothing thermal resistance I_t on

a dry manikin and then took the second step, by dressing an underwear made of hydrophilic material on the manikin as its new sweating skin, then spraying water on it, and putting the clothing on the manikin again to measure the evaporative resistance R_t . Under this situation, the evaporative heat can be calculated by subtracting the dry heat loss from the total heat loss. This two-steps method can result in gives a serious underestimate of the maximum heat loss through clothing, because of the interaction between heat and moisture transfer, the increased heat and moisture transfer through damp clothing, the buffering action of hygroscopic clothing (Spencer-Smith 1976) and the prolonged (more than 12 hours)moisture accumulation (Fan and Chen 2002).

The third generation manikins, that can simulate true perspiration and body motion, are still very rare in the world. The perspiring manikins developed in Japan (Yasuhiko et al 1992) cannot simulate movement. Out of more than 80 manikins in use worldwide, there are a few movable and perspiring manikins in the world, including “Coppelius” in Finland (Meinander 1999), “SAM” in Switzerland (Mattle 1999), “Walter” in Hong Kong (Fan and Qian 2004) and “KEM” in Japan (Fukazawa et al 2004). “Coppelius” and “Walter” could simulate “walking motion” and perspiration simultaneously (Meinander et al 2003, Fan and Chen 2002). “SAM” can do the same in principle, but few experimental results have been reported so far.

2.2.3 Sweating mechanisms and measurement methods of sweating manikins

The perspiring thermal manikin "TARO" made in Japan (Dozen et al 1992) used moisture vapor generated by vapor generators as the source of sweating. Its skin was cast in bronze with pores and allowed air and moisture vapor flow from inside to outside of the skin to simulate the body gaseous perspiration. The amount of sweating in each segment was calculated from the air flow rate, skin area and skin temperature using the following equation:

$$Q_i = 60 \times 10^{-3} \cdot q_i \cdot \frac{273 + T_{si}}{273 + T_a} \cdot \frac{D_i}{A_i} \qquad (2\text{-}38)$$

where, Q_i is sweating rate of a segment in g/m^{2}h, q_i is the amount of air supply in l/min, T_{si} is skin temperature and T_a is the temperature in ambient, D_i is a saturated absolute humidity in g/m^3, A_i is the area of the sweating skin of the segment.

The required amount of sweating was obtained by adjusting the air flow rate via the thermal mass flow controller. The accuracy of "sweating" supply is questionable since the air flow rate couldn't be controlled accurately under the small pressure difference between the inside of the skin and outside of the clothing, and since this pressure difference was affected by the nature of wearing and design of clothing. Air flow may bring vapor out of clothing mainly through the openings of clothing, not through the layers of fabric.

Another sweating thermal manikin “Coppelius” made in Finland (Meinander 1992, 1999) used an outer water supply system. There are 187 sweat glands distributed on the whole body to supply a controlled amount of water to the corresponding skin surface area to simulate desired “sweating”. The water comes from a reservoir placed on a balance; a computer controlled micro-valve system in the manikin distributes the water to the 187 sweat glands. By setting body sweating rate, the calculated proportion time of opening of each valve determined the required sweating rate of each gland. The manikin was suspended from a balance during the test. The evaporation of the moisture could be recorded as the difference between the supplied water and the weight increase of the clothed manikin. Each item of the clothing was also weighted before and immediately after the test to determine in which clothing layers the moisture is condensing. Moisture condensation in the skin material of the manikin was calculated as the total weight change subtracted by the moisture condensed in the clothing.

A sweating agile thermal manikin, called “SAM”, was developed in Switzerland (Mattle 1999) based on a principle similar to “Coppelius”. “SAM” had 125 sweat outlets (glands) distributed over its surface and the outlets have been positioned to ensure a sweat distribution roughly similar to the human. Distilled water was used to simulate sweat, supplied through its face to internal valves, which were used to regulate the flow. Special pads, which covered the outlets, ensured that all the water evaporated at low sweating rates, simulating insensible sweating or both vapor and liquid water. Water could be supplied at higher sweating rates to simulate sensible sweating. The total sweating rate was controlled using a precision balance to measure the reduction in weight of water in the supply tank external to SAM. The total rate could be varied from 20ml/h up to at least 4 liters per hour to simulate all possible activities and conditions.

Although “Coppelius” and “SAM” are made of stiff foam plastic, the force of weight may crash the balance and induced the error of measurement when they are in motion.

2.2.4 Effects of test conditions on measurements from thermal manikin

After comparing the thermal resistance values of four clothing ensembles tested on seven manikins (standing or/and walking or/and sweating) in different European research institutes, Meinander et al (2003) stated:

(1) The deviations in walking conditions were normally less than in standing conditions and the differences noticed related to the clothing size or/and step length.

(2) The clothing area factor f_c affected I_c a little.

(3) The influence of the heating regulation system on the insulation values was very small.

(4) The effect of ambient conditions was critical only in the case of air velocity, which should be defined, e.g. between 0.3 and 0.5 m/s, also the direction of air flow affected the insulation values, but this was usually less than 5%.

(5) Air humidity was not a critical parameter, the influence of humidity (20~80%RH) on the total thermal insulation can be ignored.

(6) The effect of ambient temperature on insulation depended on the accuracy of the power measurements.

2.3 Heat and moisture transfer through clothing system

By means of the evaluation method mentioned above, considerable experimental data are available in the literature. In general, heat transfer through clothing system is affected by clothing parameters, body posture and activities as well as environmental conditions.

2.3.1 Effects of clothing parameters

According to Fourier's law, the insulation of a clothing layer is generally proportional to the fabric thickness. The proportionality constant is the specific resistance with a typical value of 23.3 $m^{o}C/W$, more or less independent of the type of fiber and fabric construction (Burton and Edholm 1955, McCullogh et al 1985), except for those very loose and coating fabrics (Lotens and Havenith 1991, McCullogh et al 1985, Spencer-Smith 1977). The variations in fabric weight without major changes in thickness will not significantly affect the thermal insulation of a garment (McCullogh et al 1983).

The insulation of a clothing layer is generally proportional to the body surface area covered by clothing, but not for the clothing ensembles. (McCullogh et al 1983). This is because measurement of clothing insulation is taking average value for the whole body, in that they are equivalent to an insulation spread uniformly over the whole body that would result in the same total heat loss from the body. The body is not uniformly covered, and the heat loss from the different areas of the body will differ due to the uneven covering. Adding clothing to a particular area of the body will only reduce the heat loss from that area, it will have litter effect on the heat loss from other areas. Ultimately, adding more and more insulation to a given body area can only reduce the heat loss from that area to zero, the heat loss from the other areas may still be quite large, so that the overall heat loss will still be large. Thus the insulation value will be small, even though a part of the body is very heavily clothed. The following equation was suggested to predict the garment insulation values from fabric thickness (*th*) and the percentage of body surface area covered by garment (ψ)as follow (McCullogh et al 1985):

$$I_c = 0.0079\Psi + 0.00131 th \times \Psi - 0.0745 \qquad (2\text{-}39)$$

Whelan et al (1955) give an elegant analysis of vapor resistance data, showing that the volume percentage of fiber in the fabric is indeed a dominant factor regardless of fiber type. Very dense fabrics are usually thin, whilst thick fabrics are usually loosely woven. The net result is that the air equivalent of fabric layers exceeds the thickness of the fabric by 1 to 5 mm. This regularity makes it possible to estimate the air equivalent of fabric layers as follows:

$$d = 1.3th + 0.001 \qquad m \qquad (2\text{-}40)$$

This equation is relatively inaccurate for thin fabrics, but its absolute accuracy (standard deviation ≈ 1 mm) is satisfactory for use in ensembles. When fabrics are coated or laminated on film, the air equivalent is difficult to predict and should be specified.

The insulation provided by an ensemble will be less than the sum of thermal resistance value of the component garment. This is because that (1) the insulation is not distributed evenly over the entire body; (2) the addition of garments may cause fabric and air layer compression in some areas; and (3) the addition of more garments usually increases the surface area for heat loss.

For most indoor garment, following equations were proposed to predict the total thermal insulation of clothing ensembles from those of constituent garments:

$$I_{ctot} = 0.73 \times \sum_i I_{ci} + 0.17 \qquad Clo \text{ (Olesen and Neilsen 1983)} \qquad (2\text{-}41)$$

$$I_{ctot} = 0.676 \sum_i I_{ci} + 0.117 \qquad Clo \text{ (McCullogh et al 1985)} \qquad (2\text{-}42)$$

where, I_{ctot} is the total insulation of clothing ensembles, I_{ci} is the insulation of garment *i* in the clothing ensembles.

Design variations that affect the amount of body surface area covered and the looseness or tightness of fit produce changes in clothing insulation values. McCullogh et al (1983) compared four kinds of garments having different designs and fit, and found that:

(1) Even though the designs varied somewhat at the neck, the three long-sleeve shirts provided the same amount of insulation. These shirts were warmer than the short-sleeve shirts, which were warmer than the sleeveless, collarless top. These differences probably resulted from variations in the amount of body surface area covered by the garments. Design changes that alter the length of the skirt have more impact on thermal insulation than design variations that alter the fullness of a skirt.

(2) The loose-fitting long trousers provided more insulation than the tight-fitting trousers did. Air trapped between the garment and the manikin's legs probably contributed to a higher clo value for the loose trousers when measured on a standing manikin. However, during movement, more air would circulate inside the legs of the loose-fitting trousers than in the tight-fitting trousers, causing an increase in convective heat transfer. Havenith et al (1990a) compared the fitting of garments on subjects, the results showed that tight-fit clothing fit had 6~31% lower insulation than loose-fit.

(3) The differences in thermal insulation were minimal for the dress, belted or unbelted.

2.3.2 Effects of environmental conditions and wearer activities

Considering a clothed person in motion in windy conditions, the heat and mass transfer is not only induced by the elements which exist when the person is standing in still air, but also induced by the air ventilation and wind penetration (Parsons et al 1999). The mode of heat and mass transfer may be illustrated by the figure below:

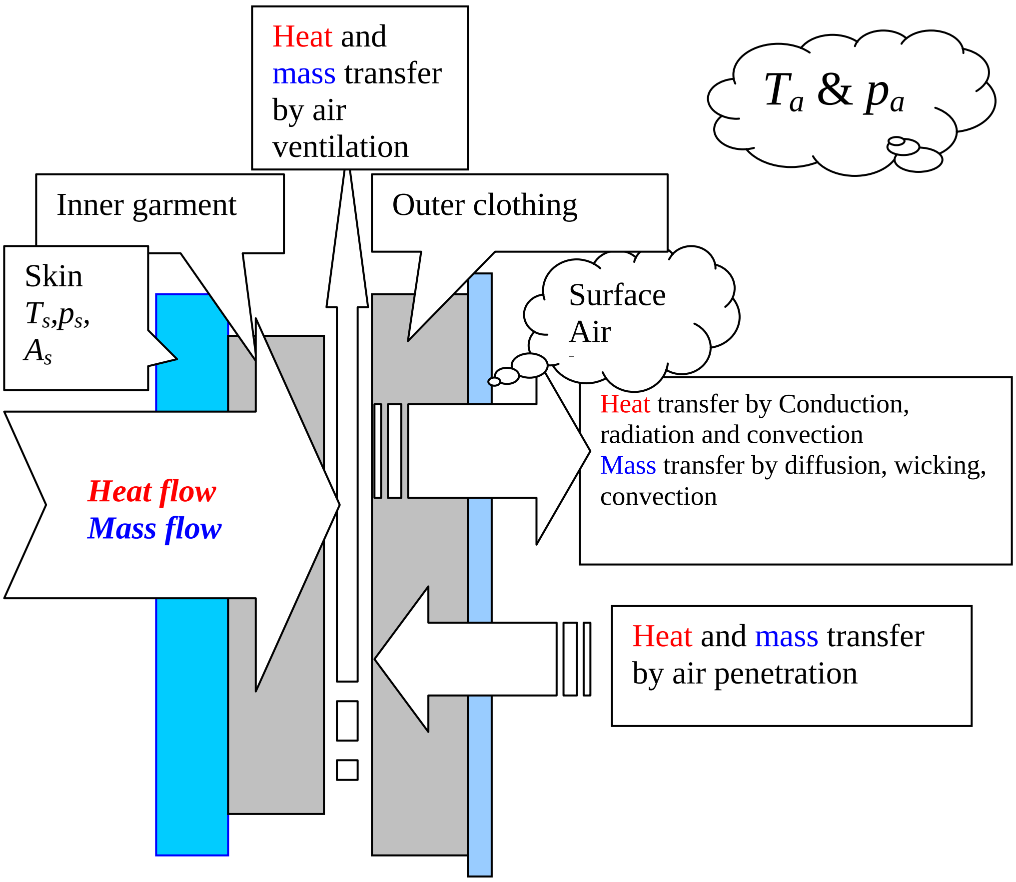


Figure 2-2 Heat and mass transfer through a clothing system

Under body motion and windy condition, the thermal insulation and the moisture vapor resistance will be reduced due to (1) the increased heat and mass transfer induced by forced convection in the air layer near to the outer clothing surface; (2)the additional heat and mass transfer induced by "bellows" action or clothing ventilation (Crockford and Rosenblum 1974, Birnbaum and Crockford 1978), viz. renewing the air trapped between tight-fitting inner garments and the loose-fitting outer garment through the clothing openings such as cuff, collar, etc; (3) the additional heat and mass transfer caused by the wind penetration through the fabrics of clothing (Stuart et al 1983, Fan and Keighley 1989)

2.3.2.1 Heat loss from the outer surface of clothing

The outer surface still air layer of clothing is the last barrier that resists the heat loss from human body. Because of the very small thermal conductivity (2.59×10^{-2}W/mK at 20) of still air, the heat lost from the outer surface is predominantly by convection (characterized by the convective coefficient: h_c) and radiation (characterized by the radative coefficient h_r), the thermal insulation of the surface still air layer, I_{oa}, can be calculated by the following equation:

$$I_{oa} = \frac{1}{h_r + h_c} \tag{2-43}$$

The convective heat loss from the surface of human body was studied by Winslow et al as early as the late 1930s. Since then, many researchers had worked on this field and investigated convective heat transfer under different conditions as well as for different parts of human body. Mochida (1977) provided an overview of some of the earlier studies. The convective heat transfer coefficient reported in the literature may be summarized in the following form:

$$h_c = A + BV^n \tag{2-44}$$

where, *A* ,*B* and n are constants, but have different value under different conditions as well as for different parts of human body. Mostly *A=0~3.5*, *B=1~12.1* and *n=0.391~1*. *V* is the air velocity. After comparing the h_c value in ISO 7730 and ISO 7933 based on the findings of a number of researchers, Holmer et al (1999) pointed out the h_c value in ISO 7730 (1994) may require adjustment. The deviation is relatively high under low air velocity.

On the basis of the examination and analysis by Kerslake (1972), the empirical formula,

$$h_c = 8.3\sqrt{V_0 + V_{wind}} \qquad (V_{wind} > 0.2m/s) \tag{2-45}$$

is recommended as the best prediction of the mean convective heat transfer coefficient. This expression is close to that measured on the human subjects by Fount et al (1970), Nelson et al (1947) and Havenith et al (1990a), and a model developed by Lotens and Havenith (1991) based on this expression showed good prediction on the clothing insulation and moisture vapour resistance.

When there is no external wind, convective heat transfer from the body continues under the influence of the buoyancy of the warmed air near the body surface. Although we are normally unaware of it, the body produces a flow of warm air, which moves upwards over the head and can be detected over 1 meter above the head. On the basis of the examination and analysis by Rapp (1973), for people in still air, the convective heat transfer coefficient

$$h_c = 4W/m^2K \quad (0.05<v<0.2m/s \text{ and } 1<\Delta T<15K)$$

is recommended as the best estimate.

As for the radiative heat transfer coefficient, it has also been studied and determined by a number of investigators (Fanger 1970, Gagge and Nishi 1977, Cain and Farnworth 1986). The radiative heat transfer coefficient h_r is dependent on the temperature and emission coefficients of clothing surface. For most common clothing system in indoor environments, the typical value of h_r is about 4.5~5.0 (W/m^2K)

Convective heat transfer is not only caused by wind, but also caused by the body activities such as walking, weight lifting, riding a bicycle and so on. The more acute the activity, the greater the metabolic rate is. So many researchers used the metabolic rate to describe the level of the muscular work. In this case, the velocity of air flow which causes convective heat loss should be corrected. Givoni and Goldman (1972) introduced an equivalent air velocity V_{eff} to quantify air motion induced by wind and body activity. V_{eff} can be calculated by (ISO 7933):

$$V_{eff} = V_{wind} + 0.0052(M - 58) \qquad m/s \tag{2-46}$$

or (Breckenridge, 1977)

$$V_{eff} = V_{wind} + 0.004(M - 105) \qquad m/s \tag{2-47}$$

where, V_{wind} is in m/s, M is the metabolic rate of body in watts.

When a clothed person is walking in wind, Lotens and Havenith (1991) proposed the following equation to estimate the value of V_{eff}:

$$V_{eff} = V_0 + V_{wind} + \beta \cdot V_{walk} \tag{2-48}$$

where, V_0 is a lower limit related to the natural convection, which can be determined from the surface thermal insulation measured in still air, β is a parameter dependent on the type of body movement, walking speed, characteristics (e.g. air permeability) of the clothing ensembles.

On the basis of the air insulation measured by Havenith et al. (1990a), the following expressions are found:

V_0=*0.11m/s* for standing, 0.07m/s for sitting

β=0.67 for treadmill walking.

Combining equations above, for the body walking in windy conditions, we have:

$$I_{oa} = \frac{1}{5 + 8.3\sqrt{v_o + \beta V_{walk} + V_{wind}}} \qquad (2\text{-}49)$$

The experimental results given by Havenith et al (1990a) and Nelson et al (1947) and Fount et al (1970) showed a good agreement with the predicted clothing surface insulation I_{oa} in Figure 2-3.

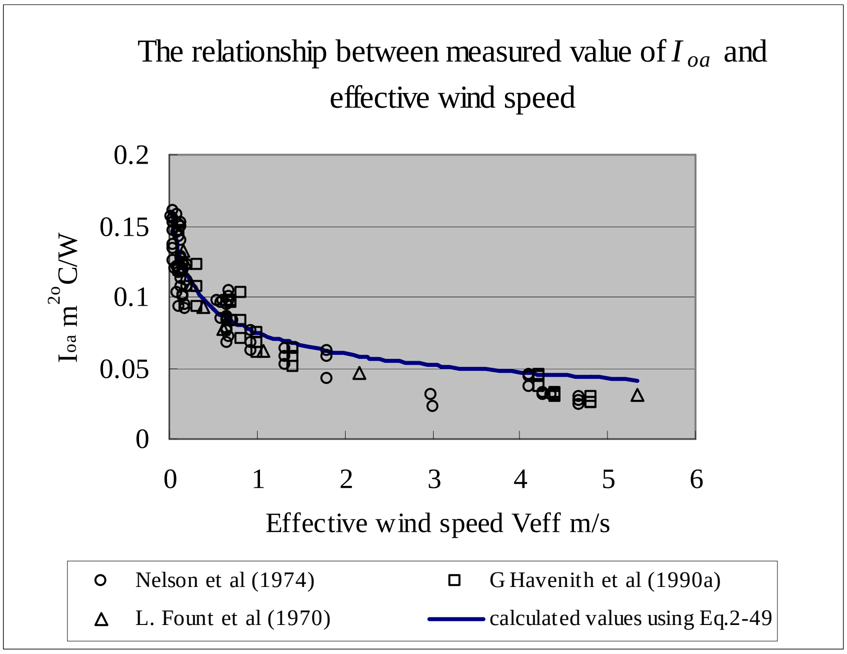


Figure 2-3 The effect of effective speed on I_{oa}

When the air adjacent to the surface of clothing is still ($v=0\ m/s$), the thermal insulation of the air layer I_{oa}=1/5=0.2 $m^{2o}C/W$. However, because the lower limit is related to natural convection induced by the gradient of temperature and mass near to the surface, some typical values of I_{oa} in still air were 0.085 (Nilsson, 2000), 1/9 (Holmer 1999), 0.112 m^2K/W (McCullough 1989), 0.129 m^2K/W (Havenith 1990a), or 0.136 m^2K/W (Nielsen et al 1985). After comparing the testing results measured on some sweating manikins located in different laboratories in the world, the values of the thermal insulation of the air layer around the nude manikins ranged from 0.051 $m^{2o}C/W$ ($V_{wind}=1.55m/s$) to 0.104 $m^{2o}C/W$ (McCellough 2001)

For the moisture vapour resistance, due to the nature convective heat transfer coefficient is 4.0 $W/m^{2o}C$, according the equation 2-18, we have:

$$d = \frac{0.026}{4} = 6.5mm$$

$$R_{oa} = F_R d = 2.3 \times 6.5 = 15.0 \qquad {p_a m^2}/{W}$$

The air equivalence was measured by Whelam (1955), it is found to be 7 mm. With the limitation of the measurement technology, this value was very difficult to measure accurately, some typical values of R_{oa} in still air are found in literature were 6.4 mm (McClough 1989) and 9.4 mm (Havenith 1990b). After comparing the testing results from sweating manikins located in different laboratories in the world, it was found that the value of the surface moisture vapour resistance of the air layer around the nude manikins ranged from 11.0 to 20.0 m^2p_a/W (McClough 2001). This large difference may be partially caused by the difficulty in determining the partial vapor pressure at the skin surface accurately.

2.3.2.2 Microclimate in clothing system

Unless the clothing is skin tight, air gaps exist both between the skin and under clothing and between different layers of clothing, these gaps also vary in size as the wearer moves or the garment flaps. It was referred as the microclimate in clothing system by Vokac et al (1973) and Crockford et al (1974). Spencer-Smith (1977) measured the heat flow across the air gaps and his results (Table 2-1) showed that convection was negligible when the air gap was less than about 0.8cm. If it exceeded about 0.8cm and the surface was vertical or lower surface was hotter than the upper surface, natural convection would occur within the air gap.

Table 2-1 Heat flow across air gaps due to convection alone and to the combined effects of conduction and convection (20 cm plates of smooth metal)

Width of air gap (cm)		Heat flow (W/m^2) due to conduction only and to convection and conduction for temperature differences of							
		1°C		5°C		10°C		20°C	
		Cond. only	Cond.+ conv.	Cond. only	Cond.+ conv.	Cond. only	Cond.+ conv.	Cond. only	Cond.+ conv.
Vertical	0.5	5.24	5.24	26.2	26.6	52.4	53.5	104.8	107.0
	1.0	2.62	2.65	13.1	13.4	26.2	27.4	52.4	56.8
	1.5	1.75	1.80	8.7	9.5	17.5	18.7	34.9	42.4
	2.0	1.31	1.36	6.6	8.1	13.1	18.8	26.2	46.6
	3.0	0.87	0.94	4.4	8.5	8.7	20.1	17.5	48.6
Horizontal (lower surface hotter than upper surface	0.8	3.28	3.28	16.4	16.6	32.8	34.0	65.5	73.6
	1.2	2.18	2.18	10.9	11.6	21.8	26.3	43.7	64.6
	2.4	1.09	1.10	5.46	10.5	10.9	27.7	21.8	71.8

Crockford and Rosenblum (1974) employed a trace gas technique to measure the clothing microclimate volume. The results are shown in the Table 2-2:

Table 2-2 The microclimate volume of garments

Clothing assembly	Mean Volume (*l*)
Shirt, Sweater, Trousers and Underclothes	26.2
Duck suit, foamed lined	23.1
Foamed neoprene coverall (3mm)	16.3
Foamed neoprene coverall (5mm)	27.9
Duck suit, spacer and fabric lined	43.9

Kind and Broughton (2000) focused their research on reducing wind-induced heat loss through multi-layer clothing system by means of a bypass layer. The results showed that wind-induced heat loss through multi-layer clothing system can be greatly reduced by introducing a layer. This layer should have low resistance to airflow between the exterior fabric sheath and the underlying batting layer. It acts as a bypass, allowing air that has penetrated the somewhat permeable sheath to flow downstream with little or no penetration of batting layer.

2.3.2.3 The air flow around the body in windy conditions

By studying the total and local heat transfer coefficients on the heated cylinders, Fonseca and Breckenridge (1965) measured the heat transfer coefficients with different wind speed and different size of airway.

Stuart et al (1983), and Fan and Keighley (1989) proved the experimental results mentioned above theoretically. In Fan and Keighley's paper, a limb or body was approximated to as an internally temperature-controlled hollow cylinder, the results showed that the distribution of the effect thermal insulation around the body is not uniform in a windy condition. While it was very dependent on the wind speed on the windward side, heat loss on the lee side was relatively low and insensitive to the wind (Kind ea al 2000).

2.3.2.4 Air penetration in clothing system

Air penetration can also induce the air exchange. In windy conditions, Stuart et al (1983) and Fan and Keighley (1989) stated that air penetration into permeable clothing is a major cause of reduction in thermal insulation and vapor resistance. The air penetration is induced by the air pressure difference between inner surface and outer surface of clothing system. Kerslake (1971) pointed out that the rate of air penetration through the clothing assembly Q (m^3/m^2hr) was approximately linearly related to the wind velocity:

$$Q = 3600Sfv \tag{2-50}$$

where, *S* is the unit surface area of the clothing assembly (1 m^2), *f* is the apparent portion of the surface area S that is open to the air-flow; *v* is the wind velocity, or flow velocity of air through the clothing assembly, which is assumed to be equal to the wind velocity (m/s).

2.3.2.5 Ventilation and ventilation index in clothing system

Obviously the temperature and humidity of the microclimate in a clothing system are very different from the surrounding environment. Vokac et al (1973) stated that the reduction of the effective insulation caused by body motion seemed to have been universally accepted and it’s attributed mainly to the loss of convective heat by forced exchange of air contained under the clothing with the ambient air. Depending on the construction of the fabrics (such as woven and knitted fabrics) and clothing (style), air could be forced through the pores in the fabrics as well as through the openings of the garments. The supposed, ill-defined mechanism was named as "internal wind" by Burton et al (1955); "bellows effect" by Fanger (1970) and Fourt (1970) or "bellows ventilation" by Renbourn (1972). Crockford et al (1972, 1974, 1978) first measured the clothing ventilation successfully by means of a trace gas dilution method, which was subsequently further developed by Lotens and Havenith (1986, 1988) and Reischl et al (1987). The rate of ventilation in volume per unit body surface area and per unit time was defined as the clothing ventilation index.

Although the clothing ventilation index is a quantitative, relatively inexpensive, fast, reliable and repeatable measure (Lumley 1991), it is difficult to distinguish the air ventilation and penetration because of their complex interaction. Furthermore, little is known on how clothing ventilation relates to different environmental and body motion conditions.

2.4 Existing Prediction models of clothing thermal Insulation and vapor resistance

2.4.1 Direct regression models

The thermal insulation and water vapor resistance values of conventional garments and clothing assemblies were measured and stored in a data base for estimating the thermal insulation of clothing systems in use (ASHRAE Standard 55-2005, Mcellllough et al 1985 and Mcellllough et al 1989, ISO 7933 and ISO

9920). For clothing on a standing manikin in the still air, McCullough et al (1985) found that the thermal insulation of a garment could be well estimated from the body surface area that the garment covers and the fabric thickness. They also found that the thermal insulation of a clothing ensemble could be accurately predicted from the sum of the insulation of constituent garments. A model was later proposed by them to predict the thermal insulation and water vapor resistance of clothing ensembles from those of component fabrics by considering the body as consisting of 11 cylinders. The prediction was quite accurate, but may not be practical as it requires difficult and tedious measurement of the coverage of each garment, thickness of fabric and trapped air layers in each cylindrical section in addition to the measurement of fabric insulation and vapor resistance, which requires very specialized equipment. They could not investigate the effect of body movement and its interaction with wind and garment design with the standing manikin.

Holmer et al (1999), based on the complete set of data (nude plus seven clothing ensembles with a walking thermal manikin, and three clothing ensembles measured on subjects), obtained the following regression equation for predicting thermal insulation:

For undressed:

$$\frac{I_{dyn}}{I_{st}} = e^{(0.126-0.899V_{wind}+0.246V_{wind}{}^2-0.313V_{walk}+0.097V_{walk}{}^2)} \qquad (2\text{-}51)$$

For dressed:

$$\frac{I_{tdyn}}{I_{st}} = e^{(0.043-0.398V_{wind}+0.066V_{wind}{}^{2}-0.378V_{walk}+0.094V_{walk}{}^{2})} \qquad (2\text{-}52)$$

where, I_{tdyn} is the total insulation under body motion, I_{st} is the insulation when standing in still air and can be calculated from given I_c and I_{oa} in still air, V_{wind} is the air velocity in m/s and V_{walk} is the walking speed in m/s.

Nilssion et al (2000) proposed another prediction model, taking into account of the influence of wind speed V_{wind} (m/s), walking speed V_{walk} (m/s) and air permeability *ap* on the thermal insulation. The model is expressed as:

$$I_{tdyn} / I_{ts} = 0.54e^{(-0.15V_{wind}-0.22V_{walk})} ap^{0.075} - 0.06\ln(ap) + 0.5 \qquad (2\text{-}53)$$

Based on three clothing ensembles which include a woman skirt, Hong (1992) used a direct regression model to predict the thermal insulation of clothing. The effect of wind can not be considered in the study.

$$I_{tdyn} = 0.537 I_{ts} + 0.0052 V_{walk} - 0.59 \qquad R^2 = 0.95 \qquad (2\text{-}54)$$

where, I_{tdyn} and I_t is in *clo*, V_{walk} is in steps/min.

At the same time, a large investigation was made on the effect of clothing fabrics properties in Hong's study. Unfortunately, only one walking speed was changed in the investigations.

2.4.2 The reduction factor models

As mentioned above, a loose garment may flap, pumping out warm air from the gap between the skin and the clothing assembly and replacing it by cool air from the surroundings in wind, and at the same time wind may penetrate the outer clothing to set up air currents within the gap, so many researchers used a reduction factor to determine the thermal insulation and the moisture vapor resistance reduced by body motion and wind.

In steady conditions, the effect of wind penetration into the air gaps within clothing can be expressed by a wind penetration factor *F* (Fonseca and Breckenridge 1965, Spencer-Smith 1977 a and b), which is defined as:

$$F_I = \frac{I_{wind}}{I_{st}} \qquad F_R = \frac{R_{wind}}{R_{st}} \tag{2-55}$$

where, I_{wind} and R_{wind} are the actual thermal insulation and moisture vapour resistance of the air gap with wind penetration respectively, I_{st} and R_{st} are the thermal insulation and moisture vapor resistance of the air gap due to convection and conduction in still air.

F was found to be (Spencer-Smith 1977 a and b):

$$F_I = 1 - 1.2 \times 10^{-4} V_{wind} \sqrt{ap} \tag{2-56}$$

$$F_R = 1 - 0.024 V_{wind} \sqrt{ap} \quad (2\text{-}57)$$

where, V_{wind} is the wind velocity in feet/minute, *ap* is the permeability of the outer garments as measured by the method described in BS 3217:1960.

2.4.3 Regression model based on the physics of heat transfer through clothing

Havenith, et al (1990a) attempted to transform the 'standing' insulation to the actual 'resultant' insulation of clothing at the workplace by developing regression equations, incorporating the effects of body posture, movements, wind and garment fit. With these regression equations, the resultant insulation when sitting or walking can be calculated from the 'standing' insulation, the effects of walking speed and wind velocity can be quantified. However, due to the very limited data in forming the regression equations, the prediction was only moderate. Furthermore, the effect of garment fit and the interaction of walking and wind were not quantified. Lotens and Havenith (1991) later modified the model developed by McCullough et al (1989) for standing persons in still air for easy use and extended the model to predict the 'resultant' insulation and vapor resistance for sitting, walking, cycling at various rates and for the combined effect with the wind. This model was based on the finding that heat transfer coefficient increases linearly with the square root of air velocity:

$$h = a + bV_{eff}^{1/2} \quad (2\text{-}58)$$

The ratio of insulation with and without wind is then:

$$\frac{I_{clwind}}{I_{clnowind}} = \frac{a/b + (V_{act} + v_0)^{1/2}}{a/b + (V_{wind} + V_{act} + v_0)^{1/2}} \qquad (2\text{-}59)$$

where, I_{clwind} and $I_{clnowind}$ are the thermal insulation of garment with wind and without wind, respectively, v_0 is a nature convective velocity of 0.11 m/s under standing in a still air, V_{act} is related to the body activity depending on the rate of motion, for a clothed person with treadmill walking, its value is 0.67 times of walking speed.

Similar equations were given for the intrinsic air equivalent d_{cl}, but d_{cl} can be calculated from I_{cl} by recognizing that the convective part of the heat transfer coefficient h_{clc} is proportional to the mass transfer coefficient 1/dcl. Thus

$$\frac{d_{cl}}{d_{cls}} = \frac{h_{cls}}{h_{clc}} \qquad (2\text{-}60)$$

where, the subscript "s" refers to the reference condition (e.g. standing in still air).

2.5 Concluding remarks

Clothing thermal insulation and water vapor resistance are two most important parameters in thermal environmental engineering, functional clothing design and end use of clothing ensembles. They can be measured by subjective wearer trials or objective simulation tests. A subjective wearer trial gives realistic results, but requires sophisticated equipment and is time consuming. The measured values may also have large variability and can sometimes expose the subjects to danger when testing under extreme conditions.

In the objective simulation tests, thermal manikins are considered as the most useful tools for evaluating thermal comfort of overall clothing systems because of its stimulation of clothed body system, but up to now there are only a few both movable and perspiring manikins in the world. Although “SAM” in Switzerland, “Coppelius” in Finland and “WALTER” in Hong Kong can be movable and perspiring in principle, they need to be further improved for routine testing.

The moisture vapor resistance were frequently measured by means of a two-step measurement method on non-perspiring manikins, but this two-step method may give a serious underestimate of the heat loss through clothing, partly because there is interaction between heat and moisture transfer, partly because of increased heat and moisture transfer through damp clothing of the buffering action of hygroscopic clothing and of the long time (more than 12 hours (Fan and Chen 2002)) required before moisture accumulation stabilizes. The previously reported experimental data should therefore been reviewed in view of this new understanding.

The thermal insulation of a garment on a standing person in still air could be well estimated from the body surface area that the garment covers and the fabric thickness. The thermal insulation of a clothing ensemble could be accurately predicted from the sum of the insulation of constituent garments. The thermal insulation and moisture vapor resistance can be calculated from those of component fabrics by considering the body as consisting of some cylinders. The prediction was quite accurate, but may not be practical as it requires difficult and tedious measurement of the coverage of each garment, thickness of fabric and trapped air layers in each cylindrical section in addition to the measurement of fabric insulation and vapor resistance, which requires very specialized equipment. The effect of body movement and its interaction with wind and garment design with the standing manikin was not investigated.

Design variations that affect the amount of body surface area covered and the looseness or tightness of fit affect the clothing insulation values. Standing in still air, the loose-fitting long trousers provided more insulation than the tight-fitting trousers did. But during movement, more air would circulate inside the legs of the loose-fitting trousers than in the tight-fitting trousers, causing an increase in convective heat transfer. The effect of garment fitting has not been systematically investigated and quantified.

The thermal insulation and water vapor resistance values of conventional garments and clothing assemblies were measured and stored in the data base for estimating the thermal insulation of clothing systems in use. Based on these data base, many prediction models including direct regression models, reduction factor models and physics models had been developed to predict the clothing thermal comfort. With these regression equations, the resultant resistances of clothing under windy conditions and body motion can be calculated from the resistance of clothing for a person standing in still air). The models, although convenient to use in a software form, have the following shortcomings:

(1) The models, which calculated the fabric insulation from the fabric thickness with proportionality constant, have not taken into account of the type of fiber and fabric construction. This is acceptable in most cases, but is not appropriate for fabrics extremely dense or bulky in construction or made of special fibers such as hollow fibers, micro-fibers, etc.

(2) The models assumed that all fabric layers and trapped air layers to be of the average thickness. This, although simplified the data input for the model, can cause unacceptable errors in cases where fabric thickness and air layer between garments vary considerably.

(3) The air permeability of the outer and inner fabrics is important to the wind induced heat and moisture transfer, but was not fully considered in the models.

(4) Garment design and fitting are important since ventilative heat and moisture transfer take place through the openings of the clothing system, yet garment design and fitting of the clothing openings have not been taken into account in the model.

Chapter 3

Development of Walk-able Sweating Fabric Manikin – Walter

3.1 Introduction

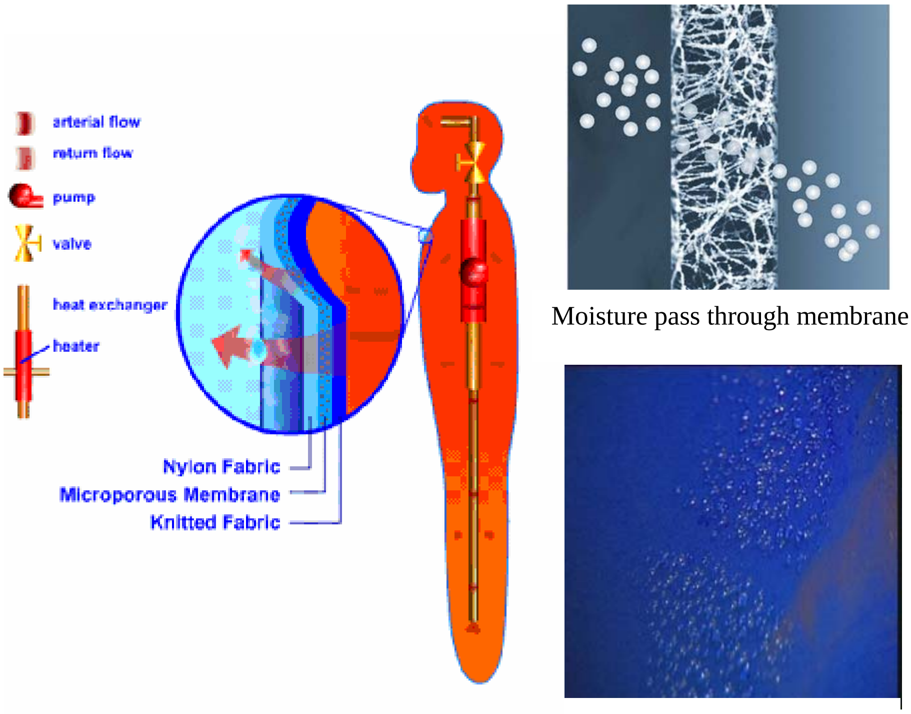
The sweating fabric manikin – Walter has a man's body. His main dimensions are listed in the following Table 3-1. Figure 3-1 is a front view of Walter.

Table 3-1 Dimensions of Walter

Height	172 cm
Neck Circumference	45 cm
Chest Circumference	95 cm
Waist Circumference	89 cm
Hip Circumference	100 cm
Surface Area	1.79 m^2

Figure 3-1 Front View of Walter

Walter simulates perspiration using a waterproof, but moisture-permeable, fabric "skin", which holds the water inside the body, but allows moisture to pass through the skin (Figure 3-2, http://www.gore-tex.co.uk). Walter achieves a body temperature distribution similar to a real person by pumping warm water at the body temperature (37°C) from its centre to its extremities. The skin of Walter can be unzipped and interchanged with different kinds of breathable fabrics to simulate different rates of perspiration. Unlike most existing manikins, Walter takes only one step to measure the two most important parameters-thermal insulation and moisture vapour resistance.



Moisture pass through membrane

Image of sweating on skin

Figure 3-2 Simulating the evaporation of sweat by Walter

The structure of Walter belongs to a hanging-type, suspended by a water pipe projecting from its head. This design not only makes Walter easy to be dressed and undressed, but also enables Walters' arms and legs to be pushed and pulled to simulate "walking" motion. Although Walter, as it was originally designed, can simulate "walking" motion in principle, the strength of the fabric and seams of its skin was a serious concern during the continuous flexing in the simulation of "walking" motion (Chen 2002). Improvements should therefore be made in order to simulate "walking" motion for prolonged periods.

To develop Walter to simulate the "walking" motion, the following factors were considered:

(1) The fabric and sealed seams should be able to withstand the weight of about 75kg water filled inside of Walter and about 1.72 m high of water pressure during continuous flexing and friction in "walking" motion.

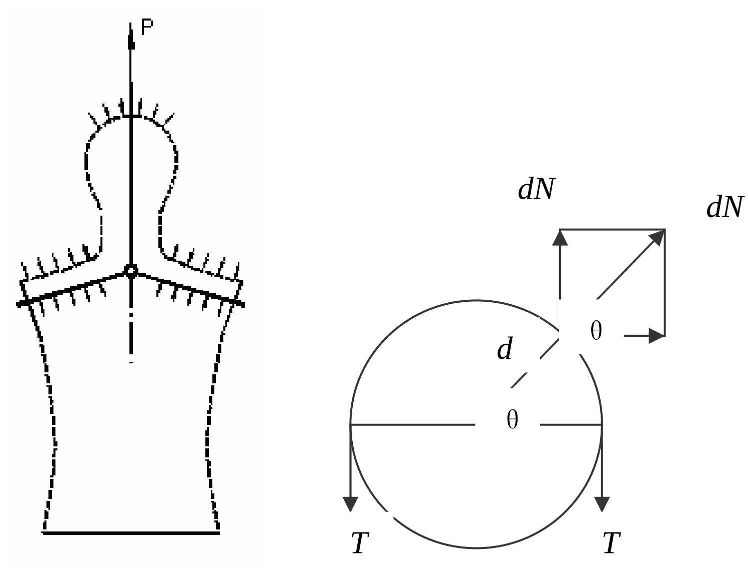
(2) Joints must be designed to connect the limbs and the main body for the purpose of "walking" motion. The joints must facilitate free movement of the limbs, but not blocking the water flow into and out of the limbs and not create abrasion onto the "skin".

(3) The speed of "walking" motion should be adjustable to simulate different walking speeds in different walking frequency and walking steps.

(4) The perspiring rate must be measured on-line, and the precision of the measurement should be improved.

3.2 The selection of the breathable fabric for skin

Walter belongs to a hanging type structure. It was hung on a girder via a pipe. Considering the volume within the manikin, the water inside the manikin should weigh about 75 kg. The weight force is concentrated on two shoulders and finally on the hanging pipe.



(a) (b)

Figure 3-3 The force distribution and the tensile calculating model on Walter

In the vertical direction, the total force acting on the fabric at the shoulder region is about 750N (i.e. weight of water times gravity). Since the shoulder width is about 460 mm and the force is acting on both front and back side of the shoulder, the required minimum strength of the fabric in the length direction under allowable extension should be:

750N/2/460 ≈0.8 N/mm = 40 (N per 50mm width of fabric)

In the horizontal direction, water pressure acting on the fabric extends the fabric in the width direction (See Figure 3-1 (b)). Assuming the cross-section of the manikin body is circular, and let T the tensile force in the fabric in the width direction, dl an infinitesimal arc, *dN* the infinitesimal tensile force created by the water pressure acting on the infinitesimal arc dl, we can have the following relationship:

$$2T = \int_0^{\pi} dN \sin\theta ,$$

$$T = \frac{1}{2}\int_0^{\pi} PWdl \sin\theta = \frac{1}{2} PW \int_0^{\pi} \sin\theta R d\theta = WPR \qquad (3\text{-}1)$$

where, P is the water pressure on the fabric at the position in consideration in mmH_2O, W is the narrow width of the circular cross section in mm, R is the radius of the cross section in mm.

Consider the two extreme positions: the hip (where the girth is maximum, thus the radius is maximum at about 150 mm and water pressure is about 950 mmH_2O) and the ankle (where the water pressure is maximum at about 1750 mmH_2O and the radius is about 40mm).

At the hip (position of maximum girth):

$T = PWR = 950mmH_2O \times 50mm \times 150mm$

$= 950 \times 9.8N/m^2 \times 0.05m \times 0.15m \approx 70$ (N per 50 mm width of fabric).

At the ankle (max. pressure):

$T = PWR = 1750mmH_2O \times 50mm \times 40mm$

$= 1750 \times 9.8 \times 0.05m \times 0.04m \approx 35$ (N per 50 mm width of fabric).

Based on the above calculation, the tensile load of the fabric at allowable extension should be greater than 40 N in the warp direction and 70 N in the weft direction for a 50 mm width fabric. Since the lower the extension, the better the shape of the manikin body is maintained, we allow maximum 5% of extension in either length (or warp) and width (or weft) direction.

Three breathable fabrics, two laminated fabric from Goretex and one coated fabric, were tested on the Instron to examine their suitability in terms of strength. The load-strain curves of these fabrics are shown in Figure 3-4. As can be seen, the new Goretex fabric is the most suitable material for making the skin in terms of strength.

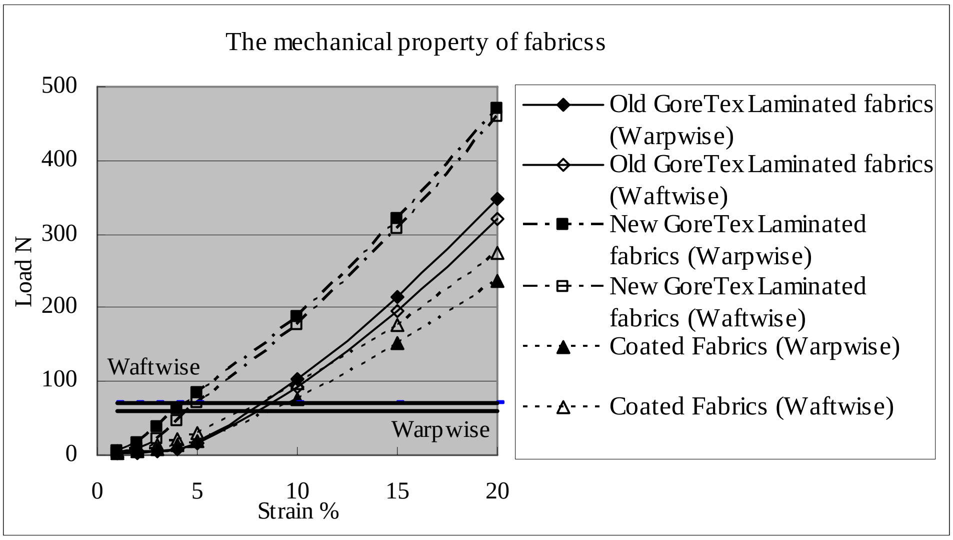


Figure 3-4 The mechanical property of “skin” fabrics

Since through the fabric skin, moisture is transmitted to simulate “perspiration”, the moisture transmission rate through the breathable fabric is also an important consideration. Since the old Goretex fabric, used by Fan and Chen (2002) was found appropriate in terms of moisture transmission rate, the newly available Gortex fabric and the coated fabric were compared to the old Goretex fabric in terms of moisture transmission. These fabrics were tested using Moisture vapor transmission tester (model CS-141). The results are plotted in Figure 3-5. The faster the relative humidity is increased indicates a greater permeability to moisture transmission. Therefore, from Figure 3-5, the new Goretex fabric is more permeable than the old Goretex fabric and can therefore simulate higher rate of "perspiration".

