THE HONG KONG POLYTECHNIC UNIVERSITY

INSTITUTE OF TEXTILES AND CLOTHING

DEVELOPMENT OF A SWEATING FABRIC MANIKIN WITH SEDENTARY AND SUPINE POSTURES

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

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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.

(Signed)

Wu Yuen Shing **(Name of student)**

Dedicated To My Parents

Abstract

Since the world first thermal manikin introduced in 1940s, thermal manikins have been widely used in research and development for more than 60 years. They have been proven to be useful tools for the measurement of clothing thermal insulation and evaporative resistance - essential parameters for evaluating the thermal comfort of clothing and environment.

In this research, a novel sweating fabric manikin system, which can be adjusted to sedentary and supine postures, was developed for thermal comfort evaluation through the objective measurement of thermal insulation and evaporative resistance of clothing. The posture adjustment from sedentary to supine was achieved by interchanging the breathable fabric skin. A novel sweating rate measurement system was specially developed for the manikin to have real time sweating rate measurement. With this new manikin, high measurement accuracy is achieved at a relatively low cost in comparison with those existing manikins in Finland, Switzerland or USA.

Two sets of experiments were conducted using the novel sedentary and supine manikin. In the first set of experiments, eleven sleeping bags were tested in terms of thermal insulation and evaporative resistance. The second set of experiments

measured and compared the thermal insulation and evaporative resistance of seven clothing ensembles in standing, sedentary and standing posture. Both experiments demonstrated high reproducibility and consistency.

For the testing of the thermal insulation of sleeping bags, standard test methods and procedures using heated manikins are provided in ASTM F1720-06 and EN 13537:2002. The testing protocol in this research followed ASTM F1720-06, except that there was no mattress, face mask and underwear. For the testing of evaporative resistance of sleeping bags, since no standard test method or procedure has so far been established, a test protocol was developed in this research. The tests for directly measuring the evaporative resistance of sleeping bags were carried out under the isothermal condition, viz. both the mean skin temperature of the manikin and that of the environment were controlled to be the same at 35 ºC, with the wind speed and ambient relative humidity at 0.3 m s^{-1} and 50%, respectively. The results showed that the novel supine sweating fabric manikin is reproducible and accurate in directly measuring the evaporative resistance of sleeping bags. The measured evaporative resistance can be combined with the thermal insulation to calculate the moisture permeability index of sleeping bags.

Evaporative resistance and thermal insulation of clothing are important parameters in the design and engineering of thermal environments and functional clothing. Past work on the measurement of evaporative resistance of clothing was however limited to the standing posture with or without body motion. Evaporative resistance of clothing when the wearer is at sedentary or supine posture and how it is related to that when the wearer is at standing posture are lacking. This research presents original data on the effect of postures on the evaporative resistance of clothing, thermal insulation and permeability index, based on the measurements under three postures, viz. sedentary, supine, and standing. Regression models are also established to predict the evaporative resistance and thermal insulation index of clothing under sedentary and supine postures from those under standing posture with high accuracy.

Publication arising from the thesis

<u>Conference papers:</u>

Wu, Y. S. and Fan, J. T. (2006). Development of Seated Sweating Thermal Manikin In: Fan J.T. ed. *Proceedings of 6th International Thermal Manikins and Modeling*, *October 16 to 18, 2006, Hong Kong.* Hong Kong, The Hong Kong Polytechnic University, pp. 210-216.

Wu, Y. S. and Fan, J. T. (2007) Development of a Lying Down Sweating Manikin In: Igor B. M., Stelios, N. K. and Nigel, A.S. T. ed. *Proceedings of the 12th International Conference on Environmental Ergonomics, August 19-24, 2007, Piran Slovenia.* Ljubljana, Biomed d.o.o., pp. 429

<u>Refereed Journal Papers:</u>

Wu, Y. S. and Fan, J. T. (2009) Measuring the thermal insulation and evaporative resistance using a supine sweating fabric manikin. *Measurement Science and Technology*, Vol. 20, 095108 (9pp)

Wu, Y. S., Fan, J. T. and Yu, Y. M., (2009) Effect of posture positions on the evaporative resistance and thermal insulation of clothing, under review by Ergonomics.

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Nomenclatures

A = Surface area in (in m^2)

A_c = the area of the exposed test fabric (m^2)

(equal to the internal area of the test dish) (in m^2)

A_{Du} = DuBois area

A_i = area percentage of a division of manikin skin surface,

A_s = the total area of manikin (in m^2), the total area of supine manikin is equal to 1.79 m^2, whereas that of sedentary manikin is equal to 1.91 m^2

d = the internal diameter of the test disk (in mm)

D_i = a saturated absolute humidity in g m^{-3}

dl = medium length that the thermal energy passes through

dT = temperature difference

E_d = heat los by water vapour diffusion

f_{cl} = the estimated clothing area factor (dimensionless)

h = convective heat transfer coefficient depending on the type of convection

H_a = the power consumed for heating the supplied water to the manikin body temperature (in W)

H_{cond} = heat transfer by conduction

H_{conv} = heat transfer by convection

H_d = the dry heat loss of manikin (in W)

H_e = the evaporative heat loss (in W)

H_p = the power consumed by pumps (in W); the pumps are totally immersed in water, so it is assumed all mechanical work would be transferred into heat energy

H_s = the power consumed by heaters (in W)

i = the i^{th} division of the manikin surface area

i_m = the moisture permeability index (dimensionless)

k = thermal conductivity

K_c = the controller gain

m = permeance coefficient of skin

n = the total number of division of manikin surface area

PB = the proportional band of the controller

P_a = the partial water vapour pressure at environment temperature

p_{as} = the saturated moisture vapour pressure at environment temperature (in Pa)

PB_u = the critical values of the control object, which can be obtained experimentally

P_s = the partial water vapour pressure at human body skin surface temperature;

p_{ss} = the saturated moisture vapour pressure at skin temperature (in Pa)

q = the final value calculated from the measurements of different components

q_i = the amount of air supply (in l min^{-1})

Q = the water loss per hour (in g h^{-1})

Q_i = sweating rate of a segment (in g m^{-2}h^{-1})

R_a = the thermal resistance of the air layer on the surface of the nude manikin (°C m^2 W^{-1})

I_{cl} = the intrinsic clothing insulation (°C m^2 W^{-1})

R_e = moisture vapour resistance of the clothing ensemble (in Pa m^2 W^{-1})

R_{es} = the moisture vapour resistance of the skin (in Pa m^2 W^{-1}), which is equal to 8.6

RH_a	=	the relative humidity of the environment (in %)
I_t	=	the total thermal insulation (resistance) of the clothing ensemble or sleeping bag, which includes surface air layer insulation (in °C m^2 W^{-1})
T	=	the time between successive weightings of the assembly (in h)
T_a	=	the environment temperature (in ºC)
T_e	=	the environment temperature (in ºC)
Td	=	the derivative time in minutes (also called rate)
T_g	=	the reading of globe thermometer (in ºC)
T_i	=	the integral time in minutes (also called reset time)
T_{ia}	=	the temperature of a division of the manikin surface area (in ºC)
T_r	=	the mean radiant temperature (in ºC)
T_s	=	the area weighted mean skin temperature of manikin (in ºC)
T_{si}	=	skin temperature (in ºC)
T_u	=	the critical values of the control object, which can be obtained experimentally
$u(t)$	=	the output of the controller
V	=	velocity (in m s^{-1})
$x, \ldots, z$	=	the measurements from different components
$\delta x, \ldots, \delta z$	=	the measured uncertainties from different components

δq = the uncertainty

Δp = equal to the water vapour pressure between manikin skin and environment, $(p_{ss} - p_{as}RH_a)$

Δt = equal to the temperature difference between manikin skin and environment, $(T_s - T_e)$

ε = thermal emissivity, which is <= 1

λ = the heat of evaporation of water at the skin temperature (in W h g^{-1}), which is equal to 0.67 W h g^{-1}

σ = the Stefan-Boltzmann coefficient, which is equal to $5.67 \cdot 10^{-8}$ (W m^{-2} °C^{-4})

Chapter 1

Introduction

1.1 Background

Nowadays, there are approximately over 100 thermal manikins around the world (Holmer 2004). Sweating manikin is a useful tool for obtaining the value of clothing thermal insulation and evaporative resistance. Both of the parameters are essential for evaluating thermal comfort of clothing ensembles. In garment manufacturing and retailing sectors, there is a strong need for enhancing the comfort level of garments. Thermal manikin serves as an indispensable tool for evaluating thermal comfort of clothing ensembles. In extreme environment, thermal insulation of cold protective clothing is strongly related to the survival of human subjects.

Apart from thermal manikins, wearer trial is an alternative for evaluating the thermal comfort of clothing ensembles. Although it provides realistic results, it is subjective in nature. The result is subject to the influence of personal bias and inconsistence. For reducing the effect of personal bias and inconsistence, a large sample size is necessary for the validation of final results and thus, it is time consuming and costly. By contrast, thermal manikin is relatively cost effective, quick, and accurate with high reproducibility for evaluating thermal comfort of clothing ensembles.

However, the development cost of thermal manikin is extremely high, especially for sweating manikins. In addition, the operation of thermal manikins requires specialists with substantial amount of experience; otherwise the standard deviation of test results may be very large. The experience and skill level of the operator will significantly affect the reproducibility of test results. As a result, they hinder the wider application of the thermal manikins.

For the wider application of thermal manikins, there is a need to reduce the cost of manikin substantially. In order to achieve this goal, Fan and Chen (2002) invented the world first fabric sweating manikin (Walter). The adoption of breathable fabric as a means of sweating simulation reduces the complexity and cost of sweating simulation substantially. Also, the test results will not be significantly affected by the operator because the operator does not need to spray water and operate over hundreds of tubes for simulating sweating.

Prior to the present development, fabric sweating fabric manikins are made in standing posture. It is therefore desirable to develop fabric sweating manikins with supine and sedentary postures for the testing of clothing thermal comfort as body posture affect the heat and moisture transfer from the body and environment. It is also desirable to predict the thermal insulation and evaporative resistance of clothing under different body postures from those tested under one posture.

1.2 Research objectives

The prime objective of this research is to develop a relatively low cost sweating fabric manikin, the posture of which is adjustable between supine and sedentary so as to enhance the application level of sweating fabric manikin in thermal comfort evaluation.

The second objective is to develop a new sweating rate measurement system, which is the most suitable for supine and sedentary manikin.

The third objective is to demonstrate the accuracy and the reproducibility of the supine and sedentary manikins being produced in this research.

The fourth objective is to measure the thermal insulation and evaporative resistance of sleeping bags as well as the resultant moisture permeability index using the supine sweating fabric manikin.

The fifth objective is to study the posture effect on the thermal insulation and evaporative resistance of clothing ensemble using the sedentary and supine sweating fabric manikin as well as the standing manikin – Walter (Fan and Chen 2002, Fan and Qian 2004, Wan and Fan 2008).

1.3 Significance of research

It is important to turn the thermal manikin from a pure research tool to a practical testing tool affordable to all interested parties. By reducing the cost of sweating manikin substantially, the sweating manikins can be made affordable for routine testing in commercial testing houses and even in the laboratories of garment manufacturers and retailers.

Thermal manikin is not only a useful tool for clothing product development in terms of evaluating clothing thermal insulation and evaporative resistance, but also is applicable for HVAC evaluation in terms of energy saving and thermal comfort assessment.

For sedentary sweating fabric manikins, it is especially suitable to test the thermal comfort inside the car, whereas supine thermal manikin is perfectly fit for evaluating the thermal comfort of sleeping bag and beddings.

Apart from clothing and HVAC, sedentary thermal manikin also is applicable in evaluating the thermal comfort of furniture.

In respect of originality, a sweating fabric manikin with supine and sedentary postures is totally original in thermal manikin development history. In addition, the sweating measurement system being developed in this research is also original. This research is useful in filling the technological gap of thermal manikin development.

1.4 Outlines of this thesis

In Chapter 1, a general background, objectives and significances of this research are given. In Chapter 2, a comprehensive literature review on the history of thermal manikins, thermal comfort evaluation of sleeping bags and posture effect on thermal insulation and evaporative resistance is given. A clear illustration and description of the design and construction of sweating fabric manikin with supine and sedentary postures is given in Chapter 3. Chapter 4 and 5 show the methods, procedures and result analysis of sleeping bag and clothing ensemble experiments, respectively. Finally, Chapter 6 is the conclusions and recommendations of this thesis.

Chapter 2

Literature Review

2.1 Thermal manikin history

In terms of thermal manikin development, thermal manikins can be grouped into four types. The first type is the standing (viz. not walkable) and non-perspiring ones (Kerslake 1963, Fonseca 1975, and McCullough, et al. 1989). The second type is non-sweating manikin but simulating sweating by wetted skin. This type of manikins are currently used by Holmer in Sweden, McCullough in USA and Havenith in Britain. The third type is movable (viz. walkable), 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). The fourth type is the perspiring and/or moveable manikin such as "Taro" in Japan (Yasuhiko et al. 1991), Kem in Japan (Fukazawa et al., 2004), "Coppelius" in Finland (Meinander 1999), "Sam" in Switzerland (Mattle 1999) and "Walter" in Hong Kong (Fan and Chen 2002, Qian and Fan 2004). All in all, Homer (2004) concluded that thermal manikin served as a reliable and accurate instrument for evaluation of thermal factors.

2.1.1 The world first thermal manikin

The world first thermal manikin is a one-segment copper manikin produced by United States Army in the early of 1940s (Belding, 1949; Holmer, 2004). The building of the thermal manikin was due to the effort of Dr. Harwood Belding. The idea of building thermal manikin was originated by the inspiration of a store fashion manikin.

The first manikin built by Dr. Harwood Belding was a rough, armless and headless manikin, which was made up of stove pipe and several sheet metals. The heat is distributed by an internal heater and fan.

In 1942, with the collaboration of General Electric Co. engineers, Belding produced a human shape copper thermal manikin. It was constructed by electroplated copper shell of 3 to 6 mm in thickness. A single electrical circuit was utilized for heating the copper shell evenly and the temperature of the hands and feet can be changed without affecting the surface temperature of the remaining parts of the manikin.

In 1945, an electroplated copper shell manikin with a total of six separate electrical circuits was constructed by General Electric and a group of thermal manikin experts under the request of the U.S. Army for the Climate Research Laboratory. The thermal manikin was built based on the anthropometric data from a study of nearly 3000 Army Air Force cadets and based on the average physical dimensions of a young U.S. military recruit (Endrusick et al., 2003). Holmer (2004) reported that the one-segment copper thermal manikin produced by U.S. Army in 1940s was one of the milestones in the thermal manikin development history.

2.1.2 Light weight multi-segment thermal manikins

After the invention of the world first thermal manikin, there was a trend of developing light weight multi-segment thermal manikins. The multi-segment thermal manikin has the advantage of movement and control flexibility. Each individual segment also provides independent temperature information for research purpose. Holmer (2004) reported that most multi-segment thermal manikins today had more than 15 segments.

In terms of weight, most of the manikins nowadays are constructed by light weight materials such as plastic and aluminum. The usage of plastic or aluminum helps to reduce the cost of production and weight for movement. However, it makes the thermal manikin deviate from real human in terms of heat capacity and weight. In cases of testing seats, mattresses and sleeping bags, it will reduce the material compression by body weight and thus affect the heat and mass transfer simulation.

2.1.3 The early development of sweating manikins

The most primitive sweating manikin used tightly fit cotton or hydrophilic underwear with initially 100% saturated water to simulate a sweat wetted skin surface. The evaporative resistance can be calculated by measuring dry heat loss and wet heat loss separately. The difference between wet and dry heat loss can be used to estimate the sweating quantity.

Theoretically, all thermal manikins can use this method to simulate sweating. However, this method cannot maintain constant sweating rate for a prolonged duration. In practice, operator needs to spray water onto the cotton underwear of skin in advance for simulating sweating. Some area of the cotton underwear will dry gradually during test and thus, evaporation will decrease gradually.

In addition, the sweating process cannot last for long time as the cotton underwear will eventually totally dry out. As a result, the testing garment may not reach steady state even up to the end of test, especially for thick garment such as down jackets. It is only usable for measuring the transient process because there is no continuous water supply.

Also, it is difficult to ensure the evenness of water content on the cotton “skin” for each test. The experience of operators would affect the reproducibility of test significantly.

2.1.4 The recent development of sweating manikins

2.1.4.1 Finnish sweating manikin Coppelius

The sweating manikin Coppelius (Figure 2-1 left side) was developed in the 1980s under a Scandinavian cooperation project (Meinander, 1997). It was the first true sweating manikin in the sense that a controlled amount of water is continuously supplied to its heated surface, where the moisture evaporates and causes an increase in the total heat loss (Meinander, 1997).

The primary objectives of constructing the manikin were for indoor climate and clothing system comfort measurement, but eventually it was mainly used for clothing system comfort evaluation.

The manikin is heated by a computer controlled heating system with 18 individual controlled body sections. It encompasses 187 sweat glands (Figure 2-1 right side) which are distributed over the whole body except head, hands, and feet. A computerized micro-valve system in the manikin is used to distribute water to each sweat gland through tubes (Figure 2-1 right side). The manikin was constructed based on anatomical body dimensions with size 40. The prosthetic joints at the knees, hips, elbows, and shoulder enable movement with different postures.

Figure 2-2 shows the cross section of a sweat gland. A tube in the shell material is used to deliver liquid water to the manikin surface. The "skin" of Coppelius consists of two layers: an inner nonwoven material which spreads the water to a larger area (max. 100 cm^2) and outer microporous membrane which transmits water in vapour but not in liquid form. The supplied water will be evaporated by the heating system and thus, the manikin surface produces heat and vapour similar to the human skin. In case of moderate sweating level, maximum amount of water supply is 200 g m^{-2} h^{-1}.

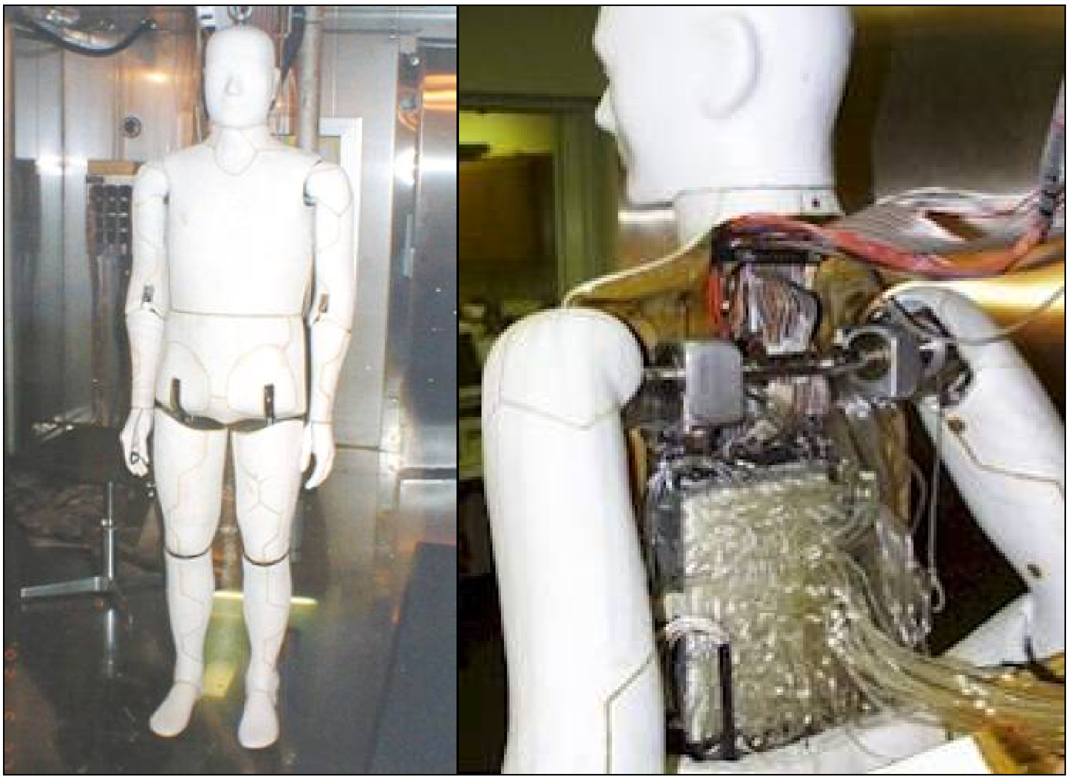


Figure 2-1. Coppelius water supply tubes (Textile Protection and Comfort Centre, 2009a)

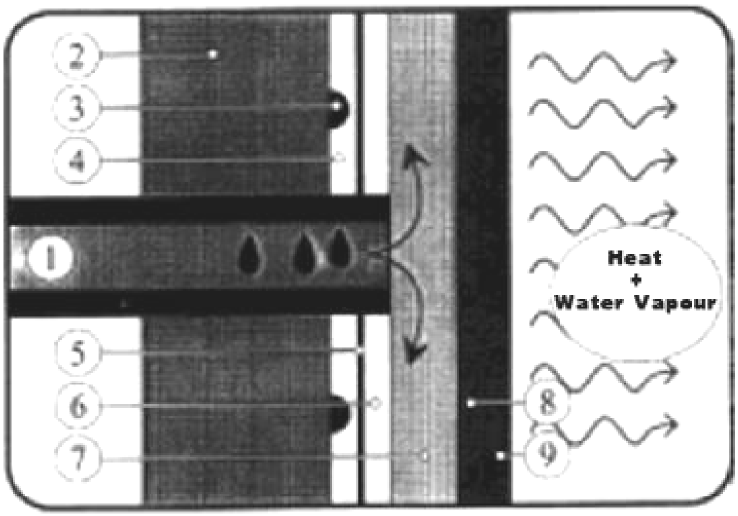


Figure 2-2. Cross section of a sweat gland (Meinander, 1997)

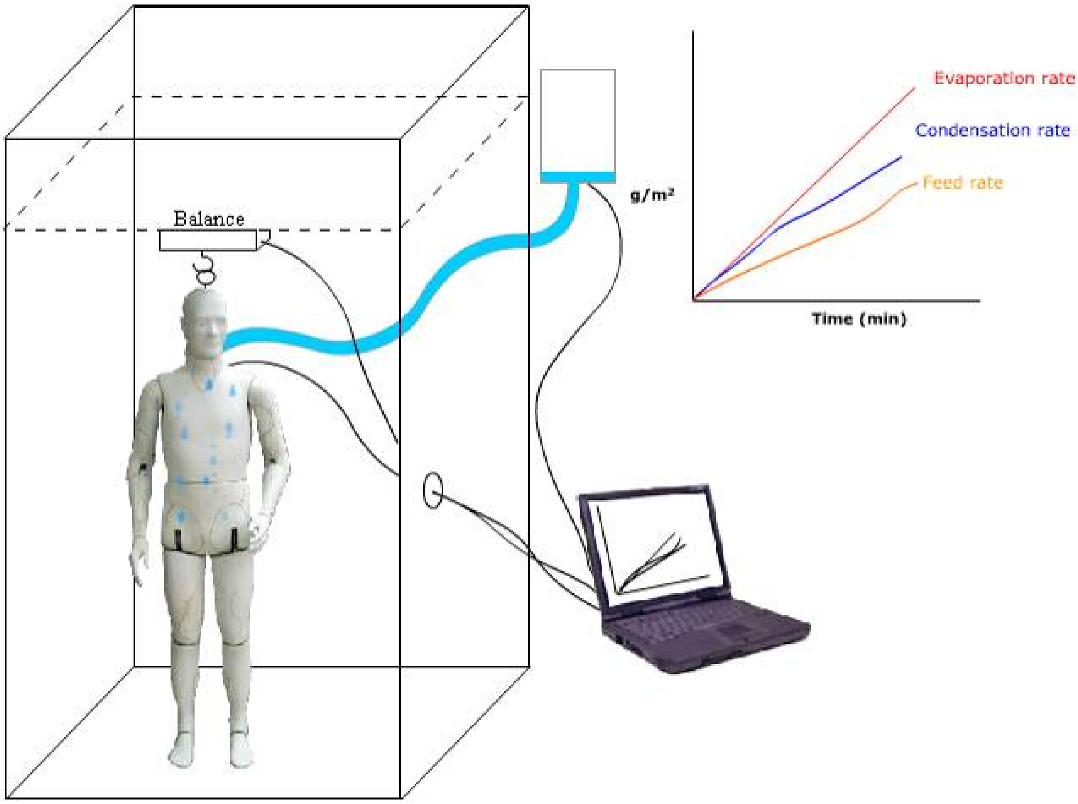


Figure 2-3. Sweating system of Coppelius (Textile Protection and Comfort Centre, 2009b)

Figure 2-3 shows the whole sweating system of Coppelius. The manikin is hanging in a climate chamber. For monitor the weight of the manikin, an electronic balance was connected to the manikin hanging system. The water comes from a reservoir which is placed on an electronic balance near the ceiling in the chamber. The electronic balance is used to monitor the amount of water supplied to the manikin. The manikin comprises a micro valve system, which distributes the water to the 187 sweat glands, and the computer system permits individual control of each sweat gland. By inputting body seating rate, the software algorithm will calculate the proportion time of opening of each valve so as to determine the required sweating rate of each sweat gland. The amount of moisture vapour evaporation can be obtained by calculating the difference between the weight of water supplied to the manikin and the weight increase of the clothed manikin. The amount of moisture condensation in the individual clothing layers can be measured by weighting the testing garments before and after test immediately, whereas the moisture condensed in the skin material of the manikin is calculated as the change of total weight deducted by the moisture condensed in the clothing.

The sweating manikin Coppelius can measure the thermal insulation and evaporative resistance of clothing ensemble with reproducible result. However, there are only two sets of Coppelius around the world. One is located in VTT Laboratories in Tampere of Finland. Another one is located in North Carolina State University. It is not available for normal commercial testing laboratory.