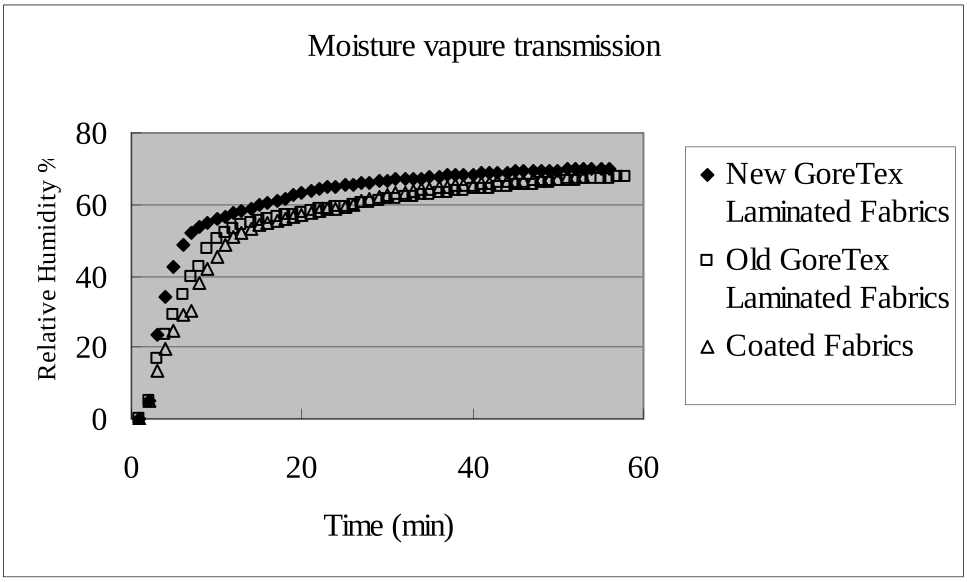
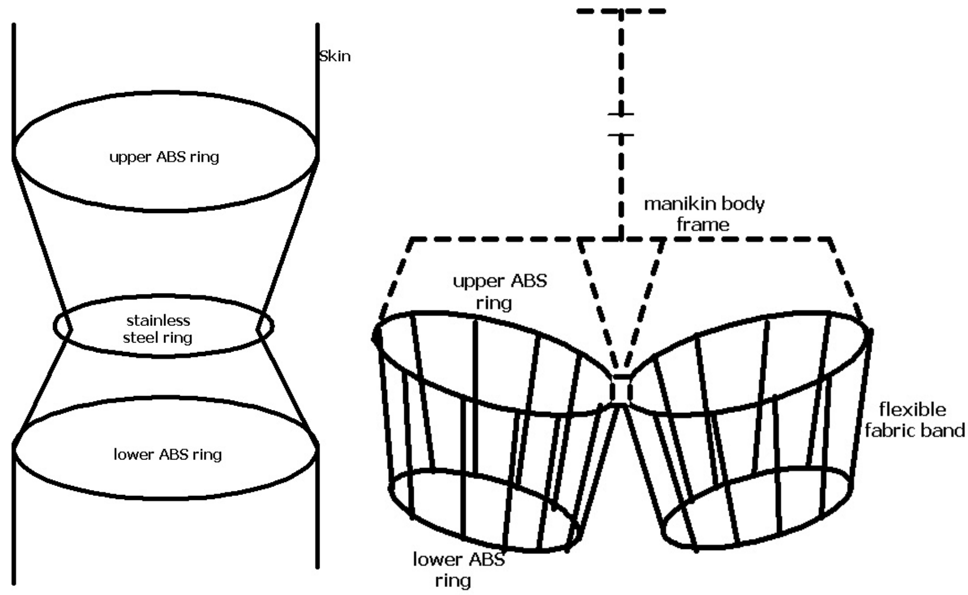


Figure 3-5 Moisture vapor transmission of "skin" fabrics

3.3 Development on hardware for Walk-able manikin

3.3.1 Design of movement joints between legs and torso for "walking" motion

The basic idea in the design of the joints is to reduce the cross section at the connection between the legs and the torso so that the legs can be bent more easily when pushed and pulled to simulate body's "walking" motion. The joints should not block the water flow into and out of the limbs. The idea is illustrated in Figure 3-6(a).



(a) (b)

Figure3-6 The design and construction of Joints for manikins "walking" motion

To achieve this idea, two plastic ABS rings were placed inside the body and one stainless steel ring was placed outside the skin on each leg. The inner plastic rings were used to keep the shape of the upper parts of the legs, whereas the external steel rings were used to limit the cross sectional area of the joints so as to facilitate bending. The diameter of the stainless steel ring was smaller than that of the ABS rings and it could be open and closed, so that the stainless steel ring could be inserted into the joint and used to reduced the cross section of the joint.

The upper plastic rings were diagonally fixed to the manikin's body frame and the lower rings were hung on the respective upper plastics rings by using flexible fabric tapes so that the lower rings were freely moveable during the simulation of "walking" motion and the cross sections between the upper and lower inner plastic rings could be varied depending the size of the external steel rings. The inner constructions of the joints are shown in Figure 3-6 (b).

With this construction, there would be frictions between the rings and the fabric skin during "walking" motion, which could damage the fabric skin. In order to prevent the skin being abraded, protective layers must be placed on the joint inside and outer side of the skin, this structure is shown as Figure 3-7.

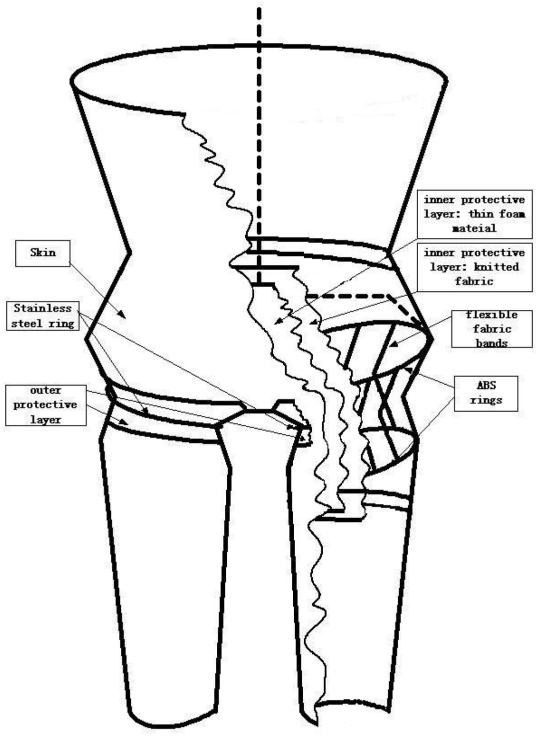


Figure 3-7 Protective fabric layers of the joint.

The inner protective layers contained two different layers, the one next to the skin was made of a thin foam material and the other was made of a highly stretchable Lycra knitted fabric. These layers were made into underwear and they could be put on the manikin body directly. The high stretch ability and low surface friction of the Lycra fabric reduced the friction between itself and the ABS plastic rings, while the foam materials adhered itself to the fabric skin so that it moved with the skin during the “walking” motion. As such, the inner protective layers prevented the inner surface of the fabric skin from being abraded. After use for a period of time, the inner protective layers can be replaced. In order to prevent the friction between the outer surface of the fabric skin and the external stainless steel ring, the joint area was covered by an outer preventive layer made of a coated fabric. The coated surface should faces the outer surface of the skin, which enables the outer protective layer adheres to the outer skin surface to move together during “walking” motion.

To achieve the functions of the protective layers, the friction coefficients of the materials should be considered. Figure 3-8 shows the different friction coefficients of the rings and the surfaces of the protective layers measured on Kawabata fabric testing system.

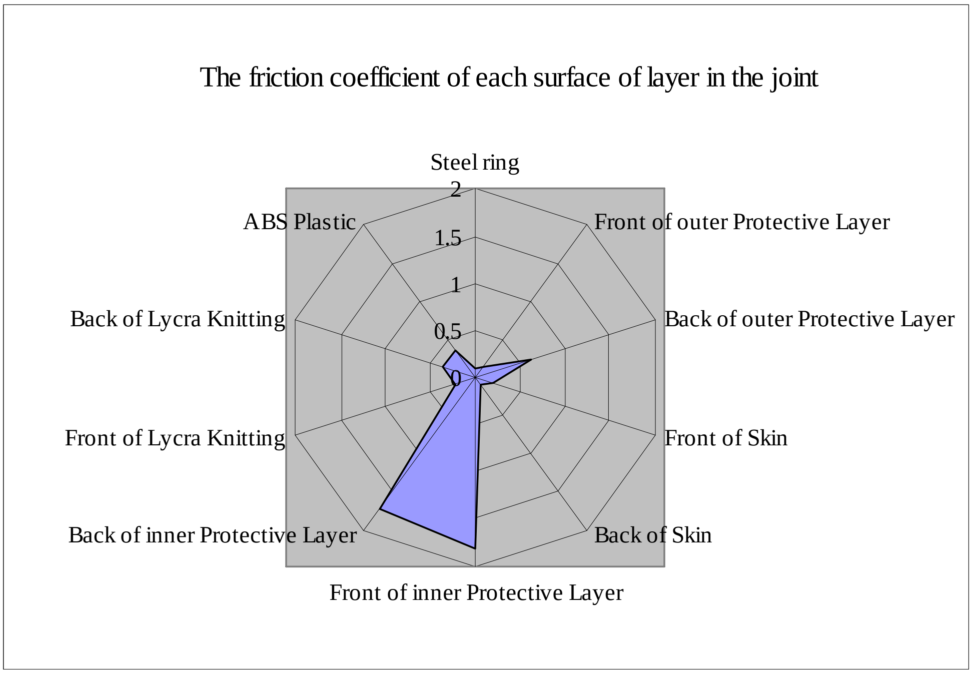


Figure 3-8 The friction coefficient of each surface of layer in the joint

The images of the joints are shown in Figure 3-9 (a) and Figure 3-9 (b). Figure 3-10 shows Walter is in "walking" motion with the joints.

Figure 3-9 (a) Inside of joint

Figure 3-9 (b) Outside of joint

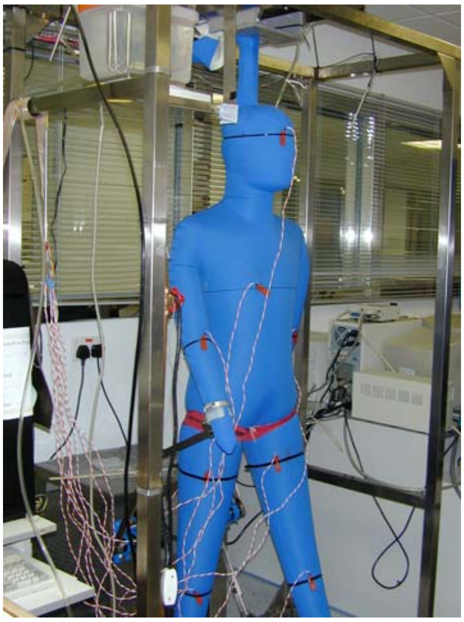


Figure 3-10 Walter is walking

The structure of the joints is very simple, and it could be made and installed easily.

3.3.2 Regulation of the speed and step size of "walking" motion

The arms and legs of Walter were pushed and pulled by using a quadric crank system, designed by Chen (2002), to simulate "walking" motion. The pace size of each step can be altered mechanicall, the maximum pace size of each step is 0.6m. In the present work, improvements were made to alter the speed of "walking" motion by changing the frequency of the AC power supply using an AC frequency regulator which was controlled by computer, the maximum frequency of AC power could be regulated to 65Hz, so that the maximum "walking" speed can be reached to 3.58 Km/hr. When the pace size of each step is fixed to 0.45 meter, the "walking" speed can now vary from 0 to about 2.48 km/hr (Table 3-2). The AC frequency regulator was controlled by a computer by means of PIC 6711 device which is a 12-bit digital-to-analog converter (DAC).

Table 3-2 Walking speed of Walter

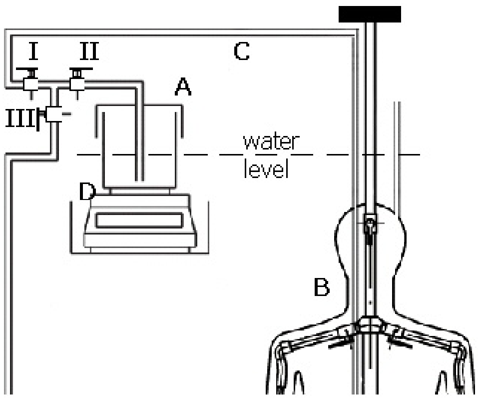
AC frequency regulator	Walking speed (step=0.45m)	
Hz	m/s	km/h
0	0.00	0
10	0.11	0.41
20	0.23	0.83
30	0.34	1.24
40	0.46	1.65
50	0.58	2.07
60	0.69	2.48

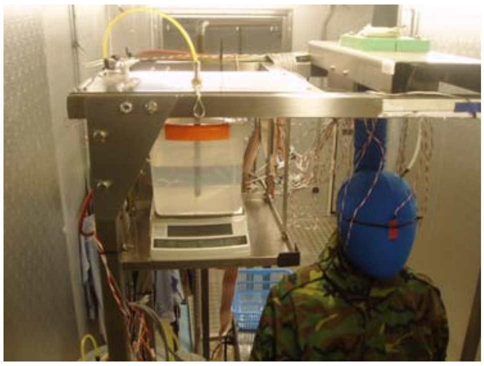
Since the regulation of AC power supply creates strong electromagnetic waves, which greatly affect electronic signals in the electronic signal measurement and control system, the AC power supply for motorizing the “walking” motion should be separated from that for the control and measurement systems and all sensing wires should be covered with shield materials.

3.3.3 Design and construction of the automatic water supply and real time perspiration rate measurement system

With the standing sweating fabric manikin – Walter design by Chen (2002), water was added to the manikin manually and periodically (typically every hour) to compensate the water loss and the amount of water required to bring the water level to the original height was a measure of the rate of “perspiration”. It had no problem while the manikin was standing, as the water level was relatively stable. But when the manikin is in motion, the water level in the manikin will be pushed up and down cyclically due to the deformation of the manikin body. In this case, it would be difficult to visually determine the amount of water required to compensate to the water loss. Automatic water supply to the manikin to compensate the water loss and the real time measurement of water loss from the sweating manikin is therefore necessary for the measurement of the dynamic responses of the manikin for ease of operation and improvements in measurement accuracy.

The basic idea for the system is to pump water from a water tank to the manikin. However, the challenge was to measure the amount of water added to or lost from the manikin. The obvious way to measure the water loss is to measure the weight of the manikin in real time using a balance. However, since the total weight of the manikin exceeds 75 kg and the water loss (or "perspiration") is less than 1kg per hour or about 1~16g per minute, an electronic balance, which can weight up to 75kg, would not be able to measure the small change of 1~16g accurately, particularly when the water level in the manikin is moving up and down and the manikin is pendulous during the simulation of body "walking" motion. In order to overcome this problem, the weight of a small water container, which connects to the manikin through tubes to create a siphon action, was weighed in real time. The designed system is illustrated schematically in Figure3-11.





(a) (b)

Figure 3-11 Auto water supply and real time measurement system

The water in the small container "A" located on an electronic balance "D" was about 6kg, sufficient for more than 10~20 hours of "perspiration" in terms of the moisture vapour resistance of clothing system. This container was not mechanically connected to the manikin, but linked through soft tubes "C", which ensured the water level in the manikin "B" being the same as that in the container "A" by siphon action. The water supply system had three switches: valve "I", valve "II" and valve "III". By opening one switch and closing the other, water could be pumped into the manikin when required to fill up the manikin with water, or pumped into the small water container periodically to fill up the small container when required. In the case of testing, valve "I" and valve "II" was open and valve "III" was closed, the water in small container "A" was connected with the water in the manikin "B" by the siphon action through the tube "C" when the soft tube "C" was filled up with water, therefore the water level in the small container "A" and in the manikin was the same.

The electronic balance model was Shimadzu BX 6200s with high performance and multiple functions. Its weighing capacity was 6200±0.1 gram, and it was connected to the computer with a RS-232C connector.

Figure 3-12 shows that the real time reading of the electronic balance against with time when the clothed manikin was standing or walking in still air.

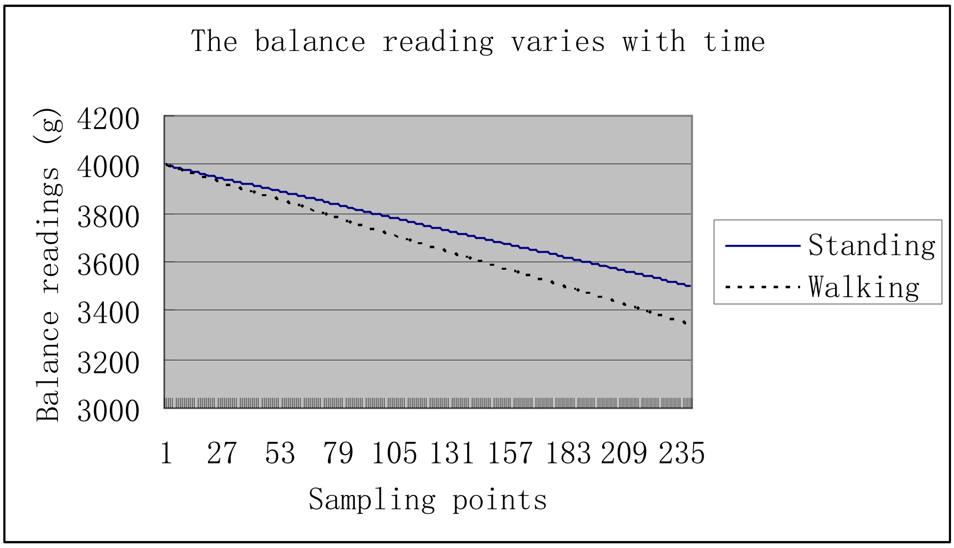


Figure 3-12 The changes of balance reading with time

Figure 3-13 shows that the reduction of the balance reading against time in every sampling interval (30 seconds).

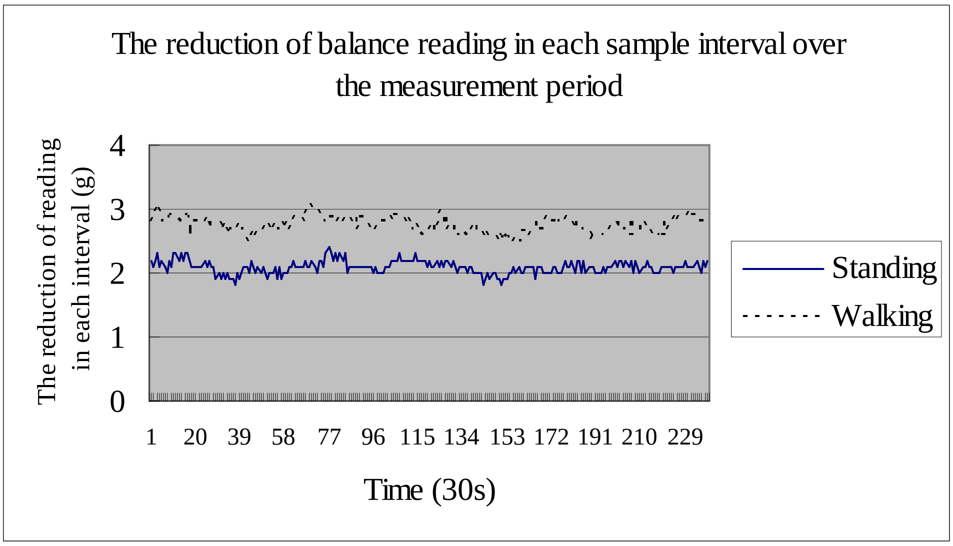


Figure 3-13 The reduction of balance reading in each sample interval over the measurement period

From Figure 3-13, it can be seen that the reduction of balance reading varied with time periodically. This periodic variation was caused by the nature of siphon action and the periodic "walking" motion. The siphon action requires a minimum difference in water level between the water container "A" and the manikin body "B" to initiate water flow to the manikin "B". Assume no difference in water level in the beginning, as water in the manikin "B" is perspired; the difference in water level between the manikin "B" and container "A" is increased. Once the potential energy induced by this water level difference is big enough to overcome the resistance of water flow through the tube "C", water will be fed into the manikin body "B" from the water container "A" and consequently the balance registers a reduction of the reading. Thereafter, water flow will stop when the increased water level in manikin body “B” is the same as the reduced water level in the container “A”. After that, a new cycle starts. The water supply to the manikin “B” from the container “A” is therefore cyclic in nature, but variation is generally very small. When the manikin is in motion, the variation tends to increase; the absolute value is less than 1 gram.

When the water loss is determined, the periodic variation of the readings of balance should be filtered or the readings at the same periodic position at different times should be used to calculate the rate of water loss. On the other hand, the changes of the balance readings was not the same as the water loss from the manikin, yet linearly related, since the water level in the manikin was only refilled to the decreasing water level in the container. The rate of water loss from the manikin could be calculated from the change of balance reading with a coefficient of calibration using the following formula:

$$Q = 3600 \times \Phi \times \frac{\varphi}{\Delta t} \qquad (3\text{-}2)$$

where, Q was the water loss (or “perspiration rate) from the manikin in g/h, Φ was the coefficient of calibration, φ was the difference of two balance readings over a time interval (the two readings should be at the same periodic position), Δt was the reading interval.

3.3.4 Regulation of the rate of the pumps inside the manikin body

When a person's activity level is increased, his metabolic rate will be increased. This will be associated with increased blood flow from the centre of the body to his extremities so as to increase the skin temperature up to about 36^{o}C, which will increase the heat loss to balance the extra heat generated by the increased level of activity. When the skin temperature reaches 36^{o}C, any further increase in skin temperature will cause hyperthermia; evaporation of sweats becomes the only mechanism to cool the body. In order to simulate the changes in skin temperature induced by the changes in blood flow, the rate of the pumps inside the manikin body was made to be adjustable by altering the frequency of the AC power supply to the pumps using an AC frequency regulator, which was controlled by the voltage of direct current generated by means of PIC 6711 device (a 12-bit digital-to-analog converter (DAC)).

3.3.5 Construction of hardware for the measurement system of the walk-able sweating fabric manikin

In addition to the parts mentioned above, the following elements were included in the measurement system:

(1). There were two heaters that control the temperature of manikin body. The output powers of these heaters were calculated by a PID controller running in the control system and are realized through duty-cycle control of the heater power supply.

(2) There were 4 pumps located inside manikin body. 2 pumps were used to pump water from torso to head and four limbs to simulate the blood circulation in the body; 2 pumps were used to pump water circulation in torso.

(3). There were 2 RTDs that sense the temperature inside the manikin, 15 RTDs for the skin and 2 RTDs for ambient. The core temperature sensors were two PT100 stainless steel probes (conformed to BS1904 and DIN43760 with a continuous temperature range of -50 to +150^{o}C) mounted at the center of the trunk. The skin and environmental temperature sensors were PT100 patch sensors. The temperature sensor was a silicon rubber patch incorporating a PT 100 thin film temperature detector (conformed to BS 1904 & DIN43760, 100Ω at 100^{o}C) with a self-adhesive backing tape and 2m, 4-wire (7/0.2mm tinned copper) PTFE leads. The accuracy of the PT100 stainless steel probes and the PT100 patch sensors was $\pm$0.1^{o}C.

(4). There were 7 Honeywell humidity sensors that sense the humidity of skin or the macroclimate of the clothing and 2 humidity sensors for the ambient. The sensors required a DC power supply of +5V, which was derived from the +5V supply on SC-2042 RTD board. The output of the humidity sensor was a DC 0-5V voltage which is related to the relative humidity by a given formula.

(4). Altogether, this system was able to measure a total of 32 signals from any combination of RTDs and humidity sensors. By default, the following quantities of signals were defined in the software system.

Table 3-3 The definition of signal channel

Channel name	Channel No.	Measurement
T01~T08	0~7	Skin temperatures
T09~T15	16~22	Skin temperatures
H16~H24	23, 32~39	Skin humidity
H25, H26	48, 49	Environment humidity
T27, T28	50, 51	Environment temperature
T29~T30	52, 53	Not used
T31, T32	54, 55	PID control temperatures

(5). Signal conditioning and data acquisition devices. SC-2042-RTD and SSR-OAC-5A from National Instruments were used to perform signal conditioning on the RTD and humidity sensors and the power output control, respectively. PCI-6033E and PCI-6711 from National Instruments served as the data acquisition device.

(6). Earth leakage and power-off protection circuit. They are illustrated in Figure 3-14.

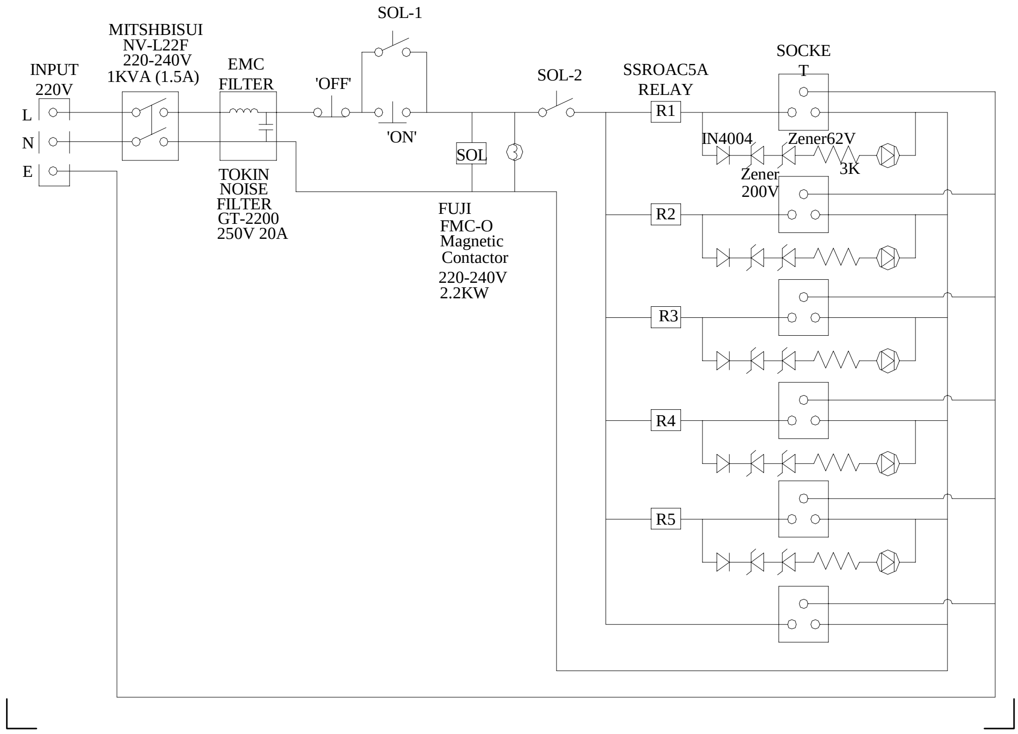


Figure 3-14 Protection circuit

The entire measurement and control system is illustrated as Figure 3-15.

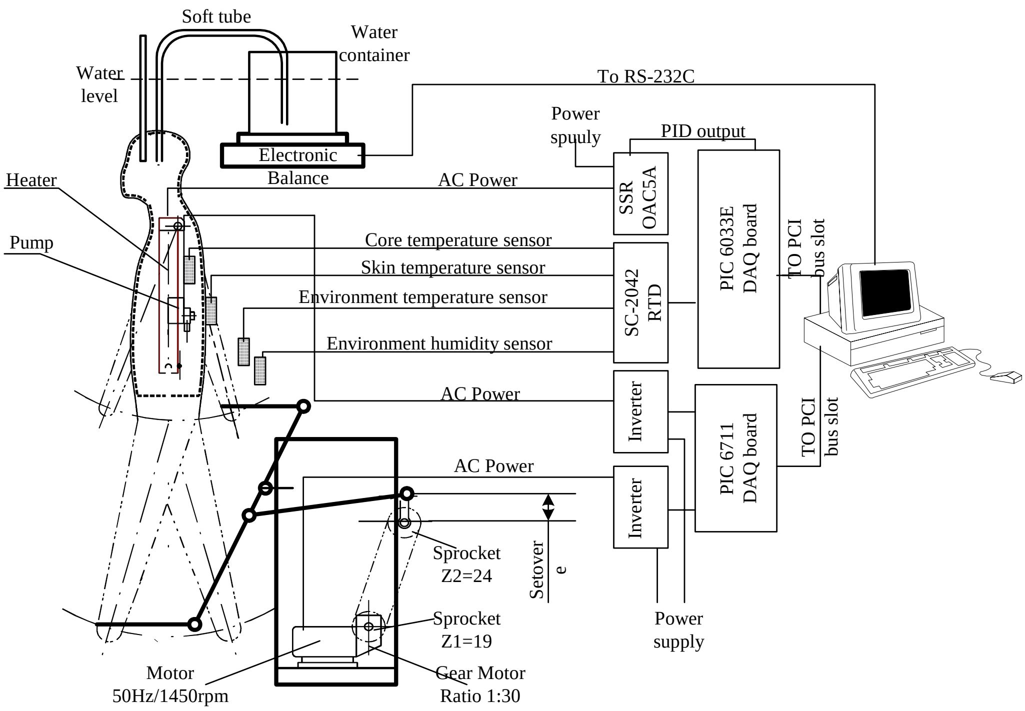
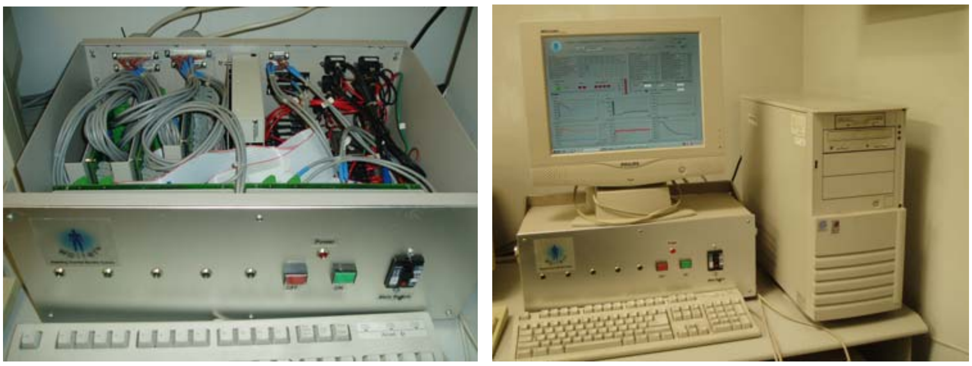


Figure 3-15 The measurement system of walk-able fabric sweating manikin

Figure 3-16 shows the control box and the computer for the control and measurement system.



(a) control box (b) control system

Figure 3-16 The images of the manikin control system

3.4 Software improvement

In order to achieve the above improvements of Walter, software was modified to perform the following functions:

(1). To regulate the AC power supply to the motor which drives the “walking” motion to change “walking” speed.

(2). To regulate the AC power supply to the pumps inside the manikin to change skin temperature.

(3). To measure, filter and display the real-time measurement of water loss.

(4). To enhance the display and user-interface.

(5). To enhance the power supply system to the heaters.

The user-interface of the software is shown as Figure 3-17.

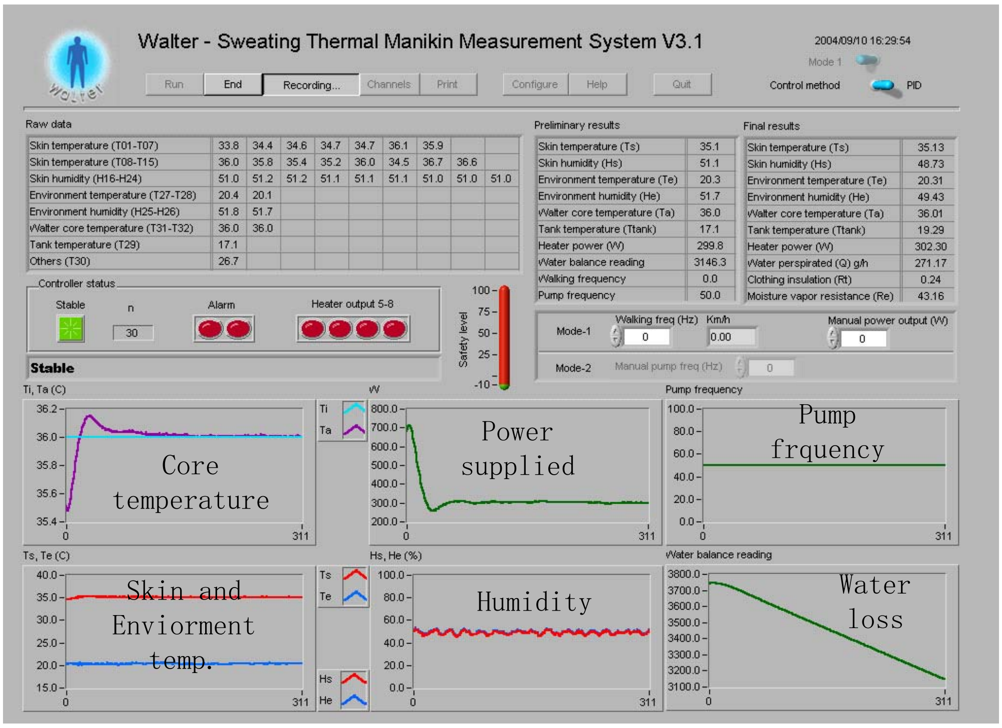


Figure 3-17 Interface of measurement system

3.5 Concluding remarks

A walk-able sweating fabric manikin – Walter has been developed. The manikin can not only simulate "walking" motion for continuous use, but also simulate the blood circulation function of human body. The maximum walking speed can be reached at 3.58 Km per hour, and the pace size of each step can be changed. The manikin can meet the demands of ISO and ASTM standards.

Chapter 4

Calibration of Walter in a Newly Constructed Climate Chamber

4.1 Introduction

As instrument for measuring the thermal parameters, the developed walk-able sweating fabric manikin - Walter had a number of data acquisition channels, such as temperature and humidity sensors, real-time water loss measurement system, power supply measurement system. And the measurement is related to the body surface area of the manikin. In order to get accurate test results, all of these data acquisition channels need to be calibrated in a stable thermal environment, i.e. climate chamber.

4.2 The climate chamber

A climate chamber is not only needed for manikin system calibration, but also essential to experiments. The environmental parameters such as temperature, humidity and wind velocity must be stable in spatio-temporal and can be adjusted.

In the present study, a climate chamber had been constructed to simulate the Hong Kong subtropical climate. It was a cubicle of sizes 9200×3250×2600 mm^3 (L×W×H) which was enveloped with thermal insulation wall. The wall thickness was 100 mm, and it consisted of aluminum plate as covers and polyurethane foam as fillings.

The temperature was achieved with cooling and heating units, the humidity was adjusted by humidifier and dehumidifier. They could be controlled at range of 10~40^{o}C±0.3^{o}C and 30%~80%RH±5%RH, respectively.

There were nine axial fans in the chamber which were evenly arranged in the wind tunnel spatially. The mean wind velocity could be adjusted by speed of the fans and the opening or closing the air return damper. Each fan's speed was controlled by a compact inverter (Tosvert VF-S9). The operation of climate chamber and its environmental conditions were controlled by a customized Netview hardware and software through a Direct Digital Controller (DDC) system as shown in Figure 4-1.

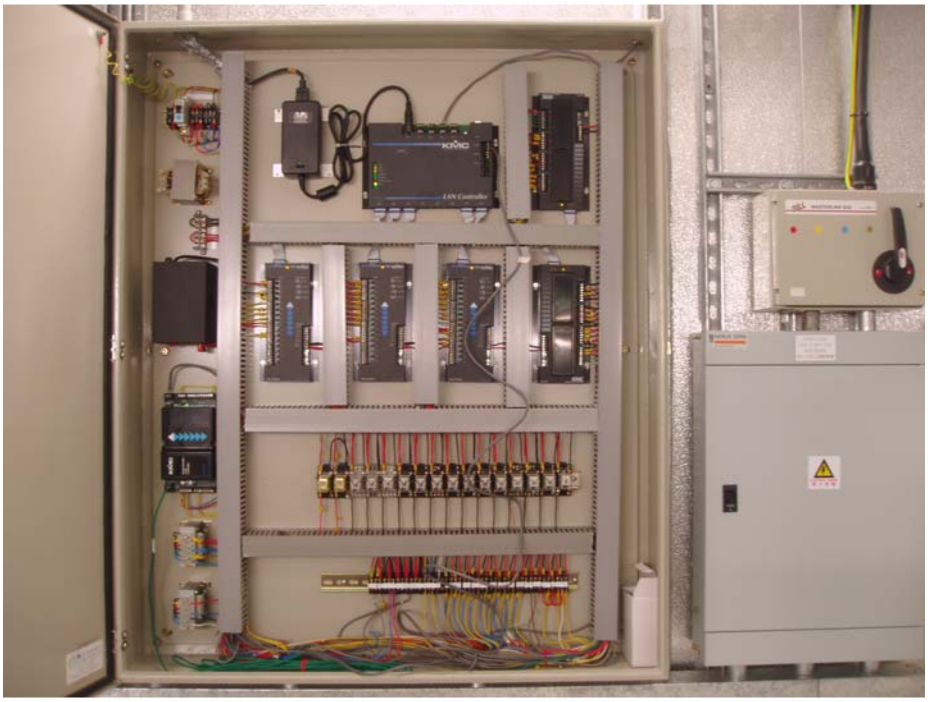


Figure 4-1 DDC system of climate chamber

The design diagram, the image of interior and exterior of the constructed climate chamber are shown in Figure 4-2 (a), (b) and (c), respectively.

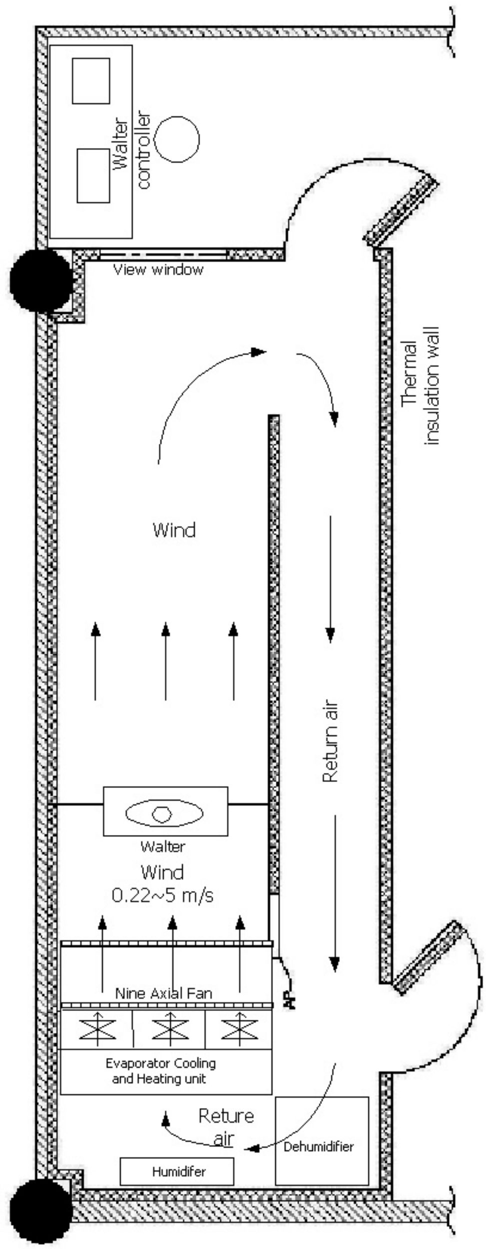


Figure 4-2 (a) The design diagram of climate chamber

Figure 4-2 (b) The image of interior of the climate chamber

Figure 4-2 (c) The image of exterior of the climate chamber

Walter was placed 2.5 meter away from the axial fans in the climate chamber. The wind velocity in the spatial plane, which was 0.5 meter far away from the front of

Walter, was measured. By varying the frequency of the inverter, different wind speeds could be achieved. In each case, the wind speeds at five points in the spatial plane (upper, middle, lower, right and left) were tested in the 3D vector. Each point was tested in three times, and each case was repeated three times to obtain average measurements. The wind velocity was measured by Testo 415 (made in Germany) with the accuracy of ±0.05 m/s (0 to 2 m/s) and ±0.5 m/s (2 to 10 m/s). The results are listed in Table 4-1.

Table 4-1 The wind velocity measured at the spatial plane at 0.5 m far away from the front of Walter in chamber

Inverter Hz	Wind		Return air damper
	mean m/s	S.D.	
10	0.22	0.03	Closed
10	0.85	0.04	Open
20	1.69	0.10	Open
30	2.48	0.09	Open
40	3.12	0.15	Open
50	4.04	0.22	Open

The wind velocity in the clamber is linearly related to the inventor frequency, as it is shown in Figure 4-3.

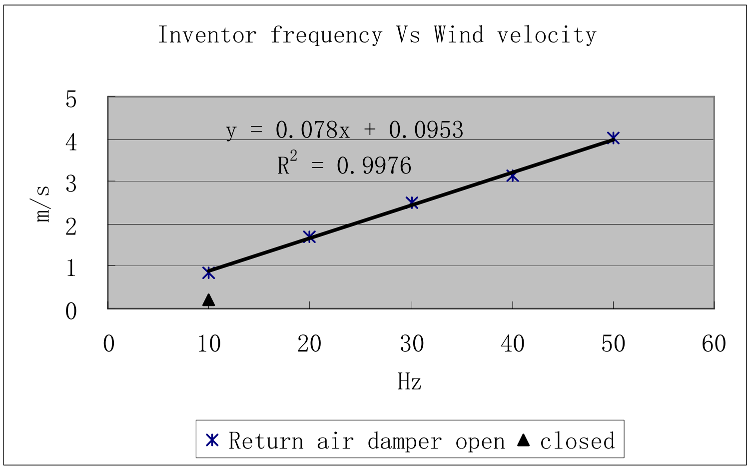


Figure 4-3 The relationship between wind velocity and inverter frequency

The wind velocity and its ranger could be varied from 0.22 m/s ±0.03m/s to 4.04 m/s±0.22m/s.

Under the stable state, the wall temperature of thermal chamber was the same as the environmental air temperature. No radiation source in the chamber except for the manikin body, the radiative heat transfer coefficient from manikin to the air is considered as $h_r=5m^{2o}C/W$ in the surface insulation.

4.3 Calibration on Walter

4.3.1 Skin area and its weighted mean skin temperature

The skin of manikin was made by a waterproof but moisture-permeable fabric. In order to fit the body shape better, the skin fabric was cut out into several parts according to the pattern, as shown in Figure 4-4 (Chen 2002)

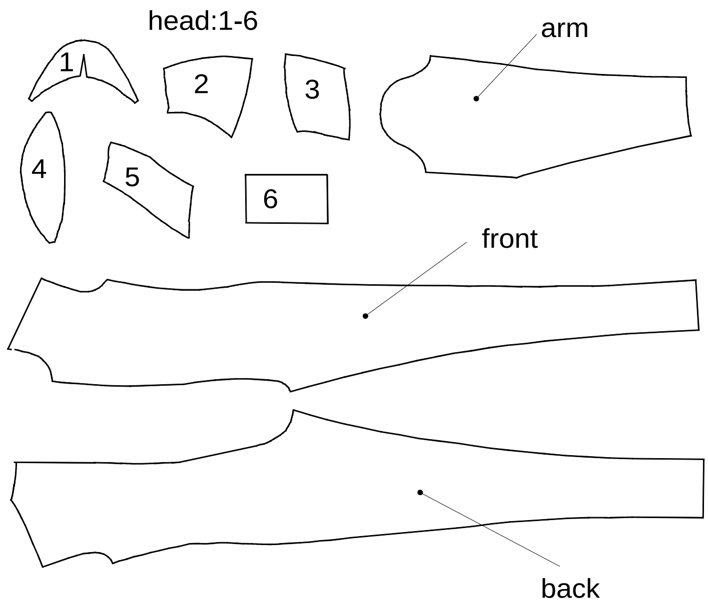


Figure 4-4 The pattern of skin

The skin was sewn using a normal sewing machine and sealed with seam taping. The outer profile of the skin with full water inside is shown in Figure 4-5.

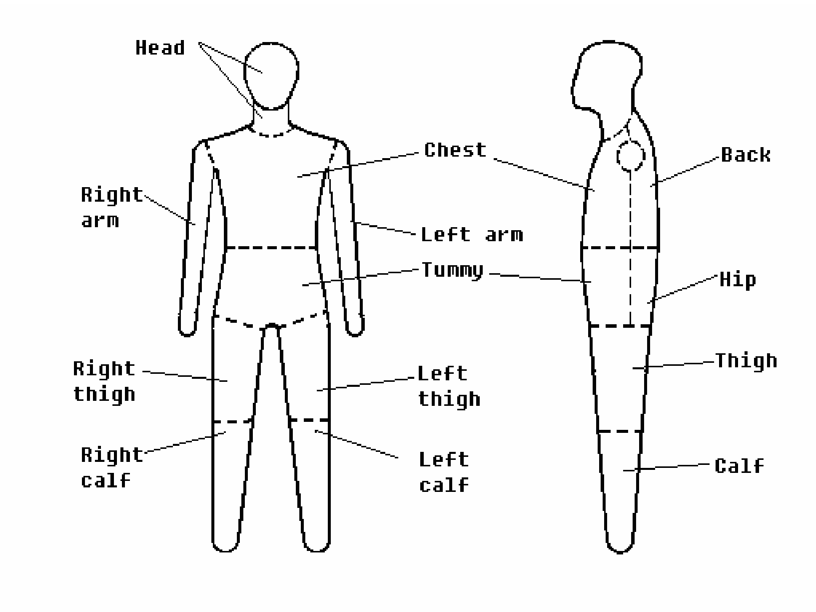


Figure 4-5 Division of the body of manikin

In order to meet the demands of ASTM F1291 and F2360, 15 skin temperature sensors are located on the different parts of skin surface, they were placed on the head, chest, back, tummy, hip, and both the right and left upper arm, lower arm, front thigh, back thigh and calf.