For calculating the evaporative resistance, the system needs to monitor the weight change of the manikin by an electronic balance (Figure 2-3) continuously. Therefore, suspension is necessary for measure the weight change of the manikin. As a result, sitting and lying down would produce difficulty for measuring the weight of manikin continuously. In addition, the portability of the manikin also restricted as the manikin need to connected to an electronic balance for measuring the weight change.

2.1.4.2 Japanese sweating manikin TARO

Dozen et al. (1992) reported a sweating manikin called "TARO" (Figure 2-4). The manikin skin was made up of bronze with pores which enabled moisture vapour flowing from the inside of the manikin to the skin surface for simulating human body's gaseous perspiration heat loss. The sweating quantity in each segment of the manikin is calculated by the equation below:

$$Q_i = 60 \cdot 10 - 3 \cdot q_i \cdot \frac{273 + T_{si}}{273 + T_a} \cdot \frac{D_i}{A_i} \qquad (2\text{-}1)$$

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;

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.

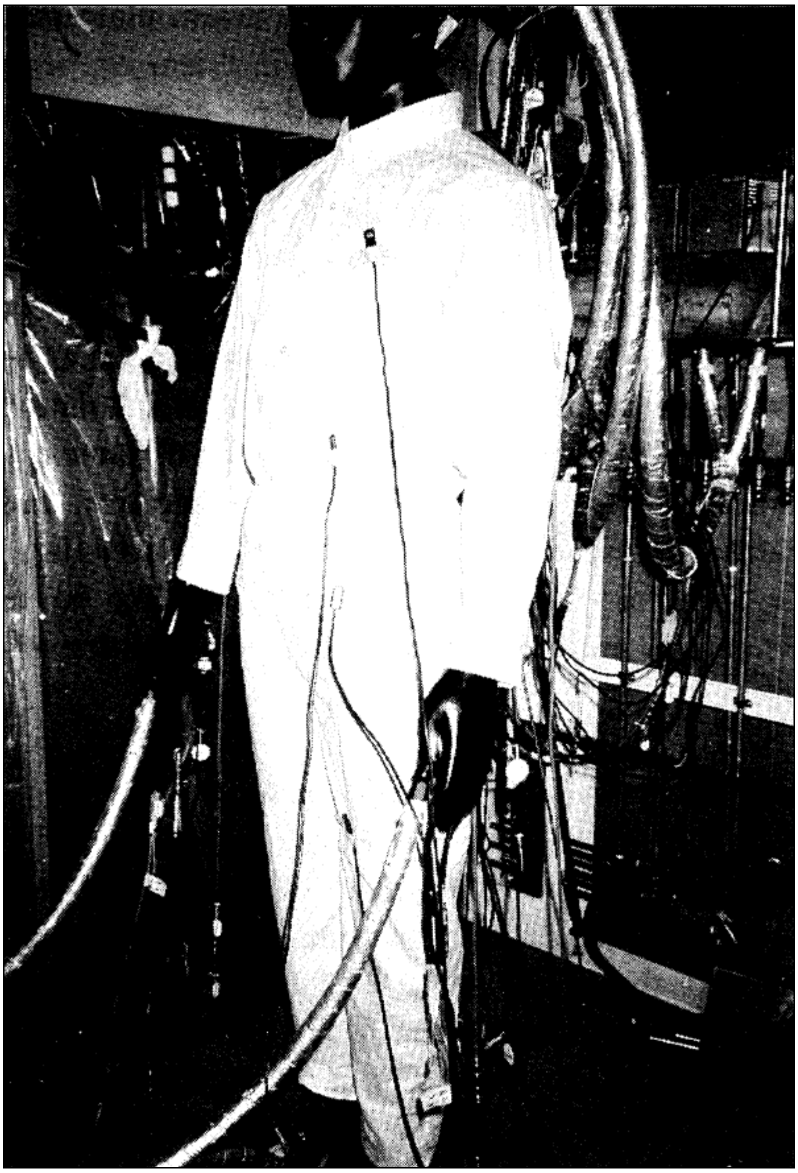


Figure 2-4. Manikin "TARO" (Dozen et al., 1992)

The sweating rate can be altered by regulating the air flow rate. However, the moisture vapour may not penetrate through the garment to the environment but just escape from the opening of garment, especially in case of increasing air flow rate.

2.1.4.3 Swiss sweating manikin SAM

The full name of SAM is Sweating Agile thermal Manikin, which was developed and produced in Switzerland within the framework of a EUREKA Project. The manikin was constructed based on the dimension of an average male adult and was anatomically formed with limbs which allowed simulating realistic human movement. The inner skeleton of the manikin is suspended from a weight system, which is covered by 26 attached shell part. Each of the shell can be heated separately and is attached with temperature sensors.

For simulating human sweating, the manikin encompasses 125 sweating outlets (Figure 2-5) distributed over the whole body surface. The vapour and liquid sweating are simulated by using internal micro valves (Figure 2-6) with adjustable sweating rate ranging from 0 to 4 l m^{-2} h.

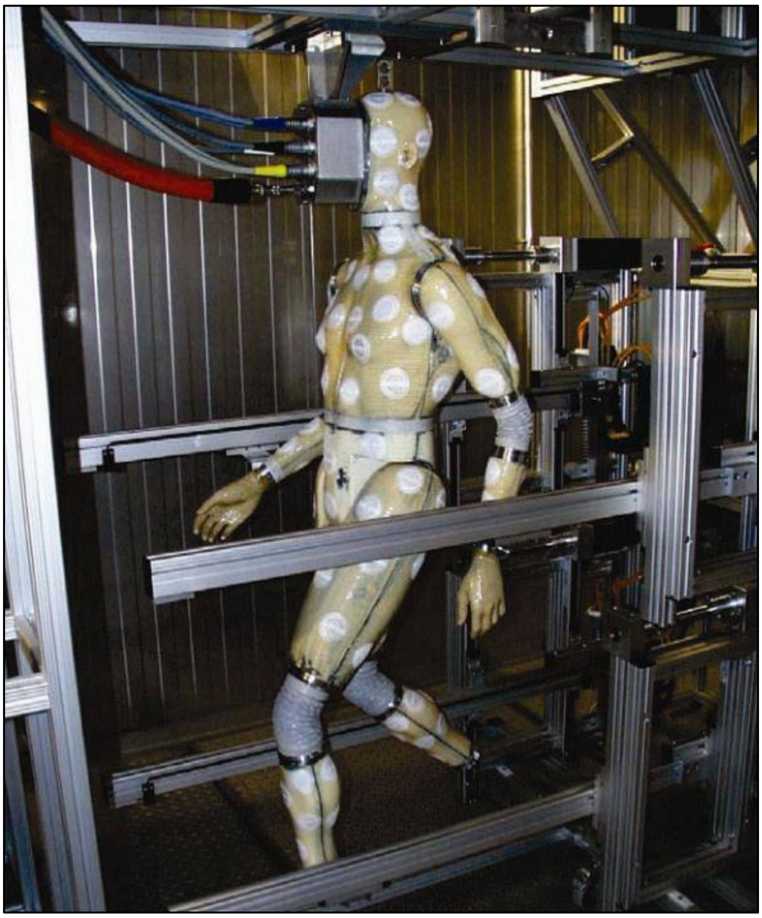


Figure 2-5. Sweating glands and realistic motion of Sweating Agile thermal Manikin "SAM" (Fries, 2003)

For simulating realistic human motion, the wrists and ankles of the manikin are connected to external drive assembles, which can move through various curves under computer control. The maximum walking speed of the manikin is 3 km h^{-1}.

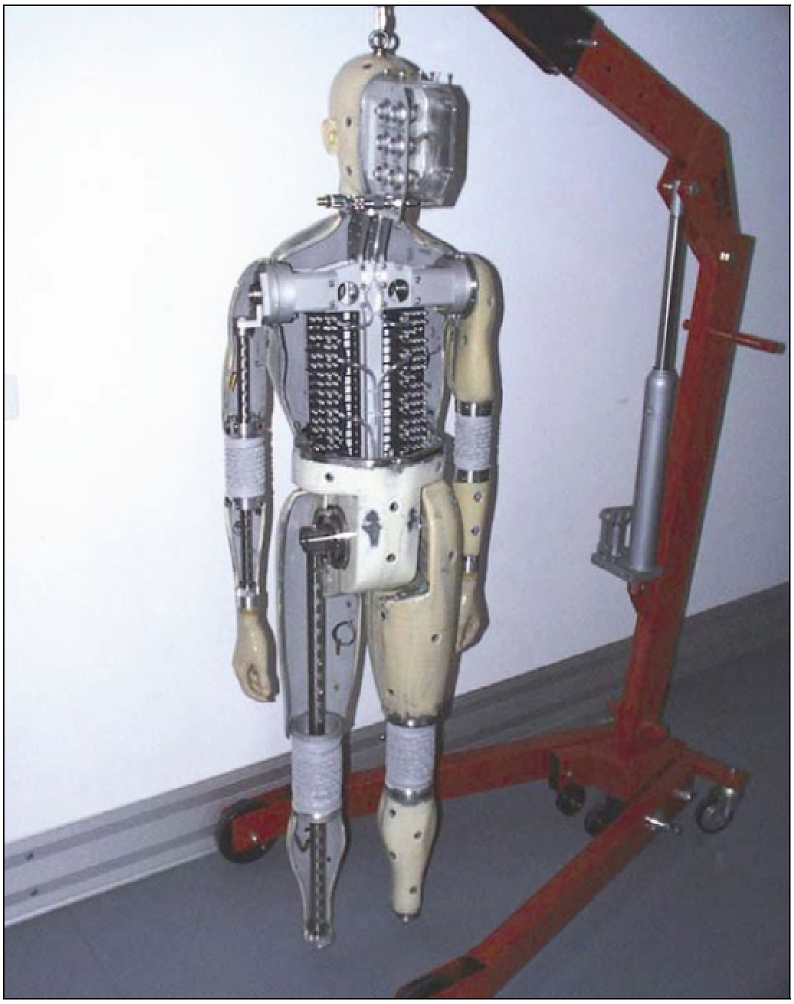


Figure 2-6. Internal skeleton of SAM (Fries, 2003)

2.1.4.4 Hong Kong sweating manikin Walter

Fan et al. (2002) released a new sweating manikin called as Walter, which can simulate human vapour sweat and walking motion (0 to 2.48 km h^{-1}). The manikin is heated and maintained constant body temperature by water circulation from the body center to extremities, whereas heaters and pumps are placed at the center of the manikin for heating and distributing heat water.

In respect of sweating mechanism, the vapour sweat of Walter is simulated by breathable fabric skin. The breathable fabric skin is a three layer laminated fabric. The middle layer of the three layer laminated fabric is a microporous polyteyrafluoroethene (PTFE) Gore-Tex membrane. In every square centimeter of Gore-Tex membrane, there are 1.4 billion tiny microporoes, which are 20000 times smaller than a drop of liquid water, but are 700 times larger than a vapour molecule. Therefore, the micropores are too small for liquid water passing through, but are large enough to let water vapour pass through.

Figure 2-7 shows a PTFE microporous membrane magnified 20,000 times using field emission scanning electron microscopy (SEM). The pores are too small to allow water molecules to pass though but large enough to allow the passage of molecules of water vapour.

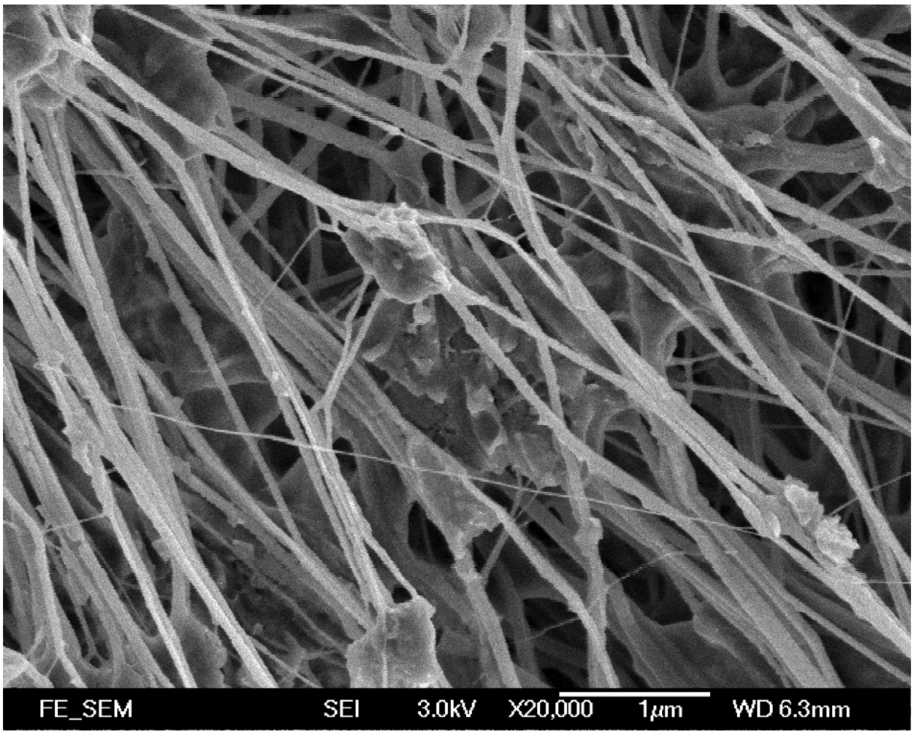


Figure 2-7. PTFE micro-porous membrane magnified 20,000 times

In terms of sweating measurement, the manikin uses direct measurement method. It is no need to measure and monitor the total weight of manikin. The use of siphon action (Figure 2-8) allows only need to measure and monitor the weight of an external water reservoir via an electronic balance. The water in the water reservoir is connected to the manikin. When the manikin is sweating, the water in the manikin will decrease and the water in the water reservoir will automatic flow to the manikin due to siphon action with same atmospheric pressure. The reduction of water in the water container above the electronic balance is proportional to the sweating rate of the manikin.

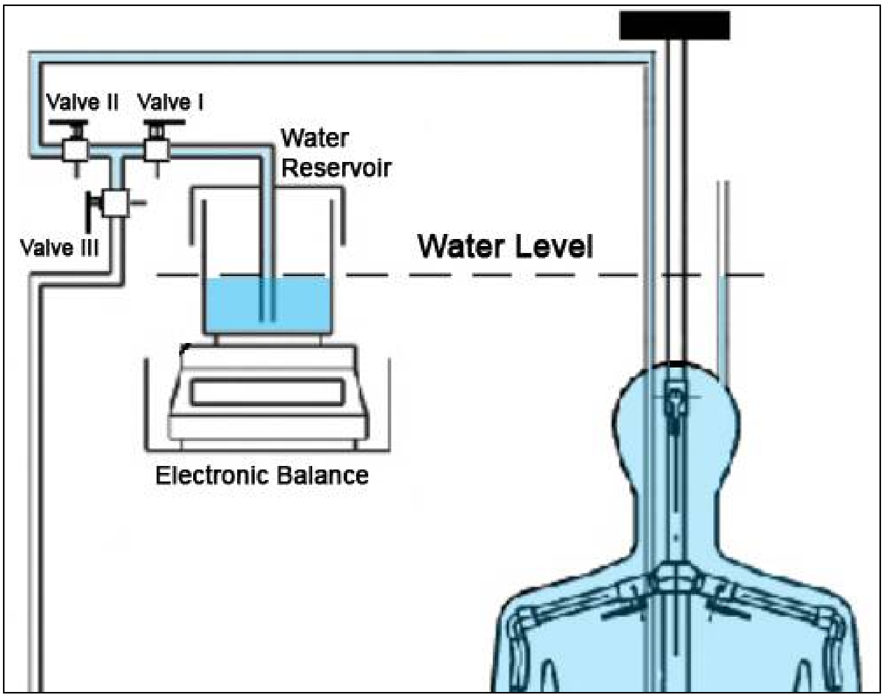


Figure 2-8. Sweating measurement system

2.1.4.5 United States sweating manikin Adam

The Advance Thermal Manikin (Adam) was developed by Measurement Technology Northwest for the Department of Energy's National Renewable Energy Laboratory (NREL) in 2003. It is mainly used to evaluate the non-uniform and transient environments in vehicles and aircraft. The manikin contains 126 individually controlled segments and sweating zones (Figure 2-9 and 2-10). The manikin is self contained with an internal battery system, which can support two hours operation, and a wireless transceiver, which can support cordless operation during test.

Figure 2-9 shows the structure of a segment of Adam. The sweating is simulated by porous metal. A low porosity metal served as the skin, whereas a high porosity metal under the skin served as a water distribution layer. The sweating rate is controlled by a fluid control valve.

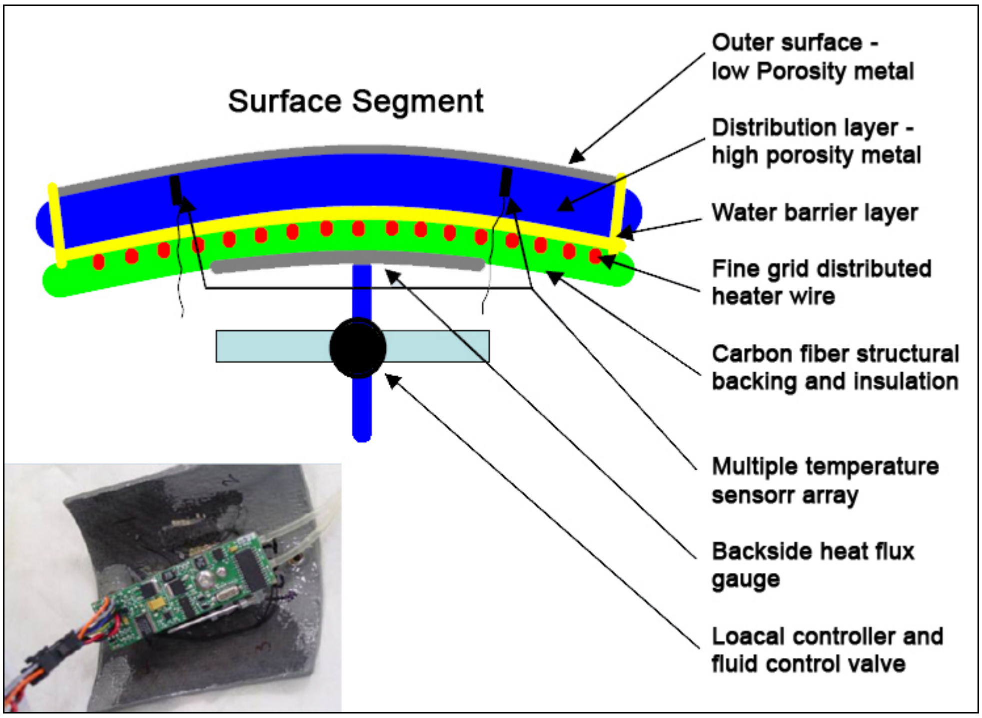


Figure 2-9. Surface segment of sweating zone details (**Rehn, 2004**)

The sweating rate and sweating distribution are determined by a physiological thermoregulation model so as to simulate human transient thermal response to specific environment such as vehicle.

Figure 2-10. Sweating simulation of Adam (Rehn, 2004)

2.1.4.6 Japanese sweating manikin KEM

The manikin KEM (Figure 2-11) was developed by Kyoto Electronics Manufacturing, which encompasses 17 segments with movable joints (Fukazawa et al., 2004). The sweating is simulated by using a thick and strong water-vapour permeable material. For distributing water, 17 sources of sweat under the water-vapour permeable material are used. In addition, the sweat sources in each segment are individually controlled by pistons. The sweating rate ranges from 0 to 1500 g m^{-2} h^{-1}.

The sweating mechanism of KEM is not a new technique. The sweating rationale is similar to Finnish sweating manikin “Coppelius”, which developed in 1980s, in terms of sweating sources and water vapour permeable skin.

Figure 2-11. Sweating thermal manikin KEM (Fukazawa et al., 2004)

2.1.4.7 Improvement on wetted cotton or hydrophilic skin method

Burke et al. (1994) showed a new technique of using pipes to supply water to cotton skin to improve the simulation of sweating. It provided a continuous water supply to the cotton skin for testing steady state evaporative resistance.

In 2005, Measurement Technology Northwest released a manikin sweating skin system (Figure 2-12) based on a matrix of fluid ports and a removable wicking fabric skin layer. In each fluid ports of manikin surface, the water will continuously flow to the wicking skin layer and the skin can maintain 100% saturation by a computerized water distribution and modulate system. A manikin called “Newton” from Measurement Technology Northwest used that sweating skin to simulate sweating.

Figure 2-12. The removable wicking fabric skin layer of Measurement Technology Northwest (Measurement Technology Northwest, 2009)

2.1.4.8 Concluding remarks of the development of sweating manikins

In terms of cost, sweating manikin normally is very expensive. SAM and Adam are the typical examples. Walter is relatively inexpensive. However, it couldn't simulate sedentary and supine postures since it is a standing manikin with walking simulation ability only.

In respect of sweating rate calculation, most of the sweating manikins require to measure the total weight of manikin. It is because the porosity layer under the manikin skin will store a certain amount of water. For accurate calculation of the sweating rate, that amount of water should be subtracted. In addition, in order to measure the weight of manikin accurately, the manikin should be in a hanging state; otherwise accurate measurement is very difficult and complicated. Such constraint exerts limitation in developing sedentary and supine sweating manikin since touching the ground and objects are necessary for sedentary and supine sweating manikin. As a result, there is a need to develop a new sweating simulation mechanism to avoid the necessity of weighting the weight of the entire manikin. The direct sweating measurement system of the existing sweating fabric manikin-Walter in the standing position is good as it does not need to measure the entire weight of manikin. However, the method still has room for improvement. The change of the weight of the water reservoir is not identical to the water loss of the manikin, and it requires a coefficient of calibration to calculate the sweating rate.

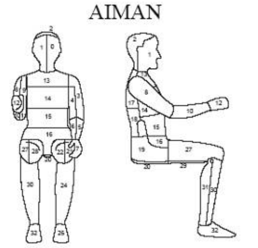
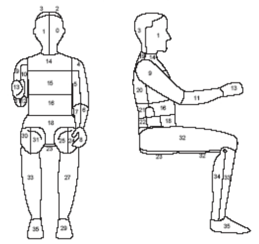
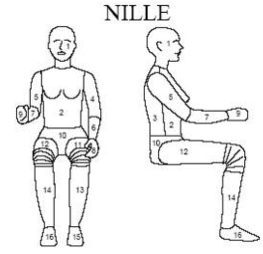
Considering the operation and maintenance of existing sweating manikins, there is also a need for further improvement. The sweating simulation method of wet cotton skin involves manual work and hence the reproducibility of test results is largely relied on the experience of operator because the evenness of water distribution over the whole cotton skin depends on the operator’s spraying skill. For the water tube method, water leakage in the joint of tubes and air trapped in tubes are the main obstacles for achieving reproducible results. The micro valve will also be blocked by impurities easily. In addition, it is also difficult to ensure that over 100 sweating glands are in sound condition. Only experienced operators with specific skill are eligible to the task. The complexity of operation and maintenance is another factor hindering the wider use of sweating manikin beyond research level.

2.1.5 The development of sedentary thermal manikins around the world

The development of sedentary thermal manikin can be divided into three stages. The first one is non sweating muti-segment sedentary thermal manikins including Sibman (Sweden 1980), Voltman (Sweden 1982), Assman (Sweden 1983), Nille (Denmark

1989), Heatman (Sweden 1991), etc. These manikins had joints to simulate sitting posture and are divided into several segments for individual control of temperature in different segments. They were generally made up of plastic or aluminum, which had advantage of light weight with higher portability (Table 2-1). However, light weight seated manikins could not give realistic compression on the seats imposed by body weight during sitting posture.

Table 2-1. Comparison of the technical data of three non-sweating sedentary manikins (Bohm et al., 1999)

Manikin	AIMAN 	HEATMAN 	NILLE 
Size	C50	Eur 42-44	Not available
Length	Sitting	173cm	166cm
Weight	16 kg	16 kg	31 kg
Number of zones	33+ 3 t_a	35 + 1	16

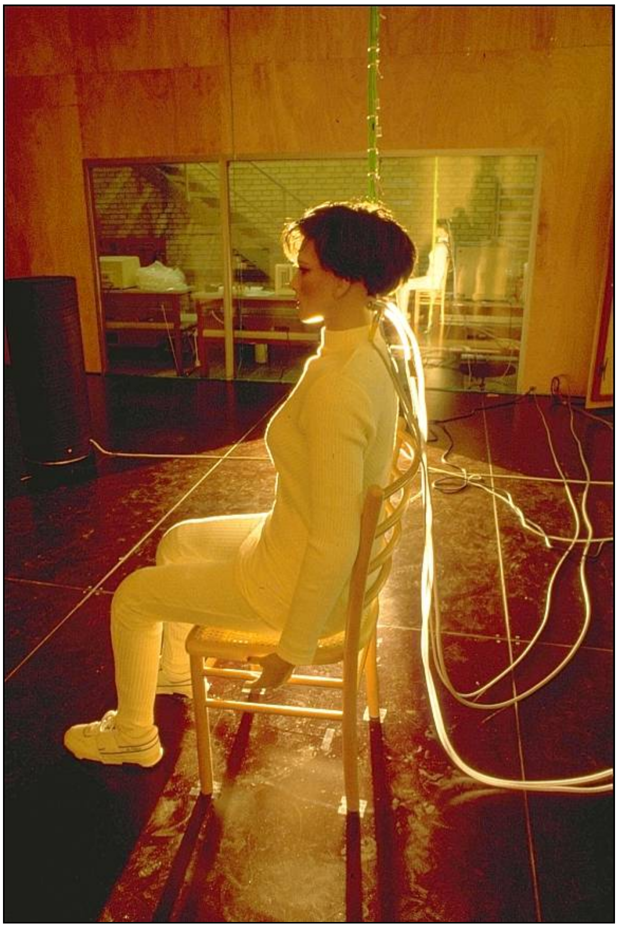


Figure 2-13. Non sweating seating breathing thermal manikin developed at Danish Technical University

The second stage is non sweating seated breathing thermal manikins. The female manikin Nille at Danish Technical University was an example (Figure 2-13). The manikin was made up of plastic with movable joints and separated into 16 zones. An artificial lung with humidification and heating units was attached to the manikin for simulation realistic human breathing (Figure 2-14). The manikin was mainly used for indoor quality evaluation with consideration of breathing zone.

Figure 2-14. The non sweating breathing manikin inhale through mouth and nose at Danish Technical University

The third stage is seating sweating thermal manikin with breathing function. The Adam (USA 2003) was an example (Figure 2-15). The detail information of Adam was mentioned in pervious section of the recent development of sweating manikin development. The manikin was specially designed for thermal comfort evaluation in car based on physiological thermal regulation model.

Figure 2-15. The seated sweating and breathing thermal manikin Adam (Rehn, 2004)

2.1.6 Supine thermal manikins

Theoretically, all segmented manikins can be put in lying down posture to become supine manikins for testing sleeping bag, mattress and bedding.

Non sweating supine manikins were used for measuring the thermal insulation of sleeping bags. In 1980s, some US sleeping bag manufacturers employed a non sweating manikin “Copperman” to measure the thermal insulation of whole sleeping bag instead of a piece of fabric. However, there was no standard for testing procedures and result interpretation at that time. Therefore, the manikin test was used for reference only and manufacturers still mainly relied on flat textile tests instead of manikin test. In 1990s, an American national standard for sleeping bag insulation test using thermal manikin was developed and the designation was F1270. The standard had revised for several times and the latest version is F1270 – 06.

In Europe, during 1990s, some European testing laboratories provided supine manikin tests for measuring the thermal insulation of sleeping bags. For example, Hohenstein Institutes used manikin Charlie to provide thermal insulation tests of sleeping bags. Also, Textile de France provided similar tests using manikin Martin. In 2000s, Hohenstein Institutes and Textile de France jointed inter-laboratory test and harmonized the test method and formed the draft of EN 13537.

Researches were also carried out to investigate the influence of sweating on thermal insulation of sleeping bags. Camenzind et al. (2001) reported using sweating torso in cylinder shape to investigate the influence of body moisture on the thermal insulation of sleeping bags. The sweating torso consisted of 54 sweating nozzles from which a specific amount of water was supplied to simulate sweating. The moisture permeability of the sleeping bags was evaluated based on the measured heat loss due to sweating. However, without a head, arms and legs, the sweating torso was very different from a human body. This technique thus significantly deviated from the real use condition. Havenith (2004) used a dry manikin covered with wet cotton underwear to simulate sweating in investigating vapour transfer and condensation in sleeping bags. Although it is a simple technique commonly used in standing manikins, it is questionable whether the wetness of the underwear can be uniformly maintained over the prolonged testing period. Furthermore, in order to determine the changing perspiration rate, the weight of the supporting board, sleeping bags and cotton underwear should be measured periodically. A real time measurement of perspiration rate was very difficult and complicated.

2.1.7 Milestones of the thermal manikin development

Table 2-2 shows the millstones of the development of thermal manikins in chronological manner. Holmer (2004) pointed out that the development of thermal manikins had separated into two main directions. One direction is toward sophistication and complexity with multi functions at extreme high cost such as SAM and ADAM. Another direction is toward simple and low cost with high reproducibility and accuracy such as Walter.

Table 2-2. The thermal manikin development milestones (modified from Wyon, 1989; Holmer, 1999; Holmer, 2004; Nilsson, 2004)

No	Segmentation	Series	Material	Regulation	Posture	Country & Year
1	1-segment	COPPERMAN	copper	analogue	standing	USA 1942
2	11-segments	ALMANKIN	aluminum	analogue	standing	UK 1964
3	radiation manikin	CEPAT400	aluminum	analogue	standing	France 1972
4	16-segments	HENRIK2	plastic	analogue	movable	Demark 1973
5	16-segments	CHARLIE	plastic	analogue	movable	Germany 1978
6	16-segments	SIBMAN	plastic	digital	sit, stand	Sweden 1980
7	19-segments	VOLTMAN	plastic	digital	sitting	Sweden 1982
8	36-segments	ASSMAN	plastic	digital	sitting	Sweden 1983
9	19-segments	TORE	plastic	digital	movable	Sweden 1984
10	7-segments	CLOUSSEAU	plastic	analogue	standing	France 1980s
11	sweating manikin	COPPELIUS	plastic	digital	movable	Finland 1988
12	female manikin	NILLE	plastic	comfort	movable	Denmark 1989
13	33+3-segment	HEATMAN	plastic	multi	sitting	Sweden 1991
14	1 segment sweating	TARO	copper	digital	standing	Japan 1992
15	breathable manikin	NILLE	plastic	multi	movable	Denmark 1996
16	26-segments sweating	SAM	plastic	digital	movable	Switzerland 2001
17	1-segment sweating	WALTER	breathable fabric	digital	movable	Hong Kong 2002
18	26-segments	TOM	copper	digital	movable	USA 2003
19	1-segment	not available	windproof fabric	digital	movable	USA 2003
20	126-segments	ADAM	porosity metal	digital	movable	USA 2003
21	17 segments sweating	KEM	Porosity material	digital	movable	Japan 2004
22	Sweating manikin	Newton	Wicking skin with water tubes	digital	movable	USA 2005

For the sweating thermal manikin like Coppelius, SAM and ADAM, the development cost were several millions of US dollars, but they are still not commercially available. The high cost and complexity hider the wider application of sweating thermal manikin. There are some highly commercialized sweating manikins such as Newton (cost around 2 hundred thousands US dollar) using hydrophilic skin method to simulate sweating. Although the hydrophilic skin method makes the manikins less expensive, but the hydrophilic skin method is difficult to maintain consistent distribution of sweating for a prolonged period, and the accuracy and reproducibility may be subject to the influence of the experience of operator. In order to widen the application of sweating manikin, simple and low cost sweating manikins with high reproducibility would be an appropriate option.

2.2 Past researches related to thermal comfort evaluation of sleeping bags

One of the main applications of supine manikin is to evaluate the thermal comfort of sleeping bags in terms of thermal insulation and evaporative resistance. In normal conditions such as mildly cold environments, the thermal properties of sleeping bags affect the quality of sleeping. However, in extreme conditions, such as mountaineer exploring in several thousand meter altitude or extreme cold environment like the arctic region, the thermal properties of sleeping bag are extremely important to survival. Therefore, supine manikins serve as essential tools for clothing engineers to assess the thermal protection of sleeping bags for the survival in extreme conditions.

2.2.1 Thermal insulation measurement of sleeping bags

The thermal comfort of sleeping bags can be measured in the material level and whole sleeping bag level. In the material level, the flat textile method is most commonly employed. The Shirley Togmeter, guarded hot plate and Kawabata (KES) Thermal Lab-II are the examples of thermal insulation testers for textiles. The Togmeter expresses the insulation of material in terms of Tog, which is equal to 0.1 °C m^2 W^{-1}, whereas the hot plate method and Kawabata system express the result in SI unit (°C m^2 W^{-1}) or Clo unit, which is equal to 0.155 °C m^2 W^{-1}. Sleeping bag is a thick and complex system, the thermal insulation of the fabric materials used for making the sleeping bags cannot fully reflect the thermal insulation of whole sleeping bag system. The thickness of the sleeping bag is not uniform and the compression effect caused by human body will reduce the thickness of a portion of sleeping bag dramatically. In order to have a more realistic measurement of the insulation of whole sleeping bag system, manikin test is preferable. A detail literature review of the development of thermal insulation measurement using supine manikin was given in Chapter 2 section 2.1.6.

For the range of thermal insulation of sleeping, Holmer (1993a) reported that the thermal insulation value (Clo) for simple single sleeping bags, double bags and triples bags using a heated manikin. The results indicated that the single bag system seldom had more than 6 Clo, whereas a composite system would provide 10 Clo or even more. The results also indicated that number of layers was an important factor affecting the thermal insulation of sleeping bags.

Apart from using fabric test and manikin test, the thermal comfort of sleeping bag also can be evaluated by human subject field test. Holmer (1995) conducted human subject field test in an igloo at -1 °C. The result verified that the bag should provide approximately 5.5 Clo to keep the subjects comfortable based on 46 human subjects. In EN13537: 2002, by combining the supine manikin and human subject tests with physiological models, thermal comfort ratings are given in the standard based on supine thermal manikin test in specified standard environment and condition.

For human subject tests, large sample size is required to verify the results because of individual difference and inconsistence. It is also time consuming and costly. In extreme environment, the life of participants is also under threat.

2.2.2 Evaporative resistance of sleeping bags

Evaporative resistance of sleeping bags is much less investigated. Most of the past researches focused on the effect of moisture accumulation and condensation on the thermal insulation using sweating torso (shown in Chapter 2 section 2.1.6), manikins (shown in Chapter 2 section 2.1.6) and human subjects instead of direct measurement of the evaporative resistance of entire sleeping bags.

In terms of condensation effect, Lotens and Havenith (1995) and Lotens et al. (1995) pointed out that the accumulation of moisture in sleeping bags over a long period of time would cause a reduction in insulation due to higher condensation cycle, which took place from warmer inner part of sleeping bag to the cooler outer parts of sleeping bag.

A group in Switzerland (Camenzind et al., 2001; Hartog et al., 2001) reported using sweating torso in cylinder shape to investigate the influence of body moisture on the thermal insulation of sleeping bags. The sweating torso consisted of 54 sweating nozzles from which a specific amount of water was supplied to simulate sweating. The moisture permeability of the sleeping bags was evaluated based on the measured heat loss due to sweating. The results showed that sweating would decrease the comfort temperature of sleeping bags by about 8 °C to 12 °C and the thermal insulation of sleeping bags would be reduced by about 20 %. However, without a head, arms and legs, the sweating torso was very different from a human body. This technique thus significantly deviated from the real use condition.

Havenith (2004) used a dry manikin covered with wet cotton underwear to simulate sweating in investigating vapour transfer and condensation in sleeping bags. Although it is a simple technique commonly used in standing manikins, it is questionable whether the wetness of the underwear can be uniformly maintained over the prolonged testing period. Furthermore, in order to determine the changing perspiration rate, the weight of the supporting board, sleeping bags and cotton underwear should be measured periodically. A real time measurement of perspiration rate was not possible.

Apart from testing using sweating torsos and manikins, tests employing human subjects were also carried out. Havenith (2002) conducted human subject tests for investigating the effect of the permeability of rain covers of sleeping bags during 6 days of use at -7 °C. The results showed that moisture accumulated is related to the vapour resistance of the materials. Havenith (2004) further investigated the effect of moisture accumulation in sleeping bags at -20 °C under 5 days prolonged use by human subjects and a simple manikin covered with cotton skin. The results indicated that the benefit of semipermeable rain cover over impermeable rain cover was lower at extreme cold condition (-20 °C). Also, the moisture accumulation was correlated with the vapour resistance of the material.

2.3 Past researches related to the posture effects on the thermal insulation and evaporative resistance

Evaporative resistance (R_e) and thermal insulation (I_t) of clothing are two important factors affecting thermal comfort. They are important parameters in the design and engineering of thermal environment and functional clothing. International standards (such as ISO 7730) have been devised based on evaporative resistance and thermal insulation of clothing and other relevant parameters to predict the comfort of thermal environments.

Thermal insulation and evaporative resistance of clothing can be measured directly on human. Holmer and Elnas (1981) developed a method to determine the effective evaporative resistance of clothing in vivo and concluded that the method, in combination with a partitional calorimetry, can determine the resistances of clothing to dry and evaporative heat loss for both resting and working subjects. Holmer (1985) investigated the thermal insulation of two types of clothing ensembles by human subject tests and no significant difference was found in heat exchange and thermal insulation of the garments when wool was compared to nylon during walking, running, and resting in wet and dry clothing. In general, human subject tests are relatively costly and not so reproducible. In order to accurately determine the thermal insulation and evaporative resistance of clothing, thermal manikins have been developed since 1940s.

For thermal manikin research, much of the past work focused on the measurement of thermal insulation and evaporative resistance of clothing under upright position with or without body motion, nevertheless it has been recognized that body posture has a significant influence on thermal insulation and evaporative resistance of clothing. With regard to thermal insulation of clothing, Havenith et al. (1990b) measured three clothing ensembles and combined the data from literature to establish a regression model for taking into account the effect of sedentary posture on thermal insulation. The study expressed thermal insulation of sedentary posture as a percentage of standing posture and concluded that the percentage decreases as the thermal insulation of clothing ensemble increases. In respect of the evaporative resistance of clothing, little past work was reported apart from the indirect measurement of evaporative resistance of clothing under sedentary posture by Havenith et al. (1990b), who estimated the evaporative resistance of three clothing ensembles under sedentary posture using the trace gas diffusion method.

2.4 Human thermal comfort

According to ASHRAE 55 (1992), thermal comfort can be defined as “the condition of mind that expresses satisfaction with the thermal environment”. Such definition leaves open in terms of what is meant by condition of mind or satisfaction. Similar definition can also be found in IUPS Thermal commission (2003), which defines thermal comfort as “Subjective indifference to the thermal environment”. Both definitions focus on the judgment of comfort, which is cognitive process encompassing many inputs under the influence of physical, physiological, psychological, and other processes. The conscious mind appears to reach conclusions about thermal comfort and discomfort from direct temperature and moisture sensations from the skin, deep body temperatures, and the efforts necessary to regulate body temperatures (Hensel 1973 and 1981, Hardy et al. 1971, Gagge 1937, Berglund 1995). In general, comfort occurs when body temperatures are held within narrow ranges, skin moisture is low, and the physiological effort of regulation is minimized (ASHRAE 55, 1992). Specifically, any environment would be regarded as comfortable, which does not require heat production or evaporative heat loss to increase by more than 25% above basal (Holdcroft, 1980). In practice, provision of clothes and bedding lowers the minimum tolerable temperature. According Fanger (1970, 1973), thermal comfort depends on:

1. Air temperature
2. Mean radiant temperature
3. Relative air velocity
4. Vapour pressure in ambient air
5. Activity level (i.e. internal heat production)
6. Thermal resistance of clothing

In order to measure the thermal insulation and evaporative resistance of clothing so as to evaluate thermal comfort objectively, sweating manikin is an essential tool. For developing a sweating manikin, it is necessary to understand the heat and moisture transfer from human body to surrounding environment through clothing system. In the next section, a brief reviews on fundamental heat and moisture transfer between human body, clothing and surrounding environment will be given.

2.4.1 Heat exchange between human and environment

There are four types of heat exchange between human body and its terrestrial environment. They are conduction, convection, radiation and evaporation. Basically, the heat transfer by the conduction, convection and radiation are proportional to temperature gradient, whereas the evaporation on the skin of human body is affected by the water vapour pressure between the human body skin surface and the environment.

2.4.1.1 Conduction

Conductive heat transfer takes place, in which, the energy of random motion of molecules of a solid or fluid with higher temperature is transferred to molecules of a solid or fluid with lower temperature. It requires no mass transfer. For human body, conduction heat transfer takes place when human body surface is in contact with a cold solid or fluid. Therefore, clothing, chair and bed will exchange heat with the human body through skin contact area. It is either positive or negative depending on the temperature of solid or fluid in contact with. It is also depending on the blood flow to the contact area. In general, the amount of conduction heat exchange is very small. However, the effect of conduction heat and convection heat exchange will be higher and important in case of human body immersion in water. According to Fourier's law, the conduction heat transfer is determined by:

$$H_{cond} = -k \cdot A \cdot \frac{dT}{dl} \tag{2-2}$$

where

H_{cond}	is	heat transfer by conduction;
k	is	thermal conductivity;
A	is	surface area;
dT	is	temperature difference;
dl	is	medium length that the thermal energy passes through

2.4.1.2 Convection

Convection heat transfer encompasses the mass transfer between human body surface and the surrounding environment. There are two types of convection heat transfer. The first type is natural convection, which takes place in still air or water without any external forces such as wind. The second type is forced convection, which involves external forces such as wind, or when the human body is moving through a still medium.

For human body, the cooler air adjacent to the human body surface contacts with warmer human body surface and becomes more buoyant. Such phenomenon occurs over the whole human body surface and result in an upward streaming sheath of warmed air. The natural heat exchange depends on the temperature gradient, and the velocity and thickness of the sheath of warmed air. In general, the overall heat loss from natural convection can be estimated for the body as a whole, which is 3 m^2 ºC W^{-1} (Clark and Edholm 1985, Mitchell 1974). In an environment of 25 ºC ambient temperature and a human body with 33 ºC mean skin temperature, the convective heat transfer is accounted for half of human body heat production in resting condition, which is 24 W m^{-2}. However, if the wind speed is 5 m/s, the convection heat transfer would be increased to about 150 W/m^2, which is three times of human body heat production in resting condition. In such condition, people would suffer serious cold stress.

In general, convective heat transfer can be expressed by following equation:

$$H_{conv} = h \cdot A \cdot (T_s - T_a) \tag{2-3}$$

where

H_{conv} is heat transfer by convection;

h is convective heat transfer coefficient depending on the type of convection;

A is surface area;

T_s is skin temperature;

T_a is environment temperature

2.4.1.3 Radiation

Electromagnetic radiation is emitted from the surface of an object and absorbed by an object due to its temperature. Electromagnetic radiation in infrared wavelengths can interact with substances by changing its kinetic energy and temperature. It transmits at the light speed and does not require medium of propagation and hence, two substances may exchange heat in such a way without physical contact. The energy emitted by radiation can be expressed as:

$$H_{radi} = \varepsilon \cdot \sigma \cdot A \cdot (T_s^4 - T_a^4) \qquad (2\text{-}4)$$

where

ε is thermal emissivity, which is <= 1;

σ is the Stefan-Boltzmann coefficient, which is equal to $5.67 \cdot 10^{-8}$ ($W \cdot m^{-2} \cdot {}^{\circ}C^{-4}$);

A is area;

T_s is the absolute temperature of the surface of object;

T_a is the absolute temperature of the environment

For a naked person, about 85% of body surface area is an effective radiating surface. It is because some area of human body surfaces are frequently faced each other such as inner aspect of thighs, in which energy is radiating each other instead of radiating to environment. In term of the amount of radiation generated by a naked human body, it is affected by cutaneous vasodilatation. If the human body is surrounded by cooler objects, then radiation will lead to heat loss. In contrast, if human body is surrounded by warmer objects, then radiation will produce heat gain. For a clothed person in a 20ºC environment temperature, the ratio of convective to radiation heat loss is about 0.7. For heat gain, the visible wavelength (solar radiation) contains a lot of thermal energy. The angle of sun will affect the heat gain of human body. At a solar altitude of 10 degree, around 25% of human body surface will intercept the direct solar beam, but it will be 5% only with 90 degree overhead sum.

2.4.1.4 Evaporation

Evaporation is a process of the conversion of water from liquid to vapour. The energy involved is called as latent heat of vaporization, which is depending on temperature. Approximately, each grams of water evaporated will consume 2.4 kJ. Specifically, the heat loss due to evaporation of water varies from 2501 J g^{-1} at 0.01 ºC to 2407 Jg^{-1} at 40 ºC. The rate of evaporation depends on the water vapour pressure between the surrounding environment and the human body skin surface. The heat loss by vapour diffusion through the skin can be calculated by (Fanger 1970):

$$E_d = \lambda \cdot m \cdot A_{Du} \cdot (P_s - P_a) \quad (2\text{-}5)$$

where

m	is permeance coefficient of skin;
A_{Du}	is DuBois area;
P_s	is the partial water vapour pressure at human body skin surface temperature;
P_a	is the partial water vapour pressure at environment temperature
λ	is the heat of vaporization

Evaporation is an important heat loss mechanism for human. It occurs in two ways including evaporation of sweat from the skin surface of human body during sweating and evaporation from respiratory tract. In general, human body under basal condition in a moderately humid environment, evaporation accounts for a quarter of total heat loss (Hey & Katz 1969). Also, two third of evaporative heat loss is from the body skin surface and one third evaporative heat loss is by the respiratory tract (Burton & Edholm 1955). For a human in resting condition with thermal comfort, the total quantity of evaporation from diffusion through skin and respiratory tract is about 30 g h^{-1}.

When a person is doing heavy exercise or exposes to very hot environment (especially environment temperature higher than skin temperature), sweating becomes the most important and effective way for thermoregulation in human body. The maximum sweating rate of human can be as high as 600 to 900 g h^{-1} m^{-2}. If all sweats are evaporated from skin surface, they will help to dissipate energy around 402 to 603 W h m^{-2}. However, in practice, evaporation of sweat is depending on many factors, such as environment water vapour pressure, wind velocity, skin temperature, environment temperature, and skin wetness.

2.4.2 Heat and mass transfer through simple clothing system

Assuming a person wearing clothing and standing in an environment without wind, the heat and mass transfer can be described by the simple clothing model as shown in

Figure 2-16.

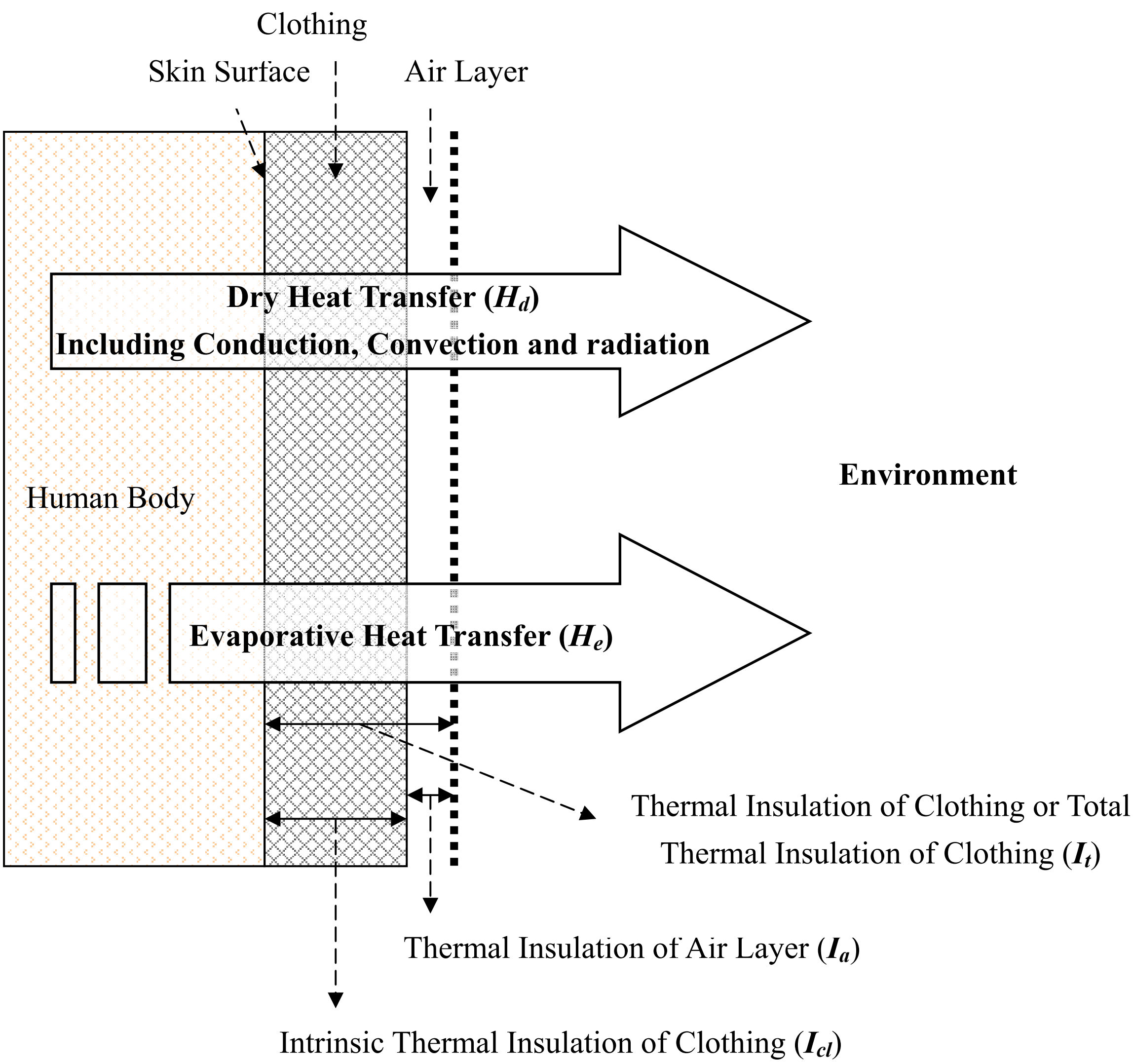


Figure 2-16. Simple clothing heat and mass transfer model

The heat generated by human body metabolism will be transferred from body to environment through clothing by conduction, convection and radiation. The heat transfer by conduction, convection and radiation are mainly governed by temperature difference between human skin surface and environment. They can be classified as dry heat transfer or direct heat loss H_d (W m^{-2}). Apart from dry heat transfer, evaporative heat transfer H_e (W m^{-2}) is another important way of heat transfer mechanism from human body to environment. It is governed by the difference in partial water vapour pressure between human body skin surface and the environment.