The parts and total surface area of the skin were calculated by the weight of the different parts of skin fabric divided with the specific weight of the skin. With loading of about 70*Kg* water and the skin temperature at 35°C, the surface area of the skin was extended. If we assume each section of manikin as a cylinder, the original girth and the height marked on the manikin surface are l and h respectively, and then the original area is:

$$S_0 = l \times h \tag{4-1}$$

After filled with water at the skin temperature of 35°C, the girth and the height will be increased to *l(1+a%)* and *h(1+b%)*, respectively, and the area would be changed to:

$$S = l(1+a\%)h(1+b\%) = S_0(1+a\%)(1+b\%) \tag{4-2}$$

The surface areas for each part were measured and the surface area ratios for the divided parts were calculated and listed in Table 4-2.

Table 4-2 Surface area ratio of divided sections of the manikin and sensors arrangement

Name of skin parts	Original area m^2	Final area when filled with water at 35^oC (m^2)	Area weighting %	Number of RTD sensor was placed
Head	0.215	0.215	12.00	1
Chest	0.148	0.163	9.12	1
Back	0.155	0.170	9.50	1
Tummy	0.099	0.107	6.01	1
Hip	0.104	0.114	6.37	1
Right upper arm	0.082	0.088	4.93	1
Right lower arm	0.055	0.059	3.30	1
Left upper arm	0.082	0.088	4.93	1
Left lower arm	0.055	0.059	3.30	1
Right thigh	0.23	0.249	13.94	2
Left thigh	0.23	0.249	13.94	2
Right calf	0.105	0.113	6.33	1
Left calf	0.105	0.113	6.33	1
Total	1.665	1.79	100.00	15

The mean values of the “skin” temperature are the area-weighting average of temperature at different parts of the manikin. The area weighted mean skin temperature T_s is therefore:

$$T_s = 0.129T_1 + 0.089T_2 + 0.093T_3 + 0.059T_4 + 0.062T_5 + 0.082(T_6 + T_7) + 0.138(T_8 + T_9) + 0.138(T_{10} + T_{11}) + 0.064(T_{12} + T_{13}) + 0.064(T_{14} + T_{15}) \quad (4\text{-}3)$$

4.3.2 Calibration of temperature and humidity sensors

HIH-3610 humidity sensors and Pt-100 RTD temperature sensors are used to measure the humidity and temperature, respectively. The RTD sensors were embedded in the PTFE protective covers, the reading of sensor could be as much as $2^{o}C$ lower than that from a non-contact infra-red thermometer. The difference was induced by the thermal insulation of the PTFE cover; at the other hand, due to the water evaporate continuously from the skin to the air, the RTD can not be adhered to the skin surface, the RTD reading is lower than infra-red thermometer reading, but this do not mean the accuracy of RTD is lower than that of infra-red thermometer.

All RTD temperature sensors and HIH humidity sensors were therefore calibrated with a HYGROMER series A1 portable thermometer, it has a high accuracy on the measurement of temperature and humidity. The measuring ranges are 5~99.9% for humidity and $-25^{o}C\sim75^{o}C$ for temperature, respectively, the precision at $23^{o}C$ are less than 1.5% for humidity and $0.3^{o}C$ for temperature, respectively. The readings from the temperature sensors and humidity sensors were correlated to the temperature and humidity readings from HYGROMER series A1 portable thermometer in Figure 4-6(a) and Figure 4-6(b), respectively.

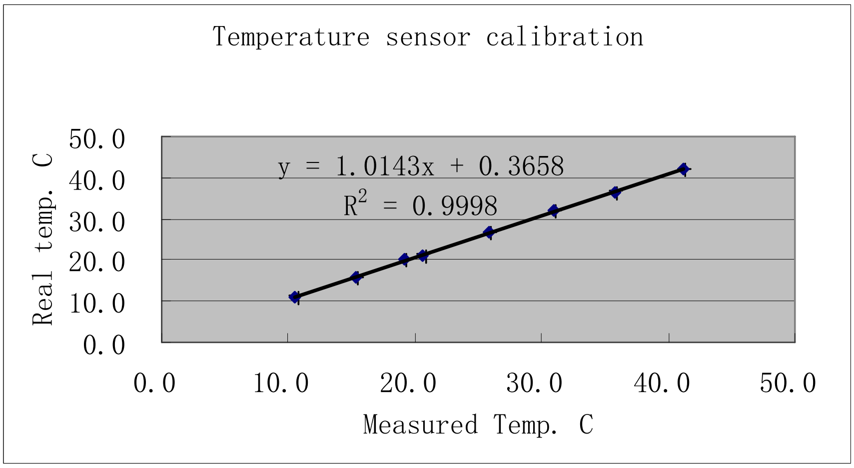


Figure 4-6 (a) Temperature sensor calibration

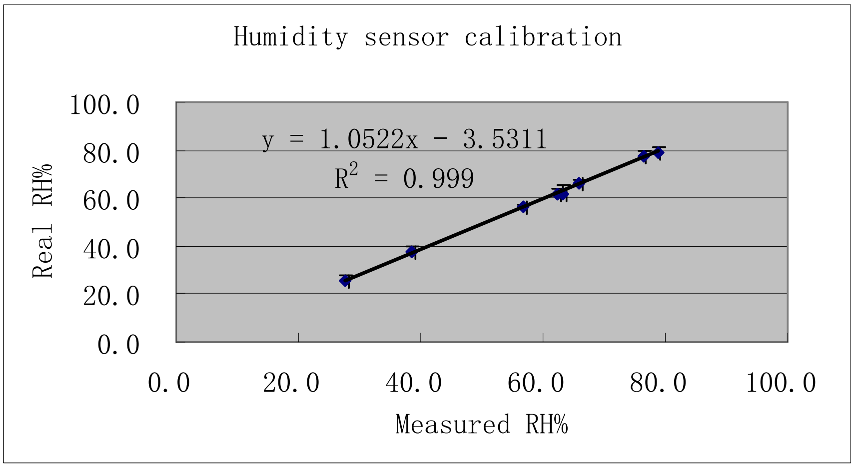


Figure 4-6 (b) Humidity sensor calibration

4.3.3 Measurement of evaporative heat loss H_e

The evaporative heat loss was calculated from the “perspiration rate”- the water loss per unit time by:

$$H_e = \lambda Q \tag{4-4}$$

In order to avoid weighing the heavy manikin directly, a water container was connected to the manikin through a soft tube. By siphon action, the water level in the container was the same as the water level in the manikin. The reduction of water in the container was therefore proportional to the "perspiration rate" of the manikin. We could therefore obtain *Q* from:

$$Q = 3600 \times \Phi \times \frac{\varphi}{\Delta t} \tag{4-5}$$

where, $(\varphi/\Delta t)$ is the rate of water reduction in gram per second in the container which could be determined from two balance readings in a time interval, Φ is a coefficient which could be determined from calibration (see Figure 4-7). During the calibration, a small quantity of water was discharged slowly through the valve at the foot of the manikin; the quantity of the water was then measured and correlated with the reduction of the readings from the electronic balance under the water container. Φ was found to be 1.12.

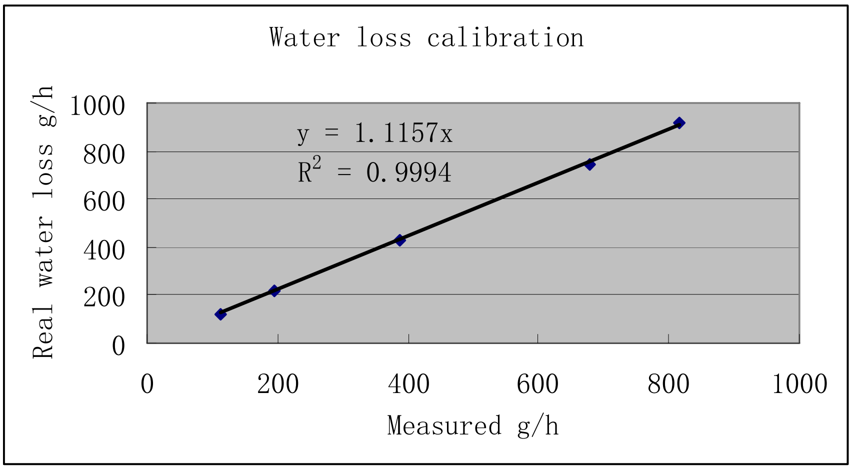


Figure 4-7 The water loss calibration

4.3.4 Heat generated by the heaters H_s

H_s was determined by measuring the power output and the "on" and "off" time of the electric heaters in real time.

$$H_s = \frac{t_{on}}{t_{on} + t_{off}} \times \frac{Volt^2}{R_\Omega} \tag{4-6}$$

The "on" and "off" time was calculated by software automatically. This function of Labview software is shown in Figure 4-8.

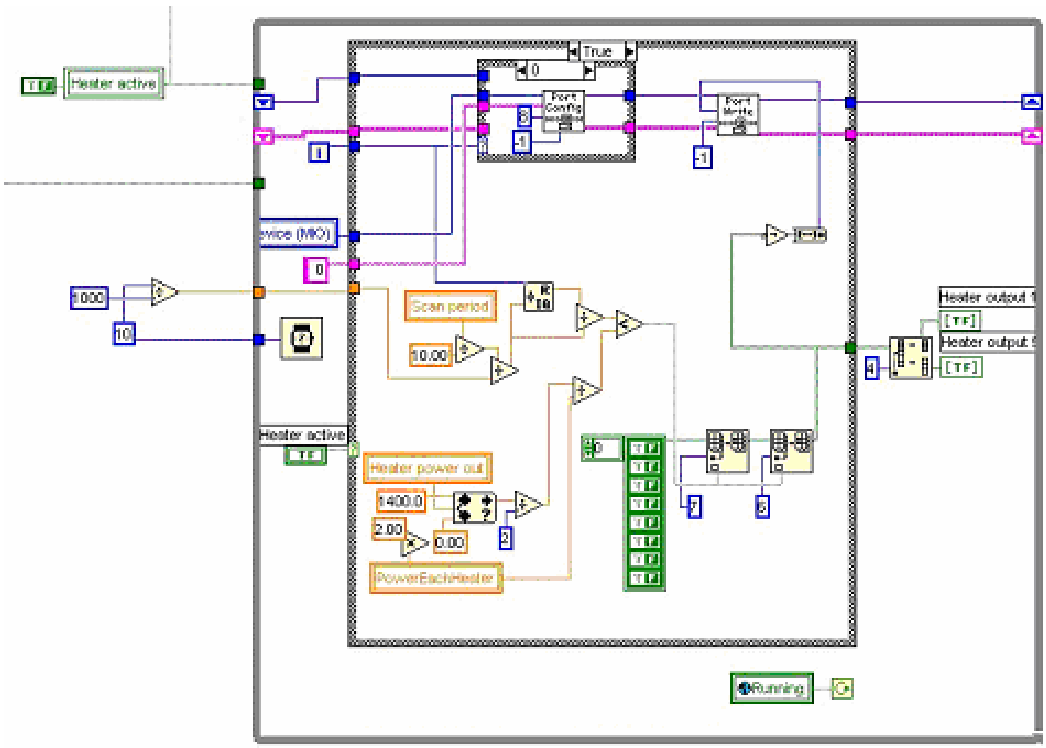


Figure 4-8 Calculation of power supply in software

An output solid state relay (SSR-OAC5A) is used to control power "on" and "off". If it got a logical low signal, the output module turned "on" and the current flowed; if it got a logical high signal, the output module turned off. The electricity voltage should be stable enough. A STAVOL automatic voltage regulator was selected for this purpose, its output voltage could be controlled in 220±3%, this variation in voltage would result in a ±6% uncertainly in power.

4.3.5 Heat generated by the pumps H_p

There were four pumps inside the manikin, two for pumping the warm water to the head and the limbs and two for the water circulation around the trunk of the body. The power supplied to pumps however also generated heat, but it does not completely convert to heat. Some power supplied to pumps will dissipate as vibration and sound foam. In order to determine the heat generated by the pumps, the mean skin temperature of the manikin was controlled to be the same as the environmental temperature. Under such condition, the sum of the heat generated by the heaters and the pumps were balanced by the evaporative heat loss. By measuring the evaporative water loss or “perspiration rate” and heat generated by the heaters, the heat generated by the pumps could therefore be calculated. By this method, the heat generated by the pumps H_p was determined to be 18.7 Watts.

4.3.6 Energy required heating the supplied water from water container to achieve the core temperature of manikin H_a

When the manikin is in operation, fresh water is added into the manikin from the water container to the manikin automatically and continuously by the siphon action. Due to the difference in the temperature of the water in the container and that in the manikin, some energy was consumed to heat the added water to the manikins' body temperature. This power was calculated by:

$$H_a = c_{pw}(T_c - T_e)\frac{Q}{\Phi}/3600 \qquad W \qquad (4\text{-}7)$$

where, Q/Φ is the rate of water supplied to the manikin from the water container.

4.3.7 Moisture vapour resistance of the skin R_{es}

Walter used Gore-Tex breathable laminated fabrics as its skin. Gore-Tex laminates are combinations of various fabrics with a micro-porous polytetrafluoroethylene (PTFE) Gore-Tex film (Tanner, et al 1979). This film is expanded to produce pore volumes of 82% and produces about 9 billion pore per square inch. The largest pore in the film is about 0.2um (2×10^{-7} m), which is actually about 700 times larger than the water vapor molecular. Liquid water on the other hand, because of free energy considerations, has tens of thousands of these molecules bonded together. Thus GORE-TEX fabric can keep water in the manikin body, but to allow moisture transmission through the "skin" to generate gaseous "perspiration". Due to the body shape, some parts of skin surface such as back and under arm are not directly exposed to the wind, the "value" of the skin moisture vapour resistance should be determined at the real conditions.

The total moisture vapour resistance of the nude sweating manikin is the sum of surface moisture vapour resistance and the moisture vapour resistance of the skin. The surface moisture vapour resistance R_{oa} is related to the air convection on the skin surface, so it will reduce with increasing wind velocity and approaches to zero at extremely high wind velocity, whereas the moisture vapour resistance of the skin R_{es} remains unchanged with increasing wind velocity. According to Kerslake's (1972) empirical formula and the work by Lotens and Havenith (1991), and consider moisture transfer is analogous to heat transfer, the surface convective moisture transfer can be assumed to be proportional to the square root of air velocity. We therefore have:

$$R_t = R_a + R_{es} = \frac{1}{A \times 8.3\sqrt{(V_0 + V_{wind})}} + R_{es} \qquad (4\text{-}8)$$

where, *A is* contant and V_0 is the equivalent air velocity due to natural convection, it equals to 0.11 m/s (Havenith,1990a). R_{es} can be determined by non-linear regression using the R_t measured at various wind velocities. The results of the experimental measurements are listed in Table 4-3.

Table 4-3 The experimental results for determination of the skin moisture vapour resistance

V_{wind} *m/s*	0.22	0.85	1.69	2.48	3.12	4.04
R_t	21.5	17.22	14.46	13.21	12.79	11.89
Stdv	0.32	0.13	0.11	0.01	0.01	0.01

From the experimental measurements listed in Table 4-3, we can obtain

$$R_t = R_a + R_{es} = \frac{1}{0.0158 \times 8.3\sqrt{(0.11 + V_{wind})}} + 8.6 \qquad (4\text{-}9)$$

The percentage of fit of Equation (4-9) is very high with a squared correlation coefficient of 0.98. From Equation (4-9), we therefore have $R_{es} = 8.6$ pam^2/W.

The value of the constant A=0.0158 is very close to the theoretical Lewis constant ($L_R=0.0165^oC/p_a$), that is to say Lewis relation applies on the surface moisture vapour resistance of nude manikin under varying wind velocity at 20^{o}C and 50%RH.

Therefore, with this manikin, the total thermal insulation I_t and the total moisture vapour resistance R_t of garment can be measured and calculated by the following equations:

$$I_t = \frac{A_s \cdot (T_s - T_a)}{H_d} \quad (\text{Km}^2/\text{W}) \qquad (4\text{-}10)$$

$$H_d = H_s + H_p - H_e - H_a \qquad (4\text{-}11)$$

In the present study, the inner surface humidity of skin was used to calculate the moisture vapour resistance instead of the outer surface humidity of skin, the value of inner surface humidity of skin is equal to 100%, due to it is in contact with water. So the moisture vapour resistance calculated include the resistance value of skin, this part should be subtracted from the result.

$$R_t = \frac{A_s \cdot (p_{ss} - p_{as} RH_a)}{H_e} - R_{es} \quad (\mathrm{P_a\ m^2/w}) \tag{4-12}$$

4.4 PID controller parameters

A PID controller was used to control the process variable by calculating the heating power needed to maintain a constant body temperature of manikin, it is a closed-loop control system. In the present study, the process variable to be controlled is T_v

$$T_v = a \cdot \overline{T}_c + (1-a) \cdot \overline{T}_s \tag{4-13}$$

where, T_v is the process variable, $\overline{T}_c$ is mean body core temperature, $\overline{T}_s$ is mean "skin" temperature, a is a coefficient, $0 \le a \le 1$. When $a = 1$, the set temperature is fully determined by the core temperature, and when $a = 0$, the set temperature is fully decided by the "skin" temperature. The process variable is compared with the set point (i.e. the required temperature) to obtain an error:

$$e = T_{sp} - T_v \tag{4-14}$$

where, e is the error between the T_{sp} and T_v, T_{sp} the set point of the required temperature, T_v the process variable to be controlled.

The output of the controller can be determined theoretically based on the PID (Proportion-Integral-Derivative) model as follows:

$$u(t) = \frac{100}{PB}\left(e + \frac{1}{T_i} \cdot \int_0^t e \cdot dt + T_d \cdot \frac{de}{dt}\right) \tag{4-15}$$

Where, *u(t)* is the output of the controller; *PB* is the proportional band of the controller, $\frac{100}{PB}$ is the controller gain, T_i is the integral time in minutes (also called reset time); and T_d is the derivative time in minutes (also called rate).

The performance of PID controller is related to the PID parameters (proportional band *PB*, integral time T_i and derivative time T_d), which are dependent on the properties of the control object.

PB, T_i and T_d can be determined, according to the optimum setting method for automatic controllers (Ziegler, J.G. and N.B.Nichols, 1942), by using the turning formulae listed in Table 4-4.

Table 4-4 Tuning formulae

Loop performance	Controller	*PB* Proportional	T_i integral minutes	T_d derivative minutes
Fast adjustment (1/4 damping ratio)	P	$2.00PB_u$		
	PI	$2.22PB_u$	$0.83T_u$	
	PID	$1.67PB_u$	$0.5T_u$	$0.125T_u$
Normal adjustment (some overshoot)	P	$5.00PB_u$		
	PI	$5.56PB_u$	$0.83T_u$	
	PID	$4PB_u$	$0.5T_u$	$0.125T_u$

In Table 4-4, PB_u and T_u are the feature parameters of the control object, which can be determined experimentally. In the experiment, the PID controller with integral time T_i and derivative time T_d being set to zero (the PID controller becoming a P controller) was used to control the temperature. The values of PB_u and T_u could be found by an iterate procedures. A PB value of the controller was first selected; then changes of *PB* were made carefully and iteratively until an oscillation of the control variable (i.e. temperature) and the control output (i.e. power output) become constant, viz. neither growing nor decaying over time. The value of *PB* which makes the constant oscillation of the control variable and control output is the value of PB_u for the control body, and the time period of the oscillation is the T_u.

For the sweating manikin (see Figure 4-9), the feature parameters PB_u and T_u were found to be 0.04 and 23 minutes, respectively. For the non-sweating manikin (see Figure 4-10), the feature parameters PB_u and T_u were found to be 0.14 and 70 minutes, respectively.

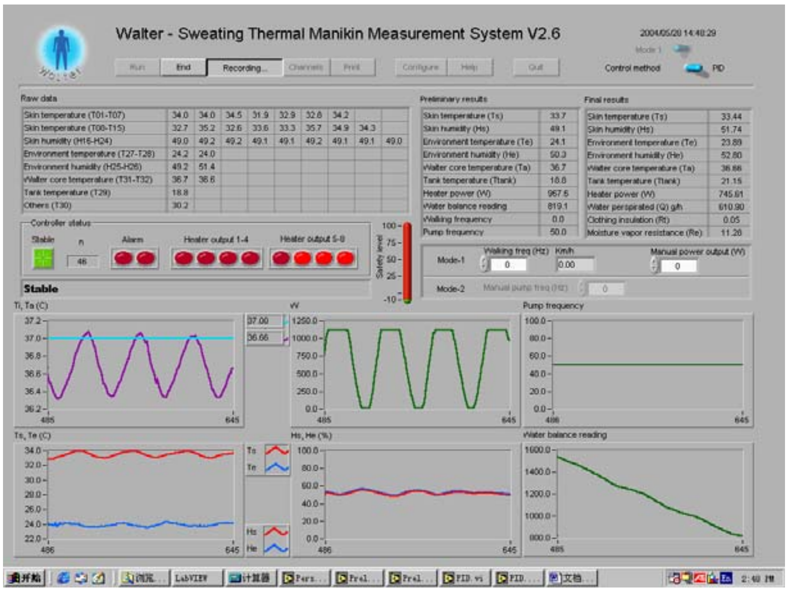


Figure 4-9 The determination of critical gain PB_u and the oscillation period T_u on the sweating skin manikin system

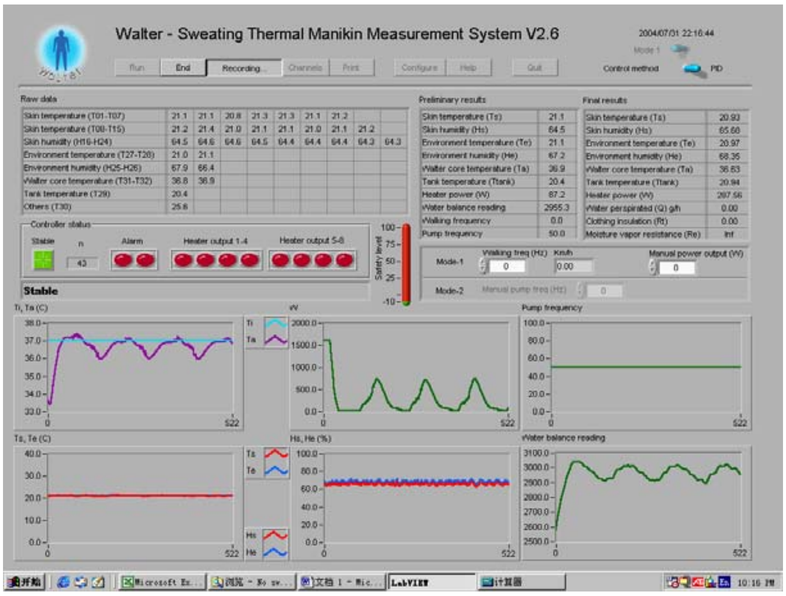


Figure 4-10 The determination of critical gain PB_u and the oscillation period T_u on the non-sweating skin manikin system

Based on these results, a very high accurate and efficient PID controller was achieved. The respond of controller was very fast (see Figure 4-11) and its control precision can be reached to 37±0.05 °C degree (see Figure 4-12).

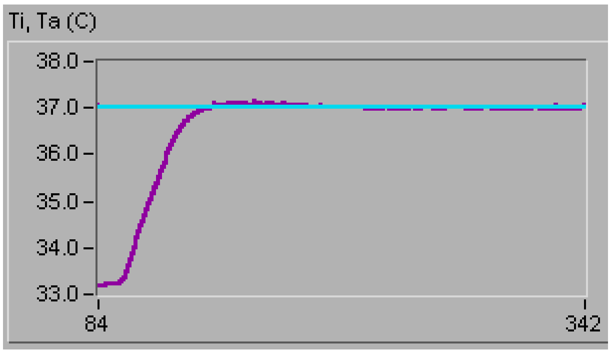


Figure 4-11 The performance of PID controller at large error between set-point and core temperature.

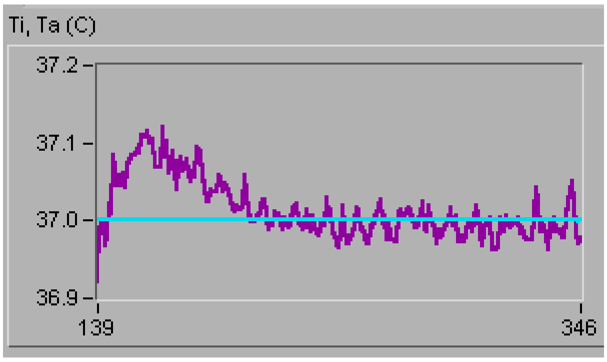


Figure 4-12 The performance of PID controller at stable states

The power output was controlled by a duty cycle control method. This means the duty cycle for the power supply to the heaters is linearly related to the PID controller's output. If the output is 20%, for example, in a adjusting periods of PID output loop, heaters are turned on 20% of the time of the output loop. There were two heaters in the trunk of the manikin operated by AC power, each was of maximum 798.5W and the total was 1597W. The heaters were switched on/off by two respective SSRs (solid state delay), which were controlled by the output of the PID controller.

4.5 The thermal performance of Walter

One of the advantages of the manikin is that it can simulate human temperature regulation. Human body always controls his core temperature constant whereas the skin temperature may change according to the surrounding conditions in which he belongs to. Walter's skin temperature can vary depending on the environmental conditions or can be controlled at a constant value.

In the case of constant skin temperature of 35°C, the core temperature varies from 38°C to 40.9°C, when the wind velocity changed from 0.22m/s to 4.4 m/s (see Figure 4-13 (a)). In the case of constant core temperature at 38°C in which the skin temperature was 35°C (see Figure 4-13 (b)) when manikin was standing in still air (it could be adjust to 37°C by the change of the position of temperature sensors inside the body), the skin temperature varied from 35°C to 32.7°C when the wind velocity changed from 0 m/s to 4.4 m/s. This is very close to the response of human body (Physiologically, a human being is regarded as feeling comfortable when his skin temperature is between 33 ~ 35°C and there is no deposition of liquid sweat on the skin.)

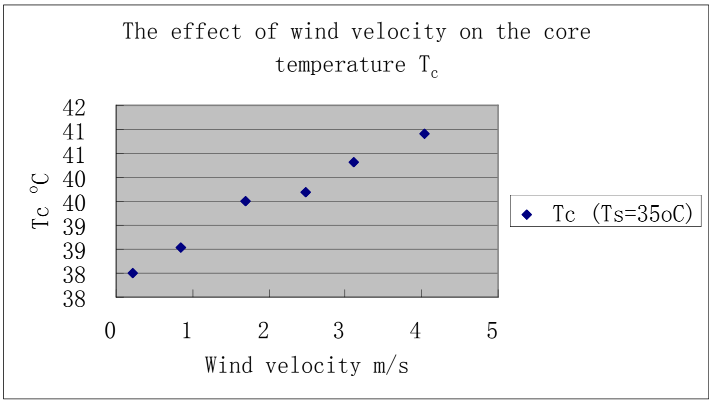


Figure 4-13 (a) The core temperature vs. wind velocity

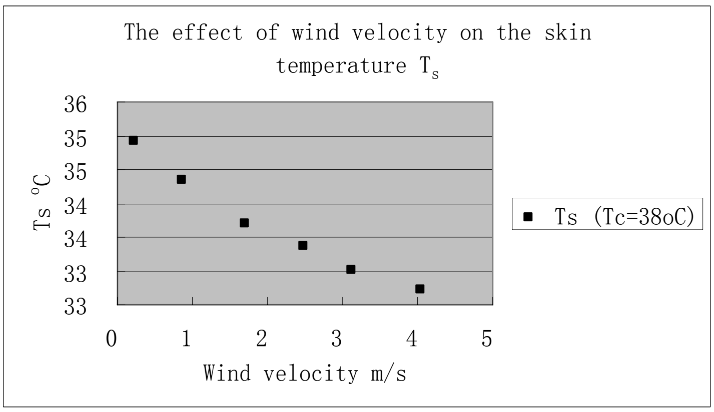


Figure 4-13 (b) The skin temperature vs. wind velocity

Under these two cases, the power supplied to the manikin and evaporative rate of manikin are plotted in Figure 4-14 (a) and (b) for comparison. It can be seen that the manikin has the thermal performances similar to a human body under these situations.

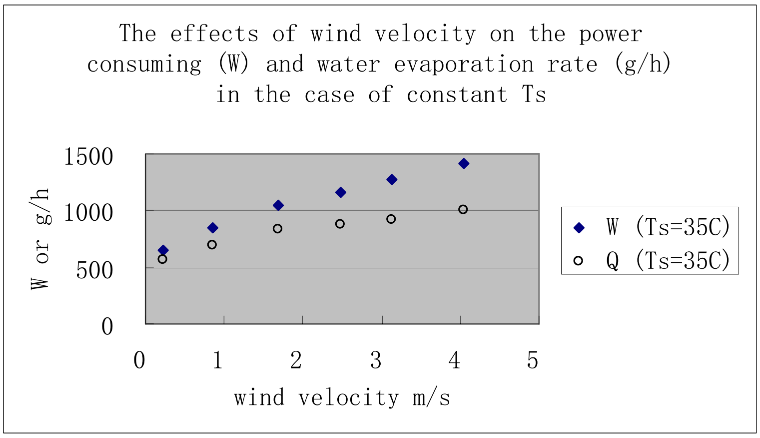


Figure 4-14 (a) Thermal performances of the manikin under constant T_s

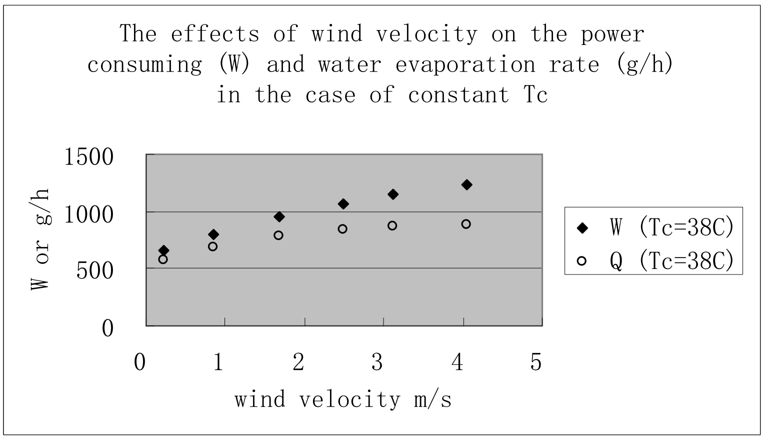


Figure 4-14 (b) Thermal performances of the manikin under constant T_c

Furthermore, it can be seen from Figure 4-15 (a) and (b) that there are litter differences on the thermal insulation and the moisture vapor resistance of the surface air layer on the nude manikin measured under these two control situations.

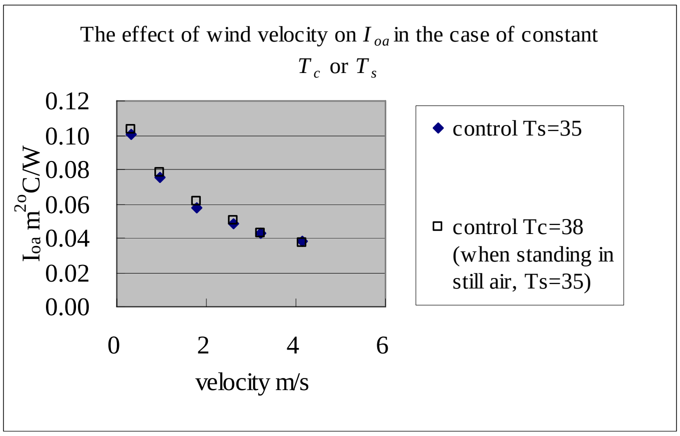


Figure 4-15 (a) The effect of wind velocity on I_{oa} in the case of constant T_c or T_s

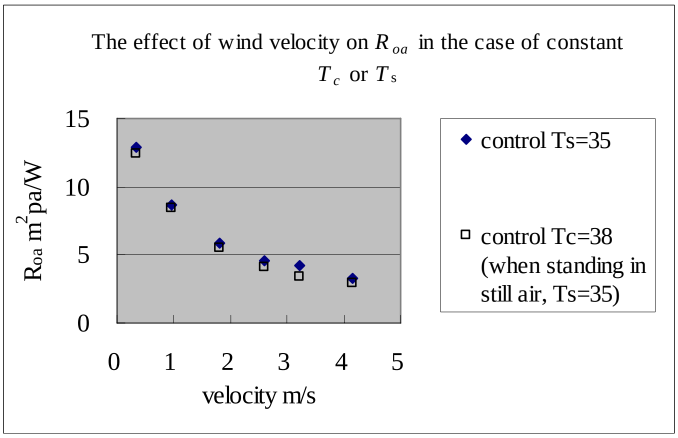


Figure 4-15 (b) The effect of wind velocity on R_{oa} in the case of constant T_c or T_s

The manikin can simulate the blood circulation of human body by regulating the AC power frequency supplied to the pumps inside the body. When the skin temperature is increased by increasing the pumping rate, the rate of "perspiration" is also increased as a result of the increased difference in water vapor pressure between the skin surface and the environment. The regulation of the skin temperature and the rate of "perspiration" is a unique feature of Walter.

The flow rate of the pumps was experimentally measured. It was found to be linearly related to the frequency of the AC power supplied to the pumps, as shown in Figure 4-16. The total heat loss and water loss were also found to be linearly related to the frequency of the AC power supply to the pumps, (see Figure 4-17). The changes of the manikin's skin temperature with the frequency of the AC power supply are shown in Figure 4-18. It's a second order polynomial relation.

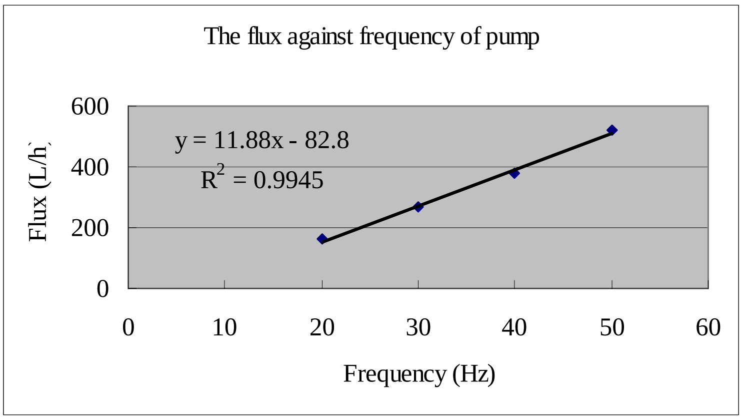


Figure 4-16 Flow rate of the pump vs. the frequency of AC power supplied to the pump

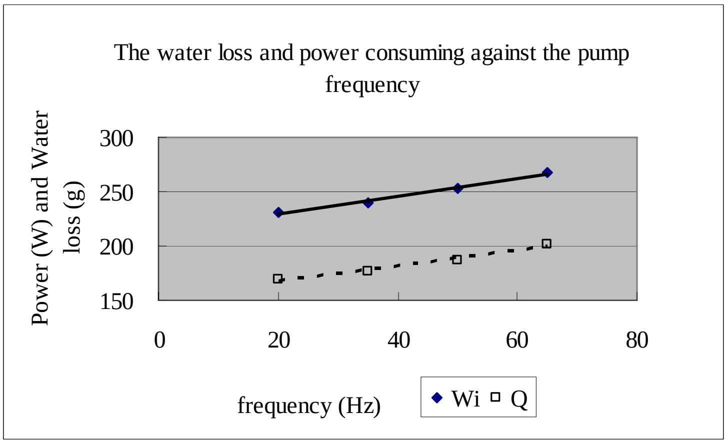


Figure 4-17 Water loss and total heat loss vs. the frequency of AC supplied to the pumps

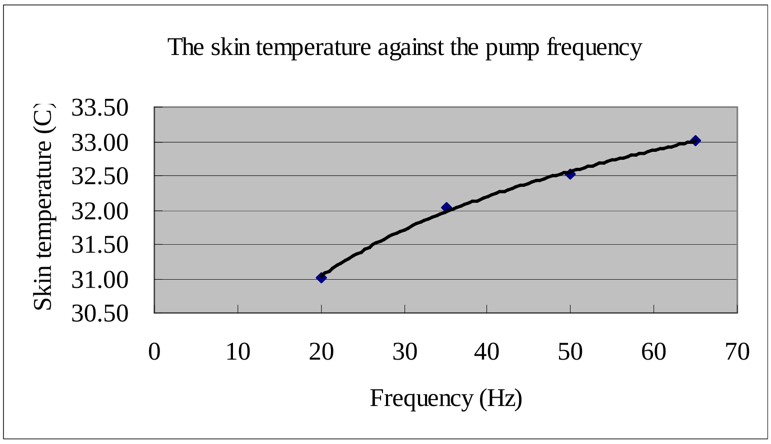


Figure 4-18 Skin temperature changes with the frequency of AC power supplied to the pumps

4.6 The accuracy and reproducibility of Walter

The surface thermal insulation and moisture vapor resistance of the nude manikin were tested repeatedly for three times in different wind velocity under 20^{o}C and 50% RH. The mean values are listed in Table 4-5(a) and the standard deviations of each value are listed in Table 4-5(b).

Table 4-5 (a) The mean values of I_{oa} and R_{oa} vary with wind velocity

V_{wind} m/s	T_s	T_e	H_e	W	Q	I_{oa}	R_{oa}
0.22	35.04	20.32	46.76	649.90	562.59	0.101	12.90
0.85	34.91	19.75	48.25	842.95	697.00	0.076	8.62
1.69	34.96	19.83	47.68	1046.46	833.76	0.058	5.86
2.48	34.82	19.89	53.87	1157.64	874.55	0.049	4.61
3.12	34.89	19.79	52.24	1271.96	916.97	0.043	4.19
4.04	34.94	19.84	49.33	1415.32	1004.19	0.038	3.29

Table 4-5 (b) The standard deviation of I_{oa} and R_{oa} measured on manikin

V_{wind} m/s	T_s	T_e	H_e	W	Q	I_{oa}	R_{oa}
0.22	0.02	0.01	0.50	4.71	6.63	0.003	0.32
0.85	0.01	0.02	0.10	1.88	5.43	0.001	0.13
1.69	0.01	0.17	0.35	0.01	6.18	0.001	0.11
2.48	0.05	0.03	0.02	18.28	3.48	0.001	0.01
3.12	0.02	0.01	0.41	10.32	5.67	$\rightarrow 0$	0.01
4.04	0.01	0.01	0.51	1.56	6.87	$\rightarrow 0$	0.01

The average thermal insulation in the case of standing in still air was found to be 0.101 °Cm^2/W with a standard deviation of 0.003, the average moisture vapor resistance of nude manikin was 12.90 Pam^2/W with a standard deviation of 0.32. These results show that the accuracy of Walter is very high.

A clothing ensemble including underwear and outer wear was used to validate the reproducibility. The ensemble was tested three times. In each independent replication, the garments were taken off and put them back on for testing. The test results are listed in Table 4-6. It can be seen that the standard deviations are generally small with a CV value of 3.3% for I_t and 2.3% for R_t.

Table 4-6 The reproducibility of measurement on manikin

	T_s	T_e	H_e	W	Q	I_t	R_e
Repeat1	35.14	20.31	49.22	314.5	279.7	0.218	34.06
Repeat2	35.01	20.38	49.25	318.5	277.9	0.206	33.89
Repeat3	35.13	20.31	49.43	315.3	271.2	0.206	35.32
mean	35.09	20.33	49.30	316.12	276.27	0.210	34.42
Std.	0.07	0.04	0.12	2.14	4.50	0.007	0.78
CV%	0.2	0.2	0.2	0.7	1.6	3.3	2.3

In Table 4-6, Std. is the standard deviation and CV% is the coefficient of the standard deviation.

4.7 Concluding remarks

In the present work, a new climate chamber had been constructed to simulate the Hong Kong subtropical climate. The temperature, humidity in the climate chamber can be controlled at a range of 10~40°C±0.3°C and 30%~80%RH±5%RH respectively, and the wind velocity inside could be changed from 0.22 m/s ±0.03m/s to 4.04 m/s±0.22m/s.

The novel manikin measurement system had been calibrated in the climate chamber. With this calibration, the average surface thermal insulation of the nude manikin out of three independent measurements in the case of standing in still air was found to be 0.101 °Cm^2/W with a standard deviation of 0.003; the average surface moisture vapor resistance of nude manikin was found to be 12.90 Pam^2/W with a standard deviation of 0.32. These results show that the reproducibility of measurement on Walter is very high.

A clothing ensemble including underwear and outwear was used to validate the reproducibility. It was shown that the coefficients of variations of three independent measurements were only 3.3% for the clothing thermal insulation I_t and just 2.2% for the clothing moisture vapour resistance R_t. It can be concluded that the reproducibility of the measurements on Walter is very high.

The experimental work reported in this Chapter has also shown that the improved manikin – Walter has a thermal performance similar to that of a human body in terms of the regulation of the skin temperature and the rate of "perspiration" is a unique feature of Walter; no other sweating manikin can perform this function.

Chapter 5

Surface Thermal Insulation and Moisture Vapour Resistance under Varying Environmental Conditions and Walking Speeds

5.1 Introduction

Surface thermal insulation and moisture vapour resistance of human body are important parameters for predicting thermal comfort. While surface thermal insulation had been determined by experiments using human subjects or dry manikins (Fan and Keighley 1991, Olesen 1982), the surface moisture vapour resistance was largely estimated from surface thermal insulation based on Lewis relation. Such estimation was not validated by direct experimental measurements. Furthermore, the interactions of heat and moisture transfer at the surface of human body under varying environmental conditions and body motions have not been investigated. In this study, the "walk-able" sweating fabric manikin – WALTER developed in the project (Fan and Qian 2004) was used to directly measure the surface thermal insulation and moisture vapour resistance simultaneously under various environmental conditions and "walking" motion. The relationship between the surface insulation and moisture vapour resistance under varying conditions are investigated.

5.2 Related past work

The heat and mass transfer through the air layer of the outer surface of human body plays a very important role on the thermal comfort, heat and cold-stress analysis. The surface thermal insulation and moisture vapour resistance are essential input datum for the thermal comfort prediction models developed recently (Havenith 1990a, 1990b, 1999; ISO 7933; ISO 9920; Holmer 1999; Lotens and Havenith 1991; McCullough et al 1985, 1989; Parsons et. al 1999).

The heat loss from the skin of a nude body to the environment is predominantly transferred by convection, radiation and evaporative heat loss (The conductive heat transfer coefficient of 2.59×10^{-2} *W/mK* of still air at 20°C is relatively small). The convective heat loss from the surface of human body was studied by Winslow et al (1936) as early as 1930s. Since then, many researchers had worked on the field and investigated convective heat transfer under different conditions as well as for different parts of human body. Critical tabulations and comparisons of the findings were made by Mochida (1977), McIntyre (1980) and Holmer et al (1999).

Kerslake's (1972) empirical formula,

$$h_c = 8.3\sqrt{V_0 + W_{wind}} \qquad (V_{wind} > 0.2m/s) \qquad (5\text{-}1)$$

is widely considered as the best practical estimation. This expression is close to that measured on the human subjects by Fount et al (1970), Nelson et al (1947) and Havenith et al. (1990a), and a model developed by Lotens and Havenith (1991) based on this expression showed good prediction on the clothing insulation and moisture vapour resistance.

When a clothed person is in activity in a windy condition, the effect of body movement should be considered. Givoni and Goldman (1972) suggested using an equivalent air velocity V_{eff} corrected by body metabolic rate, which corresponds to the body activity level, to take into account the combined effects of wind and body motion. After analyzing the thermal insulation data measured on human subjects by Havenith (1990a), Lotens and Havenith (1991) redefined the equivalent air velocity V_{eff} and proposed to use V_{eff} instead of air velocity for predicting the surface thermal insulation for a man walking in windy conditions. V_{eff} was re-defined as:

$$V_{eff} = 0.11 + V_{wind} + \beta \cdot V_{walk} \qquad (\beta = 0.67 \text{ for walking}) \qquad (5\text{-}2)$$

where, β is an equivalent air velocity for "walking" motion on the surface insulation and moisture vapour resistance of clothing. β is less than unity partly because the trunk of the human body is relatively immobile during walking and partly because walking motion is intermittent.

As for the radiative heat transfer coefficient h_r, it has also been investigated by a number of investigators (Cain and Farnworth 1986; Fanger 1970; Gagge and Nishi 1977). The radiative heat transfer coefficient h_r is dependent on the temperature and emission coefficients of clothing surface. The typical value of

h_r is 4.5~5 W/m^{2o}C (ASHRAE 1989; Lotens and Havenith 1991; McCullough et al 1985, 1989).

The inverse of the heat transfer coefficient through the surface air layer is defined as the surface insulation.

$$I_{oa} = \frac{1}{h_r + h_c} \qquad (5\text{-}3)$$

Substitute Equations (5-1) and (5-2) into (5-3), and let h_r be 5 W/m^{2o}C, we have:

$$I_{oa} = \frac{1}{5 + 8.3\sqrt{0.11 + V_{wind} + \beta V_{walk}}} \qquad (5\text{-}4)$$

The surface thermal insulation I_{oa} in “still” air (i.e. when no apparent wind exists) is related to natural convection induced by the gradient of temperature and mass near to the surface. Apart from the critical effect of air movement, environmental temperature was found to have considerable effect. Fan and Keighley (1991) reported that the surface insulation in “still” air decreases 25% with the environment temperature reducing from 20^{o}C to -20^{o}C. On the other hand, environmental humidity (Meinander et al 2003), and the size and shape of the body (Kuklane 2004) was found to have little effect on the surface insulation. Due to the variations in the so called “still” air conditions, this value varies in the literature. Some typical values of I_a in still air are 0.112 m^2K/W (McCullough 1989), 0.129 m^2K/W (Havenith 1990a), or 0.136 m^2K/W (Nielsen et al 1985), 1/9

m^2K/W (Parsosns et al 1999), 0.085 m^2K/W (Nisson et al 2000). Lotens and Havenith (1991) suggested the value of these resistances should be standardized.