Woodcock (1962) assumed that the dry heat transfer H_d (W m^{-2}) and evaporative heat transfer H_e (W m^{-2}) are independent of each other and thus, they can be measured independently. Based on Woodcock (1962a&b) assumption, the total heat transfer H_t from human body surface to environment through clothing can be expressed as:

$$H_t = H_d + H_e \tag{2-6}$$

where

H_t is total heat transfer

In addition, the thermal insulation of clothing (I_t) and evaporative resistance of clothing (R_e) can be expressed as following equations:

$$I_t = \frac{A_s \cdot (T_s - T_e)}{H_d} \tag{2-7}$$

$$R_e = \frac{A_s \cdot (p_s - p_e)}{H_e} \tag{2-8}$$

where

I_t is the thermal insulation or total thermal insulation of clothing

R_e is the evaporative resistance or total evaporative resistance of clothing

A_s is the skin surface area (m^2)

T_s is the area weighted mean skin temperature of manikin (in ºC)

T_e is the environment temperature (in ºC)

p_s is the water vapour pressure of skin surface

p_e is the water vapour pressure of environment

By excluding the resistance of boundary air layer (I_a) as shown in Figure 2-16, the intrinsic thermal insulation of clothing and intrinsic evaporative resistance of clothing can be calculation as following equations:

$$I_{cl} = I_t - {}^{I_a}\!/_{f_{cl}} \tag{2-9}$$

$$R_{ecl} = R_e - {}^{R_{ea}}\!/_{f_{cl}} \tag{2-10}$$

where

I_{cl} is the intrinsic thermal insulation of clothing

R_{ecl} is the intrinsic evaporative resistance of clothing

I_a is the thermal insulation of boundary air layer in nude condition

R_{ea} is the evaporative resistance of boundary air layer in nude condition

f_{cl} is clothing area factor

For the calculation method of thermal insulation, there are two types of methods. They are serial method and parallel method. The serial method focuses on local thermal insulation and the overall thermal insulation is equal to the summation of the insulation of different segments of a manikin. By contrast, the parallel method focuses on the total heat loss with the consideration of area ratio of difference segments of a manikin. The EN 13537 sleeping bag standard only accepts serial method for the calculation of thermal insulation, whereas the ASTM F-1270 and 1291 only accept parallel method. In ISO standard, ISO 15831E accepts both serial and paprallel method.

Past researches showed than thermal insulation calculated by serial method was higher than the parallel method. Meinander et al (2003) showed serial method was around 20% higher than parallel method for thermal insulation measurement using standing manikin. Kuklane and Dejke (2010) showed that thermal insulation of sleeping bag using serial method was higher than parallel method’s. The serial method also would lead to unrealistic result for sleeping bag using auxiliary heating system.

2.4.3 Units of thermal insulation of clothing

In International System of Unit, the clothing thermal insulation is expressed as a physical unit of ºC m^2 W^{-1}. This expression cannot let people easily visualize and relate to the clothing worn on their body. Therefore, Gagge et al. (1941) proposed a unit called as Clo for denoting the thermal insulation in a recognizable “human scale”. One Clo represented the thermal insulation required to maintain a sedentary person in comfortable condition at 21 ºC, less than 50% relative humidity, and wind velocity less than 0.1 m/s with metabolic rate of around 58 W m^{-2}. Based on physical measurement, the Clo was determined by:

$$1Clo = 0.155\ {}^\circ Cm^2 / W \qquad (2\text{-}11)$$

Apart from SI unit and Clo value, Tog (Pierce and Rees, 1946) also was used as a unit of thermal insulation of clothing. However, it is intended for clothing materials in flat manner only, so it cannot reflect the thermal insulation of whole garment and clothing ensemble. It is defined as:

$$1Tog = 0.1°Cm^2/W \tag{2-12}$$

2.4.4 Definition of moisture permeability index (i_m)

In 1962, Woodcock (1962a&b) introduced i_m (the moisture permeability index) as a dimensionless parameter to reflect the vapour permeability of clothing in equilibrium or steady-state condition. In ASHRAE (2009), i_m is defined as the ratio of the actual evaporative heat flow capability between the skin and the environment to the sensible heat flow capability as compared to the Lewis Ratio. According to Woodcock (1962a&b), i_m is defined as:

$$i_m = \frac{I_t/R_e}{I_a/R_{ea}} \tag{2-13}$$

The ratio of R_a/R_{ea} is assumed to be a constant, which can be measured by using a wet-bulb column in a strong wind environment. The ratio of R_a/R_{ea} is equal to 2.2 ºC/mmHg = 0.0165 ºC/Pa. Using 0.0165 as a substitute of the ratio of R_a/R_{ea}, i_m can be calculated by:

$$i_m = \frac{I_t}{0.0165 \cdot R_e} = 60.6 \times \frac{I_t}{R_e} \qquad (2\text{-}14)$$

The i_m is an efficiency index, which gives a quantitative measurement of the human clothing environment. The theoretical range of i_m is from 0 to 1, it is because the ratio of I_t/R_e is always smaller than the ratio of I_a/R_{ea}. McCullough (1989) reported that the average i_m value for indoor clothing is around 0.4 on the basis of the tests of 22 clothing ensembles. Havenith (1999) and ISO 9920 2007 reported that the average i_m value of outdoor one to two layer clothing was around 0.38.

Chapter 3

Design and Construction of Sedentary and Supine Manikins

3.1 Design and construction mechanism

This research was inspired by the standing sweating fabric manikin “Walter” (Fan and Chen 2002) and the improved version (Fan and Qian 2004). The idea of single segment sweating fabric manikin was originated from the non-sweating fabric manikin reported earlier (Fan 1989, Fan and Keighley 1990). Walter used waterproof breathable skin to imitate human skin and used water to form the human body shape in standing posture. By imitating the human blood circulation system, heaters, pumps and tubes were used to form warm water circulation system to maintain target body temperature distribution.

In designing a new sweating fabric manikin with sedentary and supine postures, the following factors were considered:

(1) how to change posture in single segment manikin construction;

(2) the shape of the manikin in sedentary and supine postures;

(3) the total skin area of the manikin in sedentary and supine postures;

(4) the pattern design of manikin's waterproof breathable skin and seam sealing process;

(5) the heating method and position;

(6) the heat distribution system;

(7) the sweating rate measurement system;

(8) the possible oxidization of mechanic components immersed in water;

(9) how to water-proof the electronic components immersed in water.

The interchange of sedentary and supine posture was achieved by changing manikin's fabric skins. Two type manikin fabric skins were developed. The first type skin was for the sedentary posture and the second was for the supine posture. For saving cost, the sedentary sweating fabric manikin and supine sweating fabric manikin shared the same body. Internal adjustable joints were made for altering the posture from supine to sedentary. For changing manikin postures, skins and clothing, a moveable lifting up machine was constructed (Figure 3-1).

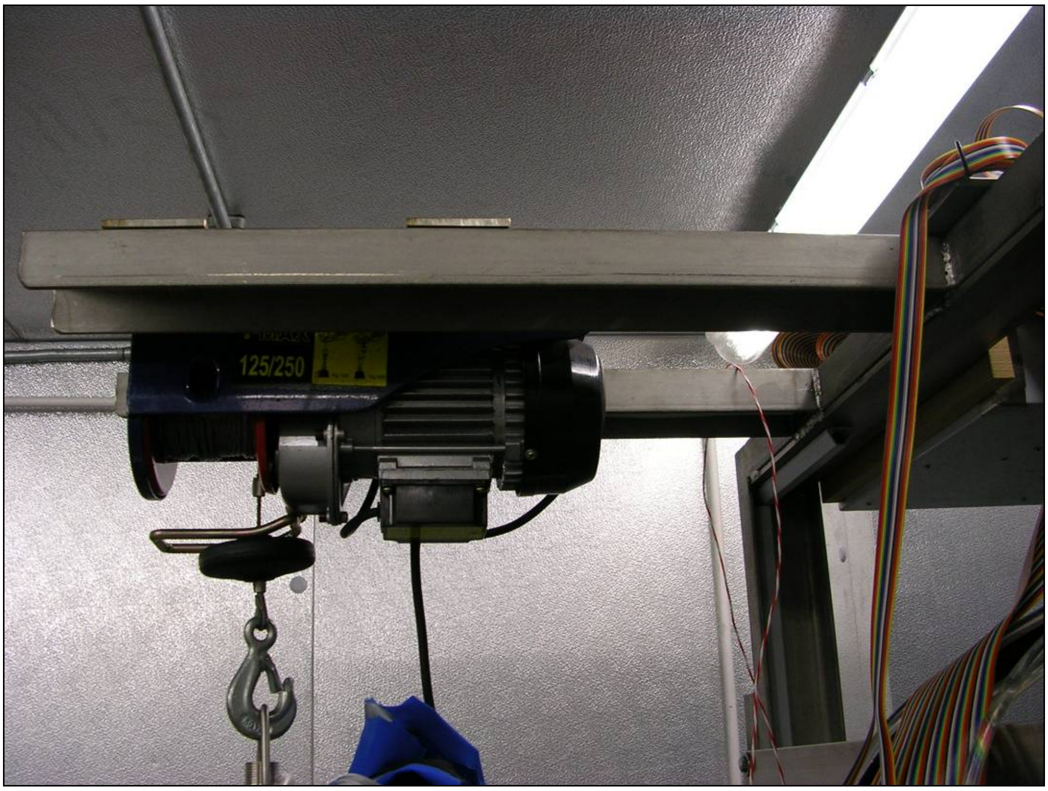


Figure 3-1. The movable lifting up machine for changing manikin postures, skins and clothing

3.1.1 Sedentary sweating fabric manikin body specification

(1) The developed manikin (Figure 3-2) is similar to a typical adult man in sedentary posture.

(2) The total skin surface area is equal to 1.91 m^2 and the total body weight is 75 kg.

(3) The manikin skin has a soft touch and the body is flexible. The manikin can simulate the compression effect of a sitting man due to the body weight and flexible body being similar to a real human body

(4) The manikin has a head, arms, chest, abdomen, legs and feet, but it has no hands.

(5) The manikin is a single segment manikin without any detachable joints

Figure 3-2. The developed sweating fabric manikin in sedentary posture

3.1.2 Supine sweating fabric manikin body specification

(1) The developed supine manikin (Figure 3-3) is similar to a typical adult man in supine posture.

(2) The total area of skin is 1.79 m^2 and the total weight is equal to 70 kg.

(3) The shape of body is similar to a lying down man. The manikin skin has a soft touch and the body is flexible. The manikin can simulate the compression effect of a lying down man due to the body weight and flexible body being similar to real person.

(4) The statue of manikin is 1.72 m.

(5) The manikin has head, chest, abdomen and legs, but it has no hands and feet.

(6) The manikin is a single segment manikin without any detachable joints.

Figure 3-3. The developed sweating fabric manikin in supine posture

The size of the sedentary manikin is slight higher than the supine manikin being developed in this study. It is because both sedentary and supine manikins share the same frame. In sedentary posture, the fabric skin must be slightly larger for putting onto the sedentary posture's internal frame.

Most manikins around the world are made of hollow plastic or metal (copper or aluminum). The lightweight body has an advantage of being portable and easier for operator to handle. However, lightweight manikins cannot give realistic simulation of the compression effect on the clothing or the area the manikin sitting or lying on. Also, the hollow plastic or metal shell adopted by most manikins makes the heat capacity of the manikin very different from that of a human body. The manikin developed in this study used water to form the shape of body. Because the heat capacity of water is very close to human body, the heat capacity of the developed manikin is very similar to that of a human body, which offers advantage in giving realistic simulation of the temperature response of the manikin when subjected to transient conditions.

3.1.3 Heating mechanism

The newly developed manikin in this research was heated by two tube shaped heaters with a total power of 1617.35 Watts. The resistance of each heater is around 60 Ohm. The heaters used 220V AC power. In order to have a stable power supply, a voltage regulator was used to stabilize the voltage within 220V ±3%. The power of heaters were calculated by Voltage^2 divided Resistance, which were measured by multimeter with accuracy of 0.04 % for AC voltage and 0.15% for current measurement.

The power required for heating the manikin to target temperature was determined by following equation:

$$H_s = \frac{t_{on}}{t_{on} + t_{off}} \times 1617.4 \tag{3-1}$$

where

H_s is the power consumed by heaters for heating the manikin to the target temperature;

t_{on} is "on" time of solid state rely which connected to the heater

t_{off} is "off" time of solid state rely which connected to the heater

For controlling the "on" and "off" of the heaters, two highly robust solid state relays were installed. The core and surface of the manikin were totally heated because the manikin was fully filled with water. The heaters were installed at the center of manikin near the chest. The heaters were totally immersed in the water and completely sealed for avoiding electric leakage. For longer durability, the heater shell was made of titanium to avoid oxidation. Tube shaped heaters for heating has the following advantages:

a) *Substantially low cost.* The cost of installing tube shaped heaters is substantially lower than that of mounting heating wire on the manikin plastic or copper shell because it avoids huge amount of manual work. Also, the price to a tube shaped heater is around 50 US dollar only and thus, it is cost effective to replace a broken heater;

b) *Easy maintenance.* The tube shaped heaters can be easily installed by just inserting it in the center of manikin with a fixation ring. The broken heater can be easily exchanged by taking it out and no additional mechanical work is required. In contrast, the method of mounting heating wire requires substantially large amount manual work and special skill. Also, it is very difficult to detach the broken heating wire because the wire is physically fixed on the manikin copper or plastic shell. Figure 3-4 shows the location and installation of tube shaped heaters for the newly developed sweating manikin.

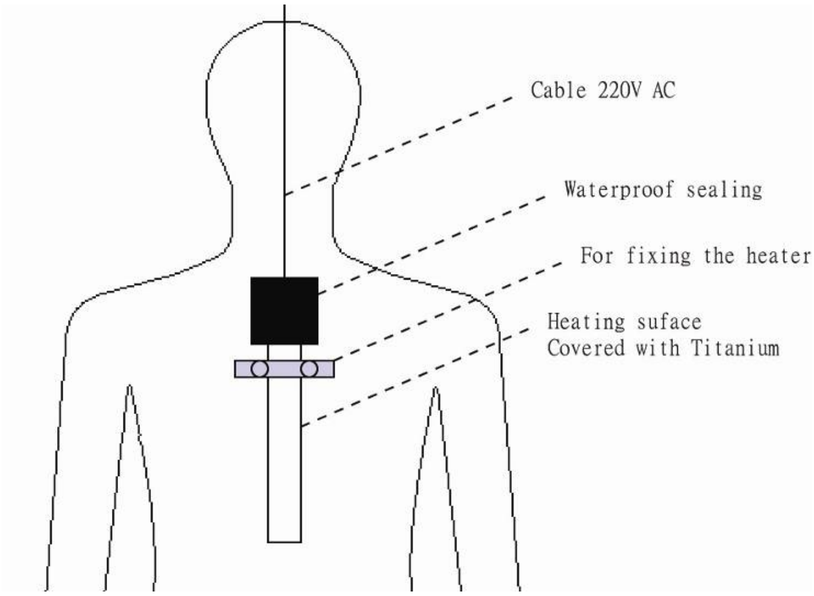


Figure 3-4. Tube shape heaters of the newly developed sweating manikin

c) *Heat capability similar to human*. In terms of heat capacity, method of heating wire mounded on manikin shell is much lower than that of the tube shaped heater method. It is because the former is heating the thin shell of manikin only, whereas the latter heats the manikin at the core with the surrounding water and the manikin is filled with water. As a result, the heat capacity is similar to that of a human.

3.1.4 Heat distribution mechanism

The newly developed manikin was heated at the center near the chest front and back area with surrounding water. For distributing the heated water to extremities, six DC

12 V water pumps (Figure 3-5) were installed near the heaters. The water pumps were totally sealed and can be immersed in water. Figure 3-4 shows the location of six pumps. The six pumps were connected with water tubes to transport water from the core of manikin to head, left arm, right arm, left leg, right leg and tummy. The water pumps together with the water tube network serve as human heart and blood circulation system. By changing the voltage of the pumps, the water circulation speed can be individually adjusted. The range of the voltage was from 6 to 12 V. The power consumption of pumps was measured by a millimeter with accuracy of 0.025 % for DC voltage and 0.15% for current measurement.

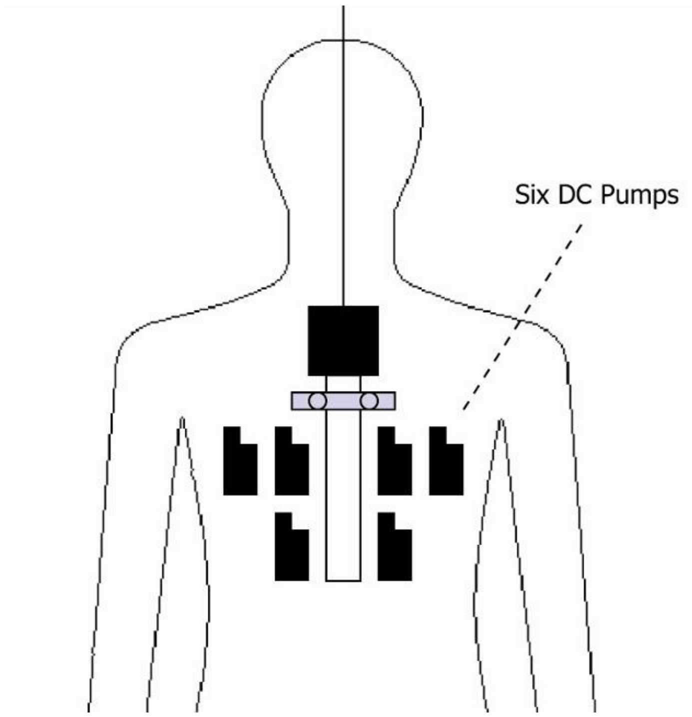


Figure 3-5. The location of six water pumps

3.1.5 Sweating mechanism

In this research, sweating was simulated in the form of perspiration through the high strength breathable fabric skin. The high strength breathable fabric skin is a 3 layer fabric. The middle layer is a PTFE membrane, Figure 3-6 and 3-7 show the enlarged image of PTFE membranes. The high strength breathable fabric skin sweating simulation method was originated from manikin “Walter” (Fan and Chen 2002).

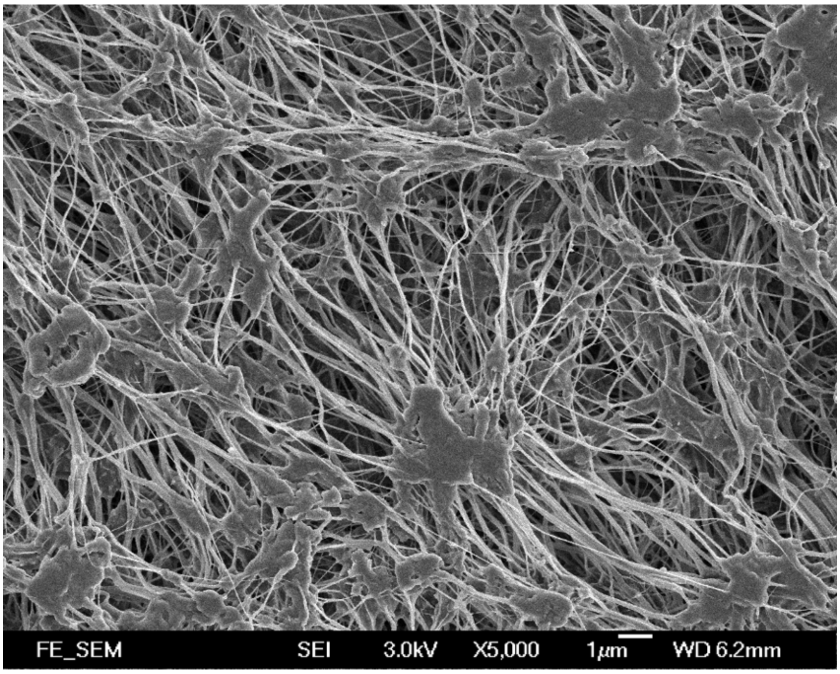


Figure 3-6. SEM image of PTFE membrane enlarged 5000 times

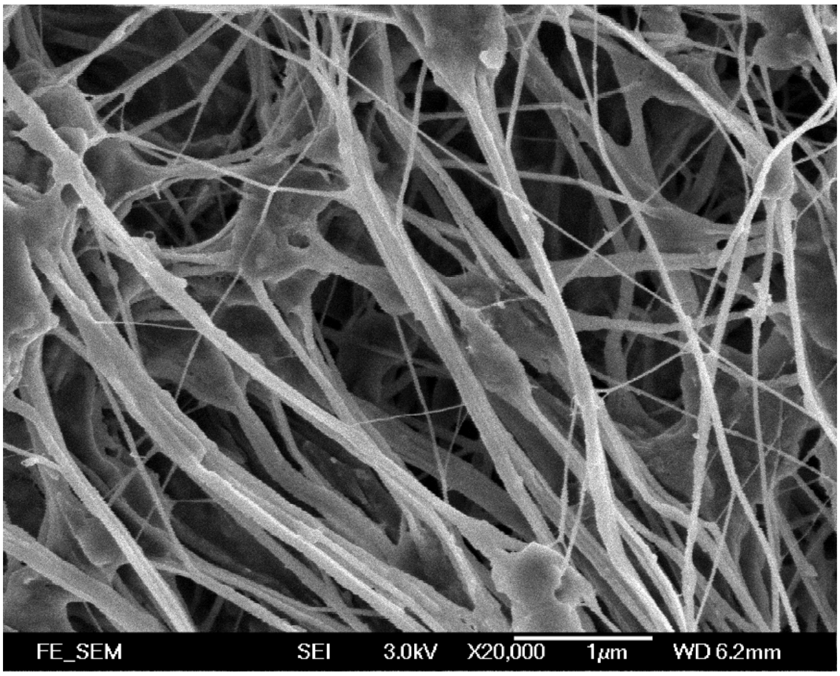


Figure 3-7. SEM image of PTFE membrane enlarged 20000 times

Using high strength breathable fabric skin to simulate sweating in form of perspiration has following advantages:

a) *Relatively high reproducibility*. The high strength breathable skin method can ensure full body perspiration, because under the skin is fully filled with water and the micro-pores are evenly distribution around the whole manikin body. In contrast, the conventional cotton skin method requires manual work to spray water to achieve full body sweating. The experience of operators would affect the evenness of skin wetness. In addition, the water tube sweating gland method requires manual work to handle the problem of blocked tubes and sweating glands due to impurities and trapped air. Also, the skin area remote from the artificial "sweating glands" would not be completely wetted. Moreover, the quality of cotton skin would decrease in times and it would affect the reproducibility as well. All in all, since the skin wetness of high strength breathable skin method is always 100%, its reproducibility is relatively higher than conventional cotton skin method and water tube sweating gland method.

b) *Simplicity*. The high strength breathable sweating skin method is relatively simple. It does not incur any mechanical work such as opening holes and electronic components such as micro valves. Also, old breathable skin can be easily exchanged with a new one just by unzipping the zipper.

c) *Relative lower cost*. The cost of making high strength breathable sweating skin is relative lower than the sweating gland method.

Two sets of manikin high strength breathable fabric skin were developed in this research. The first set was for the manikin in sedentary posture and the second was for the manikin in supine posture. They were developed based on the dummy and human body anthropometric data. The total area of sedentary manikin skin is 1.91 m^2 and the total area of supine manikin is equal to 1.79 m^2. The area of sedentary manikin skin is slightly higher than that of supine manikin because in sedentary posture, the manikin's internal frame and skeleton requires the skin size being larger to be put onto the manikin.

3.1.6 Skin area and area ratio

The manikin skins were made of a breathable fabric. A flat fabric was cut into different pieces of patterns so as to form human body shape properly. By summation of the area of all manikin skin patterns, the total area of manikin surface area can be obtained. The area of manikin skin pattern was measured by area to mass method. The area to weight ratio was calculated by measuring the mass of 1 m^2 (100 cm X 100 cm) skin pattern material with an electronic balance in 0.2 mg accuracy. The weights of all individual manikin skin patterns were also measured by an electronic balance with 0.2 mg accuracy.

In respect of parts and total surface area of manikin skin, they were calculated by the weight of the different parts of skin fabric divided with the specific weight of the skin. The surface area of skin will extend under a loading of about 70 to 75 Kg of water with 35ºC skin temperature. Assuming each division of manikin as a cylinder, the original girth and the height marked on the manikin surface are *g* and *h* respectively, and then the original area (S_o) is:

$$S_o = g \times h \tag{3-2}$$

Once the manikin was filled with water and heated with 35ºC skin temperature, the girth and the height would be increased to $g(1+a\%)$ and $h(1+b\%)$, respectively, and the final area (S_1) is:

$$\begin{aligned} S_1 &= g(1+a\%)h(1+b\%) \\ S_1 &= S_o(1+a\%)(1+b\%) \end{aligned} \tag{3-3}$$

For sedentary and supine manikin, the surface areas for each division and their area ratios are shown in Table 3-1 and Table 3-2, respectively.

Table 3-1. Sedentary manikin surface areas for each division and their area ratios

Location	**Original area (m^2)**	**Final area (m^2)** (filled with 35ºC water)	**Area-weight (%)**
Head Front	0.107	0.107	5.62
Head Back	0.107	0.107	5.62
Chest	0.148	0.163	8.55
Back	0.155	0.170	8.91
Tummy	0.099	0.108	5.63
Hip A	0.063	0.069	3.59
Hip B	0.041	0.045	2.38
Right upper arm	0.082	0.088	4.62
Left upper arm	0.082	0.088	4.62
Right lower arm	0.055	0.059	3.10
Left lower arm	0.055	0.059	3.10
Right thigh front	0.153	0.166	8.71
Right thigh back	0.077	0.083	4.35
Left thigh front	0.153	0.166	8.71
Left thigh back	0.077	0.083	4.35
Right calf front	0.070	0.076	3.96
Right calf back	0.035	0.038	1.97
Left calf front	0.070	0.076	3.96
Left calf back	0.035	0.038	1.97
Right foot top	0.042	0.045	2.36
Left foot top	0.014	0.015	0.78
Right foot bottom	0.042	0.045	2.36
Left foot bottom	0.014	0.015	0.78
Total	1.776	1.910	100

Table 3-2. Supine manikin surface areas for each division and their area ratios

Location	**Original area (m^2)**	**Final Area (m^2)** (filled with 35ºC water)	**Area-weight (%)**
Head Front	0.108	0.107	6
Chest	0.148	0.163	9.12
Back	0.155	0.170	9.5
Tummy	0.099	0.108	6.01
Hip	0.104	0.114	6.37
Right upper arm front	0.055	0.059	3.28
Left upper arm front	0.055	0.059	3.28
Right lower arm front	0.037	0.030	2.2
Left lower arm front	0.037	0.030	2.2
Right thigh front	0.115	0.125	6.97
Right thigh back	0.115	0.125	6.97
Left thigh front	0.115	0.125	6.97
Left thigh back	0.115	0.125	6.97
Right calf front	0.070	0.076	4.22
Left calf front	0.070	0.076	4.22
Head Back	0.108	0.107	6
Right upper arm back	0.027	0.030	1.65
Left upper arm back	0.027	0.030	1.65
Right lower arm back	0.018	0.030	1.1
Left lower arm back	0.018	0.030	1.1
Right calf back	0.035	0.038	2.11
Left calf back	0.035	0.038	2.11
Total	1.665	1.79	100

3.1.7 Sweating rate measurement mechanism

A novel constant water level sweating rate measurement system was developed for real-time monitoring the sweating rate of manikin in this research. Figure 3-8 shows the newly developed sweating rate measurement system. The water tank B is used to maintain a constant water level corresponding to the top of the manikin. A separator in the water reservoir B sets the upper limit of water level, so any additional water came from water tank A through a water pump will cause overflow and thus, the overflowed water will flow back to water tank A via Tube 4 due to gravitation. Apart from flowing back to reservoir A, the water in water reservoir B also will flow to the manikin automatically through Tube 3 due to siphon action when the manikin is sweating. As a result, the losing amount of water in water tank A is identical to the sweating rate of manikin. For measuring the changing weight of water tank A precisely, the Tube 1 and Tube 4 must be in a suspension state without any contact to water tank A and the electronic balance.