The moisture vapor resistance R_{oa} is defined as:

$$R_{oa} = h_e A_s (p_s - p_a) = \frac{A_s (p_s - p_a)}{H_e} \quad (5\text{-}5)$$

The evaporative heat loss from the human body can be determined by the sublimation method (e.g. using naphthalene) (Nishi and Gagge 1970) or direct colorimetry method (Winslow 1936; Mitchell et al 1969). Based on the ideal gas law, Holmer and Elnas (1981), employing an oxygen analyzer associated with partitional calorimetry method, simultaneously measured the thermal insulation and moisture vapor resistance of clothing on human subjects. They have also used the method to determine the moisture vapor resistance of air layer adjacent to the skin, but unfortunately no such data was reported.

Sweating manikins have been used to measure the surface moisture vapour resistance. After comparing the testing results from sweating manikins located in different laboratories in the world, it was found that the value of the surface moisture vapour resistance of the air layer around the nude manikins ranged from 11 to 20 m^2p_a/W (McClough 2001). This large difference may be partially caused by the difficulty in determining the partial vapor pressure at the skin surface accurately. Although there are humidity sensors which can have a very high accuracy in measuring the humidity of an environment, their measurements of the humidity of a surface air layer is not accurate as the measurements are significantly affected by the distance between the humidity sensor and the surface as well as dependent on which side of sensor was against the surface, the deference being as much as 20% *RH* (Fan and Chen 2002).

Due to the complexity and high cost of actual measurements of surface moisture vapor resistance as well as the difficulty in achieving a good accuracy, there is a great lack of such data in the literature, especially for human subjects undertaking activities in windy conditions. Practically, surface moisture vapour resistance is therefore estimated from the surface thermal insulation according to Lewis relation (ISO 11079; ISO 9920; ISO 7933; Havenith 1990b; Lotens and Havenith 1991; McCullough 1998).

Lewis relation can be expressed in different forms:

$$h_c = 0.913\rho C_{pa} h_m \cong \rho C_{pa} h_m \tag{5-6}$$

$$h_e = L_R h_c = 2.34 h_c \qquad L_R = 2.34 ^oCm^3/g \tag{5-7}$$

$$h_e = L_R h_c = 0.0165 h_c \qquad L_R = 0.0165 ^oC/p_a \tag{5-8}$$

$$\frac{I_t}{R_t} = L_R i_m = 0.0165 i_m \qquad or \qquad i_m = 60.6 \times \frac{I_t}{R_t} \tag{5-9}$$

$$R = \frac{1}{L_R k} d = 2.33 \times 10^3 \times d \qquad (5\text{-}10)$$

where *d* is the moisture vapour resistance expressed in air equivalence in meter introduced by Whelam (1955) and i_m is the moisture vapour permeability index introduced by Woodcock (1962a).

R_{oa} is induced only by the mass convective transfer, applying Lewis relation to Equations (5-4), we have:

$$R_{oa} = \frac{1}{0.0165 \times 8.3\sqrt{0.11 + V_{wind} + \beta V_{walk}}} \qquad (5\text{-}11)$$

However, since Lewis relation represents an ideal situation (Cengel 2003), its validity for predicting the surface moisture vapour resistance of human body should be evaluated.

5.3 Measurement of surface thermal insulation and moisture vapour resistance

5.3.1 Calculation of surface thermal insulation and moisture vapour resistance

The surface thermal insulation I_{oa} and the surface moisture vapour resistance R_{oa} of the air layer surrounding the nude manikin can be measured and calculated by the following equations:

$$I_{oa} = \frac{A_s \cdot (T_s - T_a)}{H_d} \tag{5-12}$$

where, $H_d = H_s + H_p - H_a - H_e$ (5-13)

$$R_{oa} = \frac{A_s \cdot (p_{ss} - p_{as} RH_a)}{H_e} - R_{es} \tag{5-14}$$

5.3.2 Experimental conditions

Experiments were conducted in the climatic chamber of our laboratory. The experiments were conducted under the ambient temperature of either 20^oC or 35^oC with wind velocity varying from 0.22 *m/s* ±0.03*m/s* to 4.04 *m/s*±0.22*m/s*. The 20^oC environment simulates the conventional office condition and the 35^oC environment simulates the isothermal condition. Measurements were also taken when the manikin was covered with sweating skin and with non-sweating skin to see the effect of moisture transfer on heat transfer, and when the manikin was controlled with a constant core temperature and a constant skin temperature to see the effect of skin temperature variation on the measurement results.

5.3.3 Experimental results

The experimental results are listed in Table 5-1.

Table 5-1 Surface thermal insulation and moisture vapor resistance measured under various environmental conditions

Remark	V_{wind} m/s	V_{walk} m/s	Set point	*Ta*	*Ts*	*Te*	*He*	*W*	*Q*	*Ia*	*Rt*	*Roa*
Non- sweating manikin (covered with non-sweating skin)	0.22	0.00	37.5	37.50	34.92	19.85	51.28	278.79	0.00	0.103		
	0.85	0.00	38.3	38.33	35.04	19.78	47.54	354.57	0.00	0.082		
	1.69	0.00	38.8	38.82	34.82	19.75	47.45	467.17	0.00	0.061		
	2.48	0.00	39.2	39.20	34.96	20.15	46.99	570.45	0.00	0.049		
	3.12	0.00	39.8	39.77	34.98	20.11	47.01	667.26	0.00	0.043		
	4.04	0.00	40.5	40.54	35.23	20.08	46.76	746.41	0.00	0.039		
Sweating manikin at Isothermal condition (T_s=T_e=35^{o}C)	0.22	0.00	35.2	35.20	35.04	35.21	39.82	221.49	333.66		27.04	18.44
	0.85	0.00	35.4	35.40	35.01	34.91	39.84	307.16	455.43		19.94	11.34
	1.69	0.00	35.6	35.60	35.01	35.03	40.04	376.76	563.57		16.01	7.41
	2.48	0.00	35.7	35.70	35.00	35.11	39.94	408.88	633.05		14.21	5.61
	3.12	0.00	35.8	35.79	34.93	34.92	39.88	442.20	691.46		13.03	4.43
	4.04	0.00	35.9	35.91	34.98	34.98	39.43	465.13	721.01		12.63	4.03
Sweating manikin at T_s=35^{o}C, T_e=20 C	0.22	0.00	38	38.00	35.04	20.32	46.76	649.90	562.59	0.101	21.50	12.90
	0.85	0.00	38.7	38.53	34.91	19.75	48.25	842.95	697.00	0.076	17.22	8.62
	1.69	0.00	39.5	39.50	34.96	19.83	47.68	1046.46	833.76	0.058	14.46	5.86
	2.48	0.00	39.7	39.70	34.82	19.89	53.87	1157.64	874.55	0.049	13.21	4.61
	3.12	0.00	40.3	40.31	34.89	19.79	52.24	1271.96	916.97	0.043	12.79	4.19
	4.04	0.00	40.9	40.90	34.94	19.84	49.33	1415.32	1004.19	0.038	11.89	3.29
Sweating manikin at T_c=38^{o}C (T_s=35^{o}C standing in still air)	0.22	0.00	38.0	38.00	34.92	19.78	45.72	660.87	577.55	0.103	21.04	12.44
	0.85	0.00	38.0	38.00	34.36	19.75	46.93	804.27	679.94	0.078	17.08	8.48
	1.69	0.00	38.0	38.00	33.71	19.70	47.95	951.88	785.99	0.061	14.06	5.46
	2.48	0.00	38.0	38.00	33.37	19.92	48.68	1066.09	842.24	0.050	12.71	4.11
	3.12	0.00	38.0	38.00	33.00	19.90	49.10	1142.75	866.67	0.043	12.01	3.41
	4.04	0.00	38.0	38.01	32.73	19.89	49.15	1233.55	885.96	0.037	11.51	2.91
	0.22	0.00	38.0	38.00	34.94	20.04	52.66	646.40	552.56	0.101	21.16	12.56
	0.22	0.04	38.0	38.00	34.91	20.18	51.88	656.41	561.14	0.098	20.82	12.22
	0.22	0.23	38.0	38.00	35.05	20.15	50.95	676.82	570.89	0.095	20.79	12.19
	0.22	0.34	38.0	38.00	35.01	20.17	49.22	686.42	595.68	0.097	20.04	11.44
	0.22	0.46	38.0	38.00	35.34	20.19	50.72	713.18	602.28	0.091	20.11	11.51
	0.22	0.58	38.0	38.00	34.93	20.17	53.46	719.27	602.52	0.087	19.25	10.65
	0.22	0.69	38.0	38.00	35.05	20.21	51.87	738.63	624.30	0.086	18.91	10.31
	0.85	0.00	38.0	38.00	34.24	19.58	53.47	776.08	658.20	0.082	16.94	8.34
	0.85	0.23	38.0	38.00	33.93	19.77	54.50	800.47	658.67	0.073	16.40	7.80
	0.85	0.69	38.0	38.00	34.76	19.71	52.98	864.90	715.13	0.073	16.20	7.60
	2.48	0.00	38.0	38.00	33.02	19.50	53.19	1027.83	784.32	0.050	13.06	4.46
	2.48	0.23	38.0	38.00	32.91	19.48	53.83	1069.98	811.31	0.047	12.48	3.88
	2.48	0.69	38.0	38.00	33.61	19.49	54.24	1135.10	850.22	0.047	12.50	3.90

5.4 Results and discussion

5.4.1 The effects of the environment temperature and humidity on I_{oa} and R_{oa}

The surface thermal insulation I_{oa} and moisture vapour resistance R_{oa} were measured under the same temperature (20^{o}C), but different humilities (30% and 80%) to investigate the effect of environmental humidity, and under the same humidity (50%), but different environmental temperature (10^{o}C and 20^{o}C) to investigate the effect of temperature.

From Figure 5-1(a), it can be seen that surface thermal insulation I_{oa} is little affected when humidity changes from 30% to 80% and environmental temperature changes from 10^{o}C to 20^{o}C. This is because the radiative and convective heat transfer is little changed with the increase of temperature in the presence of a large temperature difference. This finding is in agreement with those in the literatures (Fan and Keighley 1991; Meinander et al 2003).

With regard to surface moisture vapour resistance R_{oa} as shown in Figure 5-1(b), however, it can be seen that the increase of environmental humidity from 30% to 80% results a 9% reduction in the measured R_{oa}. Since the moisture vapour resistance of the breathable fabric skin, which consists of a PTFE membrane, an inner warp knit fabric and an outer nylon fabric, is not appreciably influenced by the relative humidity (Fukazawa et al 2000), this reduction is unlikely due to the changes in the vapour resistance of the skin, but likely induced by the reduction of the mass boundary layer. In the case of the environmental temperature reduced from 20°C to 10°C, the moisture vapour resistance decreased 14%, this reduction is likely caused by the increase in the temperature and concentration gradients.

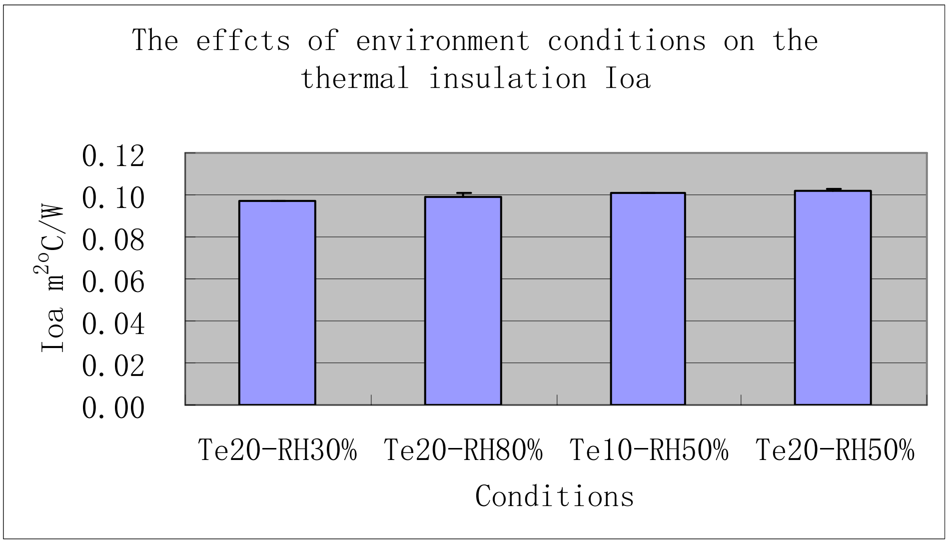


Figure 5-1 (a) The effects of the environment temperature and humidity on I_{oa}

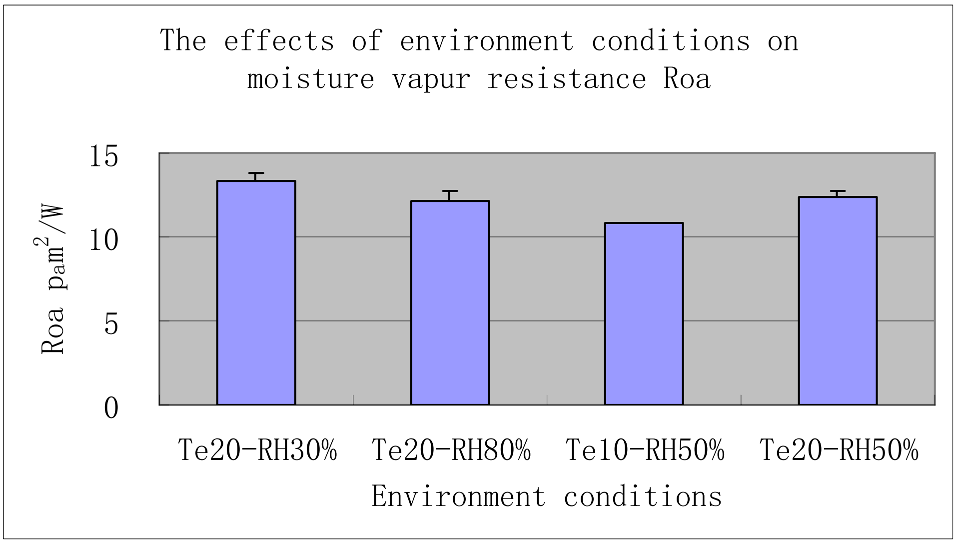


Figure 5-1(b) The effects of the environment temperature and humidity on R_{oa}

5.4.2 The interaction between heat and mass transfer

Temperature and moisture concentration gradient are the driving force for the heat and mass transfer, respectively. When they are present at the same time, they can affect each other (Cengel 2003; Spencer-Smith 1977). In order to clarify this interaction, the surface thermal insulation measured with the sweating manikin under the condition of 20 ^{o}C and 50%*RH* (i.e. having simultaneous heat and moisture transfer) with varying wind velocity is compared with that measured with the manikin covered with a non-sweating fabric skin (i.e. only heat transfer, but no moisture transfer); the surface moisture vapour resistance measured under the condition of 20^{o}C and 50% *RH* (i.e. having simultaneous heat and moisture transfer) with varying wind velocity is compared with that measured under the isothermal condition of 35^{o}C and 50% *RH* (i.e. only moisture transfer, no direct heat transfer). The results are plotted in Figure 5-2(a) and 2(b).

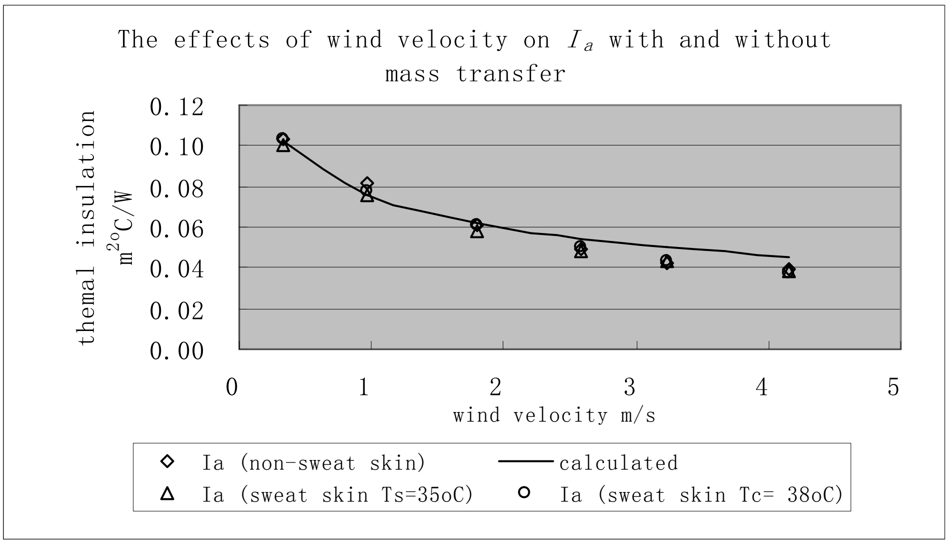


Figure5-2 (a) I_{oa} measured with and without moisture transfer

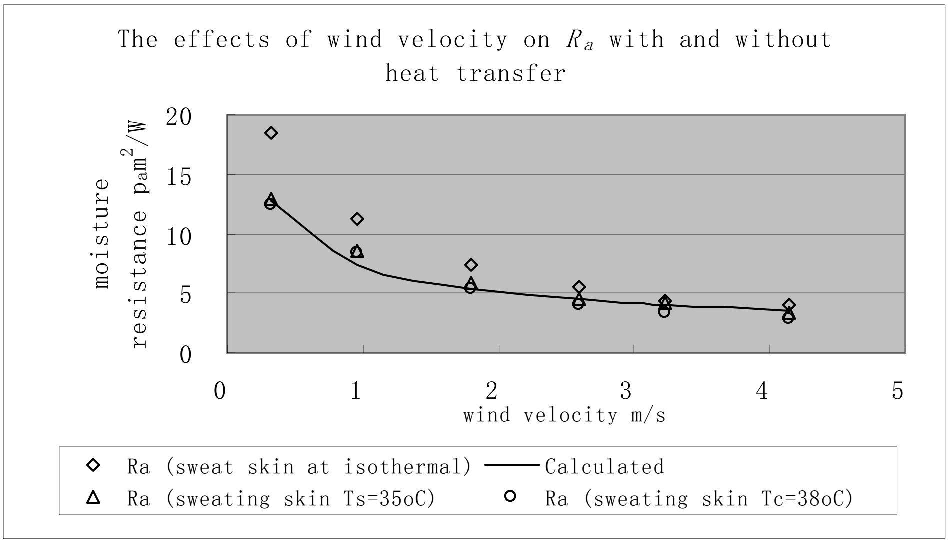


Figure 5-2 (b) R_{oa} measured with and without heat transfer

In Figure 5-2(a), the curve is the calculated surface thermal insulation according Equation (5-4) (The manikin was not in walking motion, $V_{walk}=0$). As can be seen, there is no significant difference between the surface thermal insulation measured on the non-sweating manikin and those measured on the sweating manikin, both agreeing well with the calculated values. This means that there is little effect of moisture transfer on the surface thermal insulation.

In Figure 5-2(b), the curve is the calculated moisture vapour resistance based on Equation (5-11). As can be seen, the R_{oa} measured at 20 ^oC and 50%*RH* agree well with the calculated values, but much lower than those measured at the isothermal condition of 35 ^{o}C and 50%RH, when the wind velocity is less than 2.0 *m/s*. At high wind velocity, no significant difference exists between the R_{oa} measured under non-isothermal and isothermal conditions and those predicted by Equation (5-11). The higher values of R_{oa} under isothermal conditions are likely due to the increase of surface air layer as a result of the absence of temperature gradients. At high wind velocity, such increase in surface air layer becomes insignificant. Under the isothermal condition, the effect of wind velocity on the surface moisture vapour resistance can be fitted with the following empirical equation:

$$R_{oa} = \frac{1}{0.11 \times \sqrt{V_{wind}}} \qquad (V_{wind} \leq 4m/s) \qquad (5\text{-}15)$$

with the percentage of fit (i.e. R^2) being 0.97.

Comparing the measurements obtained when the core temperature is controlled constantly at 38^oC and when the skin temperature is controlled constantly at 35^oC as shown in Figure 5-2(a) and Figure 5-2(b), there are no significant difference in I_{oa} and R_{oa} This means small variations in skin temperature (between 33~35^oC) has little effect on the measurements of surface thermal insulation and moisture vapour resistance.

5.4.3 Combined effects of wind and "walking" motion on the surface thermal insulation and moisture vapour resistance

Surface thermal insulation I_{oa} and moisture vapour resistance R_{oa} were measured under the condition of 20^oC and 50%*RH* with varying wind velocity and the speed of "walking" motion. The experimental results are listed in Table 5-1. By using nonlinear regression function of SPSS software, fitting these datum with

Eq. (5-4) and (5-11), we obtain $\beta = 0.45$ with the percentage of fit being 0.87 (i.e. $R^2 = 0.87$). Therefore, we have:

$$V_{eff} = 0.11 + V_{wind} + 0.45 \times V_{walk} \qquad m/s \qquad (5\text{-}16)$$

The surface thermal insulation and moisture vapour resistance are plotted against the equivalent air velocity V_{eff} in Figure 5-3 (a) and (b), the curve represents the calculated thermal insulation and moisture vapour resistance according to Equation (5-4) and (5-11), respectively. The thermal insulation values measured on human subjects by Havenith (1990a) are also plotted on Figure 5-3(a) for comparison. It can be seen that both our data and Havenith's data are close to the fitting curves.

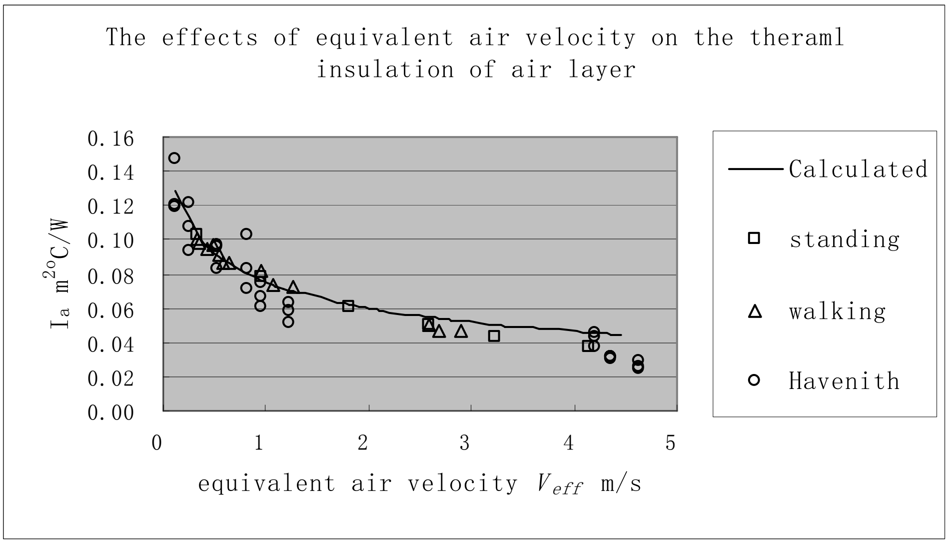


Figure 5-3 (a) The effects of equivalent air velocity on I_{oa}

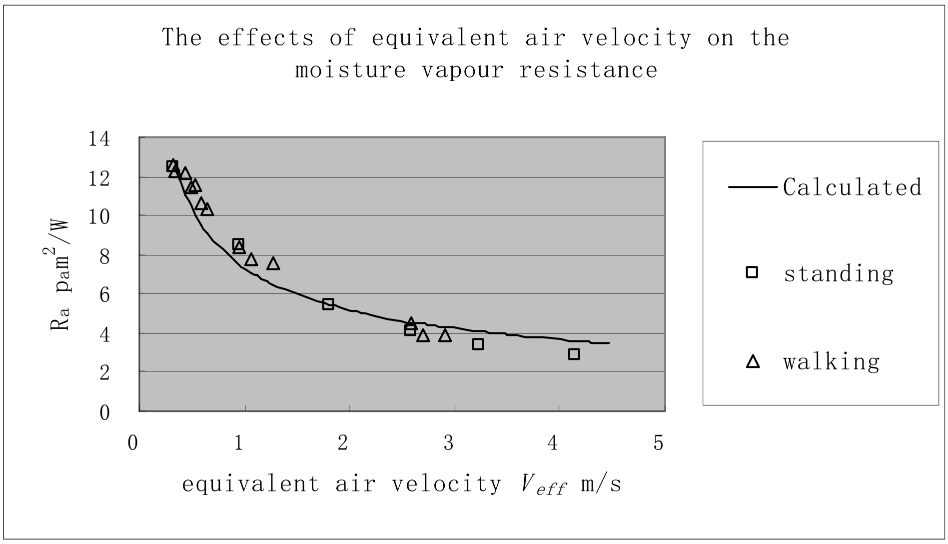


Figure 5-3 (b) The effects of equivalent air velocity on R_{oa}

The β value determined in our work is smaller than that proposed by Havenith (1990a) (*β=0.67)*, who obtained it by analyzing the thermal insulation measured on human subjects. The smaller value of β could be due to the fact that, when human subjects are walking, the lower legs swing against the upper legs at the point of knee and the forearms swings against the upper arms at the point of elbow, whereas the entire arms and legs remain straight when our manikin was in "walking" motion.

5.5 Concluding remarks

Using the sweating fabric manikin-Walter, the surface thermal insulation I_{oa} and moisture vapour resistance R_{oa} adjacent to the skin were investigated under different environmental conditions (viz. varying temperature, humidity and wind velocities) and under varying speeds of "walking" motion. It was found that,

(1) there is no significant difference between the surface thermal insulation measured on the non-sweating manikin and those measured on the sweating manikin, indicating the moisture transfer having little effect on the direct heat transfer through the surface air layer;

(2) the surface moisture vapour resistances R_a measured under isothermal conditions tend to be greater than those measured under non-isothermal conditions, especially when the wind velocity is less than 2.0 m/s. The higher R_a under isothermal conditions is likely due to the increase of surface air layer with the absence of the temperature gradients.

(3) the study also showed that Lewis relation holds under non-isothermal conditions.

(4) the study further confirmed that the effect of "walking" motion can be regarded as an equivalent air velocity.

Chapter 6

A Direct Regression Model for Predicting the Clothing Thermal Insulation and Moisture Vapour Resistance

6.1 Introduction

Heat and mass transfer and its interaction in clothing system are very complex processes. In order to predict or achieve the optimum performance with regards to clothing thermal comfort, knowledge of the effects of body motion and environmental parameters, especially wind velocity and walking speed, is essential.

Although considerable work has been carried out so far for predicting the clothing thermal insulation and moisture vapour resistance under various conditions, existing models still have much limitations particularly with respect to the effects of clothing characteristics such as fabric air permeability, garment style, garment fitting and construction.

In this study, clothing thermal insulation and moisture vapour resistance of various types of clothing ensembles were measured using the walk-able sweating manikin-Walter under various environmental conditions and walking speeds. Based on the experimental data, a new empirical model has been established for predicting the clothing thermal insulation and moisture vapour resistance under wind and walking motion from those when the manikin is standing in still air. The new model considered the effects of clothing characteristics such as fabric air permeability, garment style, garment fitting and construction.

6.2 Review of existing prediction models

The static thermal insulation and water vapor resistance values (viz. for persons standing in still air) of conventional garments and clothing assemblies were measured and kept in a data base for estimating the thermal insulation of clothing systems in use (ASHRAE Standard 55-2005, McCullough, et al 1985 and McCullough, et al 1989, ISO 7933 and ISO 9920). For clothing on a standing manikin in still air, McCullough et al (1985) found that the thermal insulation of a garment could be well estimated from the body surface area that the garment covers and the fabric thickness. They also found that the thermal insulation of a clothing ensemble could be accurately predicted from the sum of the insulation of constituent garments. A model was later proposed by them to predict the thermal insulation and water vapor resistance of clothing ensembles from the component fabrics by considering the body as consisting of 11 cylinders. The prediction was quite accurate.

Furthermore, considerable work has also been dedicated towards the prediction of dynamic clothing thermal insulation and moisture vapour resistance (viz. when the wearer is in motion under varying environmental conditions). Gagge and Burton (1941), Belding et al (1947), Vogt et al (1983) and Olesen et al (1982) investigated the effects of body motion; Belding et al (1947), Burton and

Edholm (1955) and Chen et al (2004) studied the wind effects; and Nielsen et al (1985), Havenith et al (1990a), Fan and Keighley (1991) and Holmer et al (1999) investigated the combined effects of body movement and wind on the clothing thermal insulation.

To better understand the effects of body motion, a tracer gas technology was developed and used for investigating the ventilative heat (Reischl et al 1987) and mass (Havenith et al 1990b, Lotens and Wammes 1993) transfer through clothing systems induced by wind and body motion. However, due to the limitation of this method, the effects of moisture condensation and absorption within clothing can not be taken into account.

All of the studies mentioned above revealed that wind and body motion will reduce thermal insulation and moisture vapour resistance of clothing. This attributed mainly to the loss of convective heat and mass transfer by forced exchange of air contained within clothing with the ambient air. Depending on the construction of the fabrics (e.g. woven and knitted fabrics) and clothing (e.g. style and fit), air can be forced through the pores in the fabrics (viz. air penetration) as well as through the openings of the garments (viz. air ventilation).

Based on the cylinder model, in steady state conditions, Spencer-Smith (1977a and 1977b) considered the wind induced reduction of the thermal insulation and moisture vapour resistance as a linear function of the product of the wind velocity and the squared root of fabric air permeability of fabrics:

$$\frac{I_{tdyn}}{I_{st}} = 1 - 1.2 \times 10^{-4} V_{wind} \sqrt{ap} \tag{6-1}$$

$$\frac{R_{tdyn}}{R_{st}} = 1 - 0.024 V_{wind} \sqrt{ap} \tag{6-2}$$

Where, I_{tdyn}, R_{tdyn} are the total thermal insulation and total moisture vapour resistance of clothing system in windy conditions, respectively. I_{st}, R_{st},are the total thermal insulation and total moisture vapour resistance of garment in the case of a person standing in still air; *ap* is the air permeability (l/m^2s) of clothing.

Also base on the findings obtained on cylinder model, Lotens and Havenith considered the wind increase the heat transfer coefficient linearly with the square root of air velocity, i.e.

$$h = a + bV_{eff}^{1/2} \tag{6-3}$$

where, *a* and *b* are constants, V_{eff} is the equivalent air velocity.

The ratio of insulation with and without wind is then:

$$\frac{I_{clwind}}{I_{clnowind}} = \frac{a/b + \sqrt{V_{act} + v_0}}{a/b + \sqrt{V_{wind} + V_{act} + v_0}} \tag{6-4}$$

where, I_{clwind} and $I_{clnowind}$ are the intrinsic thermal insulation of garment with wind and without wind, respectively. V_{act} is an equivalent walking speed with respect to body activity level.

By fitting the data listed in some publications, for a body walking in windy conditions, they had:

$$\frac{I_{cldyn}}{I_{scl}} = e^{-\frac{I_{scl}V_{walk}}{0.45}} \times \frac{3+\sqrt{0.67V_{walk}+0.11}}{3+\sqrt{V_{wind}+0.67V_{walk}+0.11}} \quad (6\text{-}5)$$

where, I_{cldyn} is the thermal insulation of garment in the case of walking in windy conditions.

Holmer et al (1999) also investigated the reduction of clothing thermal insulation induced by wind and body motion, and proposed the following prediction equation:

$$\frac{I_{tdyn}}{I_{st}} = e^{(0.043-0.398V_{wind}+0.066V_{wind}^2-0.378V_{walk}+0.094V_{walk}^2)} \quad (6\text{-}6)$$

Nilssion et al (2000) further considered the effects of the air permeability of the fabrics of clothing ensembles, and proposed another prediction equation as:

$$\frac{I_{tdyn}}{I_{st}} = 0.54e^{(-0.15V_{wind}-0.22V_{walk})}(ap)^{0.075} - 0.06\ln(ap) + 0.5 \quad (6\text{-}7)$$

where, ap is the air permeability (l/m^2s) of clothing.

For the moisture vapour resistance of clothing, Nishi et al (1975) evaluated the thermal efficiency factor F_{cl} and permeable efficiency factor F_{pcl} (adopted by ISO 7933) by means of Lewis relation and permeability index i_m, which was introduced by Woodcock (1962a). The method they used was based on the assumption that, for any unit area of skin surface, the sensible heat exchange with the directly adjacent clothing surface equals the sensible heat exchange from the clothing surface itself. Obviously they did not take account of the ventilation effect which can cause additional heat and mass transfer through the clothing system (Burton and Edholm, 1955; Fanger P.O., 1970; Renbourn, 1972; Crockford et al 1972).

ISO 9920 employed i_m directly to estimate the dynamic moisture vapour resistance of clothing from the dynamic clothing thermal insulation.

$$\frac{I_{tdyn}}{R_{tdyn}} = L_R i_m = \frac{I_{st}}{R_{st}} \tag{6-8}$$

Where, I_{tdyn}, R_{tdyn} are the total thermal insulation and total moisture vapour resistance of clothing system in the case of walking in windy conditions, respectively. I_{st}, R_{st},are the total thermal insulation and total moisture vapour resistance of garment in the case of standing in still air, and i_m in the moisture vapour permeability index. Equation (6-8) is very simple in form, but it needs to know the values of dynamics thermal insulation of clothing previously.

Although a number of empirical models have been proposed for predicting the clothing thermal insulation and moisture vapour resistance under wind and walking motion from those under no wind and standing position, existing models still have much limitations particularly with respect to the effects of clothing characteristics such as fabric air permeability, garment style, garment fitting and construction.

6.3 Experimental

6.3.1 Clothing samples

6.3.1.1 Description of clothing ensembles

32 sets of clothing ensembles were tested in the present study. In order to examine and compare the effects of clothing style, fit and fabric characteristics of garments on the thermal insulation and moisture vapour resistance, and to simplify this investigation under the limited time and resource, and since (1) the upper garments play a bigger role because of the larger surface area of the upper part of the body and greater importance in protecting the upper part of body; (2) under many practical situations, upper and lower garments are worn independently, viz. the upper garments may be changed, but the lower garments unchanged, or vice versa; all clothing ensembles have a same pair of pants

The pants was a pair of casual pants from Giordano, made of a fabric with a composition of 98% cotton and 2% Lycra.

The upper garments of the clothing ensembles are described in Table 6-1 (a) and (b).

Table 6-1(a) Description of clothing ensembles tested in the present study

CL-ID	Label of Clothing	Description
1	A	S size knitting jacket, casual pants
2	B	M size knitting jacket, casual pants
3	C	L size knitting jacket, casual pants
4	D	XXL size knitting jacket, casual pants
5	E	S size denim jacket, casual pants
6	F	M size denim jacket, casual pants
7	G	L size denim jacket, casual pants
8	H	XXL size denim jacket, casual pants
9	I	S size poplin jacket, casual pants
10	J	M size poplin jacket, casual pants
11	K	L size poplin jacket, casual pants
12	L	XXL size poplin jacket, casual pants
13	M	PET napping jacket, casual pants
14	N	Oxford woven cotton long-sleeve shirt, casual pants
15	O	Oxford woven cotton long-sleeve army uniform, casual pants
16	P	Two-layer design windbreaker comprised of nylon shell and PET mesh lining, casual pants
17	Q	Dacron shell with PET bedding long-sleeve shirt, casual pants
18	R	One-layer design PU coated windbreaker (leisure jacket), casual pants
19	C+S	Vest & underwear brief, cotton short T-shirt, L size knitting jacket, casual pants
20	M+S	Vest & underwear brief, cotton short T-shirt, PET napping jacket, casual pants
21	N+S	Vest & underwear brief, cotton short T-shirt, Oxford woven cotton long-sleeve shirt, casual pants
22	O+S	Vest & underwear brief, cotton short T-shirt, Oxford woven cotton long-sleeve army uniform, casual pants
23	G+S	Vest & underwear brief, cotton short T-shirt, L size denim jacket, casual pants
24	K+S	Vest & underwear brief, cotton short T-shirt, L size poplin jacket, casual pants
25	P+S	Vest & underwear brief, cotton short T-shirt, Two-layer design windbreaker comprised of nylon shell and PET mesh lining, casual pants
26	Q+S	Vest & underwear brief, cotton short T-shirt, Dacron shell with PET bedding long-sleeve shirt, casual pants
27	R+S	Vest & underwear brief, cotton short T-shirt, One-layer design PU coated windbreaker (leisure jacket), casual pants
28	U+S	Vest & underwear brief, cotton short T-shirt, PU coated breathable army outdoor leisure jacket, casual pants
29	V+S	Vest & underwear brief, cotton short T-shirt, two-layer jacket comprised of 80% nylon/20%PET napping lining and PET poplin shell, casual pants
30	U+S +T+N	Vest & underwear brief, cotton short T-shirt, Oxford woven cotton long-sleeve shirt, long cotton sweat pants, PU coated breathable army outdoor leisure jacket, casual pants
31	V+S +T+N	Vest & underwear brief, cotton short T-shirt, Oxford woven cotton long-sleeve shirt, long cotton sweat pants, two-layer jacket comprised of 80% nylon/20%PET napping lining and PET poplin shell, casual pants
32	W+S	Vest & underwear brief, cotton short T-shirt, long cotton sweat pants, nylon film leisure jacket
	S	Vest & underwear brief and with short T-shirt, cotton
	T	sweat pants, cotton

Table 6-1(b) Description of clothing ensembles tested in the present study

CL_ID	Label of Clothing	Style	Thickness T_2(mm)	Permeability *ap* (l/s.m^{2}pa)	Fit index
1	A	Jacket	1.405	20.6133	2.9
2	B				5.2
3	C				8.7
4	D				11.6
5	E		0.939	1.0761	2.9
6	F				5.2
7	G				8.7
8	H				11.6
9	I		0.443	0.0392	2.9
10	J				5.2
11	K				8.7
12	L				11.6
13	M	Jacket	3.891	4.2415	10.3
14	N	Shirt	0.406	1.7480	11.3
15	O	Uniform	0.724	1.4488	11.1
16	P	Jacket_2	0.720	0.0280	12.2
17	Q	Shirt	3.250	0.0280	12.2
18	R	Jacket_1	0.113	0.0166	14.5
19	C+S	Jacket	1.405	20.6133	8.7
20	M+S	Jacket	3.891	4.2415	10.3
21	N+S	Shirt	0.406	1.7480	11.3
22	O+S	Uniform	0.724	1.4488	11.1
23	G+S	Jacket	0.939	1.0761	8.7
24	K+S	Jacket	0.443	0.0392	8.7
25	P+S	Jacket_2	0.720	0.0280	12.2
26	Q+S	Shirt	3.250	0.0280	12.2
27	R+S	Jacket_1	0.113	0.0166	14.5
28	U+S	Jacket_1	0.469	0.0000	24.3
29	V+S	Jacket_2	3.952	0.0000	23.9
30	U+S+T+N	Jacket_1	0.469	0.0000	24.3
31	V+S+T+N	Jacket_2	3.952	0.0000	23.9
32	W+S	Jacket_1	0.113	0.0000	20.3

In table 6-1(b), Jacket_1 and Jacket_2 represent a casual jacket and a jacket which fabrics is combined with two layer fabric, respectively. The thickness and the air permeability are the thickness and the air permeability of the shell fabric measured using the FAST system and ASTM D737-96 method, respectively.

In table 6-1(b), the garment fit index is defined as the area weighted average of the percentage difference between the inner circumferences of different parts of the garment and the corresponding circumferences of body. It is calculated by:

$$Fit = \left(\frac{Lc_{cl} + Lw_{cl}}{2} - \frac{Lc_{nu} + Lw_{nu}}{2}\right)wei1 + \left(\frac{Lw_{cl} + Llap_{cl}}{2} - \frac{Lw_{nu} + Lhip_{nu}}{2}\right)wei2 + \left(\frac{Lsu_{cl} + Lsl_{cl}}{2} - \frac{Lsu_{nu} + Lsl_{nu}}{2}\right)wei3 \quad (6\text{-}9)$$

where, Lc_{cl}, Lw_{cl}, $Llap_{cl}$, Lsu_{cl} and Lsl_{cl} are the girth of clothing at chest, waist, lap, armhole and wristband, respectively; Lc_{nu}, Lw_{nu}, $Lhip_{nu}$, Lsu_{nu} and Lsl_{nu} are the girth of nude manikin at chest, waist, lap, armhole and wristband, respectively; *wei1*, *wei2* and *wei3* are the area weighting at the related parts, respectively. The values of fit index are calculated and list in Table 6-2:

Table 6-2 Geometric description of clothing ensembles tested in the experiment

CL_ID	Nude/weighting	1,5,9	2,6,10	3,7,11 19,23,24	4,8,12	13,20	14,21
chest	95.0/18.62	98.7	105.7	112.0	115.7	110.0	114.0
waist	85.0/12.38	92.3	97.7	103.3	108.7	104.0	112.0
Lap (hip)	97.0/-	98.0	104.0	110.7	115.3	106.0	116.0
armhole	40.5/16.46	42.7	43.0	46.3	50.0	50.0	50.0
wristband	19.0/-	21.3	21.7	23.7	24.7	27.0	22.0
Fit index		2.9	5.2	8.7	11.6	10.3	11.3
CL_ID	15,22	16,25	17,26	18,27	28,30	29,31	32
chest	110.0	114.0	116.0	112.0	136.0	136.0	122.0
waist	100.0	112.0	116.0	114.0	134.0	134.0	122.0
lap	104.0	112.0	116.0	112.0	120.0	114.0	112.0
armhole	50.0	52.0	50.0	56.0	64.0	62.0	60.0
wristband	33.0	24.0	22.0	28.0	32.0	34.0	36.0
Fit index	11.1	12.2	12.2	14.5	24.3	23.9	20.3

6.3.1.2 Images of clothing ensembles

The images of clothing ensembles to be tested in the present study are shown in Figure 6-1.

nude Clothing S underwear & pants

Clothing A, B, C & D Clothing E, F, G & H Clothing I, J, K & L

Figure 6-1 The images of clothing to be tested

Clothing M

Clothing N

Clothing O

Clothing P

Clothing Q

Clothing R

Clothing U

Clothing V

Clothing W

Figure 6-1 The images of clothing to be tested (continued)

6.3.2 Experimental conditions and procedure

All tests were conducted in the Walter Lab's climatic chamber under the environmental temperature of 20±0.3^{o}C and humidity of 50±5%. Each of the 32 sets of clothing ensembles was tested under 6 levels of wind velocity (V_{wind} = *0.22*, 0.85, 1.69, 2.48, 3.12 and 4.04 m/s with V_{wind} = *0.22 m/s* representing the no wind condition) when the manikin was in standing position. At the wind velocity of 0.22 and 2.48 m/s, the clothing ensembles were also tested at 4 levels of walking motion (V_{walk} = 0, 0.23, 0.46 and 0.69 m/s with V_{walk}= *0 m/s* representing the standing position). So for each clothing ensemble, there are 12 conditions investigated.

The experiments were carried out according to the following procedure:

1. Put the clothing ensemble to be tested onto the manikin, wait at least 12 hours for the stabilization of moisture accumulation within clothing under the wind velocity of 0.22 m/s (minimum air current for the climatic control of the Chamber) and in standing position.

2. Control the mean skin temperature T_s at 35^{o}C, and wait for the mean skin temperature to be balanced at 35^{o}C. Record the core temperature T_{ci} at this time. Change to control the core temperature T_c at the recorded value of T_{ci}.

3. Supply water into the container up to about 4 liter. Once the T_c reached T_{ci} with a very small error (±0.1^{o}C) (This procedure will take about 30

minutes), the software will automatically record all measurements including 15 points of local temperatures, 2 points of environmental temperatures, 9 points of humidity values, power supplied to the manikin, rate of water loss from the container, respectively. If the value of T_c in one hour (after 120 continuous reading points) was within the range of $T_{ci}\pm0.1^{o}C$, the software will calculate average values of all measurements and then the total clothing thermal insulation and moisture vapour resistance.

4. Repeat Step 3 to get another set of measurements to check the reproducibility and obtain the mean values of all measurements.

5. Start walking motion at the speed of 0.23 m/s, 0.46 m/s and 0.69 m/s respectively, repeat Step 3 and 4 to obtain measurements under different walking speeds under the wind velocity of 0.22 m/s.

6. Set manikin in the standing position, set the wind velocity at 0.85 m/s, 1.69 m/s and 2.48 m/s respectively, repeat step 3 and 4 to obtain measurements under the three different wind velocities.

7. Keep the wind velocity at 2.48 m/s, and change the manikin from the standing position to walking motion at the speed of 0.23 m/s, 0.46 m/s and 0.69 m/s respectively, repeat step 3 and 4 to obtain measurements under different walking speeds under the wind velocity of 2.48 m/s.

8. Set manikin in the standing position, and set the wind velocity at 3.12 m/s and 4.04 m/s respectively, repeat Step 3 and 4 to obtain measurements under the two different wind velocities.

Repeat all steps for another clothing ensemble. With overnight operation, it took about 2 days to complete all measurements for each clothing ensemble.

6.3.3 Experimental results

The results of the measurements are listed in Table 6-3.