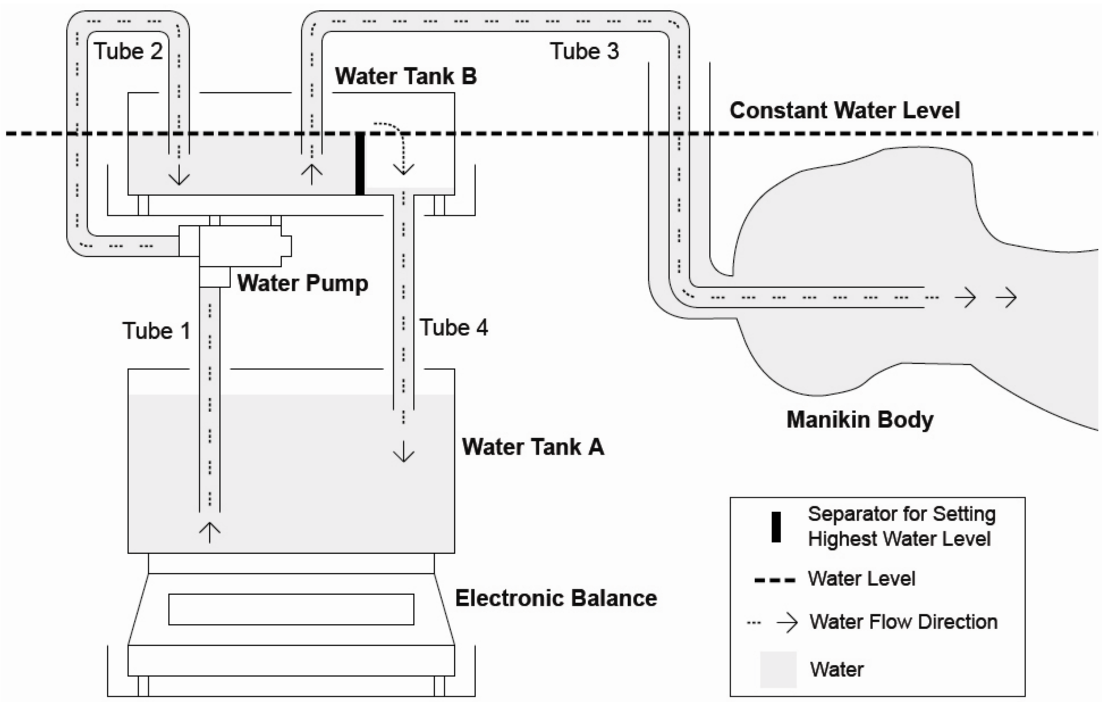


Figure 3-8. The design of the newly developed sweating rate measurement system

The sweating rate measurement system was developed without the necessity of measuring the weight of manikin. The basic rationale of direct measurement system was based on siphon action. An electronic balance with precision of 0.1 gram and maximum capacity of 22000g was used for measuring the water loss of a water tank A. The water loss in the water tank A is identical to the water loss from the manikin.

3.1.7.1 Comparison with the existing standing Walter system

Compared with the existing sweating rate measurement system of the standing Walter, the newly developed sweating rate measurement can maintain constant water level inside the manikin. Figure 3-9 shows the sweating rate measurement system of Walter and the newly developed system. The shaded areas with diagonal lines including A and B are the real sweating amount of Walter. The electronic balance only can monitor the water loss of A. Therefore, a coefficient of calibration is required to calculate real sweating amount because the change of the weight of water in the water reservoir is proportional to the water loss of manikin. By contrast, the newly developed sweating rate system can maintain constant water inside the manikin and only the water level of the water tank on the electronic balance will drop as sweating occurs. As a result, the sweating rate can be directly measured by the electronic balance.

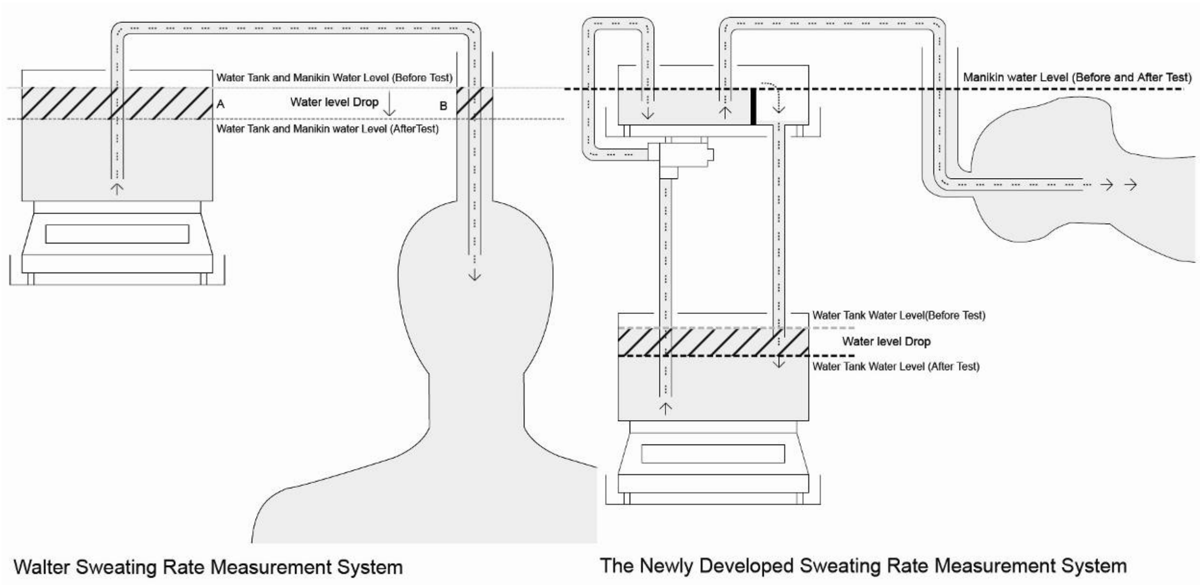


Figure 3-9. The sweating rate measurement system of Walter and the newly developed system

3.1.7.2 Comparison with other methods

a) *Conventional two step subtraction method.* The cotton skin method does not measure the amount of water loss during sweating. It estimates the water loss by subtracting the dry heat loss from the wet heat loss. It is a kind of indirect method. In contrast, the newly developed sweating rate measurement system can direct measure the water loss due to sweating in real time.

b) *Monitoring the weight change of manikin.* The manikin Coppelius can monitor the sweating quantity in real time by measuring both manikin weight change and water quantity supplied to the manikin for sweating. This method only is applicable for the manikin in suspension state. It is very difficult and complicate to measure the weight of manikin if the manikin touches other objects. As a result, the method would be inappropriate for manikins in supine and sedentary posture.

3.1.8 Temperature sensing system

a) *Selection of temperature sensors:* According to ASTM F 1291 (2005), both point sensor and distributed temperature sensors were accepted for measuring manikin skin temperature. In this research, point sensor was selected for measuring manikin skin temperatures based on the consideration of simplicity, flexibility and accuracy. The distributed sensor needed to be permanently fixed to the shell material of the whole surface of manikin evenly, whereas point sensors only need to be attached to a specific point of the surface of manikin firmly. For the types of point sensors, the standard accepts thermocouples, resistance temperature devices (RTD) and thermistors. In this research, a PT100 RTD Class A temperature point sensor with accuracy of ±0.15 ºC was selected for developing the sweating thermal manikin. Also, all temperature sensors used in this research were calibrated by the manufacturer. The thickness of temperature sensor with covering material was less than 3 mm.

b) *Selection of wiring method:* PT100 4-wire temperature sensors were chosen in this study (Figure 3-10 bottom and Figure 3-11). The accuracy of temperature measurement from the two-wire RTD (Figure 3-10 top) is lowest among three-wire and four-wire connection method. It is because the lead wire resistance would induce additional measurement error. The accuracy of temperature measurement from three-wire (Figure 3-10 middle) connection method is better than that of two-wire method. It is because in a three-wire hookup provided a reference connection for the lead wires. The four-wire connection method (Figure 3-10 bottom) provides best accuracy because it takes into account of all wires except the RTD sensing element.

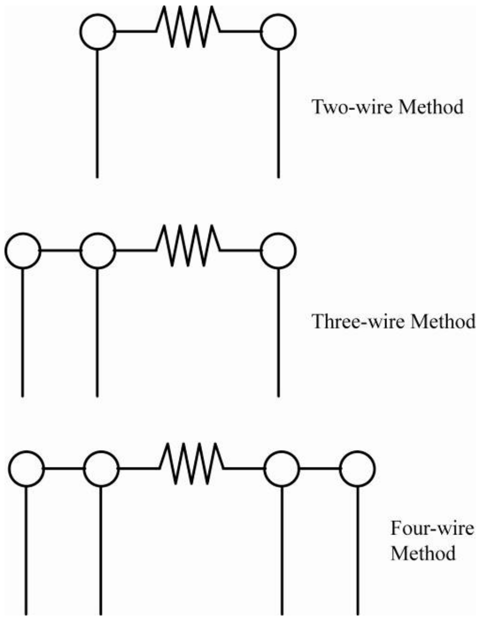


Figure 3-10. RTD temperature sensor wiring methods

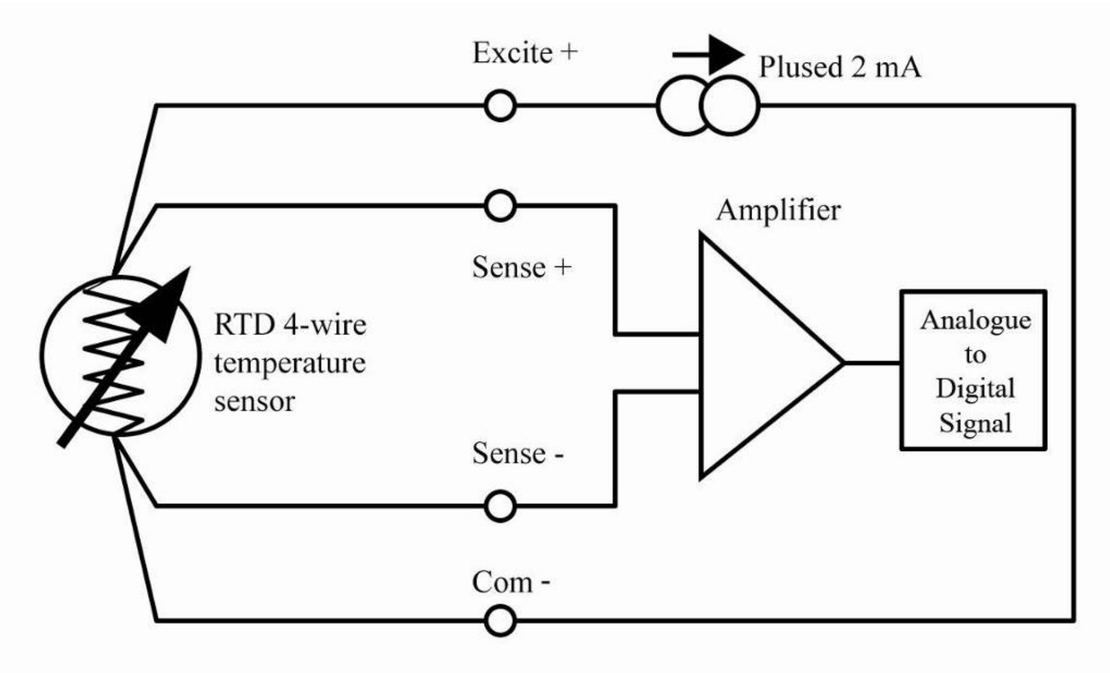


Figure 3-11. Wiring of RTD Temperature Sensor (modified from National Instrument RTD 124 manual)

c) *Number of temperature sensors:* 23 RTD temperature sensors were attached on the sedentary sweating manikin skin surface with elastic band so as to measure the skin temperature at different locations. In respect of supine sweating manikin, 22 RTD temperature sensors were used to measure the skin temperature at different locations. Each temperature sensor was area weighted in calculating the mean skin temperature of the manikin body. Table 3-3 and 3-4 show the distribution of temperature sensors and their area weighting for the manikin in the sedentary and supine posture, respectively. Figure 3-12 and 3-13 show the location of temperature sensors in the manikin in sedentary and supine postures, respectively.

According to ASTM standard F-1291 and F-2370, at least 15 temperature point sensors is recommended for standing manikin. In general, more temperature sensor would yield higher accuracy. For supine manikin, the mean skin temperature measurement using 22 temperature point sensors is slightly lower than the measurement made by 15 temperature point sensor in nude condition (environment temperature = 12 °C, wind speed < 0.3 m/s). It is about 0.5%. For sedentary manikin, the mean skin temperature measurement using 23 temperature point sensors is slightly lower than the measurement made by 15 temperature point sensor in nude condition (environment temperature = 13, wind speed < 0.3 m/s). It is about 0.3%.

Apart from measuring the skin temperatures, four RTD temperature sensors were used to monitor the environmental temperature. The mean environment temperature was calculated from averaging the readings of the two sensors.

Table 3-3. Distribution of temperature sensors around the sedentary manikin and their area weighting

Temperature Senor Code	Location	Area-weight (%)	Area (m^2)	Sensor Number
T_1	**Head Front**	5.62	0.107	1
T_{16}	**Head Back**	5.62	0.107	1
T_2	**Chest**	8.55	0.163	1
T_3	**Back**	8.91	0.170	1
T_4	**Tummy**	5.63	0.108	1
T_5	**Hip A**	3.59	0.069	1
T_{17}	**Hip B**	2.38	0.045	1
T_6	**Right upper arm**	4.62	0.088	1
T_7	**Left upper arm**	4.62	0.088	1
T_8	**Right lower arm**	3.10	0.059	1
T_9	**Left lower arm**	3.10	0.059	1
T_{10}	**Right thigh front**	8.71	0.166	1
T_{11}	**Right thigh back**	4.35	0.083	1
T_{12}	**Left thigh front**	8.71	0.166	1
T_{13}	**Left thigh back**	4.35	0.083	1
T_{14}	**Right calf front**	3.96	0.076	1
T_{18}	**Right calf back**	1.97	0.038	1
T_{15}	**Left calf front**	3.96	0.076	1
T_{19}	**Left calf back**	1.97	0.038	1
T_{20}	**Right foot top**	2.36	0.045	1
T_{21}	**Left foot top**	0.78	0.015	1
T_{22}	**Right foot bottom**	2.36	0.045	1
T_{23}	**Left foot bottom**	0.78	0.015	1
	Total	100	1.910	23

Table 3-4. Distribution of temperature sensors around the supine manikin and their area weighting

Temperature Senor Code	Location	Area-weight (%)	Area (m^2)	Sensor Number
T_1	**Head Front**	6	0.107	1
T_2	**Chest**	9.12	0.163	1
T_3	**Back**	9.5	0.170	1
T_4	**Tummy**	6.01	0.108	1
T_5	**Hip**	6.37	0.114	1
T_6	**Right upper arm front**	3.28	0.059	1
T_7	**Left upper arm front**	3.28	0.059	1
T_8	**Right lower arm front**	2.2	0.030	1
T_9	**Left lower arm front**	2.2	0.030	1
T_{10}	**Right thigh front**	6.97	0.125	1
T_{11}	**Right thigh back**	6.97	0.125	1
T_{12}	**Left thigh front**	6.97	0.125	1
T_{13}	**Left thigh back**	6.97	0.125	1
T_{14}	**Right calf front**	4.22	0.076	1
T_{15}	**Left calf front**	4.22	0.076	1
T_{16}	**Head Back**	6	0.107	1
T_{17}	**Right upper arm back**	1.65	0.030	1
T_{18}	**Left upper arm back**	1.65	0.030	1
T_{19}	**Right lower arm back**	1.1	0.030	1
T_{20}	**Left lower arm back**	1.1	0.030	1
T_{21}	**Right calf back**	2.11	0.038	1
T_{22}	**Left calf back**	2.11	0.038	1
	Total	100	1.79	22

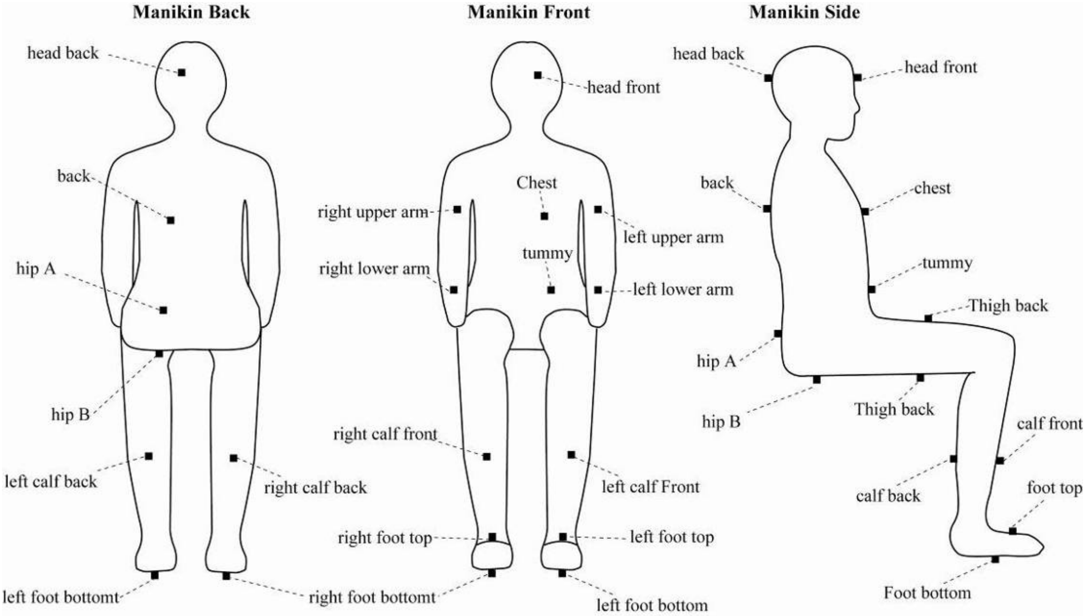


Figure 3-12. Distribution of twenty three temperature sensors around the sedentary manikin

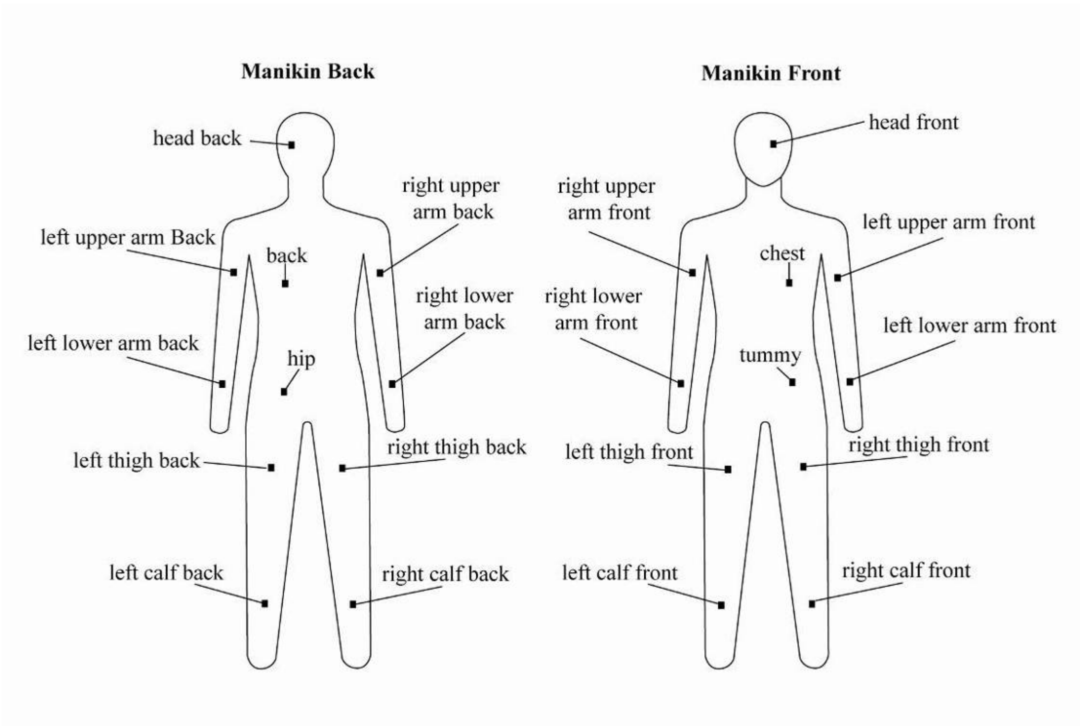


Figure 3-13. Distribution of twenty two temperature sensors around the supine manikin

d) *Core temperature sensors:* For monitoring the internal temperature of the manikin, two PT100 4-wire temperature probe sensors were installed in the chest of the manikin. The probe was made of stainless steel for avoiding oxidation. The accuracy is ±0.15 ºC. The total length of the probe is 250 mm. Each sensor was carried same weight for measuring mean core temperature.

e) *Radiant temperature sensor:* For monitoring the ambient radiant temperature, a globe thermometer was installed in a climate chamber, where the manikin was located for conducting experiments. The globe thermometer is a mercury thermometer inserted at the centre of a blackened copper sphere (Figure 3-14). Its reading (T_g) is affected by dry-bulb temperature, air velocity, and mean radiant temperature. In still air, it reads the mean radiant temperature exactly. If the air temperature (T_e and velocity (V) around the globe is known, the mean radiant temperature t_r can be calculated by:

$$T^4{}_r = T^4{}_e + 0.247\ x10^9 \cdot \sqrt{V}(T_g - T_e) \quad (3\text{-}4)$$

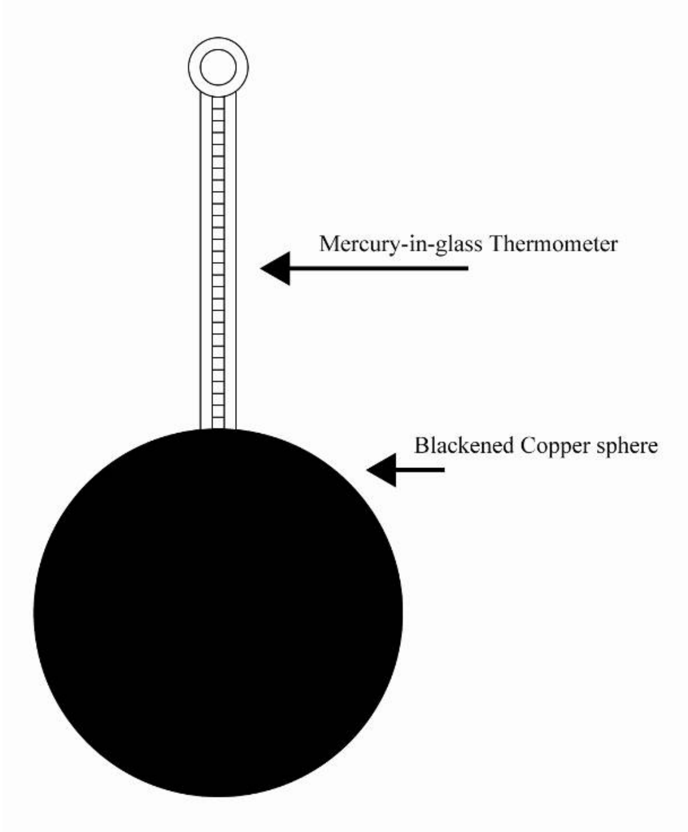


Figure 3-14. The globe thermometer for monitoring radiant temperature

3.1.9 Humidity sensing system

For humidity sensor, ASTM F 2370-05 stated that any humidity sensor with accuracy of ±5 % and reproducibility of 3% of relative humidity are acceptable. In this research, a Honeywell HIH-4000 non-condensing relative humidity sensor (Figure 3-15) with accuracy of ±5 % and reproducibility of 3% was used for measuring the relative humidity. Four humidity sensors were used to monitor the environment relative humidity. Each sensor carried same weight in calculating mean environment temperature. Figure 3-14 shows the HIH 4000 humidity sensor. The input voltage of the sensor is 5V and the output voltage is linearly related to the relative humidity. All humidity sensors were calibrated by the manufacturer.

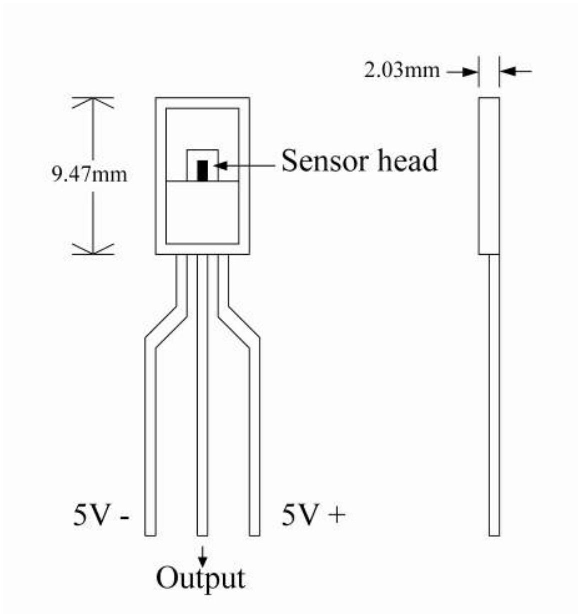


Figure 3-15. HIH 4000 humidity sensor

3.1.10 Manikin control system

3.1.10.1 Data acquisition and output

The data acquisition and output system consisted of 7 modules and one main controller connected to a personal computer via Lan cable. Each module provided 8 channels. The 7 modules included 4 Compact Fieldpoint RTD-124, 1 Compact FieldPoint AI-110, 1 Compact FieldPoint AO-220 and 1 Compact FieldPoint Relay-420. The Compact FieldPoint RTD-124 module was used for converting the temperature sensor signals from analogue to digital signals with conditioning and amplification. The Compact FieldPoint AI-110 was used for converting the humidity sensor signal from analogue to digital. Regarding analogue output, Compact FieldPoint AO-210 module was used to control the voltage of the pumps. Also, Compact FieldPoint Rely-425 was used to control the "on" and "off" of the heaters. Table 3-5 shows the details of manikin data acquisition and output system.

For performing the control function, the Compact FieldPoint 2020 was used to transfer the data from input modules to a personal computer and transfer signal from personal computer to output modules. The Compact FieldPoint 2020 was connected to the personal computer with a local area network by a Lan cable. The personal computer performed data analysis, data logging, PID control and display function.

Table 3-5. Manikin data acquisition and output system

No.	Item	Connection	Function	Resolution	Range of measurement	Channels
1	Compact FieldPoint RTD-124	PT100 RTD four wire temperature sensor	Input: Analogue to Digital	16 Bit	400 ohm	8
2	Compact FieldPoint RTD-124	PT100 RTD four wire temperature sensor	Input: Analogue to Digital	16 Bit	400 ohm	8
3	Compact FieldPoint RTD-124	PT100 RTD four wire temperature sensor	Input: Analogue to Digital	16 Bit	400 ohm	8
4	Compact FieldPoint RTD-124	PT100 RTD four wire temperature sensor	Input: Analogue to Digital	16 Bit	400 ohm	8

5	Compact FieldPoint AI-110	5V humidity sensor	Input: Analogue to Digital	16 Bit	0-10.2 voltage	8
6	Compact FieldPoint AO-210	DC pump	Output: Analogue	16 Bit	0-10.2 voltage	8
7	Compact FieldPoint Relay-420	Heaters	Relay on and off	/	/	8
8	Compact Fieldpoint 2020	Input and output modules, personal computer	Transfer data between all modules and personal computer	/	/	/
9	Personal computer	Connected with Compact FieldPoint 2020 via Lan	Data analysis, data logging, PID control, display information	/	/	/

The Compact Fieldpoint 2020 controller with 7 modules was installed at climate chamber adjacent to the manikin, whereas the personal computer was located outside the climate chamber. The Fieldpoint 2020 controller with 7 modules can operate in the environment with the lowest temperature of -25 ºC and the highest of 60 ºC. In terms of relative humidity, they can operate in the environment with 10% to 90%. The size of the Fieldpoint 2020 controller with 7 modules was relative compact (length x width x height = 441mm x 127 mm x 106mm). Figure 3-16 shows the Fieldpoint 2020 controller with 7 modules.

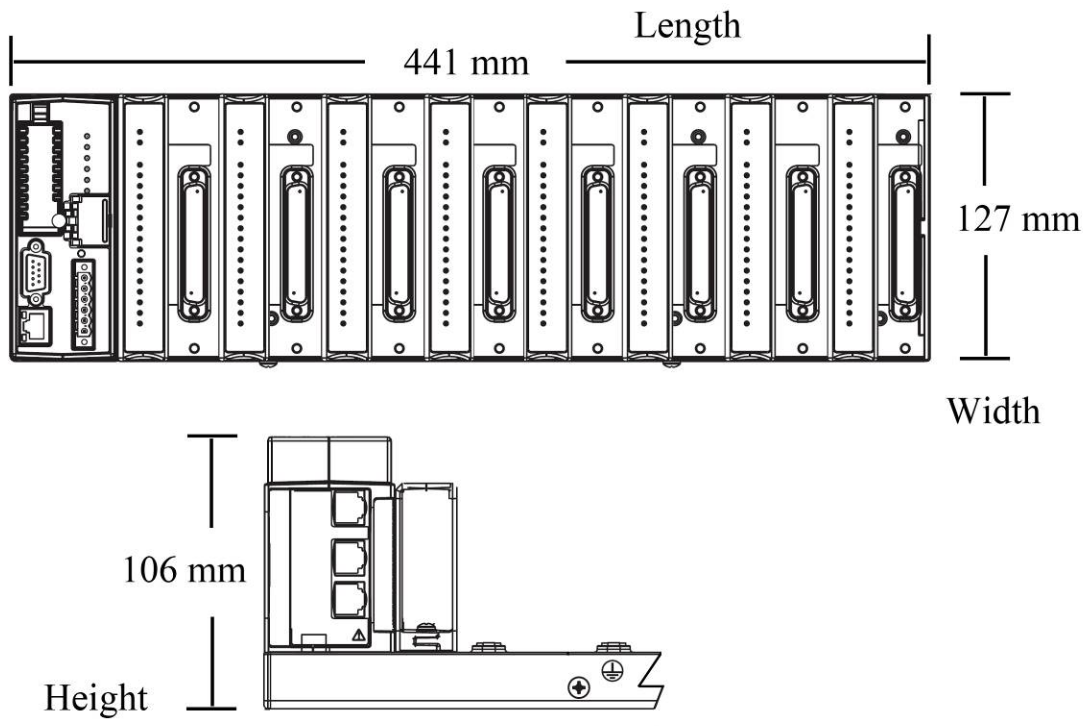


Figure 3-16. Size of Fieldpoint 2020 controller with 7 modules

3.1.10.2 Manikin control software

Regarding the manikin control software, a Labview 8.5 programming software was used to develop an interface for controlling heating with software PID (proportional-integral- derivative), receiving input command, humidity and temperature monitoring, data analysis, calculating results, and performing logical decision. Figure 3-17 shows the Manikin control software interface. The Labview 8.5 was a programming software, which used diagram to replace programming language. Figure 3-18 shows the block diagram of the manikin control software.

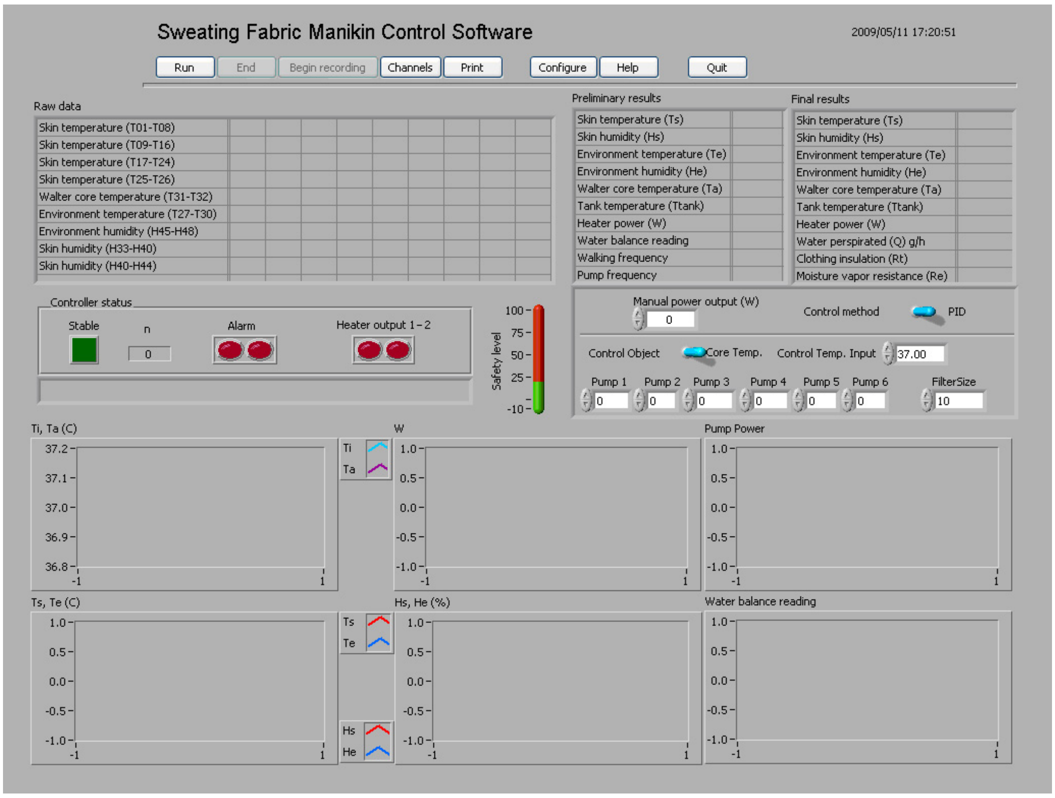


Figure 3-17. The manikin control software interface

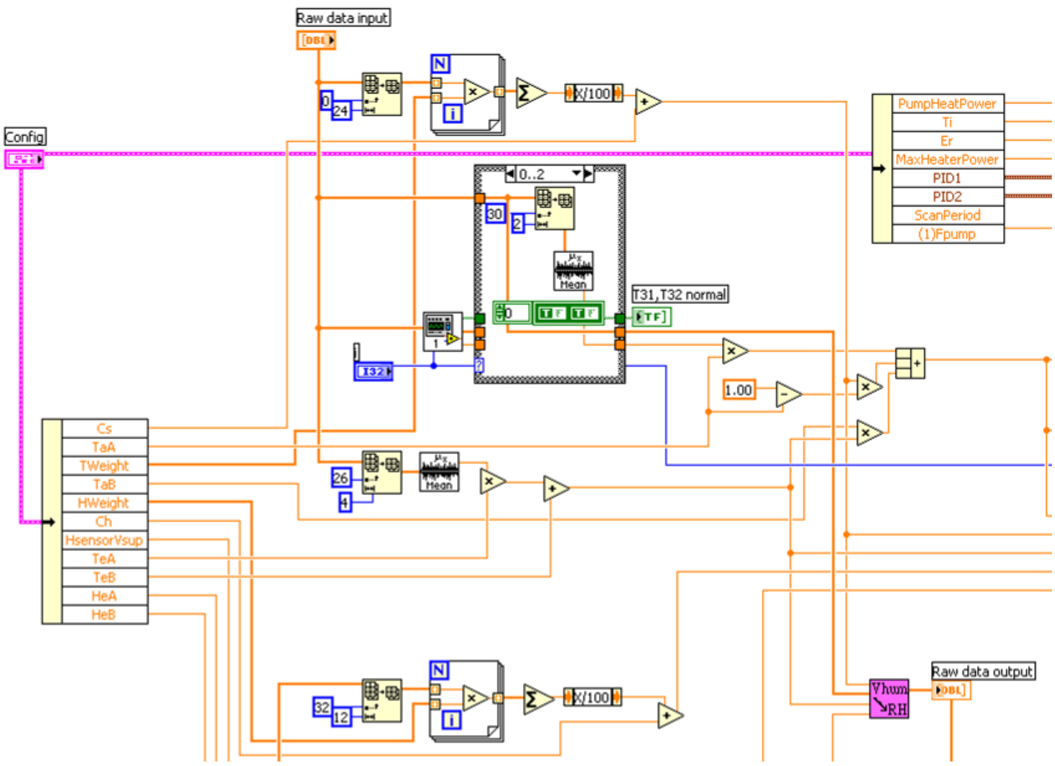


Figure 3-18. The block diagram of the manikin control software

The manikin control software could operate in one of the following three modes:

1. Heating with a constant power;

2. Heating to a target temperature based on the core temperature using PID;

3. Heating to target temperature based on the mean skin temperature using PID.

3.1.10.3 PID (Proportional-Integral-Derivative) controller for heating

In this research a software PID controller was used to calculate the power required for maintaining a constant and stable manikin body temperature. The PID controller was a kind of close loop controlling system, which compares the system output to a setpoint level so as to calculate a new control input for the system. The close loop system is illustrated in Figure 3-19.

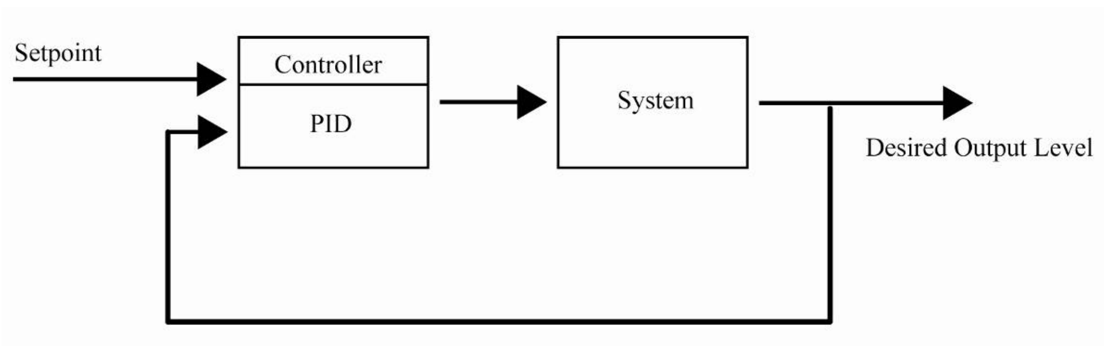


Figure 3-19. Close loop control system

The PID controller in manikin software was developed based on the formula below:

$$u(t) = K_c (e + \frac{1}{T_i} \cdot \int_0^t e \cdot dt + T_d \cdot \frac{de}{dt}) \tag{3-5}$$

$$K_c = \frac{100}{PB} \tag{3-6}$$

Where,

u(t)	is the output of the controller;
PB	is the proportional band of the controller;
K_c	is the controller gain;
T_i	is the integral time in minutes (also called reset time);
T_d	is the derivative time in minutes (also called rate).

For determining the parameters of the PID controller, Ziegler and Nichols' heuristic methods (as shown in Table 3-6 and 3-7) were used.

Table 3-6. Tuning formula: fast (1/4 damping ratio)

Controller	*PB* Proportional	T_i Integral minutes	T_d Derivative minutes
P	PB_u / 0.50		
PI	PB_u / 0.45	$0.83T_u$	
PID	PB_u / 0.60	$0.5T_u$	$0.125\ T_u$

PB_u and T_u are determined experimentally

Table 3-7. Tuning formula: normal (some overshoot)

Controller	*PB* Proportional	T_i Integral minutes	T_d Derivative minutes
P	PB_u / 0.2		
PI	PB_u / 0.18	$0.83T_u$	
PID	PB_u / 0.25	$0.5T_u$	$0.125\ T_u$

PB_u and T_u are determined experimentally

The PB_u and T_u are the critical values of the control object, which can be obtained experimentally. In PID tuning experiment, first, the T_i and T_d are set as zero, which is P-only mode controller. Second, try to change the value of PB in step incremental manner and observe the output response (temperature). Third, stop adjusting PB until a constant periodical oscillation is observed and mark the PB value as PB_u, whereas the oscillation time period is T_u. In this research the PB_u and T_u were found as 0.0375 and 38.2 minutes. The final *PB*, T_i and T_d are 0.15, 19.1 and 4.775, respectively. As shown in Figure 3-20, the precision of controller is 35ºC ±0.1º

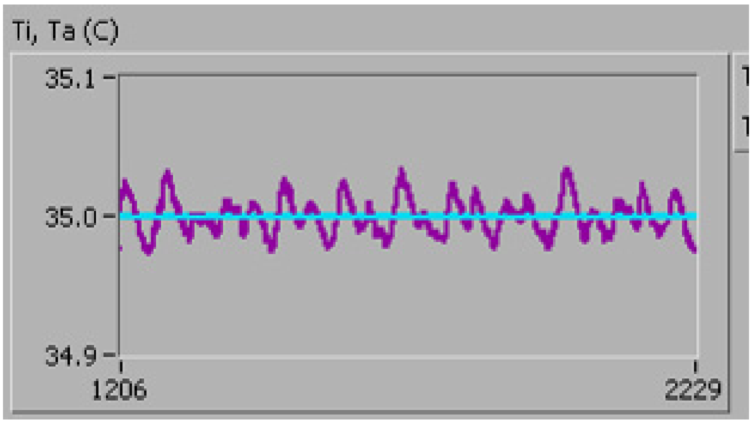


Figure 3-20. Controller performance in stable status (mean skin temperature variation less than 0.1ºC)

3.2 Accuracy and reproducibility of the sedentary and supine manikins

3.2.1 System accuracy in terms of uncertainties

All measurements, however careful and scientific, are subject to some uncertainties (Taylor, 1997). The evaluation of uncertainties help scientist to estimate how large of uncertainties in a system and help to reduce them when necessary.

In general, most physical quantities such as thermal insulation and evaporative resistance cannot be measured in a single direct measurement. In fact, they usually involve two steps. In the first place, one ore more quantities can be measured directly. In the second place, based on the measured values of these quantities, the final physical quantity can be determined from calculation.

In this study, the supine and sedentary manikins were used to measure the thermal insulation and evaporative resistance. They are determined by calculation from different measurements such as temperature, relative humidity, mass, voltage, current, etc.

Summary of the errors of each component of sedentary and supine manikins

(1) PT 100 skin temperature sensor (point sensor) with accuracy of ±0.15 ºC

(2) PT 100 core body temperature sensor (100mm probe) with accuracy of ±0.06 ºC

(3) Humidity sensor with accuracy of ±5%

(4) (Heater)AC voltage measurement accuracy of ±0.4%

(5) (Heater) Resistance measurement accuracy of ±0.05%

(6) (Water pump) DC voltage measurement accuracy of ±0.025%

(7) (Water pump) DC current measurement accuracy of ±0.15%

(8) Sweating rate measurement system (electronic balance with accuracy of ±0.1 g)

(9) Manikin skin area measurement based on weight to area method (electronic balance with accuracy of ±0.0002 g)

(10) Length measurement accuracy ±0.1 cm

The total uncertainties or (error propagation) of a system can be calculated by following formulae:

Uncertainty in Sums and Differences:

$$\delta q = \sqrt{(\delta x)^2 + \cdots + (\delta z)^2} \tag{3-7}$$

Uncertainty in products and quotients

$$\frac{\delta q}{|q|} = \sqrt{\left(\frac{\delta x}{x}\right)^2 + \cdots + \left(\frac{\delta z}{z}\right)^2} \tag{3-8}$$

where,

δq is the uncertainty;

q is the final value calculated from different components;

$\delta x, \ldots, \delta z$ are the measured uncertainties from different components;

$x, \ldots, z$ are the measurements from different components.

Given that thermal insulation (I_t) is calculated by

$$I_t = \frac{A_s \cdot (\Delta t)}{H_d} \ (\text{°C m}^2 \text{ W}^{-1}) \tag{3-9}$$

$$\Delta t = T_s - T_e \tag{3-10}$$

$$T_s = \sum_i^n A_i \cdot T_{s\,i} \tag{3-11}$$

$$H_d = H_s + H_p - H_e - H_a \tag{3-12}$$

where

A_i area percentage of a division of manikin skin surface, which is shown in Chapter 3 section 3.1.8 (Table 3-3 and 3-4)

I_t is the thermal insulation (in ºC m^2 W^{-1});

H_s is the power consumed by heaters (in W);

H_p is the power consumed by pumps (in W); the pumps are totally immersed in water, so it is assumed all mechanical work would be transferred into heat energy;

H_a is the power consumed for heating the supplied water to the manikin body temperature (in W);

i is the i^{th} division of the manikin surface area;

n is the total number of division of manikin surface area;

Q is the water loss per hour (in g h^{-1});

T_{si} is the temperature of a division of the manikin surface area (in ºC);

λ is the heat of evaporation of water at the skin temperature (in W h g^{-1}), which is equal to 0.67 W h g^{-1}

Δt is equal to the temperature difference between manikin skin and environment

Then, the accuracy of I_t is

$$\frac{\delta I_t}{|I_t|} = \sqrt{\left(\frac{\delta A_s}{A_s}\right)^2 + \left(\frac{\delta \Delta t}{\Delta t}\right)^2 + \left(\frac{\delta H_d}{H_d}\right)^2} \quad (3\text{-}13)$$

$$\delta H_d = \sqrt{(\delta H_s)^2 + (\delta H_p)^2 - (\delta H_e)^2 - (\delta H_a)^2} \quad (3\text{-}14)$$

For supine manikin in nude state, (A_s = 1.79 m^2, Δt = 23 ºC, H_d = 308.9 Watt)

$\frac{\delta I_t}{|I_t|} = 3.3$ %, whereas for supine manikin with clothing, (H_d = 96.5 Watt), $\frac{\delta I_t}{|I_t|} = 3.3$ %.

For Sedentary manikin in nude state, (A_s = 1.91 m^2, Δt = 23 ºC, H_d = 378.37 Watt), $\frac{\delta I_t}{|I_t|} = 3.5$ %, whereas for sedentary manikin with clothing, (H_d = 105.8 Watt), $\frac{\delta I_t}{|I_t|} = 3.5$ %.

Given that evaporative resistance (R_e) is calculated by

$$R_e = \frac{A_s \cdot (\overline{p}_{ss} - p_{as} RH_a)}{H_e} - R_{es} \quad (\text{Pa m}^2\ \text{W}^{-1}) \tag{3-15}$$

where

R_e is the moisture vapour resistance (in Pa m^2 W^{-1});

p_{ss} is the mean saturated moisture vapour pressure at skin temperature (in Pa);

p_{as} is the saturated moisture vapour pressure at environment temperature (in Pa);

RH_a is the relative humidity of the environment (in %);

R_{es} is the moisture vapour resistance of the skin (in Pa m^2 W^{-1}), which is equal to 8.6 Pa m^2 W^{-1} (Qian 2005 and 2006).

Let $\Delta p = (p_{ss} - p_{as} RH_a)$

Then, accuracy of R_e is

$$\frac{\delta R_e}{|R_e|} = \sqrt{\left(\frac{\delta A_s}{A_s}\right)^2 + \left(\frac{\delta \Delta p}{\Delta p}\right)^2 + \left(\frac{\delta H_e}{H_e}\right)^2} \tag{3-16}$$

For supine manikin in nude state, (A_s = 1.79 m^2, RH_a = 50 %, H_e = 91.4 Watt), $\frac{\delta R_e}{|R_e|} = 4.5$ %, whereas for supine manikin with clothing, (H_e = 27.7 Watt), $\frac{\delta R_e}{|R_e|} = 5.5$

For Sedentary manikin in nude state, (A_s = 1.91 m^2, RH_a = 50 %, H_e = 406.7 Watt), $\frac{\delta R_e}{|R_e|} = 4.5$ %, whereas for sedentary manikin with clothing, (H_e = 44.1 Watt), $\frac{\delta R_e}{|R_e|} = 5.6$

For the supine manikin in nude state, the accuracy of thermal insulation measurement is ±3.3 %, whereas the accuracy of evaporative resistance in nude state is ±4.5 %. In respect of the sedentary manikin, the accuracy of thermal insulation and evaporative resistance measurement are ±3.5 % and ±4.5 %, respectively. The accuracy level is considered to be acceptable. Another way to access the accuracy is to compare the thermal insulation and evaporative resistance measurement with other manikins and international standards, which will be discussed in next section.

3.2.2 Comparison with EN 13537 for supine manikin

In respect of thermal insulation measurement, six sleeping bags tested according to the EN13537 with given labels of comfort temperature rating were selected for making the comparison. The six sleeping bags also were tested by the newly developed supine fabric manikin according to standard conditions as stated in En 13537. Table 3-9 shows the thermal insulation values of the six sleeping bags converted from extreme temperature in EN 13537 temperature labels and the measured values in this study according to the EN 13537 method.

Table 3-8. The EN 13537 Extreme Temperature Labels, thermal insulation values converted from Extreme Temperature and measured thermal insulation values in this study according to EN 13537 methods

	EN13537 Extreme Temperature Label on sleeping bags	**I_t (Serial Method) converted from EN13537 Extreme Temperature Label**	**I_t (Parallel Method) This Study**
Sample A	-12	0.804	0.674
Sample B	-20	0.973	0.785
Sample C	-5	0.655	0.533
Sample D	-1	0.571	0.561
Sample E	-16	0.889	0.700
Sample F	-18	0.931	0.784

*I_t is thermal insulation (°C m^2 W^{-1}),

*I_t (serial method) is equal to (-0.0212 · extreme temperature + 0.5494)

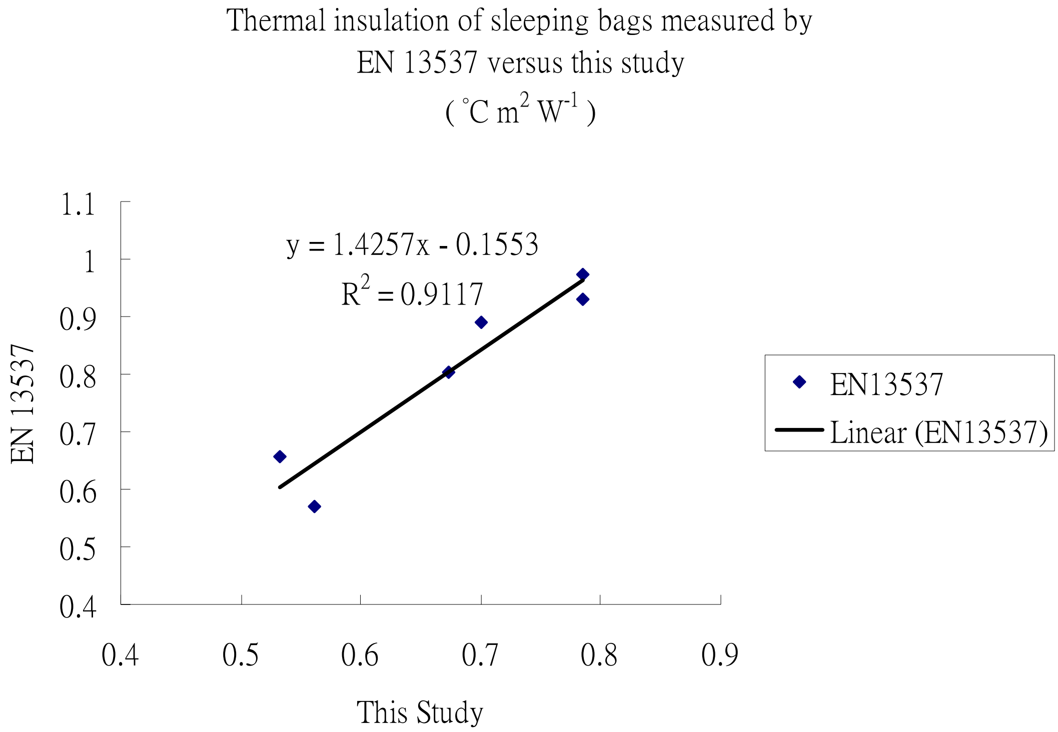


Figure 3-21. Thermal insulation converted from EN 13537 extreme temperature label in sleeping bag versus measurement of this study

As shown in Figure 3-21, the measurement made by the supine fabric manikin is highly correlated with existing EN 13537 measurement (R^2 = 0.91, P = 0.003). Since the thermal insulation calculation of present study is based on parallel method and the existing EN 13537 measurement is based on serial method, the measured values in this study are always lower than that of existing EN 13537. In present study, the discrepancy between serial and parallel method is around 18 to 28 %. It is consistent with past researches' findings. Meinander et al. (2003) reported that thermal insulation measurement from serial method was about 20% higher than parallel method for standing manikin in static condition (y = 1.2x +0.02). The greater differences between the thermal insulation values converted from the labels on the sleeping bags and those measured in our study may be due to the greater compression imposed on the sleeping bags by our supine manikin as it is heavier than those copper or plastic dry manikins.