Table 6-3 the testing results

CL_ID	V_{wind} m/s	V_{walk} m/s	I_t $m^{2o}C/W$	R_t m^2p_a/W	CL_ID	I_t $m^{2o}C/W$	R_t m^2p_a/W
1	0.22	0.00	0.187	31.70	3	0.201	32.60
	0.22	0.23	0.163	27.43		0.173	28.32
	0.22	0.46	0.159	24.20		0.171	25.15
	0.22	0.69	0.153	22.78		0.166	23.28
	0.85	0.00	0.162	25.79		0.172	26.24
	1.69	0.00	0.139	21.32		0.131	19.82
	2.48	0.00	0.121	18.06		0.125	17.43
	2.48	0.23	0.106	15.92		0.116	15.96
	2.48	0.46	0.102	15.29		0.109	14.79
	2.48	0.69	0.103	14.61		0.108	14.15
	3.12	0.00	0.105	15.04		0.105	15.82
	4.04	0.00	0.094	13.92		0.099	13.26
2	0.22	0.00	0.194	30.92	4	0.203	34.75
	0.22	0.23	0.176	27.65		0.175	28.92
	0.22	0.46	0.166	24.21		0.164	25.37
	0.22	0.69	0.160	22.96		0.152	24.43
	0.85	0.00	0.169	25.76		0.172	26.69
	1.69	0.00	0.143	20.58		0.142	20.79
	2.48	0.00	0.124	18.04		0.118	17.71
	2.48	0.23	0.111	16.09		0.108	17.25
	2.48	0.46	0.105	14.74		0.106	14.35
	2.48	0.69	0.103	14.27		0.101	14.03
	3.12	0.00	0.107	15.59		0.108	15.82
	4.04	0.00	0.099	13.92		0.100	13.37

Table 6-3 the results of all experiments (continued)

CL_ID	V_{wind} m/s	V_{walk} m/s	I_t $m^{2o}C/W$	R_t m^2p_a/W	CL_ID	I_t $m^{2o}C/W$	R_t m^2p_a/W
5	0.22	0.00	0.184	30.07	7	0.198	33.68
	0.22	0.23	0.168	26.52		0.181	29.84
	0.22	0.46	0.156	24.02		0.167	25.69
	0.22	0.69	0.156	21.92		0.150	24.65
	0.85	0.00	0.151	26.57		0.168	27.91
	1.69	0.00	0.124	21.06		0.139	21.89
	2.48	0.00	0.116	19.05		0.125	19.18
	2.48	0.23	0.105	16.67		0.115	17.09
	2.48	0.46	0.106	15.58		0.112	16.10
	2.48	0.69	0.105	15.00		0.107	15.64
	3.12	0.00	0.106	16.85		0.108	17.22
	4.04	0.00	0.096	15.05		0.103	14.76
6	0.22	0.00	0.195	32.79	8	0.200	34.34
	0.22	0.23	0.176	29.25		0.172	29.46
	0.22	0.46	0.173	25.99		0.166	25.80
	0.22	0.69	0.161	24.69		0.155	23.68
	0.85	0.00	0.174	28.23		0.165	26.93
	1.69	0.00	0.146	23.15		0.137	21.63
	2.48	0.00	0.130	20.35		0.122	18.09
	2.48	0.23	0.112	17.71		0.109	16.37
	2.48	0.46	0.110	16.82		0.109	15.03
	2.48	0.69	0.105	16.30		0.103	14.89
	3.12	0.00	0.115	18.38		0.112	16.63
	4.04	0.00	0.104	16.43		0.099	14.60

Table 6-3 the results of all experiments (continued)

CL_ID	V_{wind} m/s	V_{walk} m/s	I_t $m^{2o}C/W$	R_t m^2p_a/W	CL_ID	I_t $m^{2o}C/W$	R_t m^2p_a/W
9	0.22	0.00	0.175	31.09	11	0.192	33.16
	0.22	0.23	0.157	27.59		0.171	30.65
	0.22	0.46	0.150	24.82		0.159	26.93
	0.22	0.69	0.142	23.68		0.159	24.76
	0.85	0.00	0.155	27.15		0.173	27.84
	1.69	0.00	0.128	22.93		0.134	22.56
	2.48	0.00	0.116	19.35		0.124	19.11
	2.48	0.23	0.106	17.66		0.111	16.73
	2.48	0.46	0.099	16.66		0.107	15.75
	2.48	0.69	0.097	15.95		0.103	15.20
	3.12	0.00	0.099	18.47		0.109	16.81
	4.04	0.00	0.091	17.09		0.103	15.34
10	0.22	0.00	0.187	31.92	12	0.201	34.89
	0.22	0.23	0.179	28.41		0.179	30.43
	0.22	0.46	0.162	25.33		0.170	26.59
	0.22	0.69	0.152	24.47		0.167	24.46
	0.85	0.00	0.161	27.40		0.178	28.16
	1.69	0.00	0.135	22.60		0.143	21.71
	2.48	0.00	0.123	19.64		0.115	19.38
	2.48	0.23	0.107	17.82		0.114	16.68
	2.48	0.46	0.105	16.55		0.104	15.50
	2.48	0.69	0.106	15.88		0.109	14.95
	3.12	0.00	0.110	17.70		0.105	17.63
	4.04	0.00	0.099	15.47		0.098	15.67

Table 6-3: The results of all experiments (continued)

CL_ ID	V_{wind} m/s	V_{walk} m/s	I_t $m^{2o}C/W$	R_t m^2p_a/W	CL_ ID	I_t $m^{2o}C/W$	R_t m^2p_a/W	CL_ ID	I_t $m^{2o}C/W$	R_t m^2p_a/W
13	0.22	0.00	0.209	36.05	15	0.210	33.07	17	0.244	39.39
	0.22	0.23	0.192	31.20		0.184	28.27		0.213	33.99
	0.22	0.46	0.180	27.44		0.168	24.56		0.199	28.22
	0.22	0.69	0.176	25.16		0.157	23.14		0.187	25.40
	0.85	0.00	0.182	30.48		0.174	27.33		0.198	32.81
	1.69	0.00	0.157	23.32		0.145	21.87		0.163	23.85
	2.48	0.00	0.134	20.64		0.127	17.49		0.139	21.03
	2.48	0.23	0.125	17.52		0.110	15.80		0.125	19.08
	2.48	0.46	0.121	16.02		0.105	14.23		0.130	16.94
	2.48	0.69	0.115	16.07		0.103	13.84		0.121	16.45
	3.12	0.00	0.119	17.52		0.106	14.70		0.129	18.41
	4.04	0.00	0.109	14.67		0.098	12.92		0.119	17.59
14	0.22	0.00	0.197	33.59	16	0.219	38.98	18	0.202	38.42
	0.22	0.23	0.190	28.61		0.189	32.86		0.177	32.78
	0.22	0.46	0.165	24.72		0.184	27.74		0.160	28.15
	0.22	0.69	0.155	23.21		0.173	26.07		0.155	26.09
	0.85	0.00	0.180	26.95		0.200	30.95		0.165	31.27
	1.69	0.00	0.143	21.64		0.150	25.13		0.128	26.02
	2.48	0.00	0.124	18.36		0.129	21.72		0.120	22.09
	2.48	0.23	0.108	16.23		0.122	18.81		0.106	19.05
	2.48	0.46	0.106	14.90		0.117	17.16		0.103	17.47
	2.48	0.69	0.105	14.42		0.115	16.26		0.102	16.53
	3.12	0.00	0.105	17.18		0.125	18.54		0.109	19.16
	4.04	0.00	0.099	14.36		0.109	16.79		0.094	17.41

Table 6-3: The results of all experiments (continued)

CL_ ID	V_{wind} m/s	V_{walk} m/s	I_t $m^{2o}C/W$	R_t m^2p_a/W	CL_ ID	I_t $m^{2o}C/W$	R_t m^2p_a/W	CL_ ID	I_t $m^{2o}C/W$	R_t m^2p_a/W
19	0.22	0.00	0.216	33.63	22	0.236	34.61	25	0.234	38.70
	0.22	0.23	0.187	31.26		0.206	31.53		0.194	34.05
	0.22	0.46	0.183	27.53		0.186	27.05		0.189	29.08
	0.22	0.69	0.173	26.30		0.182	25.29		0.175	28.30
	0.85	0.00	0.174	28.14		0.192	29.37		0.208	35.74
	1.69	0.00	0.142	23.11		0.150	25.64		0.158	28.18
	2.48	0.00	0.126	20.43		0.141	22.00		0.147	25.27
	2.48	0.23	0.123	18.21		0.126	21.16		0.131	22.91
	2.48	0.46	0.122	17.43		0.123	18.88		0.123	21.54
	2.48	0.69	0.113	17.15		0.119	17.91		0.121	20.57
	3.12	0.00	0.117	18.46		0.121	20.73		0.130	22.55
	4.04	0.00	0.108	16.24		0.113	17.77		0.114	19.10
20	0.22	0.00	0.230	36.38	23	0.213	34.10	26	0.271	41.24
	0.22	0.23	0.208	32.67		0.190	30.89		0.231	36.16
	0.22	0.46	0.205	28.37		0.181	27.48		0.218	31.41
	0.22	0.69	0.195	26.50		0.169	26.18		0.203	28.07
	0.85	0.00	0.209	31.27		0.186	28.54		0.222	35.73
	1.69	0.00	0.162	25.63		0.151	24.17		0.169	30.99
	2.48	0.00	0.139	22.97		0.135	21.26		0.153	26.49
	2.48	0.23	0.129	20.40		0.123	18.85		0.144	22.13
	2.48	0.46	0.123	19.24		0.120	18.53		0.136	20.34
	2.48	0.69	0.127	18.04		0.113	17.78		0.129	18.98
	3.12	0.00	0.129	19.81		0.113	19.88		0.125	23.45
	4.04	0.00	0.118	17.85		0.104	17.94		0.130	21.23
21	0.22	0.00	0.228	33.83	24	0.202	33.87	27	0.237	39.60
	0.22	0.23	0.205	30.67		0.184	31.04		0.202	35.29
	0.22	0.46	0.187	26.83		0.178	28.40		0.190	30.74
	0.22	0.69	0.177	25.36		0.176	26.59		0.176	28.62
	0.85	0.00	0.196	29.24		0.180	29.87		0.201	34.73
	1.69	0.00	0.151	24.77		0.146	24.74		0.161	26.96
	2.48	0.00	0.144	21.44		0.137	22.81		0.135	23.71
	2.48	0.23	0.135	19.33		0.124	20.40		0.123	22.57
	2.48	0.46	0.131	17.77		0.124	19.50		0.121	20.78
	2.48	0.69	0.123	16.91		0.122	18.66		0.116	19.46
	3.12	0.00	0.139	19.53		0.125	20.35		0.129	20.83
	4.04	0.00	0.111	18.04		0.108	19.09		0.116	18.80

Table 6-3: The results of all experiments (continued)

CL_ID	V_{wind} m/s	V_{walk} m/s	I_t $m^{2o}C/W$	R_t m^2p_a/W	CL_ID	I_t $m^{2o}C/W$	R_t m^2p_a/W
28	0.22	0.00	0.246	43.94	31	0.299	51.91
	0.22	0.23	0.220	38.81		0.267	46.77
	0.22	0.46	0.204	33.44		0.252	41.36
	0.22	0.69	0.183	30.66		0.249	38.57
	0.85	0.00	0.198	35.67		0.268	44.55
	1.69	0.00	0.159	28.54		0.215	36.78
	2.48	0.00	0.137	24.57		0.174	32.23
	2.48	0.23	0.127	22.10		0.161	29.48
	2.48	0.46	0.130	21.18		0.158	27.63
	2.48	0.69	0.132	19.51		0.145	23.61
	3.12	0.00	0.131	21.11		0.166	29.73
	4.04	0.00	0.114	19.78		0.145	28.00
29	0.22	0.00	0.282	48.81	32	0.235	43.85
	0.22	0.23	0.249	42.88		0.216	37.68
	0.22	0.46	0.231	37.81		0.191	33.13
	0.22	0.69	0.212	36.15		0.186	30.36
	0.85	0.00	0.235	41.75		0.194	38.30
	1.69	0.00	0.189	34.23		0.153	31.04
	2.48	0.00	0.155	29.98		0.132	26.04
	2.48	0.23	0.156	26.18		0.130	21.50
	2.48	0.46	0.145	24.42		0.135	20.26
	2.48	0.69	0.146	23.69		0.125	19.31
	3.12	0.00	0.148	26.27		0.115	24.40
	4.04	0.00	0.132	23.16		0.108	21.54
30	0.22	0.00	0.264	47.74	33_1	0.137	18.89
	0.22	0.23	0.235	41.96	33	0.156	23.41
	0.22	0.46	0.217	37.36	34	0.173	27.25
	0.22	0.69	0.218	34.17	33_1:without the pants		
	0.85	0.00	0.227	39.58			
	1.69	0.00	0.177	33.20			
	2.48	0.00	0.163	29.05			
	2.48	0.23	0.149	25.62			
	2.48	0.46	0.147	24.43			
	2.48	0.69	0.147	23.66			
	3.12	0.00	0.151	26.58			
	4.04	0.00	0.140	23.79			

6.4 Building a new direct regression prediction model

6.4.1 Effect of wind velocity

In the existing prediction models, the reduction of thermal insulation or moisture vapour resistance by wind was considered in very different forms. Spencer-Smith used a relationship, Loten & Havenith used the square root function, whereas, Holmer and Nilsson et al used a complex exponential function to model the effect of wind velocity. It is therefore necessary to investigate the best way to model the effect of wind velocity before an improved prediction model can be established. Figure 6-2 (a) and (b) plot the clothing thermal insulation and moisture vapour resistance against the wind velocity for three clothing ensembles, respectively. It can be seen that there is a general trend that clothing thermal insulation or moisture vapour resistance decreases with the increase of wind velocity, but the rate of reduction decreases with the increase of wind velocity.

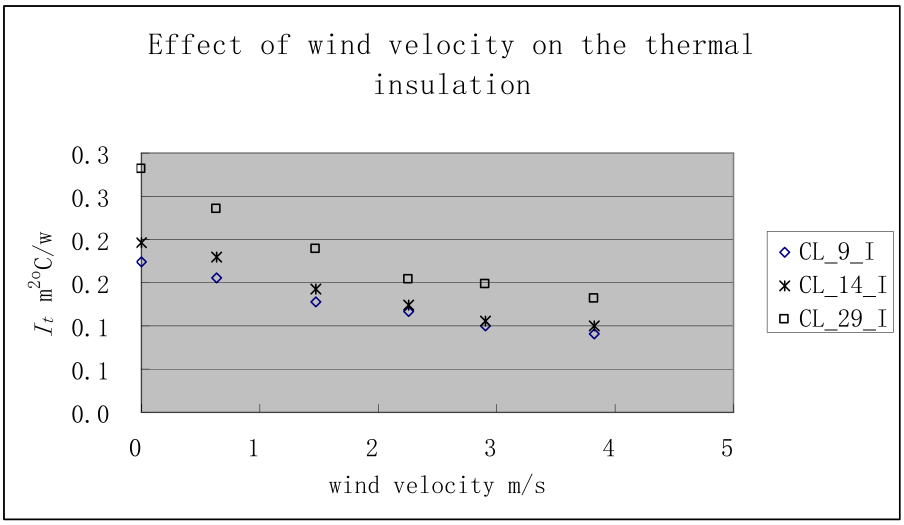


Figure 6-2 (a) Clothing thermal insulation vs. wind velocity

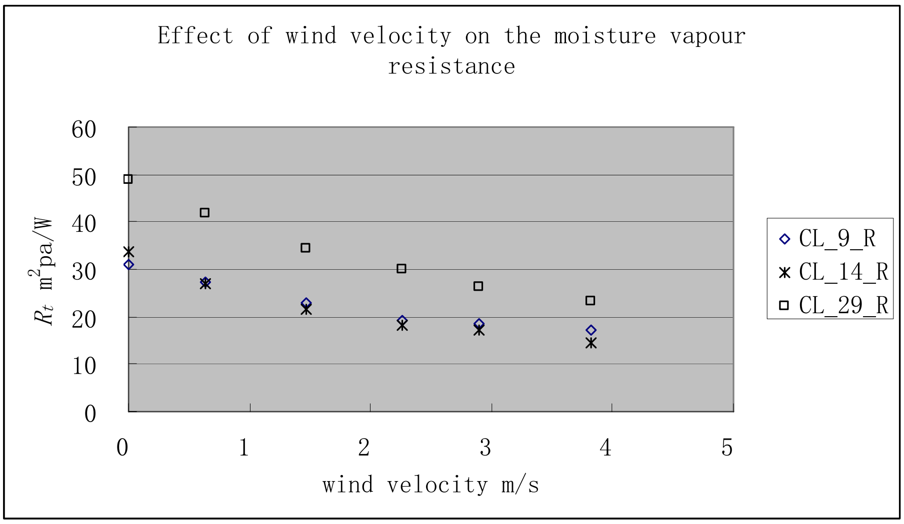


Figure 6-2 (b) Clothing moisture vapour resistance vs. wind velocity

Let the reduction ratio for thermal insulation be *FI* and that for moisture vapour resistance be *FR*, viz:

$$I_{st} = (1 + FI)I_{tdyn} \tag{6-10}$$

$$FI = \frac{I_{st} - I_{tdyn}}{I_{tdyn}} \tag{6-11}$$

$$R_{st} = (1 + FR)R_{tdyn} \tag{6-12}$$

$$FR = \frac{R_{st} - R_{tdyn}}{R_{tdyn}} \tag{6-13}$$

The reduction ratios, *FI* and *FR*, are related to the wind velocity. Figures 6-3 (a) and (b) as examples plot the reduction ratios, *FI* and *FR*, against the wind velocity for three clothing ensembles. As can be seen, the reduction ratios, *FI* and *FR*, have approximately linear relations with the wind velocity. The slopes of *FI* and *FR* versus the wind velocity may vary with different types of clothing ensembles. Figures 6-4(a) and (b) plot the *FI* and *FR* versus the wind for all clothing ensembles tested in this study. As can be seen, the approximate linear relationship between *FI* or *FR* and the wind velocity holds for all clothing ensembles tested and the slopes vary within certain ranges.

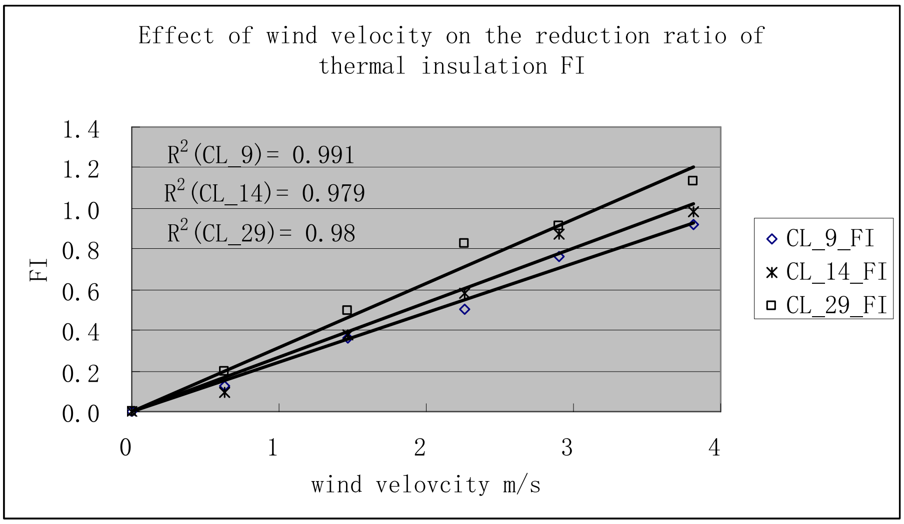


Figure 6-3 (a) *FI* vs. wind velocity for three clothing ensembles

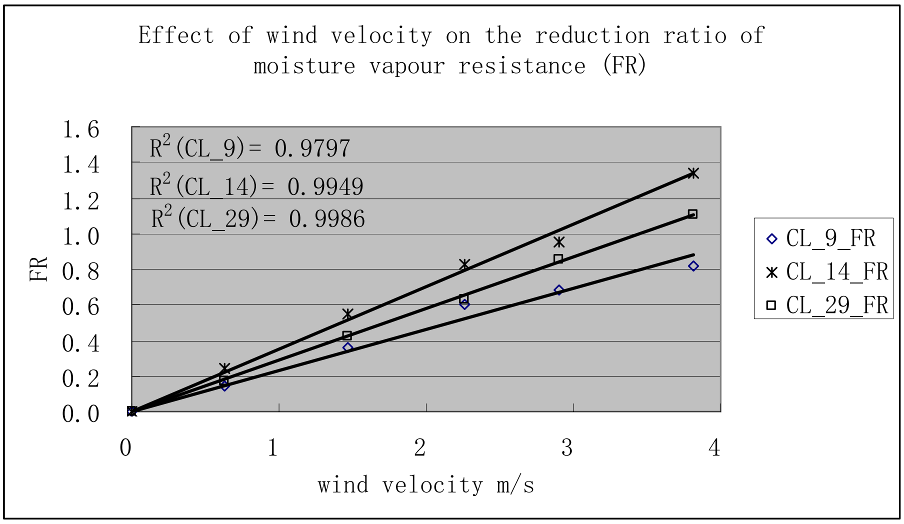


Figure 6-3 (b) *FR* vs. wind velocity for three clothing ensembles

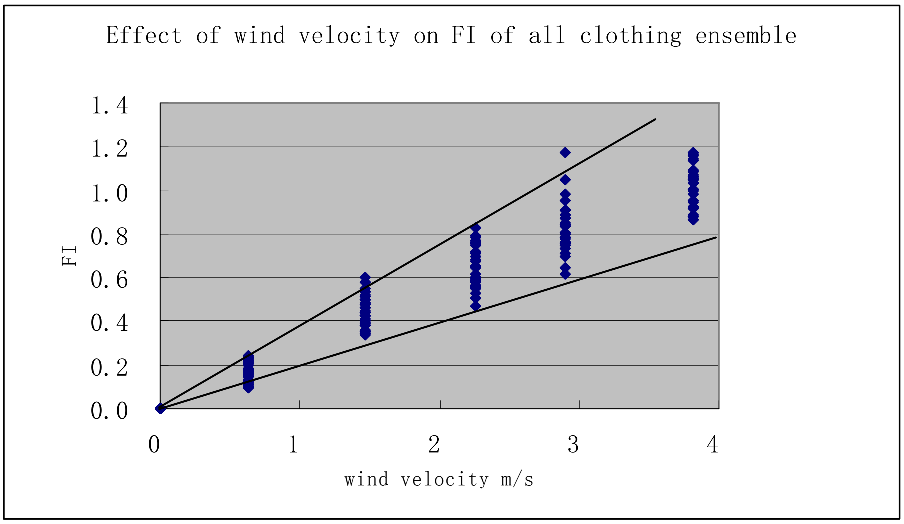


Figure 6-4 (a) *FI* vs. wind velocity for all clothing ensembles

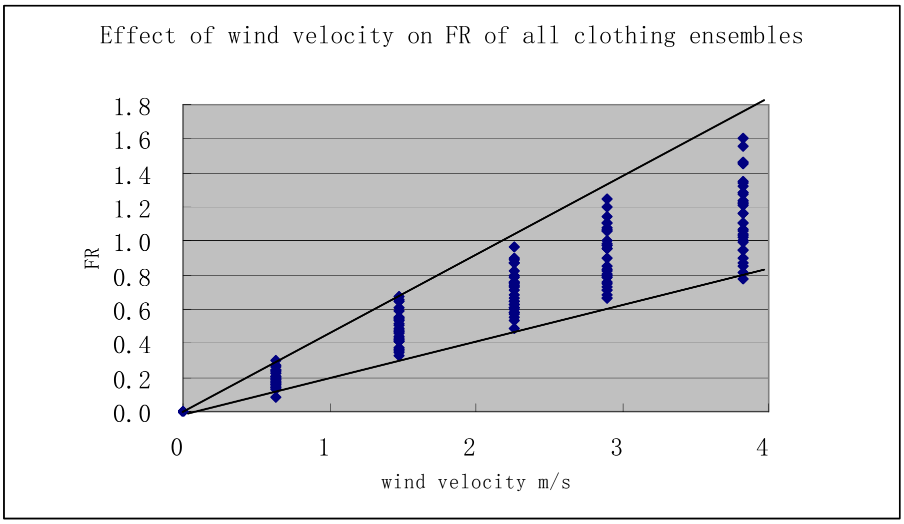


Figure 6-4(b) *FR* vs. wind velocity for all clothing ensembles

Therefore, we can assume:

$$FI = KI(V_{wind} - v_0) \quad (6\text{-}14)$$

$$FR = KR(V_{wind} - v_0) \quad (6\text{-}15)$$

where, *KI* and *KR* are the slopes of Figure 6-4(a) and (b), respectively; v_0 is the air current in the "still" air condition, i.e. the condition under which I_{st} and R_{st} are measured. In this study,

$$v_0=0.22\ m/s. \tag{6-16}$$

KI and *KR* can be obtained by linear regression for each clothing ensemble. The values are list in Table 6-4.

Table 6-4 Values of *KI* and *KR* for different clothing ensembles in the case of standing in windy conditions

CL_ID	*KI*(wind)	R^2 (*KI*)	*KR*(wind)	R^2 (*KR*)
1	0.26	1.00	0.35	0.99
2	0.26	0.99	0.33	1.00
3	0.29	0.97	0.38	0.99
4	0.29	0.99	0.42	1.00
5	0.25	0.98	0.26	1.00
6	0.23	1.00	0.27	1.00
7	0.26	0.98	0.34	1.00
8	0.28	0.99	0.37	0.99
9	0.24	0.99	0.23	0.98
10	0.24	1.00	0.28	1.00
11	0.24	0.97	0.32	0.99
12	0.29	0.98	0.34	0.99
13	0.25	1.00	0.37	0.99
14	0.27	0.98	0.35	0.99
15	0.31	0.99	0.41	0.99
16	0.27	0.98	0.36	0.99
17	0.30	0.98	0.36	0.97
18	0.31	0.98	0.33	1.00
19	0.29	0.98	0.28	1.00
20	0.26	0.98	0.28	1.00
21	0.26	0.95	0.24	0.99
22	0.31	0.97	0.24	1.00
23	0.28	0.99	0.25	0.99
24	0.22	0.99	0.22	0.99
25	0.28	0.99	0.25	0.99
26	0.34	0.92	0.25	1.00
27	0.29	0.98	0.30	0.99
28	0.32	0.99	0.34	0.99
29	0.32	0.98	0.29	1.00
30	0.25	0.97	0.27	1.00
31	0.28	0.99	0.24	0.98
32	0.33	0.98	0.28	0.99

6.4.2 Effect of walking speed

Figures 6-5(a) and (b) plots the clothing thermal insulation and moisture vapour resistance against walking speed for three clothing ensembles under two windy conditions. As can be seen that the clothing thermal insulation and moisture vapour resistance decrease with increasing walking speed, and the ratio of reduction decreases with increasing walking speed and wind velocity. This is similar to the effect of wind velocity on clothing thermal insulation and moisture vapour resistance

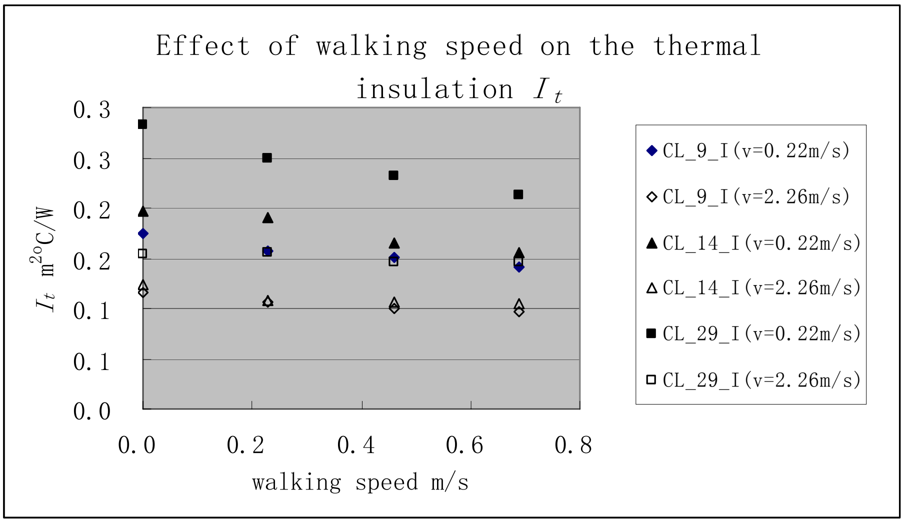


Figure 6-5 (a) Total clothing thermal insulation vs. walking speed for three clothing ensembles

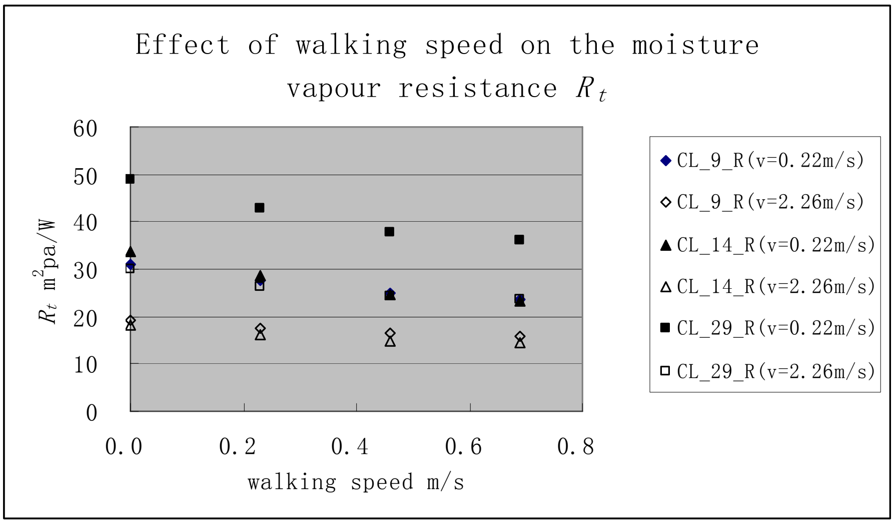


Figure 6-5 (b) Total clothing moisture vapour resistance vs. walking speed for three clothing ensembles

Therefore, we can use an equivalent wind velocity to take into account the effect of walking speed. In analogy to the definition of effective wind velocity v_{eff} for the surface thermal insulation and surface moisture vapour resistance discussed in Chapter 5, let's define an equivalent wind velocity V_F as

$$v_F = V_{wind} + \beta_F V_{walk} + v_0 \qquad (6\text{-}17)$$

where, β_F is an equivalent air velocity factor for "walking" motion on the reduction ratio of total thermal insulation and moisture vapour resistance.

Using the values of KI and KR listed in Table 6-4, β_F can be obtained by fitting Equations (6-14) and (6-15) using v_F in the place of V_{wind}. It was found:

$$\beta_F = 1.8 \qquad (6\text{-}18)$$

with a percentage of fit (R^2) being 0.97.

6.4.3 The new regression model

Substituting Equations (6-10) and (6-12) with Equations (6-14), (6-15), (6-16), (6-7), (6-18), we have:

$$\frac{I_{tdyn}}{I_{st}} = \frac{1}{1 + KI(V_{wind} + 1.8V_{walk} - v_0)} \quad (6\text{-}19)$$

$$\frac{R_{tdyn}}{R_{st}} = \frac{1}{1 + KR(V_{wind} + 1.8V_{walk} - v_0)} \quad (6\text{-}20)$$

When the body is walking in wind, according to the Equations (6-19) and (6-20), the *KI* and *KR* for each clothing ensemble can be regressed using the experimental data. They are listed in Table 6-5.

Table 6-5 Values of *KI* and *KR* for different clothing ensembles in the case of walking in windy conditions

CL_ID	*KI*	R^2	*KR*	R^2	*Style*	Fit index	*Ap* *(l/s.m^{2}pa)*	*Underwear*
1	0.26	0.98	0.35	0.99	Jacket	2.9	20.6133	without
2	0.26	0.98	0.33	0.99	Jacket	5.2	20.6133	without
3	0.27	0.96	0.38	0.99	Jacket	8.7	20.6133	without
4	0.29	0.99	0.42	0.99	Jacket	11.6	20.6133	without
5	0.24	0.95	0.28	0.99	Jacket	2.9	1.0761	without
6	0.24	0.98	0.28	0.98	Jacket	5.2	1.0761	without
7	0.26	0.99	0.34	0.99	Jacket	8.7	1.0761	without
8	0.28	0.98	0.38	0.99	Jacket	11.6	1.0761	without
9	0.24	0.99	0.25	0.96	Jacket	2.9	0.0392	without
10	0.24	0.97	0.29	0.99	Jacket	5.2	0.0392	without
11	0.25	0.97	0.33	0.98	Jacket	8.7	0.0392	without
12	0.28	0.96	0.37	0.97	Jacket	11.6	0.0392	without
13	0.24	0.99	0.37	0.99	Jacket	10.3	4.2415	without
14	0.27	0.98	0.37	0.98	Shirt	11.3	1.7480	without
15	0.31	0.99	0.41	0.99	Uniform	11.1	1.4488	without
16	0.27	0.98	0.38	0.98	Jacket_2	12.2	0.0280	without
17	0.30	0.97	0.39	0.97	Shirt	12.2	0.0280	without
18	0.30	0.98	0.36	0.98	Jacket_1	14.5	0.0166	without
19	0.27	0.96	0.29	0.99	Jacket		20.6133	with
20	0.26	0.96	0.28	0.99	Jacket		4.2415	with
21	0.26	0.97	0.26	0.97	Shirt		1.7480	with
22	0.30	0.97	0.25	0.98	Uniform		1.4488	with
23	0.27	0.98	0.26	0.98	Jacket		1.0761	with
24	0.21	0.96	0.23	0.98	Jacket		0.0392	with
25	0.28	0.99	0.26	0.98	Jacket_2		0.0280	with
26	0.33	0.95	0.29	0.93	Shirt		0.0280	with
27	0.30	0.98	0.30	0.99	Jacket_1		0.0166	with
28	0.30	0.95	0.35	0.99	Jacket_1	24.3	0.0000	with
29	0.30	0.97	0.30	0.99	Jacket_2	23.9	0.0000	with
30	0.25	0.96	0.29	0.98	Jacket_1		0.0000	with
31	0.29	0.98	0.28	0.93	Jacket_2		0.0000	with
32	0.30	0.93	0.33	0.93	Jacket_1	20.3	0.0000	with
Average	0.27		0.32					
S.D.	0.03		0.05					

Using the average values of *KI* and *KR*, we have:

$$\frac{I_{tdyn}}{I_{st}} = \frac{1}{1+0.27(V_{wind}+1.8V_{walk}-v_0)} \tag{6-21}$$

$$\frac{R_{tdyn}}{R_{st}} = \frac{1}{1+0.32(V_{wind}+1.8V_{walk}-v_0)} \tag{6-22}$$

With Equations (6-21) and (6-22), clothing thermal insulation and moisture vapour resistance under windy conditions and walking motion can be predicted from those measured when the manikin is standing in "still" air condition. Figures 6-6(a) and (b) plot the predicted clothing thermal insulation and moisture vapour resistance against the measured values. As can be seen, the model fit the testing data very well with a percentage of fit (R^2) of 0.97.

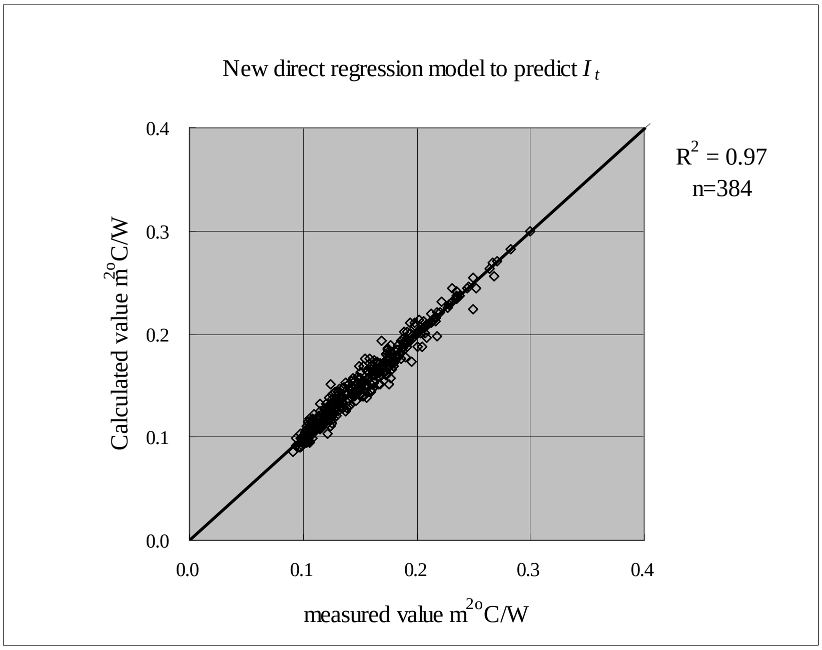


Figure 6-6 (a) Measured thermal insulation vs. predicted values using the new model

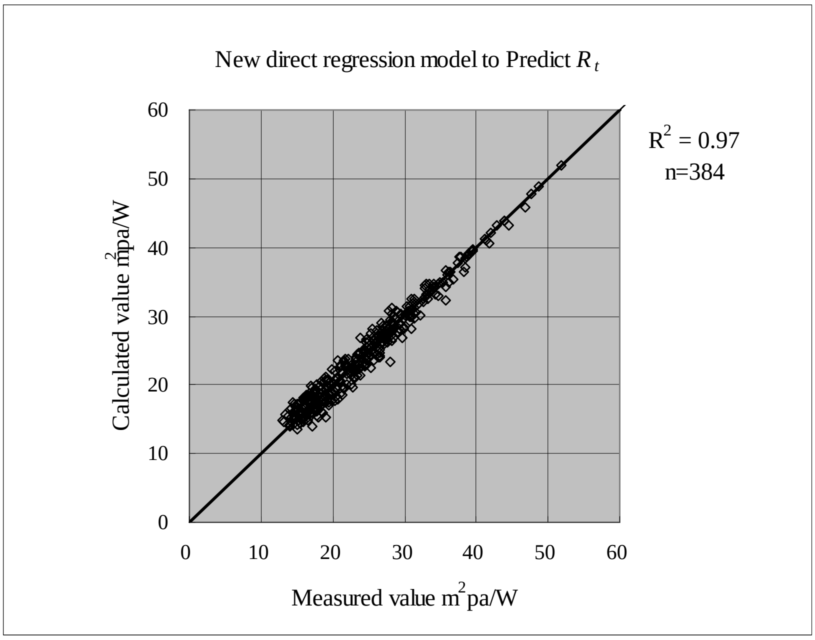


Figure 6-6 (b) Measured moisture vapour resistance vs. predicted values using the new model

6.4.4 Effects of clothing characteristics on *KI* and *KR*

In Table 6-5, it can be seen that *KI* may vary from 0.24 to 0.31, and *KR* may vary from 0.23 to 0.42, depending on the characteristics of clothing ensembles. In order to establish how clothing parameters relate to *KI* and *KR*, an ANOVA analysis was conducted and the results are listed below.

Table 6-6 (a) ANOVA results of the effects of clothing parameters on *KI*

Tests of Between-Subjects Effects

Dependent Variable: KI

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.975E-02[a]	18	1.097E-03	6.958	.000
Intercept	1.712	1	1.712	10855.00	.000
AP	7.167E-04	2	3.583E-04	2.272	.142
FITINDEX	4.866E-03	7	6.951E-04	4.408	.010
STYLE	1.600E-03	1	1.600E-03	10.146	.007
UNDERWEA	1.333E-04	1	1.333E-04	.846	.375
Error	2.050E-03	13	1.577E-04		
Total	2.398	32			
Corrected Total	2.180E-02	31			

a. R Squared = .906 (Adjusted R Squared = .776)

Table 6-6 (b) ANOVA results of the effects of clothing parameters on *KR*

Tests of Between-Subjects Effects

Dependent Variable: KR

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	7.893E-02[a]	18	4.385E-03	9.554	.000
Intercept	2.319	1	2.319	5052.773	.000
AP	8.267E-03	2	4.133E-03	9.006	.004
FITINDEX	2.036E-02	7	2.909E-03	6.338	.002
STYLE	4.000E-04	1	4.000E-04	.872	.368
UNDERWEA	3.413E-02	1	3.413E-02	74.369	.000
Error	5.967E-03	13	4.590E-04		
Total	3.368	32			
Corrected Total	8.490E-02	31			

a. R Squared = .930 (Adjusted R Squared = .832)

It can be seen from Table 6-6 (a) and (b), that *KI* and *KR* are significantly affected by the garment air permeability of the outer fabric, fit index and garment style as well as whether or not there is underwear on the body.

To estimate the values of *KI* and *KR* for prediction in convenience, clothing ensembles may be categorized according to the garment fit, the air permeability of the outer fabrics and whether there is underwear. If we categorize the air permeability and garment fit according to Table 6-7, the values of *KI* and *KR* for each category may be derived (garment style is were not classified due to insufficient data on the variation). They are listed in Table 6-8 (a) and (b).

Table 6-7 Categorization of clothing ensembles based on garment fit and air permeability

Air permeability category	*ap* value	Fit category	*Fit index*
Low	< 1 l/sm^{2}pa	S	2.9 ~ 5.2
Moderate	1~4 l/sm^{2}pa	M (fit to body)	8.7 ~ 14.5
High	> 4 l/sm^{2}pa	L	20.3 ~ 24.3

Table 6-8(a) *KI* values for each category of clothing ensembles.

Case Summaries

KI

UNDERWER	AP	FITINDEX	Mean	Std. Error of Mean	Minimum	Maximum
with	High	M	.2650	.00500	.26	.27
		Total	.2650	.00500	.26	.27
	Low	L	.2880	.00970	.25	.30
		M	.2800	.02550	.21	.33
		Total	.2844	.01168	.21	.33
	Moderate	M	.2767	.01202	.26	.30
		Total	.2767	.01202	.26	.30
	Total	L	.2880	.00970	.25	.30
		M	.2756	.01119	.21	.33
		Total	.2800	.00791	.21	.33
without	High	M	.2667	.01453	.24	.29
		S	.2600	.00000	.26	.26
		Total	.2640	.00812	.24	.29
	Low	M	.2800	.00949	.25	.30
		S	.2400	.00000	.24	.24
		Total	.2686	.00986	.24	.30
	Moderate	M	.2800	.01080	.26	.31
		S	.2400	.00000	.24	.24
		Total	.2667	.01085	.24	.31
	Total	M	.2767	.00607	.24	.31
		S	.2467	.00422	.24	.26
		Total	.2667	.00542	.24	.31
Total	High	M	.2660	.00812	.24	.29
		S	.2600	.00000	.26	.26
		Total	.2643	.00571	.24	.29
	Low	L	.2880	.00970	.25	.30
		M	.2800	.01155	.21	.33
		S	.2400	.00000	.24	.24
		Total	.2775	.00788	.21	.33
	Moderate	M	.2786	.00738	.26	.31
		S	.2400	.00000	.24	.24
		Total	.2700	.00799	.24	.31
	Total	L	.2880	.00970	.25	.30
		M	.2762	.00575	.21	.33
		S	.2467	.00422	.24	.26
		Total	.2725	.00469	.21	.33

Table 6-8 (b) *KR* values for each category of clothing ensembles.

Case Summaries

KR

UNDERWER	AP	FITINDEX	Mean	Std. Error of Mean	Minimum	Maximum
with	High	M	.2850	.00500	.28	.29
		Total	.2850	.00500	.28	.29
	Low	L	.3100	.01304	.28	.35
		M	.2700	.01581	.23	.30
		Total	.2922	.01176	.23	.35
	Moderate	M	.2567	.00333	.25	.26
		Total	.2567	.00333	.25	.26
	Total	L	.3100	.01304	.28	.35
		M	.2689	.00754	.23	.30
		Total	.2836	.00843	.23	.35
without	High	M	.3900	.01528	.37	.42
		S	.3400	.01000	.33	.35
		Total	.3700	.01517	.33	.42
	Low	M	.3660	.01030	.33	.39
		S	.2700	.02000	.25	.29
		Total	.3386	.01957	.25	.39
	Moderate	M	.3750	.01443	.34	.41
		S	.2800	.00000	.28	.28
		Total	.3433	.02201	.28	.41
	Total	M	.3750	.00733	.33	.42
		S	.2967	.01498	.25	.35
		Total	.3489	.01120	.25	.42
Total	High	M	.3480	.02709	.28	.42
		S	.3400	.01000	.33	.35
		Total	.3457	.01888	.28	.42
	Low	L	.3100	.01304	.28	.35
		M	.3233	.01886	.23	.39
		S	.2700	.02000	.25	.29
		Total	.3125	.01199	.23	.39
	Moderate	M	.3243	.02515	.25	.41
		S	.2800	.00000	.28	.28
		Total	.3144	.02028	.25	.41
	Total	L	.3100	.01304	.28	.35
		M	.3295	.01283	.23	.42
		S	.2967	.01498	.25	.35
		Total	.3203	.00925	.23	.42

It can be seen from Table 6-8 that *KI* and *KR* increase with increasing air permeability and garment size.

6.4.5 Quantitative relationship between *KI* and *KR* and clothing fit, air permeability and thickness of outer fabric

Nonlinear regression was conducted to establish the quantitative relationship between *KI* and *KR* and garment fit index, air permeability and fabric thickness for one style of clothing which consists of a jacket and a pairs of pants without underwear. We can obtain the following equations:

$$KI = 0.0122\ln(\frac{Fit^2\sqrt{ap}}{th^2}) + 0.2106 \qquad R^2 = 0.80 \qquad (6\text{-}23)$$

$$KR = 0.0222\ln(\frac{Fit^3\sqrt{ap}}{th^{0.2}}) + 0.2143 \qquad R^2 = 0.81 \qquad (6\text{-}24)$$

where, *Fit* is the value of fit index, and *th* is the thickness of garment fabrics.

The values of *KI* and *KR* for the clothing ensembles without underwear in Table 6-5 are compared with those predicted using Equations (6-23) and (6-24) in Figures 6-7(a) and (b).