Due to lack of publications or reports related the evaporative resistance of supine manikin, there is no comparison of evaporative resistance of supine manikins in this research. In addition, evaporative resistance measurement using supine manikin is also not included in any international test standard. Therefore, it is not possible to make direct a comparison. Furthermore, in the general standard for evaporative resistance measurement using sweating manikin of ASTM F2370-05, it was pointed out that there were generally large inter-lab variations due to the complex nature of apparatus and most manikins were one-of-a-kind instruments. The variations of evaporative resistances, measured by different sweating manikins, reported by Richards (2005) were as high as 41 to 138%. As a result, the evaporative resistance values measured in different labs using difference sweating manikins are still not comparable.

3.2.3 Comparison with other manikins' data for the sedentary sweating fabric manikin

As shown in Table 3-9, in nude (without garment) condition, the thermal insulation (I_t) of the newly developed fabric sedentary manikin with chair is 0.117 °C m^2 W^{-1}, which is similar to the manikin test result of Olesen et al. (1982), but it is lower than the value of Nielsen et al. (1985). The result of Nielsen et al. (1985) was obtained from human subject test and thus, it is difficult to make comparison with that of the manikin test. The result of Olesen et al. (1992) was obtained by a manikin test, so the result was relatively closer to that of the present study. Also, according to ISO 9920, the thermal insulation in sedentary posture depends on the height of backrest and thickness. In general, office chairs would produce an increase in insulation by about 0.0062 to 0.0264 °C m^2 W^{-1}.

For the evaporative resistance measurement, it is very difficult to make comparison, because there is lacking of data from literature and no international standard governing the measurement method, procedures and conditions.

Table 3-9. Thermal insulation of sedentary manikins in nude condition with chair

Test method	**Source**	**Sedentary Posture (nude) Included chair I_t (°C m^2 W^{-1})**
Manikin Test	Olesen et al. 1982	0.116
Manikin Test	This study	0.117
Human Subject Test	Nielsen et al. 1985	0.152

3.2.4 Reproducibility of supine manikin tests

As shown in Table 3-11, the coefficients of variance of thermal insulation of 19 samples using the supine manikin developed in this study are around 3% or less. The results indicate that the reproducibility of the supine manikin is high and is acceptable in EN 13537, ASTM F1720-06 and ASTM F1291-05 in terms of reproducibility. For thermal insulation measurement, according to EN 13537, it requires the coefficient of variance of sleeping bag thermal insulation test within 5%. In ASTM F1720-06, it requires the thermal insulation test of sleeping bag within 3%. For the general standard of thermal insulation test using heated manikin, ASTM F1291-05 requires the coefficient of variance to be within 5%.

Table 3-10. Coefficients of variance of the thermal insulation (I_t) and evaporative resistance (R_e) tests using the sweating fabric supine manikin developed in this study

Supine Manikin							
No.	**Sample**	**Mean I_t $^oC\ m^2\ W^{-1}$**	**STDEV**	**CV %**	**Mean R_e ($Pa\ m^2\ W^{-1}$)**	**STDEV**	**CV %**
1	Nude (supine)	0.13	0.001	0.68	46.5	1.5	3.29
2	Sleeping bag sample 1	0.37	0.01	2.6	137.9	3.4	2.46
3	Sleeping bag sample 2	0.45	0.003	0.77	167.1	3.3	2
4	Sleeping bag sample 3	0.51	0.012	2.27	169.7	8.6	5.06
5	Sleeping bag sample 4	0.49	0.007	1.38	208.7	11.6	5.57
6	Sleeping bag sample 5	0.39	0.006	1.46	176.7	4.9	2.79
7	Sleeping bag sample 6	0.42	0.004	0.92	203.8	7.4	3.63
8	Sleeping bag sample 7	0.37	0.006	1.58	158.7	5.8	3.63
9	Sleeping bag sample 8	0.49	0.006	1.13	191.9	2.3	1.18
10	Sleeping bag sample 9	0.46	0.004	0.95	169.4	8.2	4.81
11	Sleeping bag sample 10	0.47	0.008	1.64	179.6	4	2.23
12	Sleeping bag sample 11	0.38	0.006	1.53	120.6	2.1	1.76
13	Clothing ensemble 1	0.19	0.001	1.61	69.1	1.61	2.33
14	Clothing ensemble 2	0.22	0.004	2.26	72.9	2.26	3.1
15	Clothing ensemble 3	0.28	0.002	0.59	114.8	0.59	0.51
16	Clothing ensemble 4	0.4	0.008	3.24	175.6	3.24	1.85
17	Clothing ensemble 5	0.23	0.002	2.14	102.9	2.14	2.08
18	Clothing ensemble 6	0.18	0.001	1.34	64.2	1.34	2.09
19	Clothing ensemble 7	0.14	0.001	1.51	47.2	1.51	3.2

In respect of evaporative resistance measurement, there is a lack of research related to the evaporative resistance of clothing or sleeping bag using supine manikin. In fact, there is no international testing standard related to the measurement of evaporative resistance of sleeping bag or clothing using supine manikin. One of the reasons is low reproducibility. The conventional cotton or hydrophilic skin method would have a relatively larger variation in measuring the evaporative resistance of clothing or sleeping bag in supine posture. In the present study, as shown in Table 3-10, the coefficient of variance of the evaporative resistance measurement using the supine manikin is around 5 % or less, which is relatively low and thus, it is eligible for conducting evaporative resistance test for clothing and sleeping bag in supine posture.

The sample details, environment condition, testing method and testing procedures will be discussed in Chapter 4.

3.2.5 Reproducibility of sedentary manikin tests

For thermal insulation (I_t) measurement using heated manikin, ASTM F1291-05 requires the coefficient of variance should be within 5 %. As shown in Table 3-12, the coefficients of variance of thermal insulation measurement using the sedentary manikin developed in this study are around 3 % or less, which are within the requirement of ASTM F1291-05. The reproducibility of thermal insulation test is considered to be high.

In respect of evaporative resistance (R_e) measurement using sedentary manikin, as shown in Table 3-11, the coefficients of variance are around 3% or less. The reproducibility is high and meets the requirement of ASTM F2370-05. The ASTM F2370-05 is not a standard specially designed for sedentary manikin, but it still can be used as a reference for sedentary manikin.

The sample details, environment condition, testing method and testing procedures will be discussed in Chapter 5.

Table 3-11. Coefficients of variance of the thermal insulation (I_t) and evaporative resistance (R_e) tests using the sweating fabric supine manikin developed in this study

Sedentary Manikin							
No.	**Sample**	**I_t (°C m^2 W^{-1})**	**SD**	**CV (%)**	**I_e (Pa m^2 W^{-1})**	**SD**	**CV (%)**
1	Nude	0.117	0.002	2.02	33.6	0.44	1.31
2	Clothing ensemble 1	0.183	0.003	1.64	48.1	0.97	2
3	Clothing ensemble 2	0.196	0.006	3.06	51.4	1.23	2.39
4	Clothing ensemble 3	0.263	0.007	2.66	85.4	0.48	0.56
5	Clothing ensemble 4	0.418	0.002	0.48	114.8	1.13	0.99
6	Clothing ensemble 5	0.198	0.007	3.54	70.5	0.63	0.9
7	Clothing ensemble 6	0.157	0.005	3.18	43.9	0.65	1.48
8	Clothing ensemble 7	0.118	0.003	2.54	34.6	0.12	0.34

Chapter 4

Measuring the thermal insulation and evaporative resistance of sleeping bags using a supine sweating fabric manikin

4.1 Introduction

This chapter reports on the use of sweating supine manikin for the measurement of thermal insulation and evaporative resistance of sleeping bags.

A detail review of the development of supine manikin and thermal comfort evaluation of sleeping bag can be found in Chapter 2 section 2.1.6 and section 2.2, respectively.

4.2 Methods

4.2.1 Supine sweating fabric manikin

Figures 4-1 and 4-2 show the novel supine sweating fabric manikin, which is developed in this research, covered with a sleeping bag and uncovered, respectively.

Figure 4-1. Supine sweating fabric manikin (with a sleeping bag)

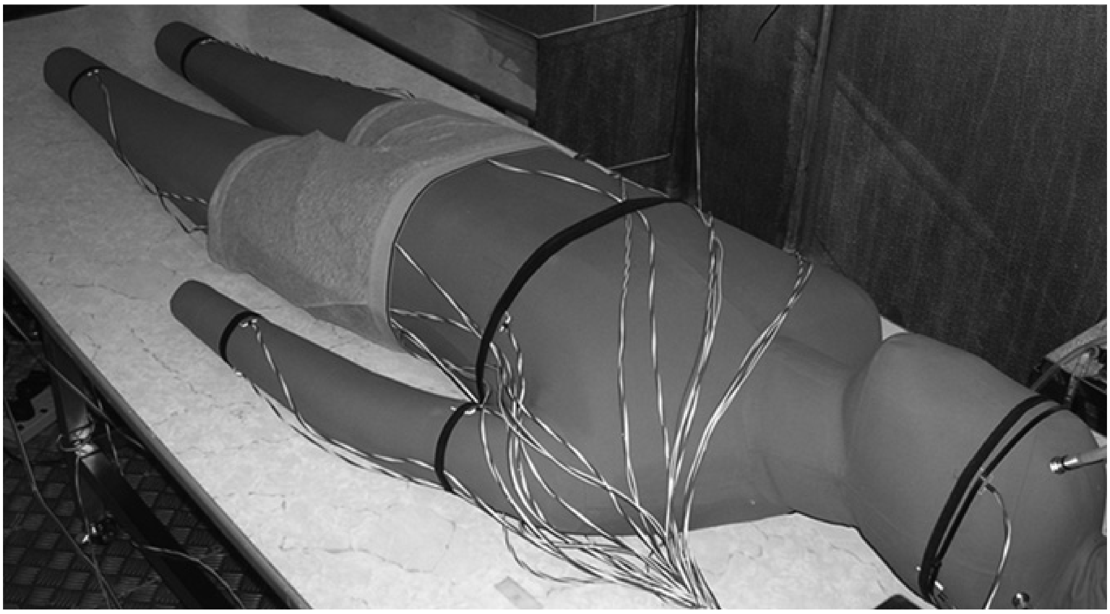


Figure 4-2. Supine sweating fabric manikin (without a sleeping bag)

The detail description of the supine manikin is shown in Chapter 3 section 3.1.

4.2.2 Thermal insulation (I_t), Evaporative resistance (R_e) and Moisture permeability (I_m)

The calculation of thermal insulation (I_t) and evaporative resistance (R_e) are shown in Chapter 3 section 3.2 equation (3-9) and equation (3-15), respectively The determination of moisture permeability index (i_m) defined in Chapter 2 section 2.4.4 equation (2-14).

4.2.3 Climate Chamber

All experiments were carried out in a climate chamber with stable wind velocity, relative humidity and temperature. The climate chamber was in cubic size 9.20 × 3.25 × 2.60 m^3 (L × W × H). The thickness of wall was equal to 0.1 m. The shell of wall was made of aluminum and the inside of wall was totally filled with polyurethane foam. The temperature was controlled by heating cooling system with a range from 11 to 40 ºC. The relative humidity was controlled by humidifier and dehumidifier with a range from 30% to 80% relative humidity. For maintaining a uniform and parallel wind velocity, nine axial fans were installed in the climate chamber. The wind speed can be adjusted from 0.22 to 4 m/s. The setting of environment condition of the climate chamber was controlled by KMC Netview hardware and software controller with an input interface for setting target wind speed, relative humidity and temperature. The climate chamber layout and KMC Netview controller of climate chamber are shown as Figure 4-3 and 4-4, respectively.

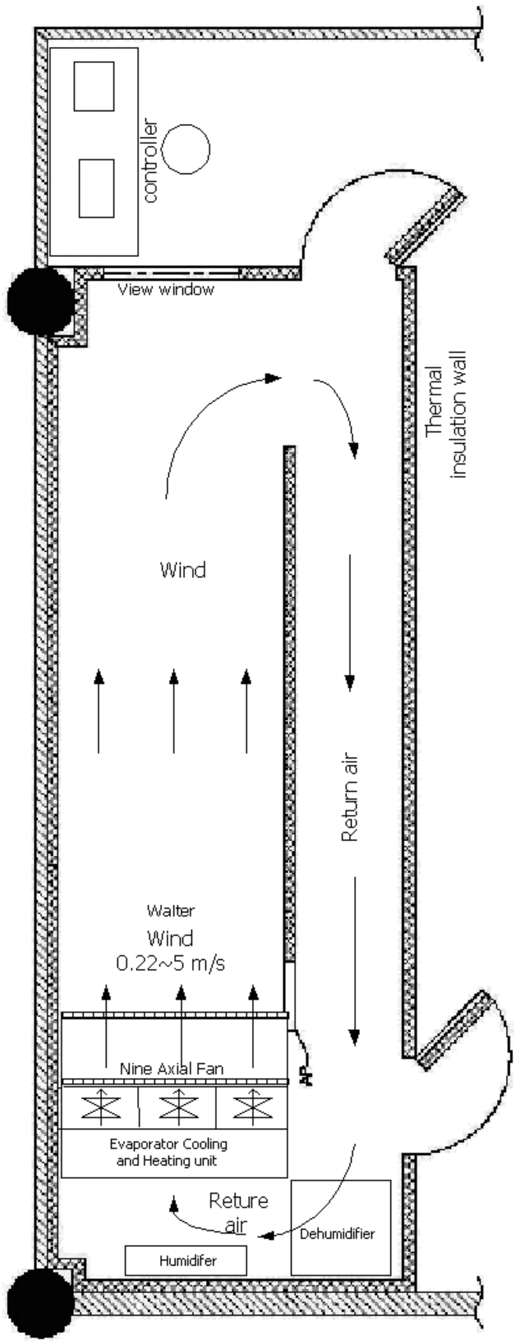


Figure 4-3. Layout of climate chamber

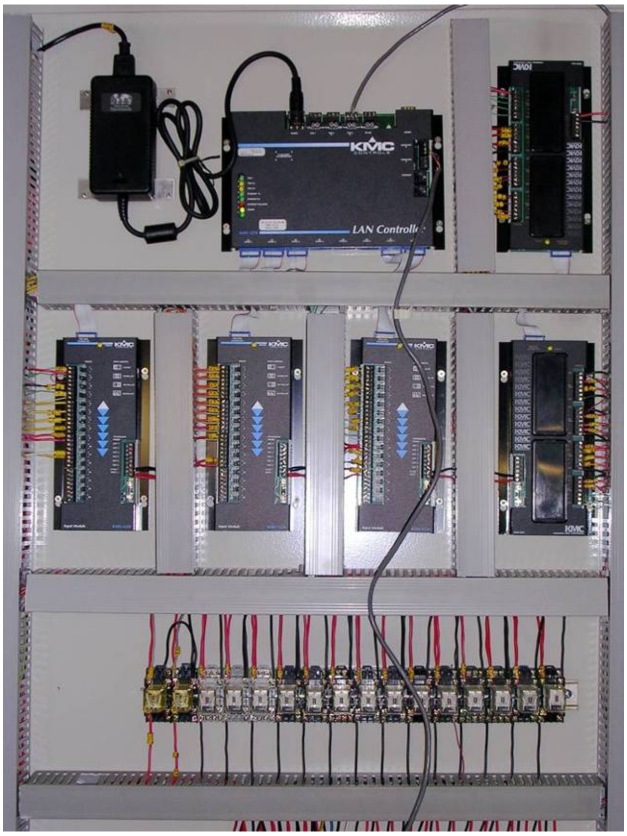


Figure 4-4. KMC Netview controller of climate chamber

4.2.4 Testing procedures using the supine manikin

Figure 4-5 shows the position of the manikin in the chamber. The supine manikin was placed horizontally in supine posture on a 20 mm thick artificial wooden ground with an impermeable plastic layer of 1 mm in thickness to prevent the moisture penetrating into the artificial wooden ground. The artificial wooden ground was located 0.69 m above the chamber floor to create an empty space for airflow under the artificial wooden ground. As shown in Figure 4-5, the legs of the manikin were facing the axial fans during testing. The air flowed from manikin legs to the head. For all tests, the wind velocity, generated by nine axial fans, was controlled at 0.3 ± 0.1 m s^{-1} and the relative humidity at 50% ± 3%. The difference between the air and radiant temperature was less than 0.1 °C.

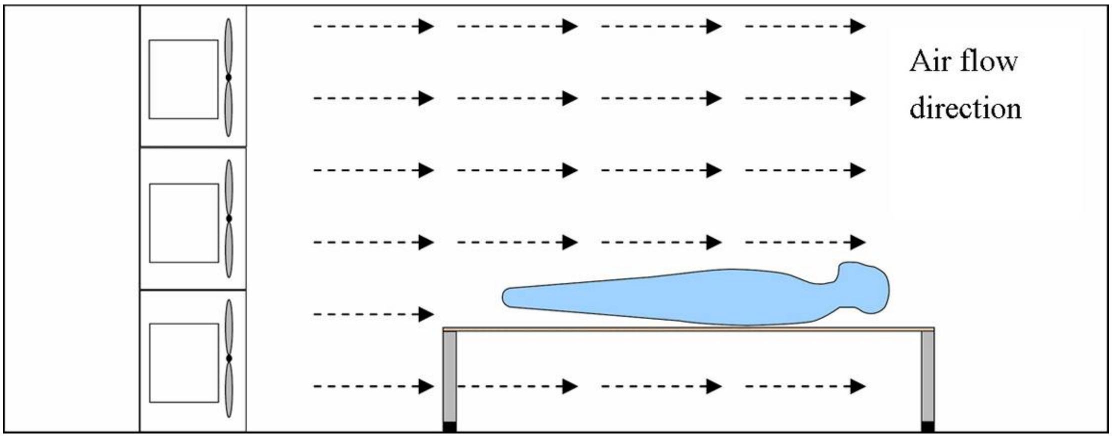


Figure 4-5. Supine manikin position

Before testing, all samples were hung in the climate chamber for at least 24 h and were shaken for 1 min for expansion. All tests were repeated four times, and the sleeping bags were put off and put on again between repetitions.

For the measurement of the thermal insulation of the sleeping bags, the mean skin temperature of the supine manikin was maintained at 35 °C and the air temperature of the climate chamber at 12±0.3 °C. A fabric skin of very low permeability was used when measuring the thermal insulation of the sleeping bags. The perspiration rate of the supine manikin in the nude under the above-described testing condition was 16 ±

2 g h^{-1}, which simulates the insensible perspiration of man while sleeping. Each test lasted for 12 h.

For measuring the evaporative resistance of the sleeping bags or the nude manikin, tests were conducted in the isothermal condition, that is, both the air temperature of the climatic chamber and the mean skin temperature of the manikin were set to be the same at 35 °C. The isothermal condition prevents condensation from taking place within the sleeping bag under testing. To achieve good measurement accuracy, a highly breathable fabric skin was used to simulate gaseous perspiration. The perspiration rate of the manikin in the nude under the described isothermal condition was 136 g h^{-1}. On the basis of preliminary tests, measurements should be taken after covering the manikin with the sleeping bag for at least 7 h to allow sufficient time for the sleeping bag to reach saturation in moisture absorption. For practical convenience, measurements were taken after 24 h.

4.2.5 Measurement of the water vapour permeability (WVP) of shell and lining fabrics

The BS7209:1990 control disk method is a widely used method for measuring the water vapour permeability (WVP) of fabrics. It was used by McCullough et al. (2003) to measure and compare the WVP of 26 different waterproof or windproof breathable shell fabrics, by Kar et al. (2007) to measure and compare the WVP of knitted T-shirt fabric. The same method is used here to measure the WVP of the shell and lining fabrics of sleeping bags. In this method, the test sample cut in circle shape with a defined area was sealed over the open mouth of test dish. The dish contained 46 ml of distilled water and had an air gap of 10 ± 1 mm between the sample and the water surface (see Figure 4-6). The dishes were put on a rotating plate and the test lasted for 24 h. The test of each sample was repeated three times.

The water vapour permeability (WVP) (in g m^{-2} day^{-1}) of fabric is calculated by the following equation (BS7209 1990):

$$WVP = \frac{24\,M}{A_c t} \tag{4-1}$$

$$A_c = \left(\frac{\pi d^2}{4}\right) \times 10^{-6} \tag{4-2}$$

where

M is the water loss over the testing period (in g);

T is the time between successive weightings of the assembly (in h);

A_c is the area of the exposed test fabric (m^2)

(equal to the internal area of the test dish (in m^2));

d is the internal diameter of the test disk (in mm).

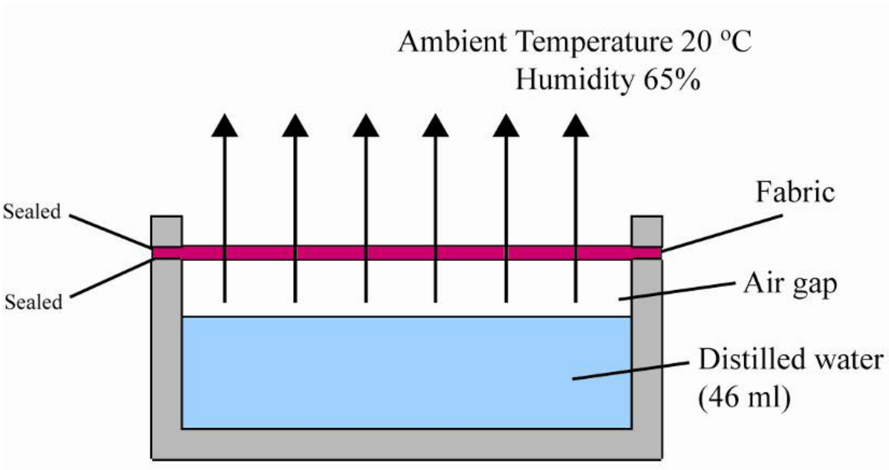


Figure 4-6. WVP tester

4.2.6 Measurement of mass and thickness of sleeping bags

The mass of the sleeping bags was measured at 35 °C and 50% relative humidity. The thicknesses of sleeping bags were measured in terms of top and bottom in a climate chamber (35 °C ambient temperature and 50% relative humidity). The thicknesses of the top part, bottom part and overall (from bottom to top) of the sleeping bag were measured on the basis of the average value of three locations as shown in Figure 4-7. A circle-shape hard foam plate with a surface area of 803.84 cm^2 and a total weight of 41 g (equivalent to 5.0 Pa) was placed on the surface of measurement points for measuring the resultant thickness. Before the mass and thickness measurement, the samples were hung in the climate chamber for over 24 h and were shaken for 1 min for expansion.

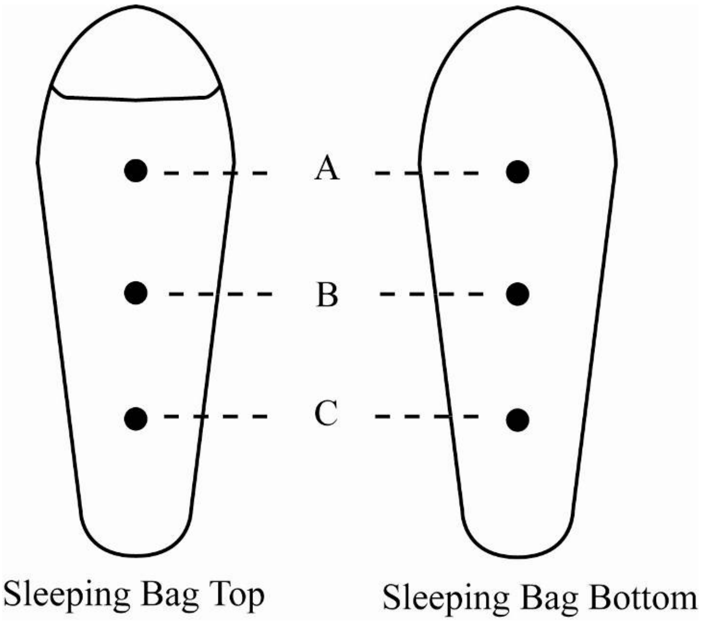
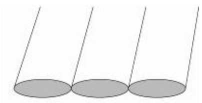
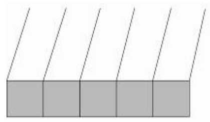
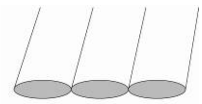
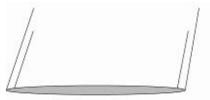


Figure 4-7. Sleeping bag thickness measurement locations of top and bottom

4.3 Samples

In total, 11 sleeping bags all in mummy shape were tested in this study. The specifications and construction techniques of the samples are listed in Table 4-1.