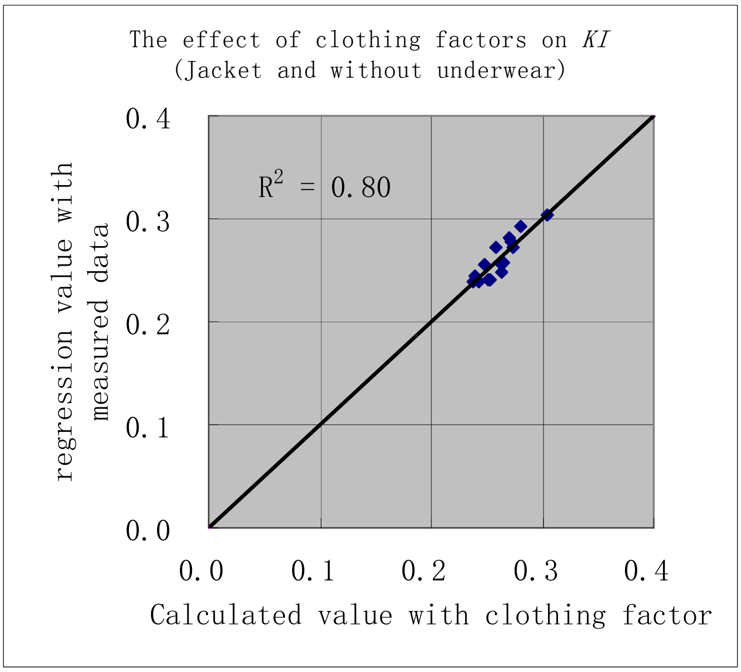


Figure 6-7 (a) Value of *KI* in Table 6-5 vs. predicted *KI* value using Equation (6-23)

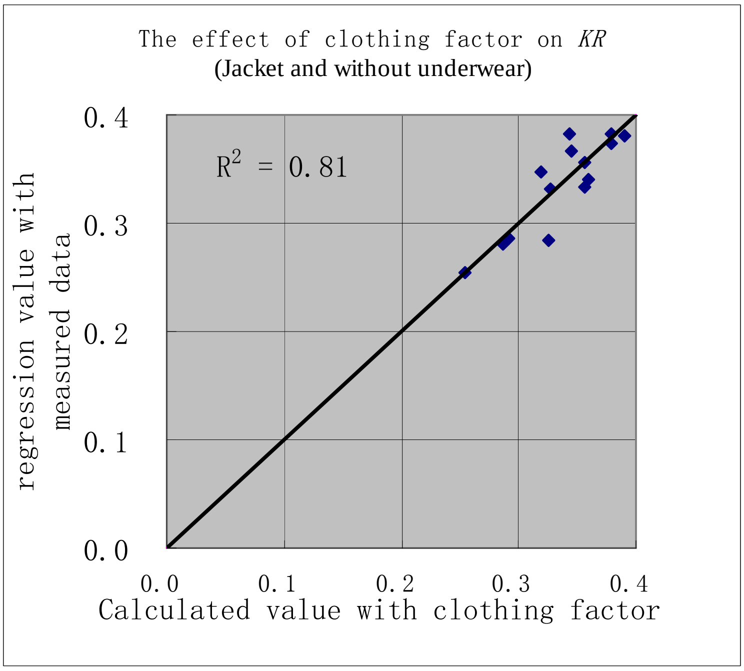


Figure 6-7 (b) Value of *KR* in Table 6-5 vs. predicted *KR* value using Equation (6-24)

Similarly, we can also establish the prediction equations for the style of ensemble which consists of inner underwear, an outer jacket and a pair of pants. These are:

$$KI = 0.0141\ln\left(\frac{Fit^3\sqrt{ap}}{th}\right) + 0.1774 \qquad R^2 = 0.32 \qquad (6\text{-}25)$$

$$KR = 0.0331\ln\left(\frac{Fit^3\sqrt{ap}}{th^{0.5}}\right) + 0.0609 \qquad R^2 = 0.65 \qquad (6\text{-}26)$$

The values of *KI* and *KR* for the clothing ensembles with underwear_1 in Table 6-5 are compared with those predicted using Equations (6-25) and (6-26) in Figures 6-8(a) and (b).

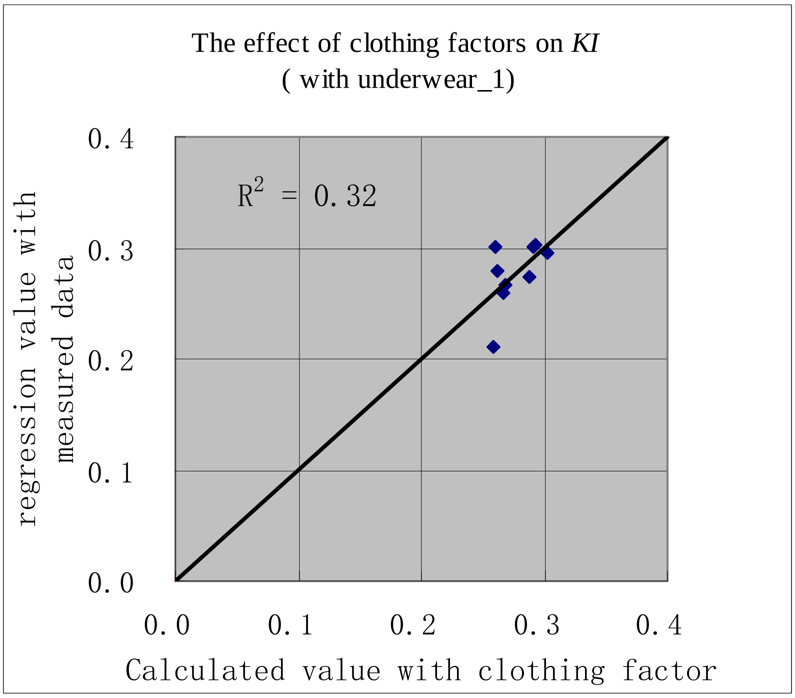


Figure 6-8 (a) Value of *KI* in Table 6-5 vs. predicted *KI* value using Equation (6-25)

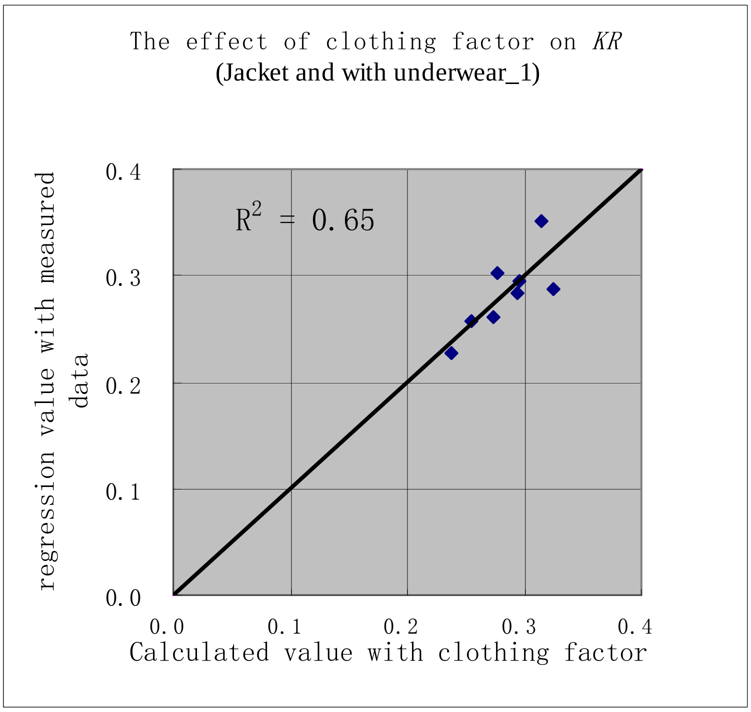


Figure 6-8 (b) Value of *KR* in Table 6-5 vs. predicted *KR* value using Equation (6-26)

6.5 Concluding remarks

Based on the improved understanding of the effects of wind and walking motion on the clothing thermal insulation and moisture vapour resistance, a simple, but effective regression model is established. The model can take into account the effects of clothing characteristics through the relationship between the two ratios in the model, viz. *KI* and *KR*, and the clothing parameters. The new model fit the testing data very well with a percentage of fit being as high as 0.97.

Chapter 7

A Quasi-physical Model for Predicting the Clothing Thermal Insulation and Moisture Vapour Resistance

7.1 Introduction

The direct regression model reported in Chapter 6, although very simple and accurate in predicting the dynamic clothing thermal insulation and moisture vapour resistance under body movement and windy conditions from the clothing thermal insulation value measured when the person is standing in the still air, has not considered the fundamental mechanism of heat and moisture transfer.

In this chapter, a new model has therefore been derived. This model is a hybrid of physical and regression model in that the fundamental mechanisms of heat and moisture transfer, which include conduction, diffusion, radiation, natural convection, wind penetration and air ventilation, are considered and the key parameters in the model, which is relate to the clothing physical characteristics such as clothing style, fit, air permeability of clothing fabrics, are determined by statistical regression.

7.2 Description of model

7.2.1 Heat and mass transfer through clothing systems

Consider a typical clothing system which consists of close-fitting inner garment(s) and a loose-fitting outer garment(s) as shown in Figure 7-l.

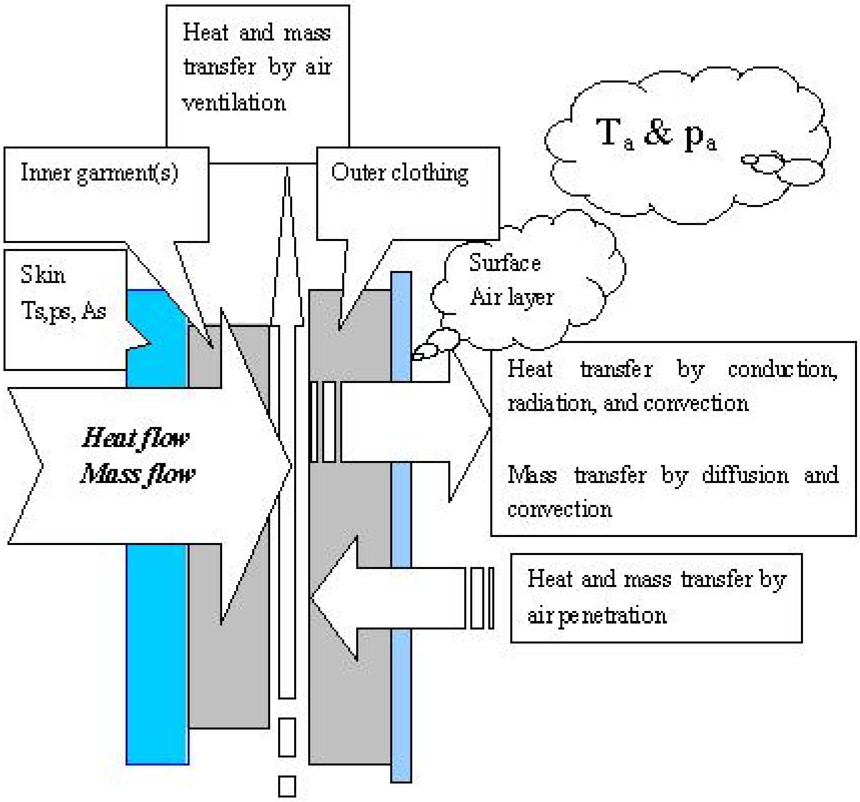


Figure 7-1 Heat and mass transfer from human body covered with a clothing ensemble

When a clothed person is walking in wind, the loose outer garment(s) may flap, pumping out warm air and moisture vapor from the air gap between the tight-fitting inner garment(s) and the loose-fitting outer garment(s) and replacing it by cooler air from the surrounding environment, and at the same time wind may penetrate through the outer garment(s) to create heat and mass exchange. Consequently, if there is no condensation and absorption of moisture vapour in the clothing layer, the heat generated by body metabolism will be transferred to the environment as sensible and evaporative heat by radiation, conduction, convection, air ventilation and penetration.

The actual process of the heat and mass transfer through clothing system is generally very complicated. In order to simplify the analysis under steady state, the dry heat flow through clothing is considered as consisting of two parts; the part induced by conduction, convection and radiation, and the other part induced by air ventilation and wind penetration. Similarly the evaporative heat is also regarded as consisting of two parts; the part induced by diffusion and convection and the other part induced by air ventilation and wind penetration.

"Air ventilation" can be further classified into direct ventilation and indirect ventilation. Direct ventilation refers to the exchange of garment microclimate air with ambient air through openings of the garment itself or those which result from the manner in which it is worn (Crockford, et al 1972). Indirect ventilation refers to the exchange of garment microclimate air which passes through the materials from which the garment assembly is made. That is to say the air exchanges between the microclimate and ambient caused by ventilation is irrespective of the avenue through which it passes (Laing and Sleivert 2002). It is difficult to clearly distinguish wind or air penetration and indirect air ventilation through clothing systems. The amounts of indirect ventilation may include those of wind penetration.

As Figure 7-1 shows, the dry heat (H_{dt}) generated by human body will pass through the inner clothing system (H_{dci}) and then separated into two parts. The first part (H_{dcom}) is lost by conduction (H_{dcon}), convection (H_{dc}) and radiation (H_{dr}) through the outer garments, and the second part is lost by air ventilation and/or wind penetration (H_{dv}) directly into the environment, viz.

$$H_{dt} = H_{dci} = H_{dcom} + H_{dv} = H_{dcon} + H_{dc} + H_{dr} + H_{dv} \quad (7\text{-}1)$$

Since H_{dcom} must pass through the outer garments and the outer surface of the clothing ensemble, we have

$$H_{dcom} = H_{dco} = H_{doa} \quad (7\text{-}2)$$

where, $H_{dco}$is the dry heat loss through the outer garments and H_{doa} is the dry heat loss from the outer surface of clothing ensemble.

Similarly, after passing through the inner garment(s) (H_{eci}), the total evaporative heat (H_{et}) generated by sweat evaporation will be separated into two parts: evaporative heat loss through the outer garments (H_{ecom}) and evaporative heat loss directly into the environment by air ventilation and/or wind penetration (H_{ev}), viz.

$$H_{et} = H_{eci} = H_{ev} + H_{ecom} \quad (7\text{-}3)$$

Since the evaporative heat loss by moisture transfer must go through the outer garments and the outer surface of the ensemble, we have

$$H_{ecom} = H_{eco} = H_{eoa} \qquad (7\text{-}4)$$

where, H_{eco} is the evaporative or latent heat transfer through outer garments and H_{eoa} is the evaporative or latent heat loss from the outer surface of the clothing ensemble.

7.2.2 Derivation of model

According to the heat transfer principle, for total dry heat transfer, we have:

$$H_{dt} = \frac{A_s(T_s - T_a)}{I_t} \qquad (7\text{-}5)$$

where, T_s and T_a are the mean skin temperature and the environment temperature, respectively. A_s is the surface area of the human body or a manikin. I_t is the total thermal insulation of the clothing system;

For heat transfer through inner garments, we assume the temperature of the outer surface of the inner garments is the same as the temperature of the inner surface of the outer garments. This is justifiable as the air movement within the inner microclimate will make the temperature difference very small. We therefore have

$$H_{dci} = \frac{A_s(T_s - T_{ci})}{I_{ci}} \tag{7-6}$$

where, T_{ci} is the mean temperature of the air gap in-between the inner and outer garment(s). I_{ci}, *is* the thermal insulation of the inner garment(s).

$$H_{dco} = \frac{A_s f_{ci}(T_{ci} - T_{co})}{I_{co}} \tag{7-7}$$

where, T_{co} is the mean outer surface temperature of outer garments, f_{ci} is the area factors of the inner garments.. I_{oa} is the thermal insulation of the outer garment(s).

$$H_{doa} = \frac{A_s f_{co}(T_{co} - T_a)}{I_{oa}} \tag{7-8}$$

where, f_{co} is the area factor of the outer garments. I_{oa} is the thermal insulation of the outer surface still air layer of the clothing system.

$$H_{dcom} = \frac{A_s f_{ci}(T_{ci} - T_a)}{I_{com}} \tag{7-9}$$

where, I_{com} is the total of thermal insulation including the outer garment(s) and the outer surface still air layer.

Assuming all dry heat loss by air ventilation and wind penetration is resulted from the exchange of warm air in-between the inner and outer garments and the cold air in the environments, we have

$$H_{dv} = h_{dv} A_s f_{ci} (T_{ci} - T_a) \quad (7\text{-}10)$$

where, h_{dv} is the equivalent dry heat transfer coefficient induced by ventilation and/or wind penetration.

From the above heat transfer equations, for a clothed person standing in still air, the total intrinsic thermal insulation of the clothing ensemble can be calculated by:

$$I_c = I_{ci} + \frac{I_{co}}{f_{ci}} \quad (7\text{-}11)$$

Let m be the fraction of the intrinsic thermal insulation of the inner garment(s) from that of the total clothing system for a clothed person standing in still air, viz

$$m = \frac{I_{ci}}{I_c} \quad (0 \le m \le 1), \quad (7\text{-}12)$$

We have:

$$I_{co} = (1 - m) f_{ci} I_c \tag{7-13}$$

Let I_{mix} be the thermal insulation of the outer garments reduced by air ventilation and/or wind penetration, viz.

$$H_{dv} + H_{dcom} = \frac{A_s f_{ci} (T_{ci} - T_a)}{I_{mix}} \tag{7-14}$$

From Equation (7-9), (7-10) and (7-14), we can have

$$\frac{1}{I_{mix}} = h_{dv} + \frac{1}{I_{com}} \tag{7-15}$$

From Equation (7-2), (7-7), (7-8) and (7-9), we have

$$I_{com} = I_{co} + \frac{f_{ci}}{f_{co}} I_{oa} \tag{7-16}$$

From Equation (7-1), (7-5), (7-6) and (7-14) we have

$$I_t = I_{ci} + \frac{I_{mix}}{f_{ci}} \tag{7-17}$$

The total thermal insulation of the clothing system can therefore be calculated by

$$\begin{aligned} I_t &= I_{ci} + \frac{I_{mix}}{f_{ci}} \\ &= mI_c + \cfrac{1}{f_{ci} h_{dv} + \cfrac{1}{(1-m) I_c + \cfrac{1}{f_{co}} I_{oa}}} \end{aligned} \qquad (7\text{-}18)$$

Similarly, we can have the following equations for calculating the moisture vapour resistance:

$$R_c = R_{ci} + \frac{R_{co}}{f_{ci}} \qquad (7\text{-}19)$$

Let n be the fraction of the intrinsic moisture vapour resistance of inner garment(s) from that of the total clothing system for a clothed person standing in still air, viz.

$$n = \frac{R_{ci}}{R_c} \quad (0 \le n \le 1), \qquad (7\text{-}20)$$

Then:

$$R_{co} = (1-n) f_{ci} R_c \qquad (7\text{-}21)$$

$$R_t = nR_c + \frac{R_{mix}}{f_{ci}}$$
$$= nR_c + \frac{1}{f_{ci} h_{ev} + \dfrac{1}{(1-n)R_c + \dfrac{1}{f_{co}} R_{oa}}} \tag{7-22}$$

where, R_t is the total moisture vapour resistance of clothing ensemble system in $p_a m^2/W$; R_{ci}, R_{co} and R_{oa} are the moisture vapour resistance of the inner garment(s), outer garment(s) and the outer surface still air layer of the clothing system, respectively. h_{ev} is the equivalent latent heat transfer coefficient induced by ventilation.

Let:

$$h_{dev} = h_{dv} f_{ci}, \tag{7-23}$$

$$h_{eev} = h_{ev} f_{ci} \tag{7-24}$$

h_{dev} and h_{eev} are defined as the effective dry heat and latent heat transfer coefficient by air ventilation and/or wind penetration, respectively. In order to distinguish the total static thermal insulation and moisture vapour resistance for a clothed person standing in still air, the symbols of I_{tdyn} and R_{tdyn} are used to substitute I_t and R_t, We have:

$$I_{tdyn} = mI_c + \frac{1}{h_{dev} + \frac{1}{(1-m)I_c + \frac{1}{f_{co}} I_{oa}}} \qquad (7\text{-}25)$$

$$R_{tdyn} = nR_c + \frac{1}{h_{eev} + \frac{1}{(1-n)R_c + \frac{1}{f_{co}} R_{oa}}} \qquad (7\text{-}26)$$

For the model described by Equation (7-25) and (7-26), there are four extreme cases as follows:

(1), A clothed person standing in still air. Due to no ventilation, the inner and outer garments can be considered as a whole, thus, $h_{dev}=h_{eev}=0$, $m=1$ $n=1$, Equation (7-25) and (7-26) can be re-written as the well known form:

$$I_t = I_c + \frac{I_{oa}}{f_{co}} \qquad (7\text{-}27)$$

$$R_t = R_c + \frac{R_{oa}}{f_{co}} \qquad (7\text{-}28)$$

(2), A nude person. In this case, $I_c=0$, $m=0$, $n=0$, $h_{dev}=h_{eev}=0$, hence:

$$I_t = I_{oa} \qquad (7\text{-}29)$$

$$R_t = R_{oa} \tag{7-30}$$

(3), No inner garment(s). In this case, $m=0$ and $n=0$, $f_{ci}=1$ and $I_{co}=I_c$, hence:

$$I_t = \frac{1}{h_{dev} + \frac{1}{I_c + \frac{1}{f_{co}} I_{oa}}} \tag{7-31}$$

$$R_t = \frac{1}{h_{eev} + \frac{1}{R_c + \frac{1}{f_{co}} R_{oa}}} \tag{7-32}$$

(4), No outer garment(s), viz. the inner garment(s) is tightly fit to the body and impenetrable to air (Otherwise, the garment(s) will be considered as the outer garment(s)). In this case, $I_{co}=0$, $I_c=I_{ci}$, $m=1$, $n=1$, hence:

$$I_t = I_{ci} + \frac{I_{oa}}{f_{ci}} \tag{7-33}$$

$$R_t = R_{ci} + \frac{R_{oa}}{f_{ci}} \tag{7-34}$$

7.2.3 Determination of parameters in the model

7.2.3.1 Thermal insulation and moisture vapour resistance of the outer surface of the clothing ensemble (I_{oa} and R_{oa})

As discussed in Chapter 5, the heat loss through the outer surface air layer of clothing ensemble is transferred by convection and radiation. The surface insulation can be estimated using the following equation:

$$I_{oa} = \frac{1}{h_r + h_c} \tag{7-35}$$

where, h_r is the radiative heat transfer coefficient ($h_r=5\ W/m^2K$)and h_c is the convective heat transfer coefficient.

Since the convective heat loss varies with body activity level and the wind velocity, the following equations were proposed to calculate I_{oa}:

For a clothed person walking in wind, we have (See Chapter 5):

$$I_{oa} = \frac{1}{5 + 8.3\sqrt{0.11 + 0.45V_{walk} + V_{wind}}} \tag{7-36}$$

For the surface moisture vapour resistance, R_{oa}, we have (See Chapter 5):

$$R_{oa} = \frac{1}{0.0165 \times 8.3\sqrt{0.11 + 0.45V_{walk} + V_{wind}}} \tag{7-37}$$

The values of I_{oa} and R_{oa} used in the present study are calculated by using equation 7-36 and 7-37 and listed in Table 7-1.

Table 7-1 The calculated thermal insulation and moisture vapour resistance of outer surface air layer

V_{wind} m/s	V_{walk} m/s	v_{eff} m/s	I_{oa} $m^{2o}C/W$	R_{oa} m^2p_a/W
0.22	0.00	0.33	0.102	12.71
0.22	0.23	0.43	0.096	11.09
0.22	0.46	0.54	0.090	9.97
0.22	0.69	0.64	0.086	9.13
0.85	0.00	0.96	0.076	7.45
1.69	0.00	1.80	0.062	5.44
2.48	0.00	2.59	0.054	4.54
2.48	0.23	2.69	0.054	4.45
2.48	0.46	2.80	0.053	4.37
2.48	0.69	2.90	0.052	4.29
3.12	0.00	3.23	0.050	4.06
4.04	0.00	4.15	0.046	3.58

7.2.3.2 Other parameters in the model (I_c, R_c , I_{ci}, R_{ci} , f_{co} ,f_{ci}, m, n)

I_{ci}, R_{ci}, I_c, R_c are defined as the intrinsic thermal insulation and moisture vapour resistance of the inner garment(s), and the entire clothing ensemble, respectively. They can be calculated from total thermal insulation or moisture vapour resistance of inner garment tested alone in standing and "still" air condition, and the total thermal insulation and moisture vapour resistance of the entire clothing ensemble tested in standing and "still air" condition, viz.

$$I_{ci} = I_{cit} - \frac{I_{oai}}{f_{ci}} \qquad (7\text{-}38)$$

where, I_{cit} is the total thermal insulation of the inner garments tested alone on a standing manikin in "still air", I_{oai} is the surface thermal insulation of the inner garments when tested alone on a standing manikin in "still air", f_{ci} is the clothing area factor of the inner garment(s) when tested alone, and

$$I_c = I_t - \frac{I_{oat}}{f_{co}} \qquad (7\text{-}39)$$

where, I_t is the total thermal insulation of the entire clothing ensemble tested on a standing manikin in "still air", I_{oat} is the surface thermal insulation of the entire clothing ensemble tested on a standing manikin in "still air", f_{co} is the clothing area factor of the outer surface of the clothing ensemble.

f_{ci} and f_{co} can be estimated from the insulation value, viz.

$$f_{ci} = 1 + 1.97 I_{ci} \text{ (McClough et al 1985 and ISO 7933)} \qquad (7\text{-}40)$$

Solving Equations (7-38) and (7-40) simultaneously, we have

$$f_{ci} = \frac{1 + 1.97 I_{cit} + \sqrt{(1 + 1.97 I_{cit})^2 - 7.88 I_{oai}}}{2} \qquad (7\text{-}41)$$

Similarly, we have:

$$f_{co} = \frac{1 + 1.97 I_t + \sqrt{(1 + 1.97 I_t)^2 - 7.88 I_{oa}}}{2} \quad (7\text{-}42)$$

We can also calculate R_{ci} and R_c in the similar way, viz.

$$R_{ci} = R_{cit} - \frac{R_{oai}}{f_{ci}} \quad (7\text{-}43)$$

where, R_{cit} is the total moisture vapour resistance of the inner garments tested alone on a standing manikin in "still air", R_{oai} is the surface moisture vapour resistance of the inner garments tested alone on a standing manikin in "still air",

$$R_c = R_t - \frac{R_{oat}}{f_{co}} \quad (7\text{-}44)$$

where, R_t is the total moisture vapour resistance of the entire clothing ensemble tested on a standing manikin in "still air", R_{oat} is the surface moisture vapour resistance of the entire clothing ensemble tested on a standing manikin in "still air".

With I_{ci}, I_c, R_{ci} and R_c, the values of m and n can be determined according the equations of (7-12) and (7-20).

The static values of clothing ensemble used in present study are listed in Table 7-2.

Table 7-2 The static values of clothing ensemble used in present study

CL_ID	Label of Clothing Ensembles	I_t	R_t	$f_{co}(f_{ci})$	I_c	R_c	I_{ci}	R_{ci}	m	n
1	1	0.187	31.70	1.20	0.102	21.10	0.000	0.00	0.00	0.00
2	2	0.194	30.92	1.22	0.109	20.46	0.000	0.00	0.00	0.00
3	3	0.201	32.60	1.23	0.118	22.28	0.000	0.00	0.00	0.00
4	4	0.203	34.75	1.24	0.120	24.47	0.000	0.00	0.00	0.00
5	5	0.184	30.07	1.19	0.098	19.42	0.000	0.00	0.00	0.00
6	6	0.195	32.79	1.22	0.111	22.37	0.000	0.00	0.00	0.00
7	7	0.198	33.68	1.23	0.115	23.31	0.000	0.00	0.00	0.00
8	8	0.200	34.34	1.23	0.117	24.01	0.000	0.00	0.00	0.00
9	9	0.175	31.09	1.17	0.087	20.24	0.000	0.00	0.00	0.00
10	10	0.187	31.92	1.20	0.102	21.34	0.000	0.00	0.00	0.00
11	11	0.192	33.16	1.21	0.108	22.68	0.000	0.00	0.00	0.00
12	12	0.201	34.89	1.23	0.118	24.58	0.000	0.00	0.00	0.00
13	13	0.209	36.05	1.25	0.127	25.89	0.000	0.00	0.00	0.00
14	14	0.197	33.59	1.22	0.113	23.19	0.000	0.00	0.00	0.00
15	15	0.210	33.07	1.25	0.128	22.92	0.000	0.00	0.00	0.00
16	16	0.219	38.98	1.27	0.138	28.99	0.000	0.00	0.00	0.00
17	17	0.244	39.39	1.33	0.167	29.82	0.000	0.00	0.00	0.00
18	18	0.202	38.42	1.23	0.119	28.13	0.000	0.00	0.00	0.00
	33	0.137	18.89	1.08			0.042	7.15		
	34	0.156	23.41	1.13			0.065	12.15		
	14+34	0.173	27.25	1.17			0.085	16.36		
19	3+33	0.216	33.63	1.27	0.135	23.59	0.042	7.15	0.31	0.30
20	13+33	0.230	36.38	1.30	0.151	26.59	0.042	7.15	0.28	0.27
21	14+33	0.228	33.83	1.29	0.149	24.01	0.042	7.15	0.28	0.30
22	15+33	0.236	34.61	1.31	0.158	24.92	0.042	7.15	0.27	0.29
23	7+33	0.213	34.10	1.26	0.132	24.01	0.042	7.15	0.32	0.30
24	11+33	0.202	33.87	1.23	0.119	23.58	0.042	7.15	0.35	0.30
25	16+33	0.234	38.70	1.31	0.156	28.97	0.042	7.15	0.27	0.25
26	17+33	0.271	41.24	1.39	0.197	32.09	0.042	7.15	0.21	0.22
27	18+33	0.237	39.60	1.31	0.159	29.92	0.042	7.15	0.26	0.24
28	plus 33	0.246	43.94	1.33	0.169	34.41	0.042	7.15	0.25	0.21
29	plus 33	0.282	48.81	1.41	0.210	39.81	0.042	7.15	0.20	0.18
30	28+34+14	0.264	47.74	1.37	0.189	38.48	0.065	12.15	0.35	0.32
31	29+34+14	0.299	51.91	1.45	0.229	43.14	0.065	12.15	0.29	0.28
32	plus 33	0.235	43.85	1.31	0.157	34.14	0.042	7.15	0.27	0.21

7.3 Heat and mass transfer induced by air ventilation and wind penetration

7.3.1 Relationship between wind velocity and walking speed and heat and mass transfer coefficients

As discussed in Chapter 2 - Literature review, the heat and mass exchange between the microclimate within clothing and the environment are very complicated. The amount of heat and mass exchange is obviously related to the amount of air ventilation, a concept first proposed by Crockford et al (1972, 1974 and 1978), who successfully measured the clothing ventilation by means of a trace gas dilution method. Two enhanced techniques (Reischl et al 1987, Lotens and Havenith 1988) have also been subsequently developed for the purpose.

As far as the wind penetration is concerned, although past theoretical analysis showed that the wind induced air exchange is proportional to the square of wind velocity (Stuart and Denby 1983), there is a distinct difference between the theoretical prediction and experimental results. Since the garment(s) are naturally hanged on the body and indefinite vibration is induced by wind especially when the clothed person is moving, the efficiency of air penetration is reduced. This means the theoretical model tends to overestimate the actual amount of air penetration.

Kerslake (1971) stated that the rate of air penetration through the clothing assembly (Q m^3/m^2hr) is approximately linear to the wind velocity, i.e.:

$$Q = 3600Sfv \tag{7-45}$$

where, *S* is the surface area of the clothing assembly in m^2, *f* is the apparent portion of the surface area *S* that is open to the air-flow; *v* is the wind velocity, or flow velocity of air through the clothing assembly, which is assumed to be equal to the wind velocity in m/s.

Harter (1981) studied thirteen fabrics varying in weight, construction, and fiber content. He found that the rate of air penetration through the fabrics is in linearity of wind velocity, and is proportional to the square root of air permeability of fabrics.

$$U_{pen} = a + b(V_{wind} \times \sqrt{ap}) \tag{7-46}$$

where *ap* is the air permeability of the fabric, *a* and *b* are constants. A similar effect has also been reported by Spencer-Smith (1965).

Reischi et al (1987) evaluated the ventilation effect of walking. The results showed that ventilation is proportionally increased with walking speed (Figure 7-2).

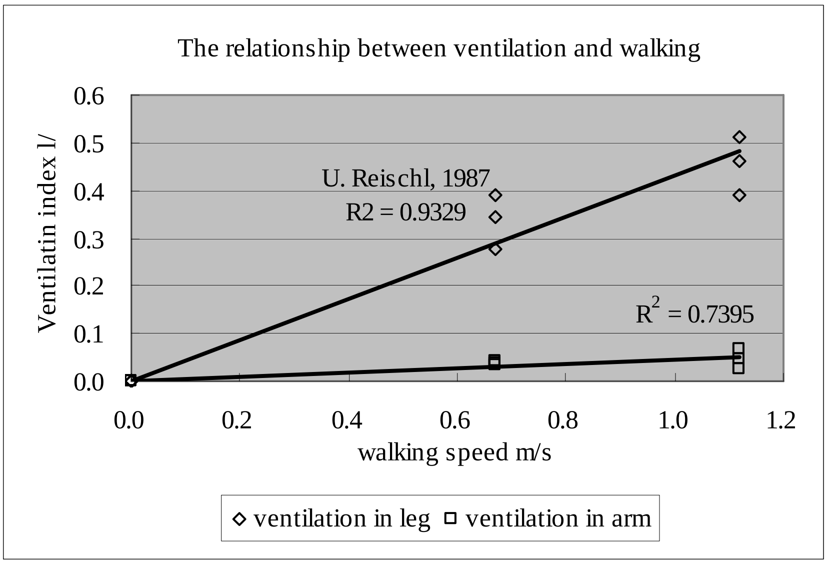


Figure 7-2 Ventilation as a function of walking speed measured by Reischl

After re-examining the results of ventilation data measured by Lotens and Wammes (1993), we found that the inverse of vapour resistance d_{vent} due to ventilation and wind penetration also increased linearly with the sum of 1.2 times walking speed and wind velocity. The relationship is shown in Figure 7-3.

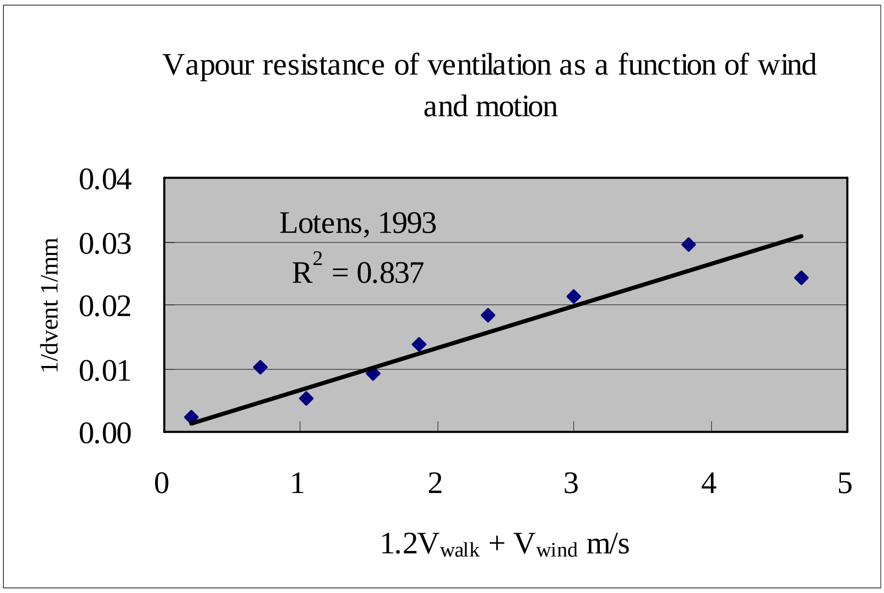


Figure 7-3 Dynamic ventilation effects measured by Lotens

Since $U_{vent}=1000D/d_{vent}$ as defined in their paper, where D is a constant, is amount of air exchange. U_{vent} must be linearly related to the sum of 1.2 times walking speed and wind velocity, the value of 1.2 here indicates that the effect of walking speed on the ventilation is 1.2 times of that of the wind velocity which has been widely recognized (Vokac et al 1973, Havenith et al 1990a).

Havenith et al (1990b) measured the total volume of ventilation and penetration. The data was presented in tabular form in their paper. After re-analyzing their data, we also found that the total volume by air ventilation and penetration is linearly related to the sum of 1.4 times walking speed and wind velocity, as shown in Figure 7-4.

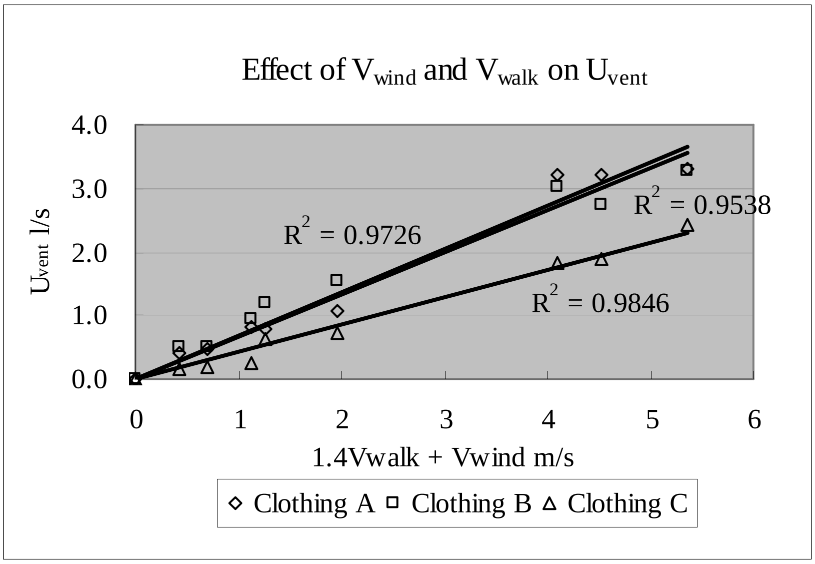


Figure 7-4 Relationship between air exchange and walking speed and wind velocity (Data from Havenith et al 1990b)

Danielsson (1993) also observed that the convective heat transfer coefficient between clothing layers varied approximately linearly from 5.25 W/m^{2o}C when standing to 11 W/m^{2o}C when walking at a speed of 2 m/s in still air.

Based on the above findings and analysis, we thus propose the following empirical equation to predict heat and mass transfer coefficients by air ventilation and wind penetration for a clothed person walking under windy conditions:

$$h_{dev} = KVI(V_{wind} + \beta_V V_{walk} - v_0) \quad (7\text{-}47)$$

$$h_{eev} = KVR(V_{wind} + \beta_V V_{walk} - v_0) \quad (7\text{-}48)$$

$$v_V = V_{wind} + \beta_V V_{walk} - v_0 \quad (7\text{-}49)$$

where, *KVI* and *KVR* are constants, which depend on garment(s) fitting, styles of design and construction of the clothing ensemble. v_V is an equivalent wind velocity taking into account the effect of walking speed, β_V is an equivalent air velocity factor for "walking" motion on heat and mass transfer induced by air ventilation. v_0 is the air current in the "still air" condition. (In any climate chamber, even at "still air" condition, there is air current. This is essential for the operation of air conditioning system in the chamber). In our study, V_0=0.22m/s. By definition, at the "still air" condition, when there is no air exchange by wind and walking motion, viz. h_{dev}=h_{eev}=0.

Substituting equation of (7-47) and (7-48) into equations of (7-25) and (7-26) respectively, we have the following equations for predicting the total thermal insulation and moisture vapour resistance of a clothing system:

$$I_{tdyn} = mI_c + \frac{1}{KVI(V_{wind} + \beta_V V_{walk} - v_0) + \dfrac{1}{(1-m)I_c + \dfrac{1}{f_{co}} I_{oa}}} \quad (7\text{-}50)$$

$$R_{tdyn} = nR_c + \frac{1}{KVR(V_{wind} + \beta_V V_{walk} - v_0) + \dfrac{1}{(1-n)R_c + \dfrac{1}{f_{co}} R_{oa}}}$$

(7-51)

7.3.2 Evaluation on the effective heat and mass transfer coefficients (h_{dev} and h_{eev}) induced by air ventilation and wind penetration

Equations (7-50) and (7-51) can be rewritten as below:

$$h_{dev} = KVI(V_{wind} + \beta_V V_{walk} - v_0) = \frac{1}{I_t - mI_c} - \frac{1}{(1-m)I_c + I_{oa}/f_c} \quad (7\text{-}52)$$

$$h_{eev} = KVR(V_{wind} + \beta_V V_{walk} - v_0) = \frac{1}{R_t - nR_c} - \frac{1}{(1-n)R_c + R_{oa}/f_c} \quad (7\text{-}53)$$

With the thermal insulation and moisture vapour resistance values of a clothed person standing in windy condition, the values of h_{dev} and h_{eev} can be calculated by Equations (7-52) and (7-53). Hence, *KVI* and *KVR* for each clothing ensemble can be obtained by linear regression.

By applying these values of *KVI* and *KVR* under walking motion and windy conditions, β_V can be obtained by fitting Equations 7-52 and 7-53 to the experimental data. We found:

$$\beta_V = 2.0 \qquad (R^2 = 0.95) \tag{7-54}$$

The effective dry heat and latent heat transfer coefficients h_{dev} and h_{eev} induced by air ventilation are plotted against the equivalent wind velocity v_v in Figures 7-5 and 7-6 as below:

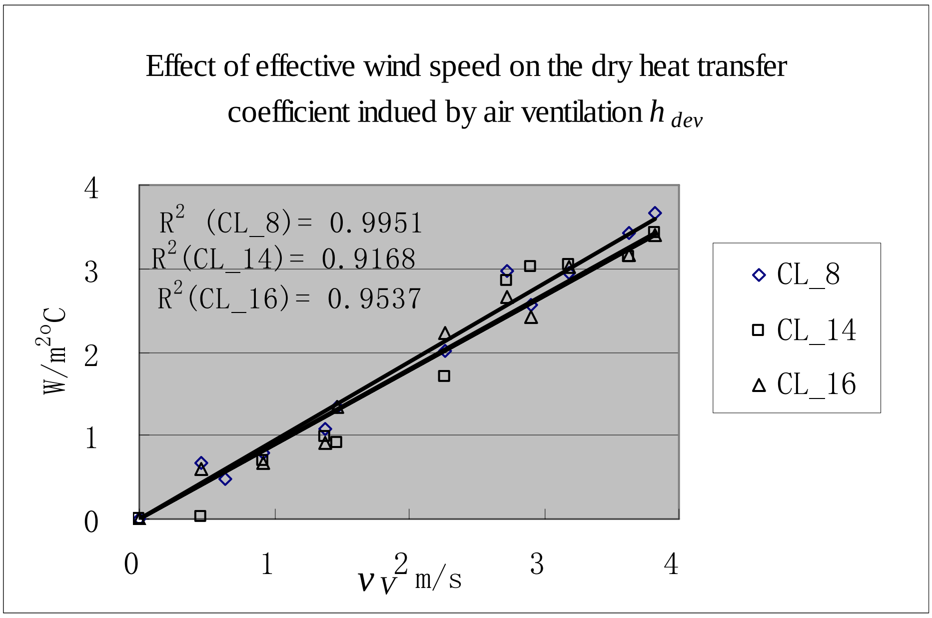


Figure 7-5 (a) Examples on the effect of equivalent wind velocity on effective dry heat transfer coefficient

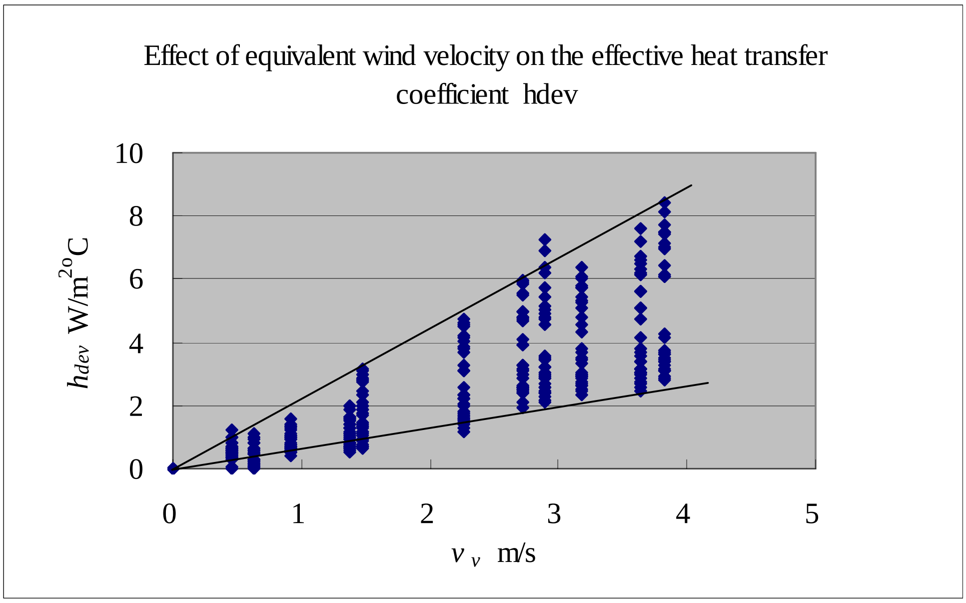


Figure 7-5 (b) Effect of equivalent wind velocity on effective dry heat transfer coefficient for all clothing ensembles

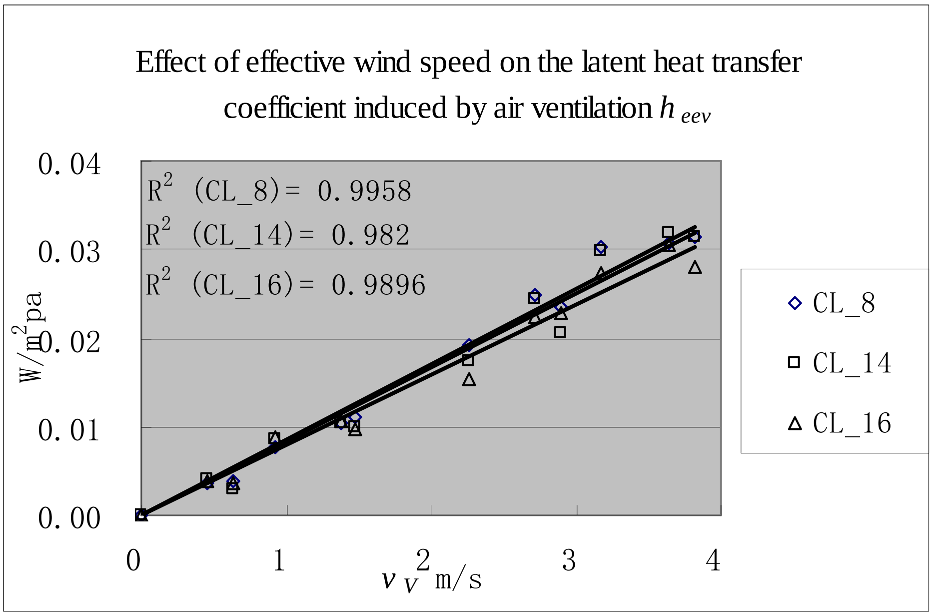


Figure 7-6 (a) Examples on the effect of equivalent wind velocity on the effective latent heat transfer coefficient

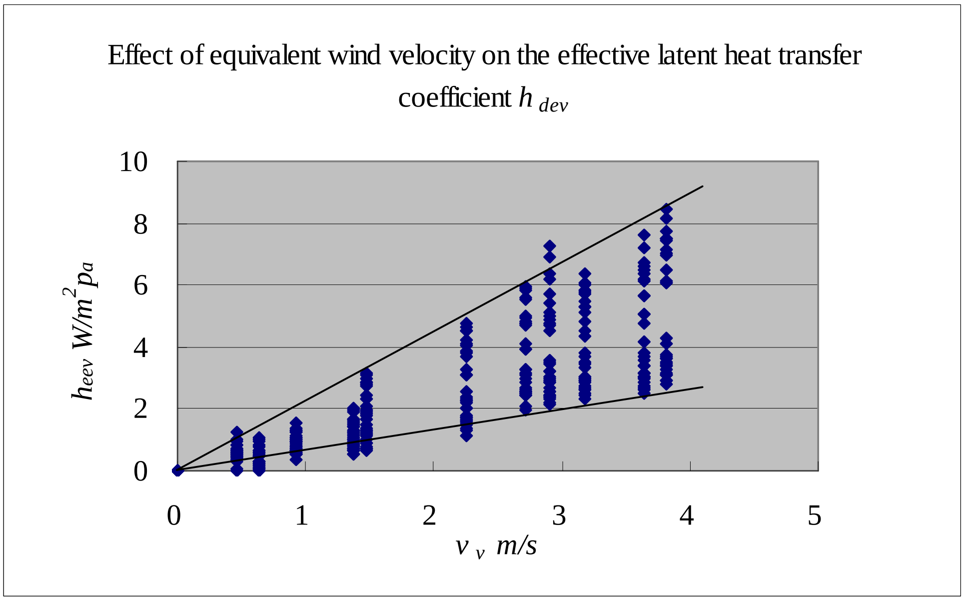


Figure 7-6 (b) Effect of equivalent wind velocity on the effective latent heat transfer coefficient for all clothing ensembles

It can be seen that the values of h_{dev} and h_{eev} were approximately linear to the equivalent air speed v_v.

7.4 Evaluation on the values of KVI and KVR

7.4.1 Determination of the values of *KVI* and *KVR*

Substituting the values of β_V and v_0 to Equations (7-50) and (7-51), we have:

$$I_{tdyn} = mI_c + \frac{1}{KVI\,(V_{wind} + 2V_{walk} - 0.22) + \frac{1}{(1-m)I_c + \frac{1}{f_{co}} I_{oa}}} \qquad (7\text{-}55)$$

$$R_{tdyn} = nR_c + \frac{1}{KVR(V_{wind} + 2V_{walk} - 0.22) + \frac{1}{(1-n)R_c + \frac{1}{f_{co}} R_{oa}}} \quad (7\text{-}56)$$

With the values of I_{tdyn}, I_{oa}, I_{ci} and I_c and R_{tdyn}, R_{oa}, R_{ci} and R_c, *m* and *n*, by means of the nonlinear regression, the value of *KVI*, and *KVR* can be obtained by fitting Equation (7-55) and (7-56) for different clothing ensemble. The values of *KVI* and *KVR* with underwear are very different from those without underwear. Table 7-3(a) and 7-3(b) list the values of *KVI* and *KVR* for each clothing ensemble with and without underwear, respectively.

Table 7-3(a) Values of *KVI* and *KVR* for different clothing ensemble without underwear

CL_ID	*m*	*KVI*	R^2	*n*	*KVR*	R^2	*style*	*Fit index*	*ap l/s.m²pa*	*Underwear*
1	0	0.84	0.97	0	0.0078	0.99	Jacket	2.9	20.6133	without
2	0	0.85	0.98	0	0.0075	0.99	Jacket	5.2	20.6133	without
3	0	0.91	0.97	0	0.0088	1.00	Jacket	8.7	20.6133	without
4	0	1.01	0.99	0	0.0096	0.99	Jacket	11.6	20.6133	without
5	0	0.77	0.97	0	0.0058	0.97	Jacket	2.9	1.0761	without
6	0	0.76	0.97	0	0.0058	0.98	Jacket	5.2	1.0761	without
7	0	0.85	0.99	0	0.0074	0.99	Jacket	8.7	1.0761	without
8	0	0.94	0.99	0	0.0085	0.99	Jacket	11.6	1.0761	without
9	0	0.73	0.97	0	0.0048	0.95	Jacket	2.9	0.0392	without
10	0	0.76	0.98	0	0.0059	0.98	Jacket	5.2	0.0392	without
11	0	0.80	0.97	0	0.0072	0.99	Jacket	8.7	0.0392	without
12	0	0.96	0.97	0	0.0080	0.98	Jacket	11.6	0.0392	without
13	0	0.91	0.97	0	0.0088	1.00	Jacket	10.3	4.2415	without
14	0	0.75	0.99	0	0.0081	0.99	Shirt	11.3	1.7480	without
15	0	0.90	0.98	0	0.0083	0.99	Uniform	11.1	1.4488	without
16	0	1.09	0.99	0	0.0095	0.99	Jacket_2	12.2	0.0280	without
17	0	0.85	0.99	0	0.0074	0.99	Shirt	12.2	0.0280	without
18	0	0.80	0.97	0	0.0072	0.99	Jacket_1	14.5	0.0166	without
Average		0.88			0.0076					
S.D.		0.10			0.0012					

Table 7-3(b) Values of *KVI* and *KVR* for different clothing ensemble with underwear

CL_ID	*m*	*KVI*	R^2	*n*	*KVR*	R^2	*style*	*Fit index*	*ap l/s.m²pa*	*Underwear*
19	0.31	1.84	0.98	0.30	0.0136	0.99	Jacket	8.7	20.6133	with
20	0.28	1.56	0.97	0.27	0.0119	0.99	Jacket	10.3	4.2415	with
21	0.28	1.55	0.96	0.30	0.0118	0.96	Shirt	11.3	1.7480	with
22	0.27	1.90	0.99	0.29	0.0107	0.97	Uniform	11.1	1.4488	with
23	0.32	1.81	0.97	0.30	0.0112	0.98	Jacket	8.7	1.0761	with
24	0.35	1.28	0.95	0.30	0.0087	0.98	Jacket	8.7	0.0392	with
25	0.27	1.72	0.99	0.25	0.0093	0.97	Jacket_2	12.2	0.0280	with
26	0.21	1.76	0.97	0.22	0.0105	0.94	Shirt	12.2	0.0280	with
27	0.26	1.90	0.99	0.24	0.0111	0.99	Jacket_1	14.5	0.0166	with
28	0.25	1.78	0.96	0.21	0.0122	0.99	Jacket_1	24.3	0.0000	with
29	0.20	1.48	0.98	0.18	0.0086	0.99	Jacket_2	23.9	0.0000	with
30	0.35	1.83	0.98	0.32	0.0134	0.99	Jacket_1	24.3	0.0000	with
31	0.29	1.84	0.98	0.28	0.0108	0.93	Jacket_2	23.9	0.0000	with
32	0.27	1.86	0.94	0.21	0.0111	0.94	Jacket_1	20.3	0.0000	with
Average	0	1.72		0	0.0111					
S.D.		0.18			0.0015					

Using the average values of *KVI* and *KVR* for clothing ensemble with and without underwear, clothing thermal insulation and moisture vapour resistance under windy conditions and walking motion can be predicted by Equations (7-55) and (7-56) from those measured when the manikin is standing in "still" air condition. Figures 7-7 (a) and (b) plot the predicted clothing thermal insulation and moisture vapour resistance against the measured values, respectively.

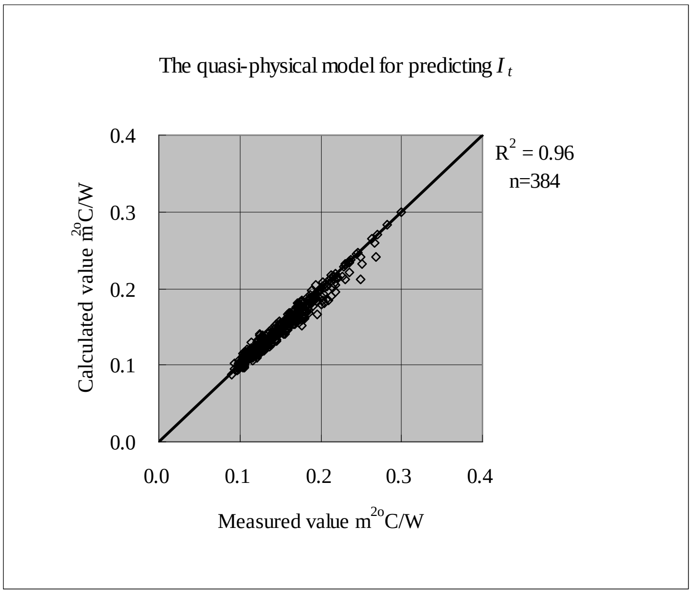


Figure 7-7 (a) Measured thermal insulation vs. predicted values using the quasi-physical model

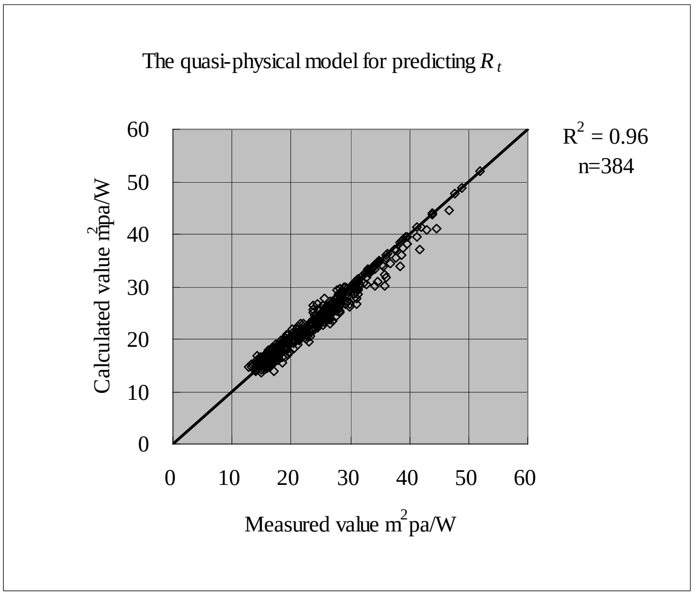


Figure 7-7 (b) Measured moisture vapour resistance vs. predicted values using the quasi-physical model

As can be seen, the model fit the testing data very well with a percentage of fit (R^2) of 0.96.

7.4.2 Average values of *KVI* and *KVR* for different clothing ensemble groups

It can be seen from the table 7-3(a) and (b), *KVI* and *KVR* are also depend on the clothing ensemble, in order to better estimate the values of *KVI* and *KVR* for different clothing ensemble, clothing ensemble are classified into groups depending on whether there is underwear, the air permeability of the outer clothing fabrics and the fit index, the grouping has been described in Chapter 6.

The values of *KVI* and *KVR* for each category are derived and listed in Table 7-4 (a) and (b).

Table 7-4(a) *KVI* values for each category of clothing ensemble.

UNDERWER	*ap*	*Fit Index*	Mean	Std. Error of Mean	Minimum	Maximum
with	High	M	1.7000	.14000	1.56	1.84
		Total	1.7000	.14000	1.56	1.84
	Low	L	1.7580	.07074	1.48	1.86
		M	1.6650	.13401	1.28	1.90
		Total	1.7167	.06819	1.28	1.90
	Moderate	M	1.7533	.10493	1.55	1.90
		Total	1.7533	.10493	1.55	1.90
	Total	L	1.7580	.07074	1.48	1.86
		M	1.7022	.06813	1.28	1.90
		Total	1.7221	.04941	1.28	1.90
without	High	M	.8900	.07572	.75	1.01
		S	.8450	.00500	.84	.85
		Total	.8720	.04294	.75	1.01
	Low	M	.9360	.04456	.80	1.07
		S	.7450	.01500	.73	.76
		Total	.8814	.04688	.73	1.07
	Moderate	M	.9450	.05172	.85	1.09
		S	.7650	.00500	.76	.77
		Total	.8850	.05012	.76	1.09
	Total	M	.9275	.02913	.75	1.09
		S	.7850	.01979	.73	.85
		Total	.8800	.02588	.73	1.09

Table 7-4 (b) *KVR* values for each category of clothing ensemble

UNDERWER	*ap*	*Fit Index*	Mean	Std. Error of Mean	Minimum	Maximum
with	High	M	.012750	.0008500	.0119	.0136
		Total	.012750	.0008500	.0119	.0136
	Low	L	.011220	.0007990	.0086	.0134
		M	.009900	.0005477	.0087	.0111
		Total	.010633	.0005302	.0086	.0134
	Moderate	M	.011233	.0003180	.0107	.0118
		Total	.011233	.0003180	.0107	.0118
	Total	L	.011220	.0007990	.0086	.0134
		M	.010978	.0004827	.0087	.0136
		Total	.011064	.0004042	.0086	.0136
without	High	M	.008833	.0004333	.0081	.0096
		S	.007650	.0001500	.0075	.0078
		Total	.008360	.0003776	.0075	.0096
	Low	M	.007660	.0001887	.0072	.0080
		S	.005350	.0005500	.0048	.0059
		Total	.007000	.0004614	.0048	.0080
	Moderate	M	.008425	.0004308	.0074	.0095
		S	.005800	.0000000	.0058	.0058
		Total	.007550	.0006168	.0058	.0095
	Total	M	.008208	.0002291	.0072	.0096
		S	.006267	.0004688	.0048	.0078
		Total	.007561	.0003057	.0048	.0096

7.4.3 Relationship between *KVI* and *KVR* and the clothing fit index, the air permeability and fabric thickness of outer clothing

By applying the nonlinear regression, the following relationships can be derived to predict *KVI* and *KVR* of clothing ensemble consisting of jackets and pants without underwear.

$$KVI = 0.0649\ln(\frac{Fit^2\sqrt{ap}}{th^2}) + 0.5897 \qquad R^2 = 0.84 \qquad (7\text{-}57)$$

$$KVR = 0.0006\ln(\frac{Fit^3\sqrt{ap}}{th^{0.2}}) + 0.0036 \qquad R^2 = 0.81 \qquad (7\text{-}58)$$

where, *Fit* is the value of clothing fit index, and *th* is the fabric thickness of the jackets.

Figures 7-8(a) and 7-8(b) compare the calculated *KVI* and *KVR* using Equations (7-57) and (7-58) with those obtained by direct regression using measured data.

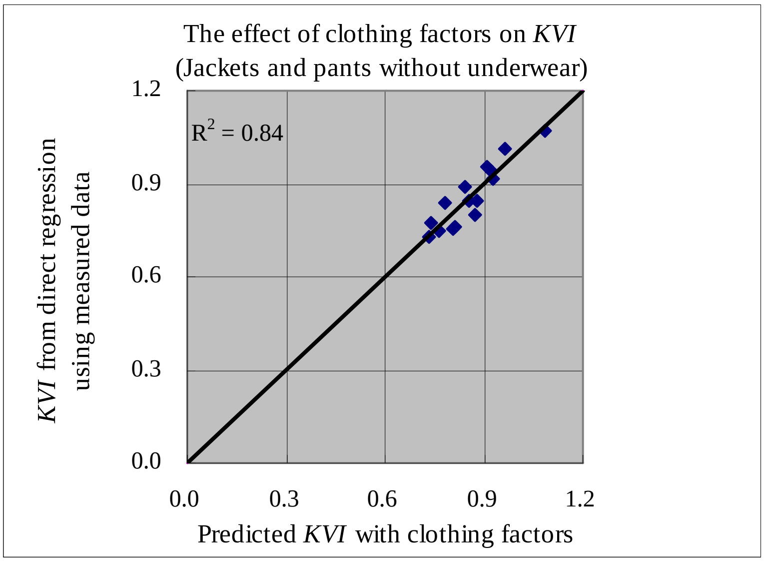


Figure 7-8(a) *KVI* in Table 7-3(a) vs. predicted *KVI* value using Equation (7-57)

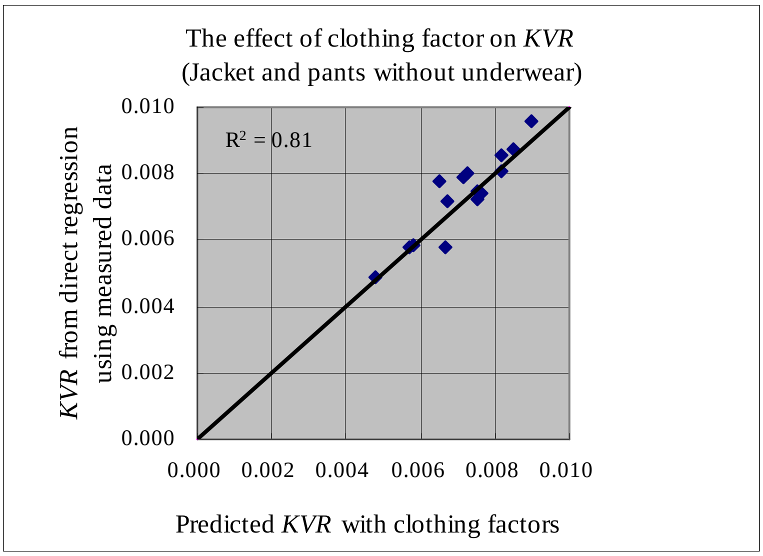


Figure 7-8(b) *KVR* in Table 7-3(a) vs. predicted *KVR* value using Equation (7-58)

Similar relations can be found for clothing ensemble consisting of Jacket and pants and underwear_1.

$$KVI = 0.1519\ln(\frac{Fit^2\sqrt{ap}}{th}) + 1.018 \qquad R^2 = 0.63 \tag{7-59}$$

$$KVR = 0.0019\ln(\frac{Fit^2\sqrt{ap}}{th^{0.5}}) + 0.0026 \qquad R^2 = 0.91 \tag{7-60}$$

Figures 7-9(a) and 7-9(b) compare the calculated *KVI* and *KVR* using Equations (7-57) and (7-58) with those obtained by direct regression using measured data.

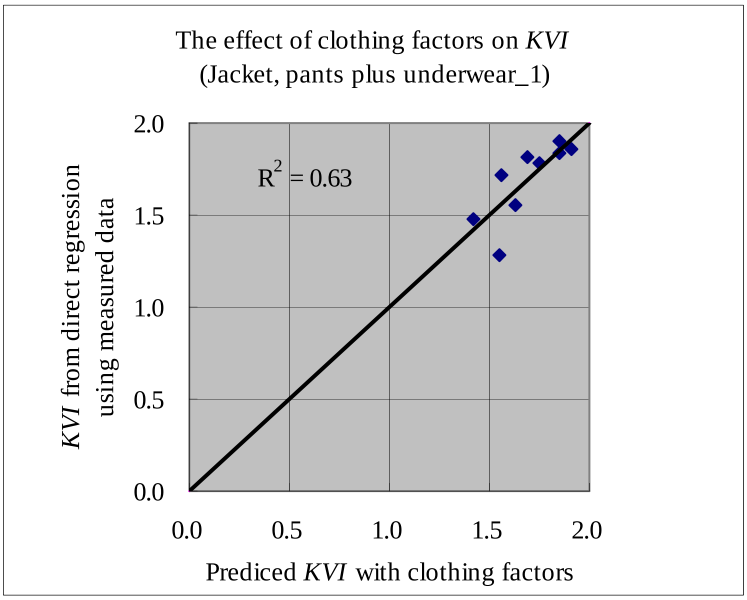


Figure 7-9(a) *KVI* in Table 7-3(b) vs. predicted *KVI* value using Equation (7-59)

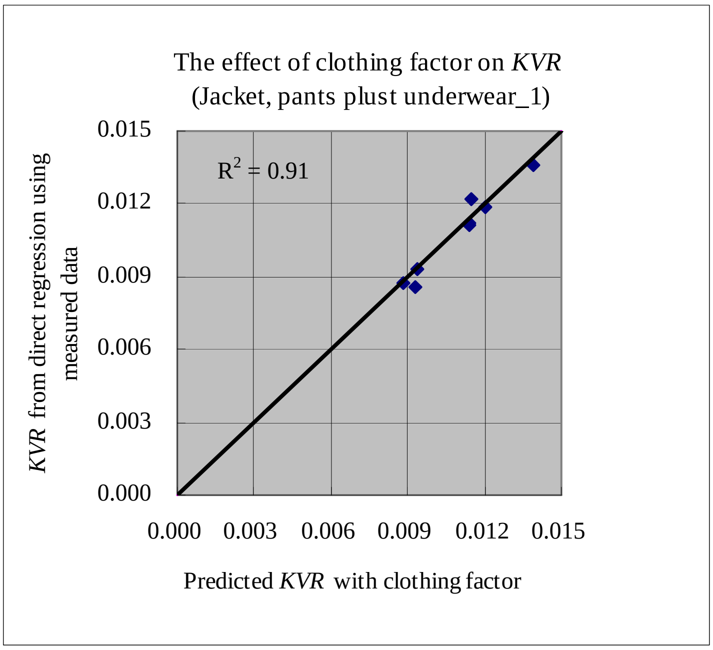


Figure 7-9(b) *KVR* in Table 7-3(b) vs. predicted *KVR* value using Equation (7-60)

7.4.4 Relationship of *KVR* and the air ventilation index.

The latent ventilation heat transfer H_{ev} can be expressed as

$$H_{ev} = \lambda \cdot U'_{vent} \cdot (\rho_{ci} - \rho_a) = h_{ev} A_s f_{ci} (p_{ci} - p_a)$$
$$= \frac{A_s f_{ci} (p_{ci} - p_a)}{R_V} \qquad (7\text{-}61)$$

where, ρ_a and ρ_{ci} are the moisture vapor concentration of environment in g/m^3 and the mean moisture vapor concentration within the clothing miroclimate in g/m^3,λ is the evaporative heat of water in J/g (λ=2419 j/g at 35^{o}C), U_{vent}' is the volume of air ventilation from the clothing system; R_v is the equivalent moisture vapour resistance.

Assume wet air mixed by dry air and moisture vapor obeys the ideal-gas relation, according to the basic principle of thermodynamics, we can have:

$$p_{ci} = \rho_{ci}\Re(273.15 + T_{ci}) \approx \rho_{ci}\Re\overline{T} \quad (7\text{-}62)$$

$$p_a = \rho_a\Re(273.15 + T_a) \approx \rho_a\Re\overline{T} \quad (7\text{-}63)$$

$$\overline{T} = 273.15 + (T_{ci} + T_a)/2 \quad (7\text{-}64)$$

where, $\Re$ is the moisture vapor constant ($\Re$=0.4615 j/gK), p_{ci} and p_a are the partial vapour pressure within the clothing microclimate and environment, respectively.

In most situations, $\overline{T}$ is about 300K. Let U_{vent} be the air ventilation per unit surface area of the body, viz.

$$U_{vent} = \frac{U'_{vent}}{A_s} \quad (7\text{-}65)$$

and

$$\eta = \frac{\lambda}{\Re\overline{T}} = 17.5 \qquad (J/m^3 p_a) \quad (7\text{-}66)$$

Substitute Equations (7-62) and (7-63) into (7-61), we have:

$$R_v = \frac{\Re \overline{T}}{\lambda} \frac{f_{ci} A_s}{U'_{vent}} = \frac{1}{\eta} \frac{f_{ci}}{U_{vent}} \tag{7-67}$$

$$h_{ev} = \frac{\lambda}{\Re \overline{T}} \frac{U'_{vent}}{A_s f_{ci}} = \frac{\eta U_{vent}}{f_{ci}} \tag{7-68}$$

$$h_{eev} = \eta U_{vent} \tag{7-69}$$

Substituting Equation (7-48) with (7-69), we have:

$$U_{vent} = \frac{KVR}{\eta}(V_{wind} + 2V_{walk} - 0.22) \qquad m/s \tag{7-70}$$

Define $KV = \frac{KVR}{\eta}$, *KV* is thus a dimensionless air ventilation coefficient of the clothing system. The air ventilation varies not only with clothing feature but also with wind velocity and walking speed, but the dimensionless *KV* is only dependent on the clothing feature such as garment style, fit and properties of garment fabrics, it can be used as an index to represent the ventilation ability of clothing.

7.5 Concluding remarks

In this chapter, a new prediction model has been derived based on fundamental heat and mass transfer mechanisms, which involve conduction, radiation and natural convection, water evaporation and air ventilation. The model predicts the total thermal insulation and moisture vapour resistance of clothing under body movement and windy conditions from the values of the intrinsic clothing thermal insulation and moisture vapoure resistance measured when the body is standing in the still air. Garment design and material properties are taken into account through the parameters of the model (*KVI* and *KVR)*. Very good agreement was found between the predicted values and experimental measurements from the sweating manikin – Walter.

The model parameters, *KVI* and *KVR*, were found to be dependent on the garment characteristics. If the garment style and dressing mode are not changed, the values of *KVI* and *KVR* can be predicted from the fit index of the garment, the air permeability and fabric thickness of the outer garments.

The present study proposed a dimensionless air ventilation coefficient of clothing system *KV* for measuring the ventilation ability of clothing. The ventilation index U_{vent} introduce by Crockford et al (1972) varies not only with clothing features but also with wind velocity and walking speed, but the value of the dimensionless *KV* is only dependent on the clothing features such as garment style, fit and properties of garment fabrics.

Chapter 8

Comparison of the Models for Predicting Clothing Thermal Insulation and Moisture Vapour Resistance

8.1 Introduction

In chapter 6 and chapter 7, a direct regression model and a quasi-physical physical and regression model for predicting clothing thermal insulation and moisture vapour resistance have been established, respectively. Both models considered the garment style, fit, and the air permeability and thickness of the outer clothing fabrics, and achieved very high prediction accuracy with a percentage of fit (R^2) of 0.96~0.97 for the experimental data obtained in our study.

The models are based on the experimental data of 32 sets of clothing ensembles, including tight to loose fit garments, jackets, shirts and uniforms with permeable and impermeable outer fabrics. These clothing assembles were tested on the walking-able sweating manikin-Walter in a climate chamber under 20^{o}C and 50% RH, with the wind velocity and walking speed varying from 0.22 to 4.04 m/s and 0 to 0.69 m/s, respectively. The static total thermal insulation and moisture vapour resistance of the clothing ensembles ranged 1.13~1.93clo (0.175 ~0.299m^{2o}C/W) and 30.07~51.91m^{2}pa/W, respectively. Although this has been a rather systematic experimental investigation, the models developed based on these limited experimental data should be validated with experimental data from other sources.

In this chapter, the two prediction models established in this study and other existing prediction models are compared and evaluated using experimental data from our study and from other published sources. Some of these data were obtained from manikins and some were from measurements on human subjects.

8.2 Summary of prediction models

Table 8-1 provides a summary of the existing models for predicting the clothing thermal insulation and moisture vapour resistance under body motion and wind from those under standing position with no wind. Table 8-2 summarizes the two newly established models.

Table 8-1 Existing models

Source	Model
Spencer-Smith (1977)	$\frac{I_{tdyn}}{I_{st}} = 1 - 1.2\times10^{-4} V_{wind}\sqrt{ap}$ $\frac{R_{tdyn}}{R_{st}} = 1 - 0.024 V_{wind}\sqrt{ap}$
Lotens and Havenith (1991)	$\frac{I_{cldyn}}{I_{scl}} = e^{-\frac{I_{scl}V_{walk}}{0.45}} \times \frac{3+\sqrt{0.67V_{walk}+0.11}}{3+\sqrt{V_{wind}+0.67V_{walk}+0.11}}$
ISO 9920 (1995)	$\frac{I_{tdyn}}{R_{tdyn}} = L_R i_m = \frac{I_{st}}{R_{st}}$
Holmer et al (1999)	$\frac{I_{tdyn}}{I_{st}} = e^{(0.043-0.398V_{wind}+0.066V_{wind}^2-0.378V_{walk}+0.094V_{walk}^2)}$
Nilssion et al (2000)	$\frac{I_{tdyn}}{I_{st}} = 0.54e^{(-0.15V_{wind}-0.22V_{walk})}(ap)^{0.075} - 0.06\ln(ap) + 0.5$

It can be seen from Table 8-1, Spencer-Smith's model only considers the effect of wind, but does not consider the effect of walking motion on the clothing thermal insulation and moisture vapour resistance. Except for ISO 9920 model, all exacting models use the static clothing thermal insulation and moisture vapour resistance (the values measured when a person or manikin is standing in still air) as input to predict the dynamic clothing thermal insulation and moisture vapour resistance when a clothed body is walking in windy conditions. Although Lotens and Havenith (1991)'s model included the prediction of the dynamic moisture vapour resistance, it requires the calculation of the heat transfer coefficient of trapped air within the clothing ensembles, which is very much a rough estimate, thus their model for the prediction of dynamic moisture vapour resistance is not included in the comparison here. Besides, Holmer et al (1999) and Nilssion et al's (2000) prediction models are only for the dynamic clothing thermal insulation, not for the dynamic clothing moisture vapour resistance. The model in ISO 9920 proposed a very simple Lewis relation between the dynamic clothing thermal insulation and the dynamic clothing moisture vapour resistance.

Table 8-2 The models developed in the present study

The new direct regression model	$\frac{I_{tdyn}}{I_{st}} = \frac{1}{1 + KI(V_{wind} + 1.8V_{walk} - v_0)}$ $\frac{R_{tdyn}}{R_{st}} = \frac{1}{1 + KR(V_{wind} + 1.8V_{walk} - v_0)}$
	Average values: ***KI=0.27, KR=0.32*** The range of *KI: 0.21~0.33;* The range of *KR: 0.23~0.42*
The quasi-physical model	$I_{tdyn} = mI_c + \frac{1}{KVI(V_{wind} + 2V_{walk} - v_0) + \frac{1}{(1-m)I_c + \frac{1}{f_{co}} I_{oa}}}$ $R_{tdyn} = nR_c + \frac{1}{KVR(V_{wind} + 2V_{walk} - v_0) + \frac{1}{(1-n)R_c + \frac{1}{f_{co}} R_{oa}}}$
	Average values: without underwear: ***KVI=0.88, KVR=0.0076*** with underwear: ***KVI=1.72, KVR=0.0111*** $I_{oa} = \frac{1}{5 + 8.3\sqrt{0.11 + 0.45V_{walk} + V_{wind}}}$ $R_{oa} = \frac{1}{0.0165 \times 8.3\sqrt{0.11 + 0.45V_{walk} + V_{wind}}}$ (normal condition) $R_{oa} = \frac{1}{0.11\sqrt{V_{wind}}}$ (isothermal condition) $m = \frac{I_{ci}}{I_c}$, $n = \frac{R_{ci}}{R_c}$ $f_{co} = \frac{1 + 1.97I_t + \sqrt{(1 + 1.97I_t)^2 - 7.88I_{oa}}}{2}$

8.3 Experimental data reported in the published literatures

The effects of wind and walking motion on the clothing thermal insulation and moisture vapour resistance have been investigated since 1940s (Gagge et al.

1941 for windy condition; Belding et al, 1947 for body movements), but systematic data on this topic are rare, especially on the moisture vapour resistance of clothing. Table 8-3 (a) and (b) summarizes the experimental data published in the past three decades. The data in the tables were converted into the standard ISO units which are used in the present study.

Table 8-3(a) Past experimental data measured on human subjects

Investigator	Method and Environment	Clothing	V_{wind}	V_{walk}	I_t	R_t
Nielsen et al 1985	Indirect calorimetry method Comfortable temperature, 50% RH	1st_CL Briefs and shorts	0.05	0.00	0.125	
			0.05	1.04	0.105	
			1.10	1.04	0.072	
		2nd_CL: Briefs, T-shirt, trousers, jacket, socks and shoes	0.05	0.00	0.263	
			0.05	1.04	0.163	
			1.10	1.04	0.139	
Lotens & Havenith 1988. (listed in Havenith 1990(b))	Trace gas method	Two-piece impermeable rain suit, no underwear	0.00	0.00		93.20
			2.00	0.00		36.12
			6.00	0.00		10.49
			0.00	1.20		21.67
			2.00	1.20		17.48
			6.00	1.20		8.16
Havenith et al 1990(a) and 1990(b)	Indirect calorimetry for I_t. Trace gas method for R_t The subjects' skin was treated as a non-sweating skin by wrapping the subject tightly in a thin water vapour impermeable synthetic foil. Comfortable temperature, 50% RH	1st_CL Ensemble-A Shoes, socks, Workpants Polo shirt sweater	0.10	0.00	0.189	43.80
			0.70	0.00	0.161	27.96
			4.10	0.00	0.124	10.95
			0.10	0.30	0.163	30.76
			0.70	0.30	0.141	20.50
			4.10	0.30	0.110	9.32
			0.10	0.90	0.156	27.49
			0.70	0.90	0.131	19.81
			4.10	0.90	0.088	8.16
		2nd_CL Ensemble-A plus: coverall	0.10	0.00	0.250	54.76
			0.70	0.00	0.184	28.19
			4.10	0.00	0.155	10.95
			0.10	0.30	0.223	37.75
			0.70	0.30	0.190	23.07
			4.10	0.30	0.139	9.79
			0.10	0.90	0.177	24.70
			0.70	0.90	0.148	16.78
			4.10	0.90	0.118	7.92
		3rd_CL Ensemble-A plus: A rain coverall (impermeable)	0.10	0.00	0.266	168.93
			0.70	0.00	0.215	70.37
			4.10	0.00	0.164	16.08
			0.10	0.30	0.224	95.30
			0.70	0.30	0.186	44.97
			4.10	0.30	0.149	13.05
			0.10	0.90	0.183	47.53
			0.70	0.90	0.149	27.73
			4.10	0.90	0.122	11.18

Table 8-3(b) Past experimental data measured on thermal manikins

Investigator	Method Environment	Clothing	V_{wind}	V_{walk}	I_t
Hong 1992	T_e=22°C±0.5°C, 50%RH T_s=33.2°C±0.5°C	1st_CL Briefs, t-shirt, long-sleeved dress shirt tie, jacket, long dress trousers, Belt, calf-length dress socks, shoes	0.15	0.00	0.251
			0.15	0.34	0.205
			0.15	0.57	0.178
			0.15	0.80	0.158
			0.15	1.03	0.141
		2nd_CL Panties, long-sleeved blouse, Jacket, skirt (straight, 6.5"below knee-length), Pantyhose, street shoes	0.15	0.00	0.254
			0.15	0.34	0.192
			0.15	0.57	0.163
			0.15	0.80	0.140
			0.15	1.03	0.126
		3rd_CL Panties, Sleeveless dress (scoop neck, A-line, knee length) sandals	0.15	0.00	0.144
			0.15	0.34	0.127
			0.15	0.57	0.115
			0.15	0.80	0.104
			0.15	1.03	0.093
Holmer et al 1996	T_a=25°C, 47%RH	1st_CL Boxer shorts, sock, shoes, gloves Tyvek coverall,	0.15	0.00	0.202
			0.15	1.00	0.160
			1.20	1.00	0.121
		2nd_CL Boxer shorts, sock, shoes, gloves PP coverall	0.15	0.00	0.207
			0.15	1.00	0.164
			1.20	1.00	0.127
	T_a=10°C, 50%RH	3rd_CL: Boxer shorts, sock, shoes, gloves Long-sleeved shirt, PET jacket & trousers	0.15	0.00	0.250
			0.15	1.00	0.144
			1.20	1.00	0.135
	T_a=-10°C, 90%RH	4th_CL:Briefs, loon-sleeved shirt & pants Fiber pile sweater & pants Jacket & overall, cap, scarf	0.15	0.00	0.395
			0.15	1.00	0.318
			1.20	1.00	0.272
		5th_CL: Briefs, loon-sleeved shirt & pants Fiber pile sweater & pants Insulated parka & overall, cap, scarf	0.15	0.00	0.539
			0.15	1.00	0.446
			1.20	1.00	0.370
Bouskill et al 2002	manikin TORE T_e=T_r=10°C, 60%RH	1st_CL: Air impermeable One-layer design	0.20	0.00	0.226
			1.00	0.00	0.167
			0.20	0.37	0.175
			1.00	0.37	0.133
			0.20	0.77	0.149
			1.00	0.77	0.118
		2nd_CL Air impermeable Three-layer design	0.20	0.00	0.394
			1.00	0.00	0.312
			0.20	0.37	0.341
			1.00	0.37	0.296
			1.00	0.77	0.335
			0.20	0.77	0.287
Adair 2005	Dry manikin	RF protective garments	0.40	0.00	0.212
			1.12	0.00	0.158
			2.24	0.00	0.118

8.4 Experiments under isothermal conditions

For tests conducted in non-isothermal conditions, particularly under relatively cold environment, condensation may take place within clothing. Two examples of condensation in clothing system are shown in Figure 8-1 (a) and (b).

(a) Te=-10^{o}C (permeable garment) (b) Te=20^{o}C (impermeable garment)

Figure 8-1 Condensation in clothing system

Since condensation can greatly affect measurements of clothing moisture vapour resistance, it is sometimes recommended (ASTM F2360, 2004) to conduct the tests under such isothermal conditions, i.e. the mean skin temperature equals the environmental temperature. In order to exam the validity of the models for predicting the clothing moisture vapour resistance under isothermal conditions, a selection of clothing ensembles were tested under the environmental temperature of 35^{o}C, the same as the mean skin temperature of 35^{o}C . These clothing ensembles included highly and moderately permeable garments as well as impermeable garments. The results are listed in Table 8-4 and plotted in Figure 8-2, which also compare with the results tested under 20^{o}C and 50% RH (a typical non-isothermal condition).

Table 8-4 Clothing moisture vapour resistances tested under the isothermal conditions

CL_ ID	clothing ensemble	V_{wind} m/s	R_t m^2pa/W		Difference %
			T_e=T_s=35°C, RH=40% (Isothermal)	$T_{e=}$20°C, RH=50% $T_{s=}$35°C (non-isothermal)	
3	Knitting jacket, without underwear	0.22	39.96	32.60	18.44
		0.85	30.10	26.24	12.82
		1.69	22.96	19.82	13.64
		2.48	18.99	17.43	8.18
		3.12	16.93	15.82	6.56
		4.04	14.69	13.26	9.74
7	Denim jacket, without underwear	0.22	43.38	33.68	22.37
		0.85	33.31	27.91	16.22
		1.69	22.68	21.89	3.46
		2.48	20.98	19.18	8.59
		3.12	18.10	17.22	4.84
		4.04	15.33	14.76	3.70
18	PET filament woven and coated semi-permeability jacket, without underwear	0.22	50.41	38.42	23.77
		0.85	36.77	31.27	14.98
		1.69	28.35	26.02	8.19
		2.48	25.55	22.09	13.54
		3.12	20.65	19.16	7.24
		4.04	18.85	17.41	7.65
23	Denim jacket, with underwear	0.22	43.31	34.10	21.28
		0.85	34.37	28.54	16.96
		1.69	27.29	24.17	11.45
		2.48	24.25	21.26	12.30
		3.12	21.00	19.88	5.32
		4.04	19.76	17.94	9.20
28	PU coated, breathable jacket, with underwear	0.22	60.70	43.94	27.61
		0.85	46.50	35.67	23.28
		1.69	35.11	28.54	18.72
		2.48	31.50	24.57	22.00
		3.12	27.36	21.11	22.85
		4.04	26.36	19.78	24.94
32	Nylon film, impermeable jacket, with underwear	0.22	64.50	43.85	32.02
		0.85	45.11	38.30	15.08
		1.69	36.21	31.04	14.27
		2.48	30.83	26.04	15.52
		3.12	28.39	24.40	14.05
		4.04	25.08	21.54	14.13

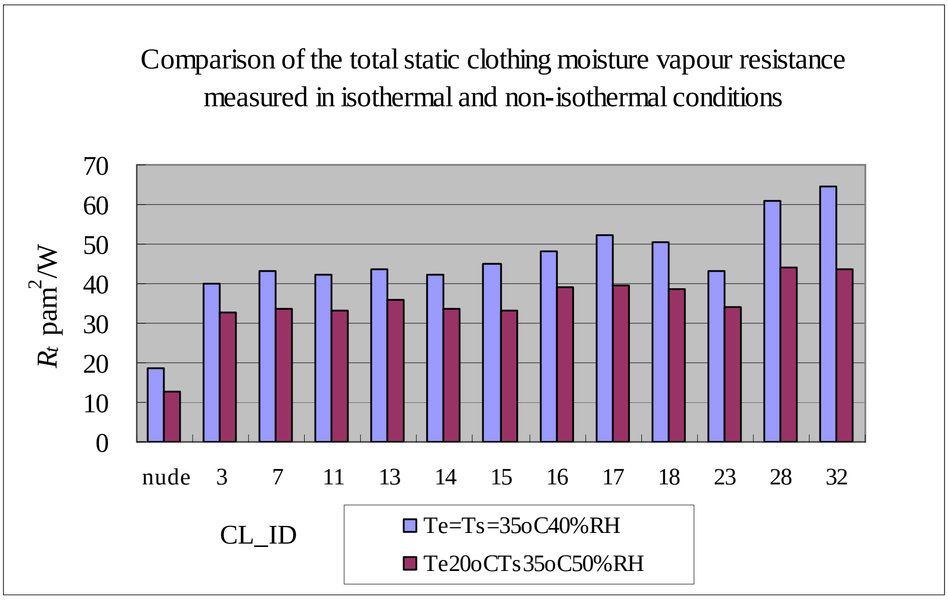


Figure 8-2 Comparison of clothing moisture vapour resistance measured in isothermal and non-isothermal conditions.

It can be seen that the total static clothing moisture vapour resistance measured under the typical non-isothermal condition (i.e. 20°C and 50% RH) is less than that measured under the isothermal condition, and the reduction varies from 17 to 32%. The amount of reduction is related to the clothing moisture vapour resistance. Generally, greater differ reduction takes place in clothing systems having higher clothing moisture vapour resistance (See Figure 8-3).

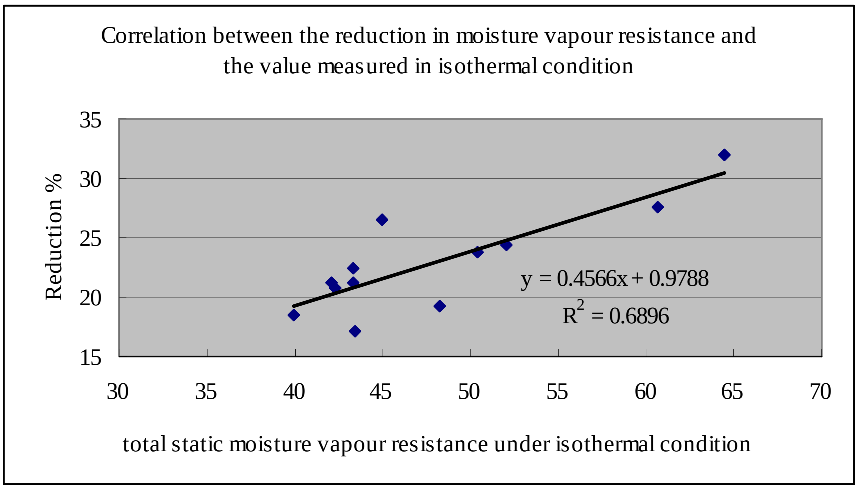


Figure 8-3 Effect of clothing moisture vapour resistance on the reduction of the clothing moisture vapour resistance.

There are two possible reasons for the lower moisture vapour resistance under the non-isothermal condition in comparison with that under the isothermal condition. Firstly, the presence of the nature convection induced by the temperature gradients in the non-isothermal condition increases the transmission of moisture vapour not only within the clothing layers, but also at the outer surface. The second reason for the reduction in the measured moisture vapour resistance is the moisture absorption and condensation within clothing. This means some of the “perspiration” from the manikin or human body is not transmitted through the clothing system, but accumulated within the clothing, resulting in an apparently lower moisture vapour resistance than the actual value. Furthermore, the higher moisture content and condensation within the inner layers of clothing creates higher rate of moisture transmission through the outer layers of the clothing system (Ren and Ruckman, 1999; 2003).

The reduction induced by the first cause will reduce with the increase of wind velocity, and diminish under strong windy condition (see Chapter 5). Figure 8-4 plots an example of the change of clothing moisture vapour resistance tested under isothermal and no-isothermal condition with wind velocity. As can be seen, the difference between the clothing moisture vapour resistance tested under isothermal and no-isothermal condition reduces with the wind velocity increasing from 0 to about 1.8 m/s, thereafter the difference remains almost unchanged with the increase of wind velocity. The remaining difference is believed to be induced by the second cause, i.e. the moisture absorption and condensation within clothing.

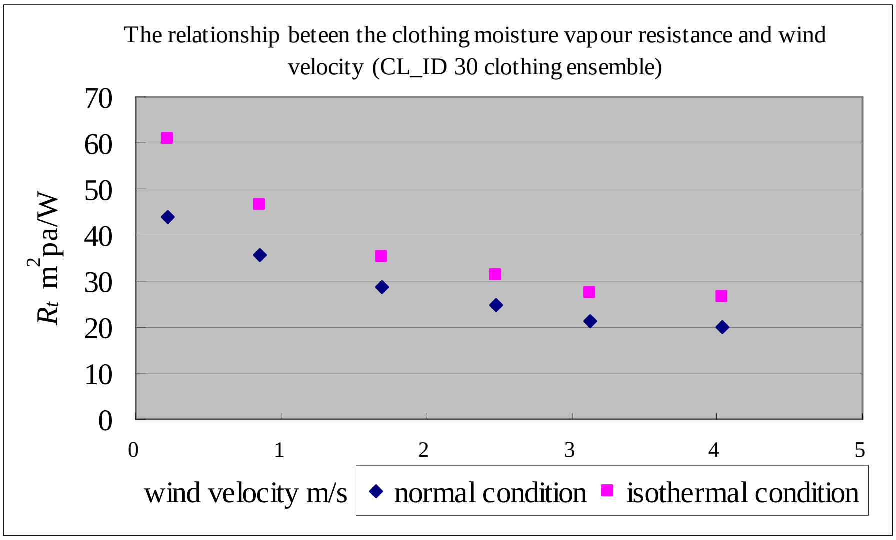


Figure 8-4 Effect of wind velocity on the clothing moisture vapour resistance tested under isothermal and non-isothermal condition

Tests under isothermal condition will result in the real resistance of clothing to moisture transmission in that condition, but tests under the non-isothermal condition is closer to the actual use condition of the clothing. From the present investigation, it can be observed that the clothing moisture vapour resistance measured under the isothermal and that under non-isothermal conditions are linearly related. Its relationship is shown in Figure 8-5.

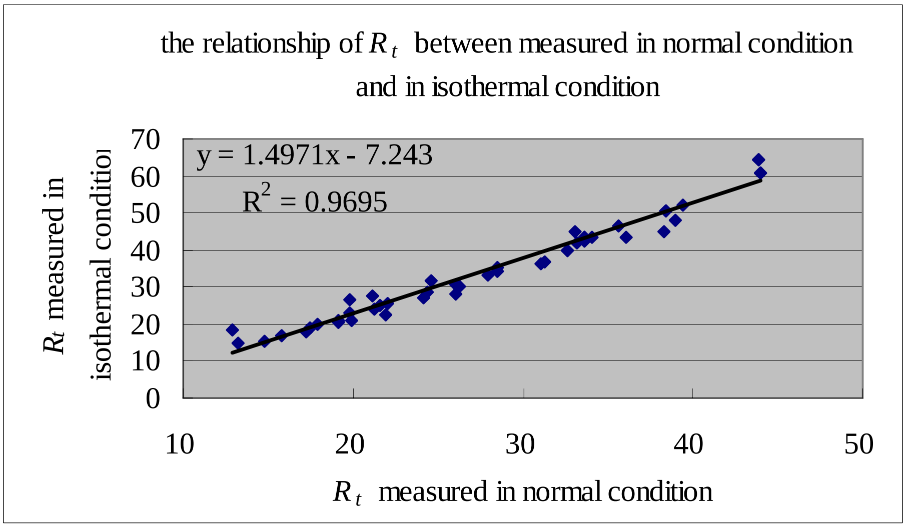


Figure 8-5 The relationship between R_t in isothermal and R_t in non-isothermal condition

8.5 Evaluation of the prediction models using all experimental data

In order to validate and compare the prediction models, experimental data from the literature and our investigation were used. These data were measured for different clothing ensembles such as highly permeable clothing, impermeable clothing, formal wear and outdoor activity wear, under different experimental conditions: some from tests on human subjects and some from tests on thermal manikins; some by direct measurements and some by the indirect trace gas methods; under different environment conditions such as typical indoor conditions, very cold conditions or isothermal conditions.

Since the air permeability values of many clothing assembles reported in the literature are not known, in applying Spencer-Smith and Nilssion et al's models, the air permeability values of the outer fabrics of different clothing assembles were assumed to be the values with which the models provided the optimum fitting to experimental data. These air permeability values were found by non-linear data regression.

In applying the direct regression model and the quasi-physical model established in the present study, average values of model parameters, i.e. *FI, FR, KVI, and KVR* were used for different clothing assembles.

8.5.1 Comparison of prediction models for clothing thermal insulation

The clothing thermal insulation values predicted using different models are plotted against the experimentally measured values (from both the present experiment investigation and from published literature) in Figures 8-6 to Figure 8-12.

Figure 8-6 plots the measured thermal insulation against the values predicted using the Spencer-Smith's model. It can be seen that there are considerable over estimation for insulation values less than 0.15$m^{2o}C/W$. This may be because, at high wind velocity, the reduction of clothing thermal insulation is more than what is predicted in the model, which assumes a linear reduction with the increase of wind velocity.

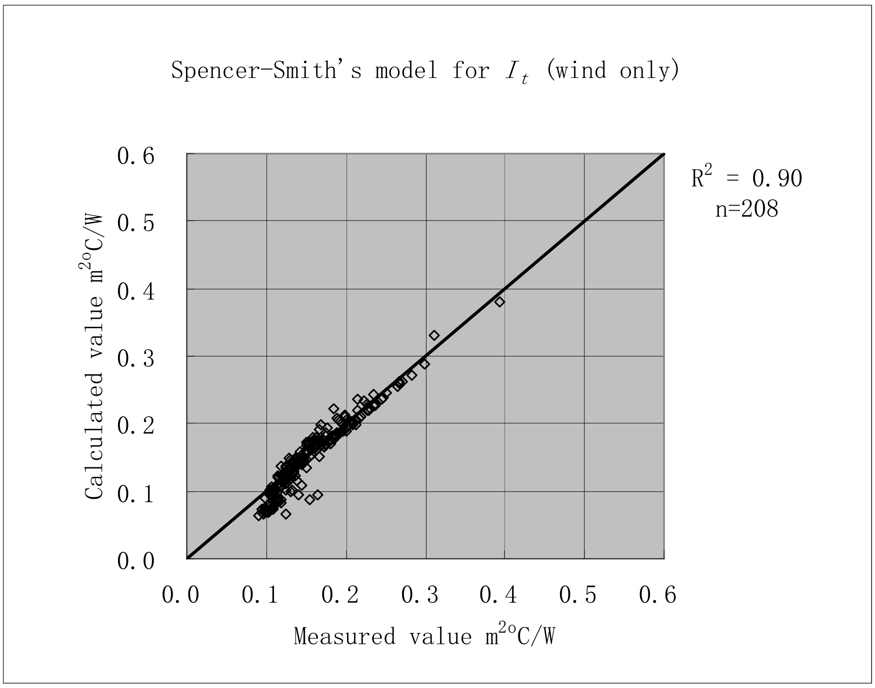


Figure 8-6 Measured thermal insulation vs. the values predicted using Spencer-Smith's model

Figure 8-7 plots the measured dynamic thermal insulation against the values predicted using the Lotens and Havenith's model. As can been seen, the predicted values deviate greatly from the measured data. One possible source of errors is the value of β (viz. equivalence of walking speed to wind velocity). They used the value of β=0.67, which was derived from the reduction of surface thermal insulation by walking motion and wind (Havenith et al 1990a). The present study showed (See Chapter 5 and 6) that the value of β for the surface thermal insulation is different from that for the clothing thermal insulation. In the present study, the value of β were found to be 0.45 for surface thermal insulation and 1.8~2.0 for clothing thermal insulation.

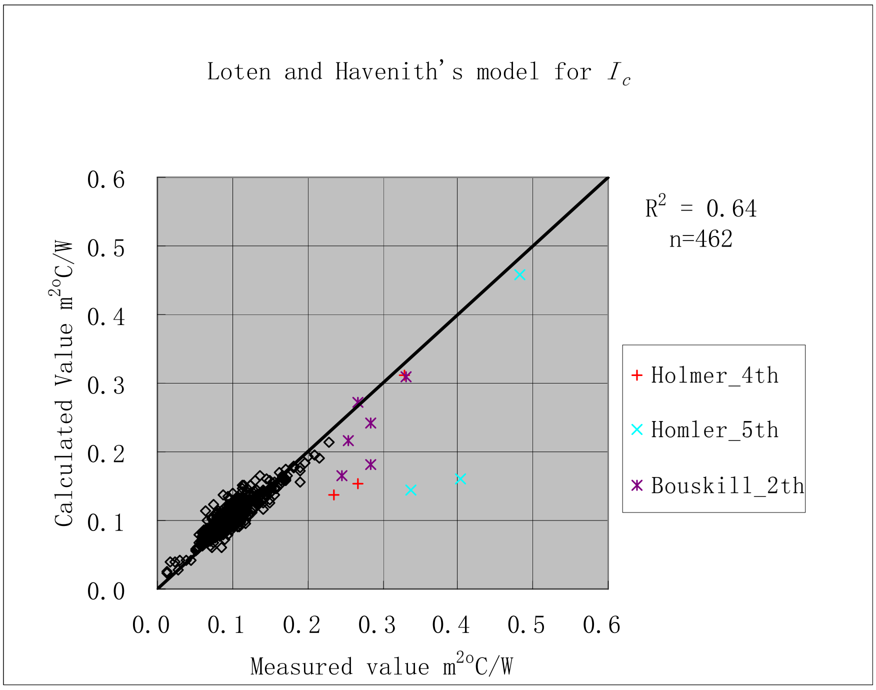


Figure 8-7 Measured the dynamic thermal insulation vs. the values predicted using Lotens & Havenith's model

The Lotens & Havenith's model is especially poor for the data of Holmer et al's 4th and 5th clothing ensembles and Bouskill et al's 2nd clothing ensemble measured by thermal manikins. Holmer et al's 4th and 5th clothing ensembles are winter clothing which included a cap and a scarf, and they were tested in the sub-zero climate of -10^oC. The static thermal insulation values are 2.55*clo* (0.395 $m^{2o}C/W$) and 3.48*clo* (0.539 $m^{2o}C/W$), respectively. Bouskill et al's 2nd clothing ensemble consisted of an air impermeable three-layer overcoat with gloves and a cap. It was tested in the environmental temperature of 10^oC, and its static thermal insulation is 2.54*clo* (0.394 $m^{2o}C/W$).

Figure 8-8 plots the measured dynamic thermal insulation against the values predicted using the Holmer et al's model. This model was based on seven ensembles tested on a "walking" manikin and three ensembles tested human subjects by Havenith (1990a). The range of clothing thermal insulation was 1.33~1.84clo (0.206~0.285 $m^{2o}C/W$). As can be seen, Holmer et al's model predicts the clothing thermal insulation quite well both for the data obtained in the present work on the sweating manikin-Walter and those reported in the literature, with a percentage of fit (R^2) of 0.91, except for some overestimation for the thermal insulation less than 0.2 $m^{2o}C/W$ and underestimation for values higher than 0.28 $m^{2o}C/W$.

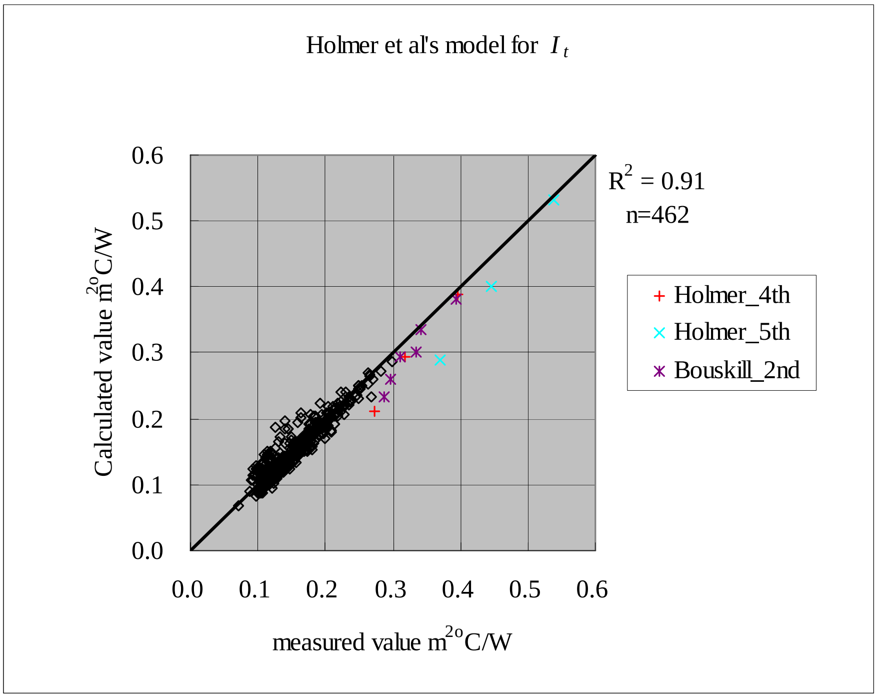


Figure 8-8 Measured thermal insulation vs. the values predicted using Holmer's model

Figure 8-9 plots the measured thermal insulation against the values predicted using the Nilsson et al's model. Compared with Holmer's model, Nilsson et al's model gives better prediction for clothing ensembles having higher thermal insulation, but worse for clothing ensembles having lower thermal insulation. This is understandable as the model was established based on 10 cold protective work wear, which had relative high thermal insulation.

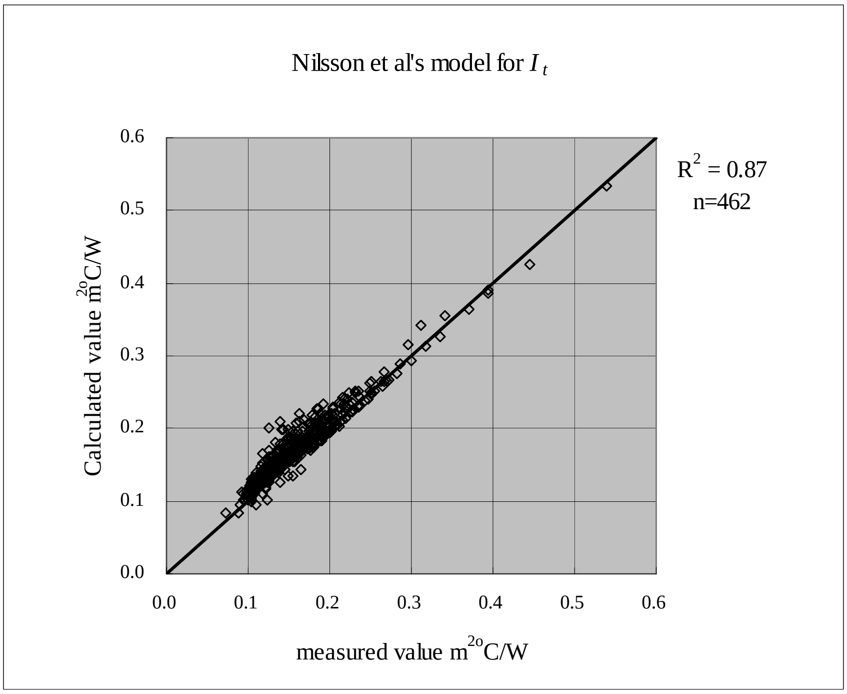


Figure 8-9 Measured thermal insulation vs. the values predicted using Nilsson et al's model

Figure 8-10 plots the measured dynamic thermal insulation against the values predicted using the new direct regression model developed in the present study. As can be seen, the new direct regression model predicts the measured thermal insulation from both our experiments on the sweating manikin-Walter and those reported in the literature quite well, with a percentage of fit (R^2) of 0.95. There is however some underestimation for clothing ensembles with high thermal insulation, particularly for the two winter ensembles tested by Holmer et al and one winter ensemble tested by Bouskill et al. This may be due to the fact that, in the experimental data used for establishing the new direct regression model, there is no winter clothing ensemble having such higher insulation to those tested by Holmer et al and Bouskill et al.

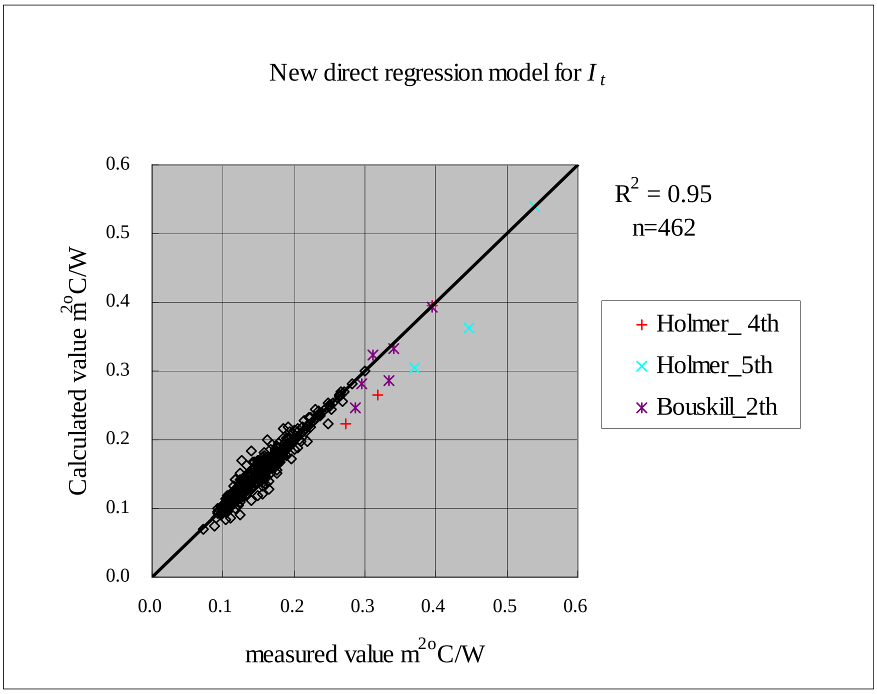


Figure 8-10 Measured thermal insulation vs. the values predicted using the new direct regression model

Figure 8-11 plots the measured dynamic clothing thermal insulation against the values predicted using the quasi-physical model developed in the present study. As can be seen, the quasi-physical model predicts the measured thermal insulation from both our experiments on the sweating manikin-Walter and those reported in the literature very well, except for the large underestimation for the two heavy winter ensembles tested by Holmer et al and one heavy winter ensemble tested by Bouskill et al. These three ensembles were relatively heavy having the static thermal insulation greater than 0.4 $m^{2o}C/W$ or 2.6clo. They also consisted of caps, gloves or scarf, making them highly enclosed from air ventilation and penetration. Consequently, the average model parameter (*KVI*), which was averaged from relatively lighter clothing ensembles in the present work, would not be appropriate for these three heavy and highly enclosed winter ensembles.

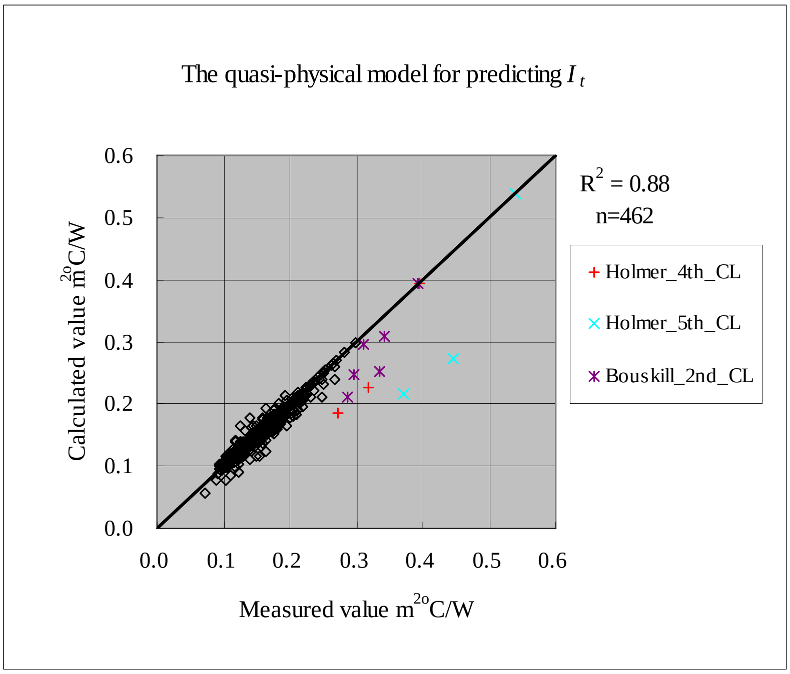


Figure 8-11 Measured clothing thermal insulation vs. the values predicted using the quasi-physical model

With a special *KVI* value of 0.26, the thermal insulation of the three heavy and highly enclosed winter ensembles was predicted by the new quasi-physical model with a percentage of fit (R^2) of 0.96 (see Figure 8-12).

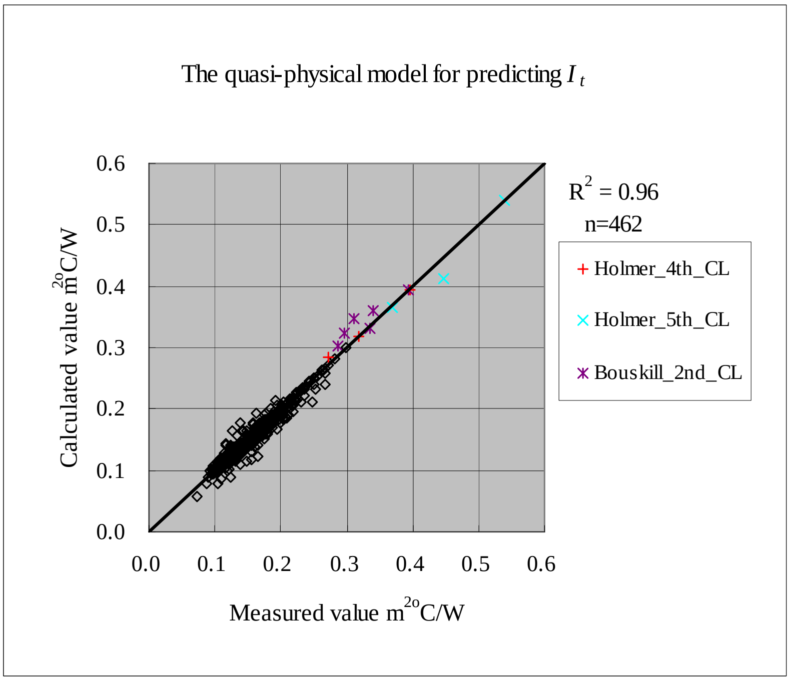


Figure 8-12 Measured clothing thermal insulation vs. predicted values using the quasi-physical model with a specific *KVI* value for the three heavy and highly enclosed winter ensembles

From the analysis above, it can be seen that, except for the heavy and highly enclosed winter ensembles as the 4th and 5th clothing ensembles tested by Holmer et al and the 2nd clothing ensemble tested by Bouskill et al, the new direct regression model and the new quasi-physical model provide very good prediction with the percentage of fit (R^2) of 0.95 and 0.94, respectively. For heavy and highly enclosed clothing ensembles (with the static thermal insulation greater than 0.4 $m^{2o}C/W$ or 2.6clo), Nilsson et al's model provides the best prediction. Improved prediction by the new quasi-physical model can be achieved by using the model parameter (*KVI*) specific for the heavy and enclosed winter ensembles.

8.5.2 Comparison of prediction models for clothing moisture vapour resistance

Figure 8-13 plots the measured moisture vapour resistance against the values predicted using the Spencer-Smith's model. It can be observed that there is a large deviation for the 3rd clothing ensemble tested by Havenith et al using trace gas method on human subjects. This clothing ensemble consists of a rain coverall which is moisture impermeable. There is also some over estimation for the clothing moisture vapour resistance values less than 30 m^2 Pa/W, probably because the wind induced reduction in moisture vapour resistance is greater than what is predicted in the model.

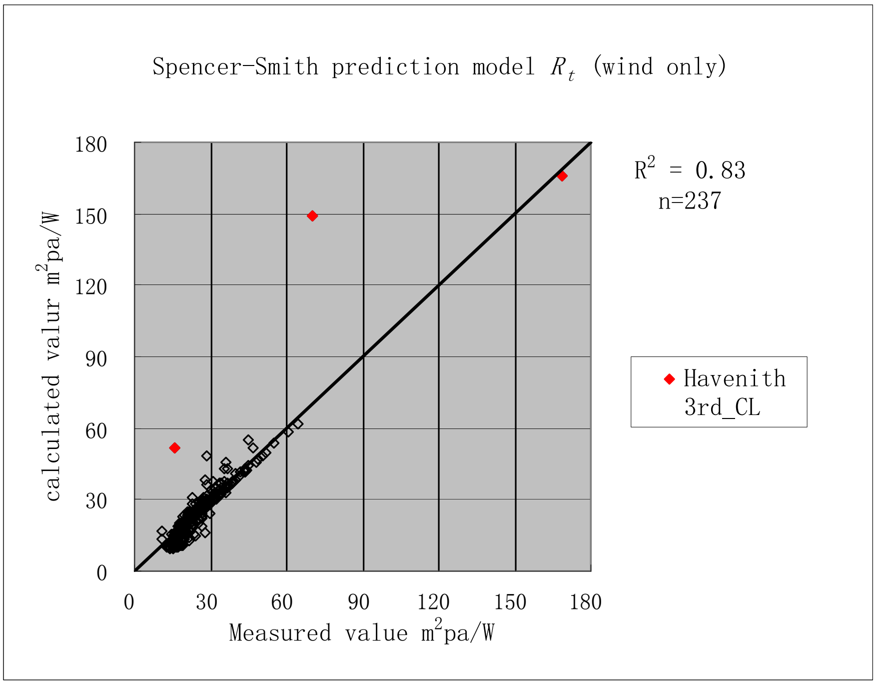


Figure 8-13 Measured moisture vapour resistance vs. the values predicted using Spencer-Smith's model

Figure 8-14 plots the measured clothing moisture vapour resistance against the values predicted using the model adopted by ISO9920. As can be seen, ISO9920 generally predicts the measured data well except for the impermeable rain coverall tested by Havenith et al and there is some over estimation for clothing moisture vapour resistance less than 30 m^2Pa/W.

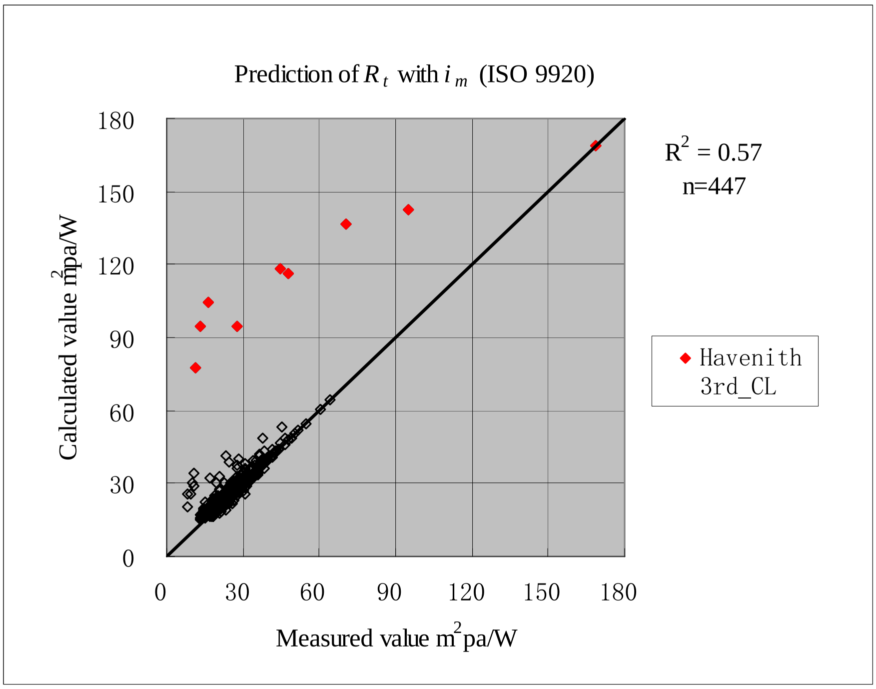


Figure 8-14 Measured moisture vapour resistance vs. the values predicted using ISO9920's model

Figure 8-15 plots the measured clothing moisture vapour resistance against the values predicted using the new direct regression model. Again, with the exception for the data of the impermeable rain coverall tested by Havenith et al on human subjects using the trace gas method, the new direct regression model provides very good prediction. The percentage of fit of the new direct regression model would be 0.91, if the data of the impermeable rain coverall tested by

Havenith et al on human subjects using the trace gas method was omitted in the analysis.

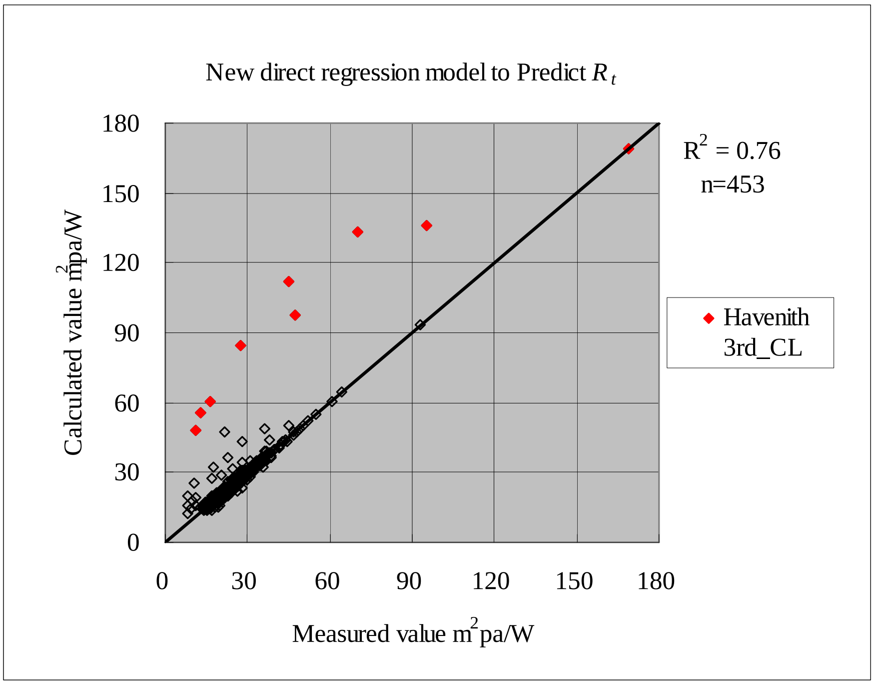


Figure 8-15 Measured clothing moisture vapour resistance vs. the values predicted using the new direct regression model

Figure 8-16 plots the measured moisture vapour resistance against the values predicted using the quasi-physical model. Although there is still a slight overestimation for the impermeable rain coverall tested by Havenith et al, the model provides very good overall prediction with a percentage of fit (R^2) of 0.95.

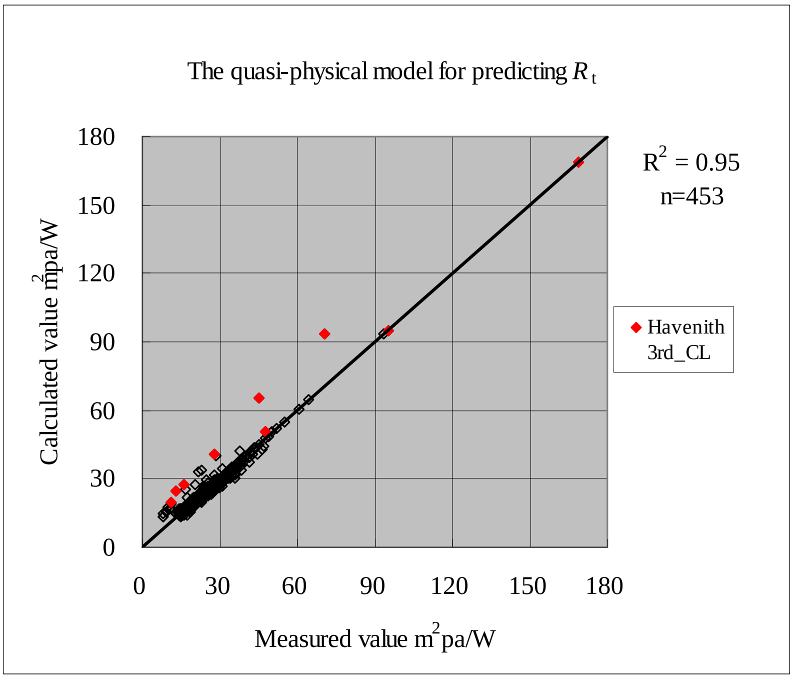


Figure 8-16 Measured moisture vapour resistance vs. the values predicted using the quasi-physical model

Based on the above analysis and discussion, it is clear that the new quasi-physical model is the best in predicting the dynamic clothing moisture vapor resistance in the examined models.

The reason why all models have difficulty in fitting the data of the impermeable rain coverall tested by Havenith et al (1990b) using the trace gas method is rather incomprehensible, as the models have no particular problem in fitting the data of similar impermeable ensembles tested by Lotens & Havenith (1988) using the same trace gas method, and similar ensembles tested on sweating manikins.

Table 8-5 provides a summary of the prediction accuracy of the various models.

Table 8-5 The comparisons of models

	Fit for all databases		Fit for all databases except for I_t measured with Holmer 4th and 5th clothing, and Bouskill 2nd clothing, R_t measured with Havenith 3rd clothing	
Model	I_t	R_t	I_t	R_t
Spence-Smith' model	R^2=0.90 n=208	R^2=0.83 n=237	R^2=0.89 n=206	R^2=0.88 n=234
Lotens & Havenith' model	R^2=0.64 n=462		R^2=0.74 n=450	
ISO9920' model		R^2=0.57 n=447		R^2=0.8 n=438
Holmer et al' model	R^2=0.91 n=462		R^2=0.89 n=450	
Nilsson et al's model	R^2=0.87 n=462		R^2=0.78 n=450	
Direct regression model	R^2=0.95 n=462	R^2=0.76 n=453	R^2=0.94 n=450	R^2=0.91 n=444
Quasi-physical model	R^2=0.88 n=462	R^2=0.95 n=453	R^2=0.96* n=462	R^2=0.94 n=444

*: Using special *KVI* value to predict the thermal insulation of these three heavy and highly enclosed winter ensembles.

8.6 Prediction of clothing moisture vapour resistance tested under isothermal and non-isothermal conditions

Figure 8-17 compares the ISO9920 model, the direct regression model and the quasi-physical model in predicting the dynamic clothing moisture vapour resistance tested under the non-isothermal condition (i.e. 20^{o}C and 50% RH) for a selection of clothing ensembles listed in Table 8-4. As can be seen, all three models provide very good prediction.

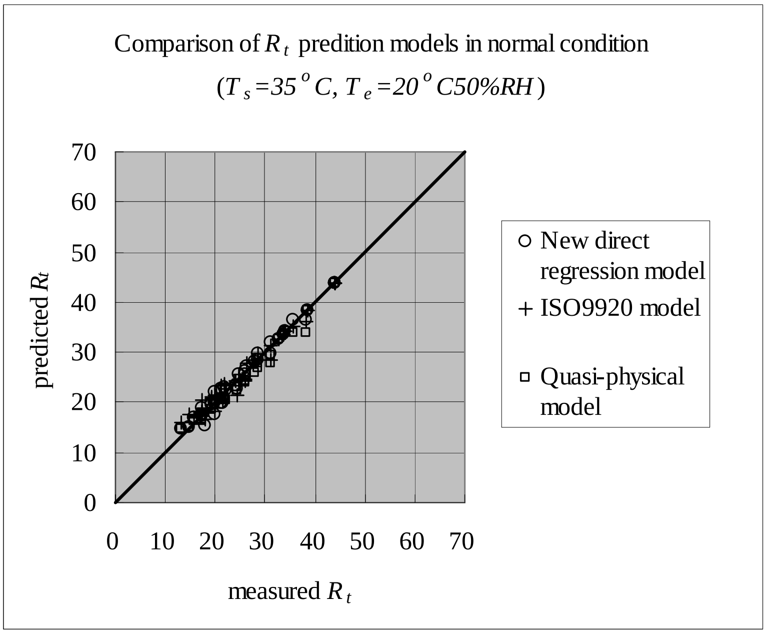


Figure 8-17 Comparison of R_t prediction models in a non-isothermal condition

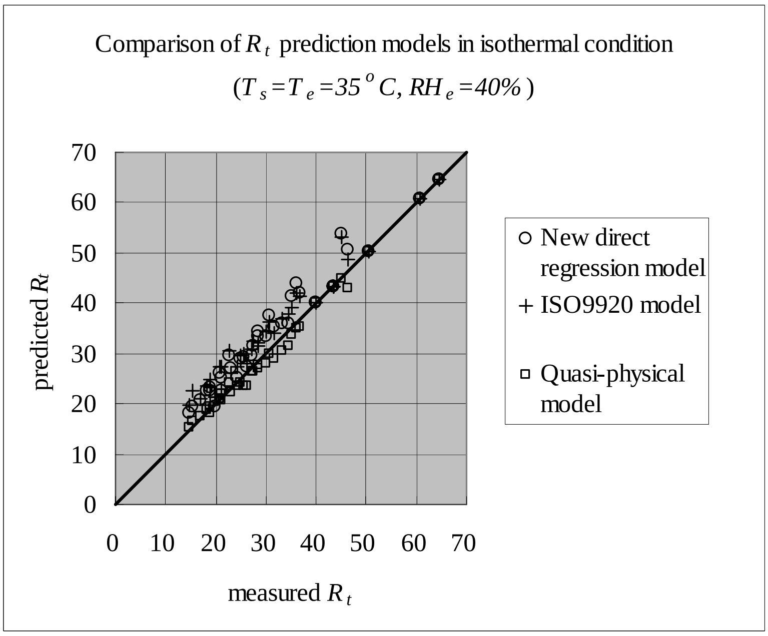


Figure 8-18 Comparison of R_t prediction models in an isothermal condition

This however is not the case in predicting the dynamic clothing moisture vapour resistance tested under the isothermal condition (i.e. 35°C and 40% RH). As can be seen from Figure 8-18, there is slight overestimation in the values predicted using the direct regression model and the ISO9920 model. The quasi-physical model gives the best prediction. This is because the quasi-physical model considered the change of the resistance of the surface air layer under isothermal condition.

8.7 Concluding remarks

In this chapter, the two new models developed in the present study and the existing models are compared and validated by using experimental data reported in the literature and obtained in the present investigation. These experimental data were measured using different measurement methods on human subjects or thermal manikins under various environmental conditions.

With respect to the prediction of clothing thermal insulation, the analysis showed that, except for the heavy and highly enclosed winter ensembles, the new direct regression model and the new quasi-physical model provide very good prediction with the percentage of fit (R^2) of 0.95 and 0.94, respectively. For heavy and highly enclosed clothing ensembles (with the static thermal insulation greater than 0.4 $m^{2o}C/W$ or 2.6clo), Nilsson et al's model provides the best prediction. Improved prediction by the new quasi-physical model can be achieved by using the model parameter (*KVI*) specific for the heavy and enclosed winter ensembles.

As for the prediction of clothing moisture vapour resistance, it can be concluded that the new quasi-physical model is the best in predicting the dynamic clothing moisture vapor resistance.

With the data of clothing moisture vapour resistance measured under the isothermal condition and that under the non-isothermal condition, the two are compared. It has been shown that the clothing moisture vapour resistance measured under the non-isothermal condition is about 17~32% smaller than that measured under the isothermal condition. The difference is caused by the moisture absorption and condensation within clothing and the increased natural convection as a result of the increase in temperature gradients under the non-isothermal condition.

Chapter 9

General Conclusions and Suggestions for Further Work

9.1 Conclusions

The primary function of clothing is to assist human body to maintain itself in an acceptable physiological state with respect to the thermal balance. In this regard, the accurate determination of clothing thermal insulation I_t and moisture vapor resistance R_t is crucial to the appropriate use of clothing for the thermal comfort of human body, functional clothing design and thermal environmental engineering. The thermal insulation I_t and moisture vapor resistance R_t of clothing ensembles can be measured by tests on human subjects or by using thermal manikins. Tests on human subjects give realistic results, but require sophisticated equipment and are time consuming, and may expose human subjects to danger. The measurements also tend to have large variability. Thermal manikins, especially sweating manikins, have therefore been developed, which provide reproducible instrumental measurements of clothing thermal insulation and moisture vapour resistance. However, thermal manikins are still rather expensive and only a few can simulate perspiration effectively. It is therefore highly desirable to predict the clothing thermal insulation I_t and water vapor resistance R_t.

The prediction of the clothing thermal insulation and water vapor resistance is essential, not only because of the variability, cost and danger in using human subjects and the availability of sweating manikins, but also because of the fact that it is practically impossible to measure I_t and R_t for endless clothing ensembles under the different body motions and various environmental conditions.

For the establishment of prediction models for clothing thermal insulation I_t and moisture vapour resistance R_t, it is necessary to acquire experimental data under various body motions and environmental conditions. To simulate different environmental climates, a new climate chamber was constructed for the present study. The climate chamber is a cubicle of size: 9200×3250×2600 mm^3 (L×W×H), which is enveloped with a thermal insulation wall of 100 mm in thickness, made of aluminum plate as outer covers and polyurethane foam as fillings. Its temperature, humidity and wind velocity can be controlled by a customized "Netview" hardware and software to any values within the range of 10~40^{o}C±0.3^{o}C, 30%~80%RH±5%RH and 0.22 m/s ±0.03m/s to 4.04 m/s±0.22m/s, respectively. The temperature control was achieved by its cooling and heating units, the humidity was balanced by its humidifier and dehumidifier and the wind was generated and controlled by nine evenly distributed axial fans in the chamber.

To simulate body motion, the sweating fabric manikin-Walter was further developed to enhance its simulation of "Walking" motion. A pair of special joints has now been designed and produced to better facilitate the "walking" motion. The joints were such that facilitated the bending of the groin joints, yet allowed the passage of water circulation within the manikin and prevented the abrasion of the fabric skin during “walking” motion. “Walking” speed could be digitally adjusted by controlling the AC frequency regulator which regulated the power supply to the motor that derived the crane mechanism which pushed and pulled the arms and legs for the simulation of “walking” motion. The “walking” speed could vary from 0 km/h (standing) to 2.7 km/h at a “walking” pace of 0.45, which was adjustable mechanically. During “walking” motion, the volume of the manikin changes cyclically due to the body motion, particularly the bending of arms and legs. In order to measure the “perspiration” rate (i.e. water loss from the manikin) accurately, it was necessary to develop an automated water supply and real-time water loss measurement system. The system enabled the on-line measurement of “perspiration” rate of the sweating manikin. A patent has been filed for the new enhancements of the sweating fabric manikin-Walter.

Surface thermal insulation and moisture vapour resistance of human body are important parameters for predicting thermal comfort. While many researchers in the past have measured the surface thermal insulation using human subjects or dry manikins, the surface moisture vapour resistance was largely estimated from surface thermal insulation based on Lewis relation. Such estimation was not validated by direct experimental measurements. Furthermore, the interactions of heat and moisture transfer at the surface of human body under varying environmental conditions and body motions have not been investigated. With the “walk-able” sweating fabric manikin – Walter, the surface thermal insulation and moisture vapour resistance were investigated under various environmental conditions and “walking” speed. It was found that: (1), there is no significant difference between the surface thermal insulation measured on the non-sweating manikin and those measured on the sweating manikin, indicating the moisture transfer having little effect on the direct heat transfer through the surface air layer. (2), the surface moisture vapour resistances R_a measured under isothermal conditions tend to be greater than those measured under non-isothermal conditions, especially when the wind velocity is less than 2.0 m/s. The higher R_a under isothermal conditions is likely due to the increase of surface air layer with the absence of the temperature gradients. (3), Lewis relation holds under non-isothermal conditions, but does not hold under isothermal condition when the wind velocity is small. (4), the effect of walking speed is equivalent to 45% of the wind velocity on the surface thermal insulation and surface moisture vapour resistance.

In order to investigate the effects of wind and walking motion on the clothing thermal insulation and moisture vapour resistance, 32 sets of different clothing ensembles were tested on Walter under 6 levels of wind velocity V_{wind}, ranging from 0.22 to 4.04 m/s (V_{wind} = 0.22 m/s represents no wind situation) and 4 levels of walking speed V_{walk}, ranging from 0 to 0.69 m/s in the climate chamber controlled at 20^{o}C and 50% RH. It was found that clothing thermal insulation and moisture vapour resistance decrease with the increase of wind velocity, and the reduction is approximately linearly related to the wind velocity and walking speed. The effect of walking speed is equivalent to 180% of the wind velocity.

Based on the improved understanding of the effects of wind and walking motion, a simple, but effective direct regression model was newly established to predict the dynamic clothing thermal insulation and moisture vapour resistance under windy conditions and walking motion from the static values when a clothed person is standing in "still" air condition, The model can take into account the effects of clothing characteristics through two model parameters, *KI* and *KR*. For the experimental data obtained in the present study, the model can fit them very well with a percentage of fit being 0.97.

The direct regression model is simple, but has not incorporated the fundamental mechanisms of heat and mass transfer. Based on theoretical analysis of the heat and moisture transfer through clothing, a novel quasi-physical model was derived. The model considered the heat and moisture transfer by conduction, diffusion, radiation, natural convection, wind penetration and air ventilation.

It was found that the effect of wind velocity is the same as 2 times of the effect of walking speed on the dry and latent heat transfer coefficients induced by air ventilation and wind penetration, and they are almost linearly related to the effective wind speed. Garment design and fit and fabric properties were taken into account in the model through its two parameters (*KVI* and *KVR)*. Different clothing ensembles would have different *KVI* and *KVR* values, which can be estimated by tabulation and prediction equations, but even if using the average values of *KVI* and *KVR* for the different clothing ensembles tested in the present study, the percentage of fit was as high as 0.96.

In order to validate the prediction models developed in the present study, the new direct regression model and quasi-physical model were compared with the published existing models by applying these models to fit the experimental data obtained in the present investigation and all of testing data published in the past three decades. The study showed that, for the prediction of clothing thermal insulation, except for the heavy and highly enclosed winter ensembles, the new direct regression model and the new quasi-physical model provide the best prediction with the percentage of fit (R^2) of 0.95 and 0.94, respectively. For heavy and highly enclosed clothing ensembles (with the static thermal insulation greater than 0.4 m^2 $^oC/W$ or 2.6 clo), Nilsson et al's model provides the best prediction. But, very high prediction accuracy can be achieved for the heavy and enclosed winter ensembles by the new quasi-physical model when using the model parameter (*KVI*) specific for such clothing. As for the prediction of clothing moisture vapour resistance, it can be concluded that the new quasi-physical model is the best among all models.

With the data of clothing moisture vapour resistance measured under the isothermal condition and that under the non-isothermal condition, the present study further showed that the clothing moisture vapour resistance measured under the non-isothermal condition is about 17~32% smaller than that measured under the isothermal condition. The difference is caused by the moisture absorption and condensation within clothing and the increased natural convection as a result of the increase in temperature gradients under the non-isothermal condition.

The present study is significant in the following aspects:

1. It provides a novel instrumental technique for the measurement of thermal comfort properties of clothing under simulated "walking" motion.

2. It provides an improved understanding of the effects of wind and body motion on clothing thermal comfort.
3. It provides accurate models for the prediction of clothing thermal insulation and moisture vapour resistance, which have important applications in thermal environmental engineering, functional clothing design and selection of clothing for different end uses.

9.2 Suggestions for future work

In the direct regression model and the quasi-physical model developed in the present study, clothing characteristics such as fit, style, air permeability and thickness of the outer fabric are taken into account through the model parameters. The relationship between the model parameters and the clothing characteristics was studied only for the jacket style due to the limited amount of experimental data. Further work is required to investigate such relationship for different style of garments.

In the present experimental investigation, 32 sets of clothing ensembles were tested. Although these clothing ensembles have reasonable variations in terms of style, fit and fabric properties, they have not included highly enclosed winter clothing ensembles. Further experiments on more types of clothing ensembles would provide a better representative database.

In the present study, the power is supplied to manikin to control the body core temperature. To be more like a human, the sweating manikin-Walter can be further enhanced by making the speed of water circulation inside the manikin adjustable depending on the walking speed.

Furthermore, the prediction models developed in the present study are for the steady state condition. Since heat and moisture transfer through clothing systems may be in transient state, research on transient heat and moisture transfer through clothing is needed in the future.

(End, Thanks!)

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