Table 4-1. The specification of eleven mummy shape sleeping bags

Sample	Filling	Size (cm x cm)	Construction method	Cross section
1	Goose Down	210 x 75	Quilted through method	
2	Goose Down	210 x 75	Quilted through method	
	Goose Down	210 x 75	Quilted through method	
4	Goose Down	198 x 77	Box baffling method	
5	Goose Down	215 x 75	Box baffling method	
6	Goose Down	215 x 75	Box baffling method	
7	Polyester	210 x 80	Quilted through method	
8	Polyester	212 x 80	Quilted through method	
9	Polyester	230 x 80	Quilted through method	
10	Polyester	215 x 80	Quilted through method	
11	Polyester	215 x 75	Edge-stabilized method	

4.4 Results and discussion

The mass, thicknesses of the sleeping bags, and the WVP of the shell and lining fabrics are listed in Table 4-2. The thermal insulation and moisture vapour resistances of the sleeping bags are listed in Tables 4-3 and 4-4, respectively.

Table 4-2. Mass, thicknesses, WVP of the shell and lining fabrics of the sleeping bags

Sample	**Mass (g)** (50% relative humidity)	**Thickness** (50% relative humidity)			**Water vapour permeability (WVP) (in g m^{-2} day^{-1})**	
		Top	**Bottom**	**Overall**	**Shell fabric**	**Lining fabric**
1	599.4	3.22 ±0.38	2.62 ±0.49	4.47 ±0.50	1020 ±18	1031 ±5
2	824.0	5.72 ±0.40	3.35 ±0.60	8.57 ±0.81	1020 ±18	1031 ±5
3	1034.2	8.42 ±1.01	5.28 ±0.31	11.77 ±1.42	1020 ±18	1031 ±5
4	1073.2	5.92 ±0.84	5.52 ±0.49	10.07 ±1.59	291 ±7	1046 ±17
5	764.8	3.62 ±1.12	3.08 ±0.49	6.47 ±0.91	686 ±22	1068 ±34
6	825.8	5.05 ±1.01	4.58 ±0.71	7.80 ±0.53	686 ±22	1068 ±34
7	843.2	2.02 ±0.06	1.95 ±0.00	4.00 ±0.46	1007 ±36	1065 ±13
8	1462.3	4.15 ±0.26	2.98 ±0.23	6.80 ±0.21	784 ±19	1029 ±34
9	1388.2	2.88 ±0.12	2.68 ±0.25	2.73 ±0.25	627 ±14	1077 ±12
10	1382.6	2.92 ±0.12	2.78 ±0.23	4.50 ±0.00	396 ±17	1057 ±11
11	906.4	1.98 ±0.25	1.75 ±0.00	2.97 ±0.06	1055 ±30	1045 ±30

Table 4-3. Thermal insulation (I_t) of sleeping bags measured at 12 ºC ambient temperature and 50% relative humidity

Sample	Mean R_t ºC m^2 W^{-1}	STDEV	CV %	Water Loss (g h^{-1})	Weight (g)		Moisture accumulation	
					before test	after test	(g)	(%)
Nude (supine)	0.13	0.0009	0.68	18.7	/	/	/	/
1	0.37	0.0097	2.60	13.7	603.3	597.5	-5.8	-1.0
2	0.45	0.0034	0.77	16.4	828.7	823.8	-4.9	-0.6
3	0.51	0.0115	2.27	14.2	1042.4	1036.3	-6.1	-0.6
4	0.49	0.0068	1.38	16.2	1082.4	1076.9	-5.6	-0.5
5	0.39	0.0057	1.46	15.9	768.4	767.9	-0.5	-0.1
6	0.42	0.0039	0.92	17.6	831.4	828.8	-2.6	-0.3
7	0.37	0.0059	1.58	14.4	846.4	843.8	-2.6	-0.3
8	0.49	0.0055	1.13	15.2	1468.3	1467.7	-0.5	0.0
9	0.46	0.0044	0.95	16.0	1391.7	1390.8	-0.9	-0.1
10	0.47	0.0077	1.64	16.6	1387.4	1386.0	-1.4	-0.1
11	0.38	0.0058	1.53	14.8	908.7	907.8	-0.9	-0.1

Table 4-4. Evaporative resistance (R_e) of sleeping bags measured in isothermal condition (35ºC ambient temperature, 35ºC mean skin temperature and 50% relative humidity

Sample	Mean R_e (Pa m^2 W^{-1})	STDEV	CV %	Water loss (g h^{-1})	Weight (g)		Moisture accumulation	
					before test	after test	(g)	(%)
Nude (standing)	17.3	0.5	2.73	288.5	/	/	/	/
Nude (supine)	46.5	1.5	3.29	136.4	/	/	/	/
1	137.9	3.4	2.46	51.4	599.4	622.9	23.5	3.9
2	167.1	3.3	2.00	43.0	824.0	857.7	33.8	4.1
3	169.7	8.6	5.06	42.8	1034.2	1080.7	46.5	4.5
4	208.7	11.6	5.57	35.1	1073.2	1111.3	38.2	3.6
5	176.7	4.9	2.79	41.2	764.8	794.0	29.2	3.8
6	203.8	7.4	3.63	36.5	825.8	857.4	31.6	3.8
7	158.7	5.8	3.63	45.2	843.2	862.9	19.8	2.3
8	191.9	2.3	1.18	37.6	1462.3	1510.3	48.0	3.3
9	169.4	8.2	4.81	42.5	1388.2	1412.0	23.8	1.7
10	179.6	4.0	2.23	40.2	1382.6	1407.6	25.0	1.8
11	120.6	2.1	1.76	58.6	906.4	926.7	20.2	2.2

4.4.1 Effects of the mass of sleeping bags on thermal insulation and evaporative resistance

In general, higher amount of filling in the sleeping bag will yield higher value of thermal insulation, but this would generally impeded the moisture transmission (i.e. increase the evaporative resistance). Figure 4-8 plots the thermal insulation of sleeping bags against the mass of the goose down filled and polyester filled sleeping bags, respectively. As can be seen, when the filling of the sleeping bags are of the same type, the thermal insulation has a strong positive relationship with the mass of the sleeping bags.

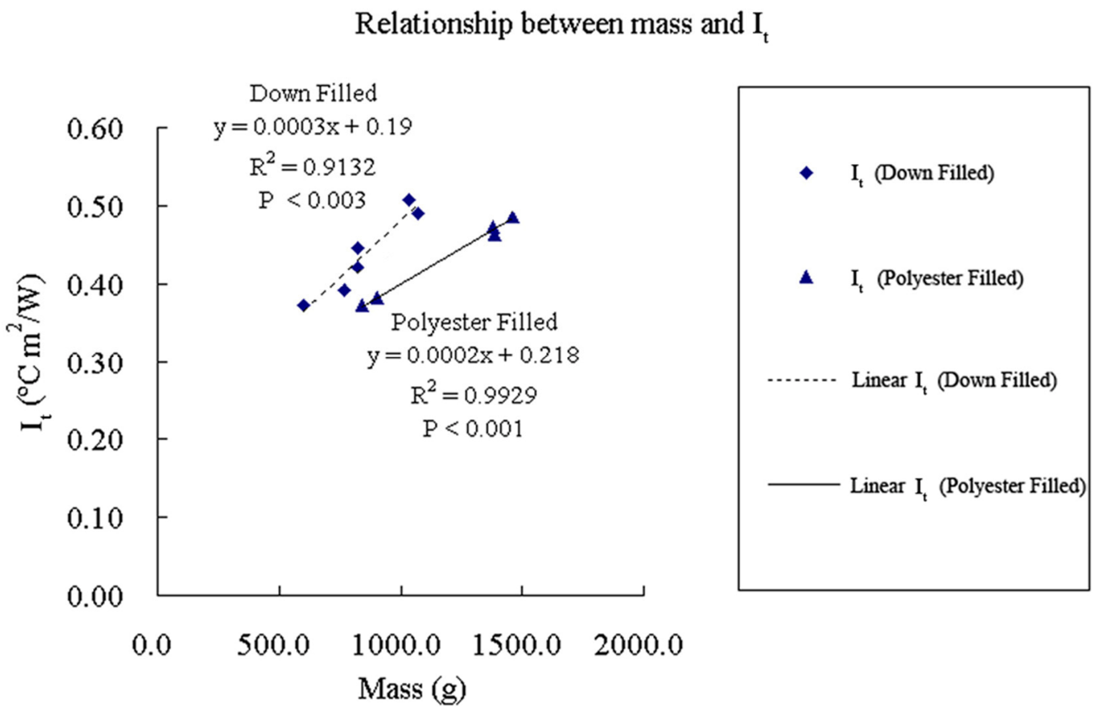


Figure 4-8. Relationship between mass and thermal insulation (I_t) of sleeping bags

As far as the evaporative resistance is concerned, however, it only has a relatively weak linear and insignificant relationship with the mass of the sleeping bag (as shown in Figure 4-9).

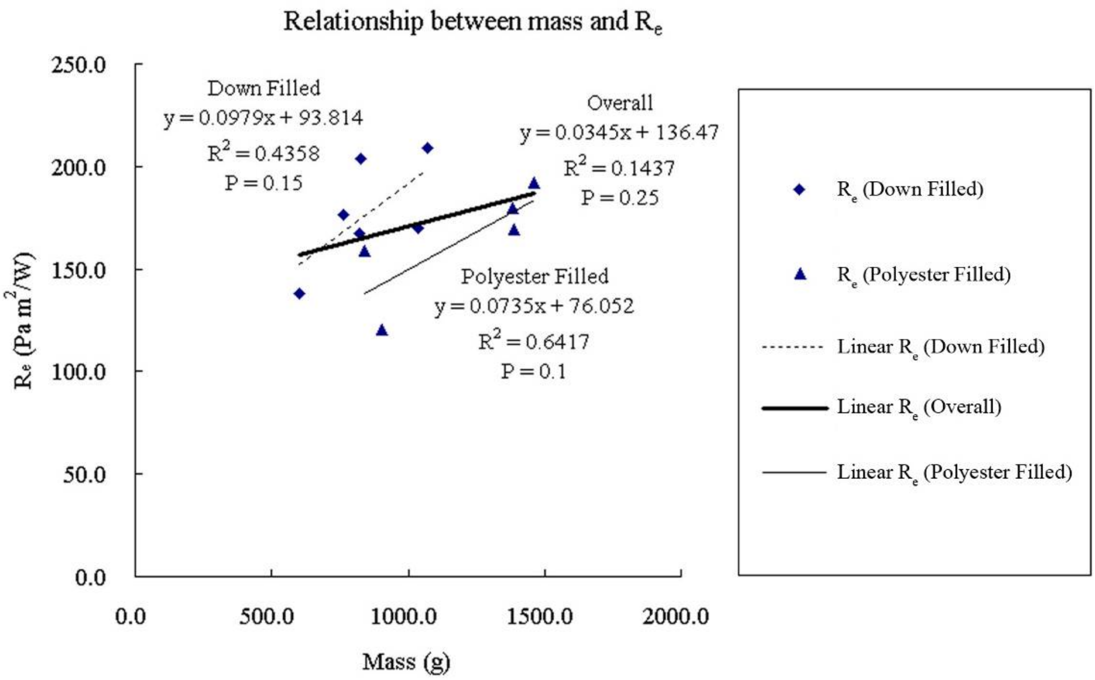


Figure 4-9. Relationship between the mass and evaporative resistance (R_e) of sleeping bags

4.4.2 Effects of the water vapour permeability (WVP) of the shell and lining fabrics and the thickness of sleeping bags

The overall evaporative resistance of the sleeping bags are related to the water vapour permeability of the shell and lining fabrics as well as the thickness of the sleeping bags, it was found that, the moisture vapour permeability of the shell fabric and the overall thickness of the sleeping bags have significant effects, but the moisture permeability of the lining fabric didn't, probably because the moisture vapour permeabilities of the lining fabrics in the 11 samples varied little. Using the WVP of the shell fabric and the overall thickness of the sleeping bags, we can derive the following relationship by multiple linear regression with a percentage of fit of 76% (R^2=0.76, P=0.003):

$$R_e = 194.309 - 0.65 \cdot \text{WVP of Shell Fabric} + 4.377 \cdot \text{Overall Thickness} \qquad (4\text{-}3)$$

4.4.3 Relationship between evaporative resistance and thermal insulation of sleeping bags

Figure 4-10 plots the evaporative resistance against the thermal insulation. As can been seen, the relationship between them is relatively weak with r^2 = 0.3688 and $P < 0.05$. Sleeping bags with similar thermal insulation can have substantial differences in evaporative resistances. For example, Sample 8 and 4 have almost the same thermal insulation values (i.e. 0.49 ºC m2/W), but the evaporative resistance of Sample 4 is 8.8% lower than that of sample 8. Also, Sample 1 and 7 have almost the identical thermal insulation values, but the evaporative resistance of Sample 1 is 15.1% lower than that of Sample 7. In addition, the thermal insulation value of Sample 3 is 17% higher than that of Sample 6, but the evaporative resistance for Sample 3 is 22% lower than that of Sample 6. This shows that the evaporative resistance of sleeping bags cannot simply be predicted from the thermal insulation values, it is essential to directly measure the evaporative resistance by using supine perspiring manikins.

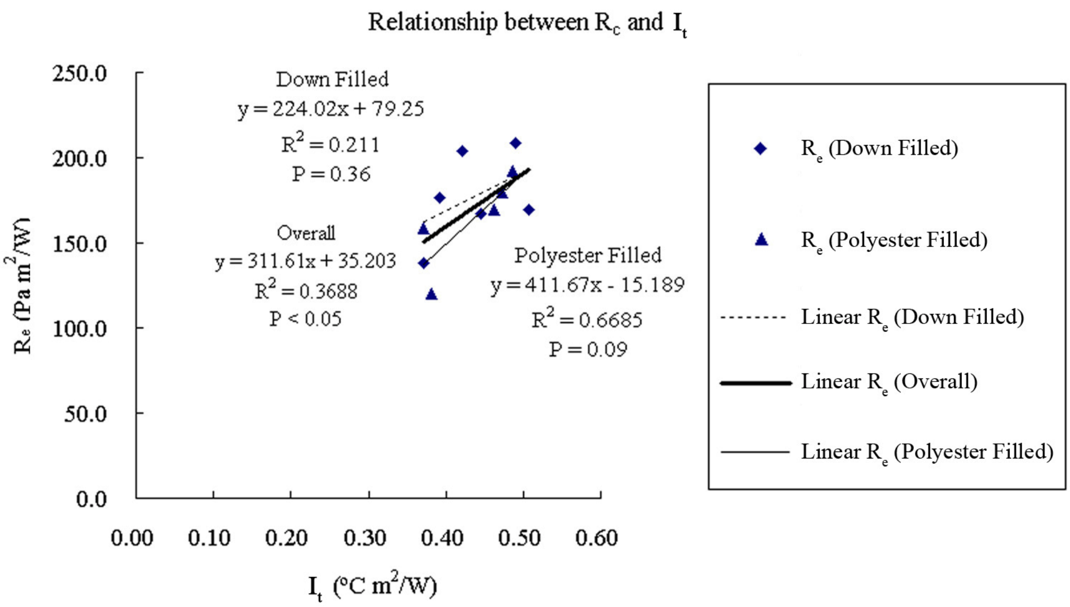


Figure 4-10. Relationship between thermal insulation (I_t) and evaporative resistance (R_e)

4.4.4 Moisture permeability index of sleeping bags

In 1962, Woodcock (1962a&b) introduced i_m (moisture permeability index) as a dimensionless parameter to reflect the vapour permeability of clothing in equilibrium or steady state condition. The i_m is an efficiency index, which gives a quantitative measurement of the human clothing environment. The theoretical range of i_m is from 0 to 1. McCullough (1989) reported that the average i_m value for indoor clothing is around 0.4 based the tests of 22 clothing ensembles. Havenith (1999) and ISO 9920 reported that the average i_m value of outdoor 1 to 2 layer clothing was around 0.38. In Table 4-5, the moisture permeability index calculated from R_c and R_e measured using the supine sweating manikin are listed. Table 4-5 indicates that the i_m of sleeping bags tested by the supine sweating thermal manikin are between 0.1 and 0.2. In supine posture, a large area of manikin skin is directly compressed by the supporting impermeable wooden ground, so the evaporative resistances of sleeping bags are substantially higher than those expected from the test results at the standing posture. Another possible reason for the higher than expected evaporative resistance values is that the evaporative resistance measured in the isothermal condition, as it is the case in our experiments, is generally greater than those measured in the non-isothermal conditions, since the natural convection is greater in non-isothermal condition (Qian and Fan 2006a&b).

Table 4-5. Calculated moisture permeability index (i_m) from the results of experiment thermal insulation and evaporative resistance tests

Sample	Mean R_c	Mean R_e	i_m
1	0.37	137.9	0.164
2	0.45	167.1	0.162
3	0.51	169.7	0.181
4	0.49	208.7	0.142
5	0.39	176.7	0.134
6	0.42	203.8	0.125
7	0.37	158.7	0.142
8	0.49	191.9	0.154
9	0.46	169.4	0.166
10	0.47	179.6	0.160
11	0.38	120.6	0.192

4.5 Concluding remarks

In this chapter, eleven sleeping bags were tested using the manikin under the isothermal condition, namely, both the mean skin temperature of the manikin and that of the environment were controlled to be the same at 35 ◦C, with the wind speed and ambient relative humidity at 0.3 m s^{-1} and 50%, respectively. The results showed that the novel supine sweating fabric manikin is reproducible and accurate in directly measuring the evaporative resistance of sleeping bags, and the measured evaporative resistance can be combined with thermal insulation to calculate the moisture permeability index of sleeping bags.

Chapter 5

Effect of posture positions on the evaporative resistance and thermal insulation of clothing

5.1 Introduction

This chapter reports on a set of the experiments carried out to investigate the effect of posture positions on the evaporative resistance and thermal insulation of clothing.

In this study, a standing sweating fabric manikin Walter (Fan & Chen 2002, Fan & Qian 2004, Wan & Fan 2008) was used to measure the evaporative resistance of clothing directly. Also, the sedentary manikin developed in this study (Wu and Fan 2006) and the supine manikin developed in this study (Wu and Fan 2007 & 2009) were used to measure the evaporative resistance of clothing in sedentary and supine postures, respectively.

5.2 Methods

5.2.1 Samples

Table 5-1 shows the seven selected clothing ensembles used in this study.

Table 5-1. The specification of seven clothing ensembles (sorted by mass)

Clothing Ensemble	Garment	Content	Mass (g)
7	Underpants	100% cotton	94.8
6	Underpants	100% cotton	94.8
	Short pants	100% cotton	264.6
	T-shirt	100% cotton	280.3
2	Underpants	100% cotton	94.8
	Trousers	Shell 100% Nylon; lining 100% Polyester	402.6
	Long sleeves T-shirt	100% cotton	233.1
5	Underpants	100% cotton	94.8
	Trousers	3-layer PTFE membrane	330.69
	Rain coat	3-layer PTFE membrane	569.72
1	Underpants	100% cotton	94.8
	Trousers	60% cotton 40 % Polyester	667.03
	Polo T-shirt	100% cotton	252.3
3	Underpants	100% cotton	94.8
	Trousers	Shell 100% Nylon; lining 100% Polyester	402.6
	Long sleeves T-shirt	100 % Cotton	233.1
	Jacket	Body 80% nylon 20% Polyester; Trim 100% Polyester	833.8
4	Underpants	100% cotton	94.8
	Trousers	Shell 100% polyamide; middle layer 100% polyamide with PTFE membrane; Filling 100% Polyester; Lining 100 % polyamide	1063.6
	Down Jacket	Shell 100% polyamide; middle layer 100% polyamide with PTFE membrane; Filing Goose Lining 100 % polyamide	2199.6

The mass in gram was measured at 35ºC and 50% relative humidity

5.2.2 Determination of thermal insulation and evaporative resistance as well as moisture permeability index

The calculation of thermal insulation (I_t) and evaporative resistance (R_e) are shown in Chapter 3 section 3.2.1 equation (3-9) and equation (3-15), respectively. The determination of moisture permeability index (i_m) defined in Chapter 2 section 2.4.4 equation (2-14).

5.2.3 Equipment

The surface areas of standing, sedentary and supine manikins were 1.79, 1.92 and 1.79 m^2, respectively, whereas the weight of standing, sedentary and supine manikins was 70, 75 and 70 kg, respectively. The detail description of standing manikin can be referred to Chapter 2 section 2.1.4.4. In respect of supine and sedentary, the full descriptions are shown in Chapter 3 section 3.1.

Figure 5-1. The photo of standing, sedentary and supine manikins (from left to right)

5.2.4 Experiment procedures

The thermal insulation and evaporative resistance of clothing ensembles were measured under the following condition and procedures:

(1) All tests were carried out in the climate chamber mentioned in Chapter 4 section 4.2.3.

(2) For measuring the evaporative resistance isothermal condition, the environment temperature, relative humidity and wind speed were set as 35ºC ±0.5, 50% ±3% and 0.3 m s^{-1} ±0.1, respectively, whereas for measuring thermal insulation, the environment temperature, relative humidity and wind speed were set at 12.5ºC ±0.5, 50% ±3% and 0.3 m s^{-1} ±0.1, respectively;

(3) For measuring the evaporative resistance of standing and sedentary postures in non-isothermal condition, the environment temperature, relative humidity and

wind speed were set as 12 ºC ±0.5, 50% ±3% and 0.3 m s^{-1} ±0.1, respectively; The non-isothermal test was used for making comparison between isothermal and non-isothermal tests;

(4) The difference between radiant temperature and environment temperature was less than 0.1ºC;

(5) The manikins were maintained at a constant mean skin temperature of 35 ºC during test;

(6) All samples were hanged in climate chamber for 24 hours before test;

(7) All samples were tested for four times and the samples were put off and put on again between repetitions;

(8) Measurements of thermal insulation and evaporative resistances were only taken after the moisture accumulation rate within the clothing were stabilized. For thermal insulation of clothing ensembles, measurements were taken after at least 8 hours, for measuring the evaporative resistance of clothing ensembles, measurements were taken after at least 12 hours..

(9) The data sampling interval was half minute and the evaporative resistance and thermal insulation were calculated every hour based on 120 data;

(10) With regard to supine manikin test, it was placed horizontally in supine posture

on a 20mm thick artificial wooden ground with an impermeable plastic layer of 1mm in thickness to prevent the moisture penetration into the artificial wooden ground. The artificial wooden ground was located 0.69m above the chamber floor to create an empty space for air flow under the artificial wooden ground. As shown in Figure 5-1 and 4-5, the legs of the manikin were facing the axial fans during testing. Air flowed from manikin legs to the head;

(11) With regard to the sedentary manikin, it was placed on a chair in sitting posture. The face of manikin was facing the nine axial fans. The bottom of manikin feet were touching the ground floor (as shown in Figure 5-1 and 3-2);

(12) The front of standing manikin was facing the axial fans. The manikin was in suspension state without touching the ground floor.

5.3 Results and analysis

Table 5-2 and 5-3 show the results of the thermal insulation (I_t) and evaporative resistance (R_e) of seven clothing ensembles including standing, sedentary and supine postures, respectively.

Table 5-2. Thermal insulation (I_t) (°C m^2 W^{-1}) of seven clothing ensembles

	Standing		Sedentary		Supine	
Sample	I_t	**SD**	I_t	**SD**	I_t	**SD**
Nude*	0.078	0.002	0.117	0.002	0.127	0.001
Clothing Ensemble 7	0.084	0.002	0.118	0.003	0.137	0.001
Clothing Ensemble 6	0.117	0.003	0.157	0.005	0.182	0.001
Clothing Ensemble 2	0.167	0.003	0.196	0.006	0.215	0.004
Clothing Ensemble 5	0.167	0.005	0.198	0.007	0.227	0.002
Clothing Ensemble 1	0.142	0.002	0.183	0.003	0.187	0.001
Clothing Ensemble 3	0.255	0.014	0.263	0.007	0.28	0.002
Clothing Ensemble 4	0.341	0.008	0.418	0.002	0.397	0.008

Testing condition: Environment temperature = 12.5 ºC ±0.5ºC; Relative humidity = 50% ±3%; Wind velocity < 0.3 m s^{-1}; Radiant temperature 12.6 ºC; Mean skin temperature = 35ºC ±0.1ºC;

*Nude The nude value for sedentary manikin test included chair; the nude value for supine manikin test included supportive wooden ground; for sedentary manikin in suspension state without clothing, the It = 0.109 m2 ºC W-1;

SD = Standard deviation

Table 5-3. Evaporative Resistance (R_e) of seven clothing ensembles measured in isothermal condition

	Standing			Sedentary			Supine		
	R_e (Pa m^2 W^{-1})	**SD**	**Water Loss (g h^{-1})**	**R_e (Pa m^2 W^{-1})**	**SD**	**Water Loss (g/h)**	**R_e (Pa m^2 W^{-1})**	**SD**	**Water Loss (g h^{-1})**
Nude*	17.1	0.62	291.8	33.6	0.44	189.2	46.5	0.76	135.6
Clothing Ensemble 7	18.9	0.26	271.2	34.6	0.12	186.2	47.2	1.51	135.1
Clothing Ensemble 6	25.7	0.77	218	43.9	0.65	152.7	64.2	1.34	104.4
Clothing Ensemble 2	38.3	0.34	158.4	51.4	1.23	134.7	72.9	2.26	92.6
Clothing Ensemble 5	58.7	0.58	111.6	70.5	0.63	102.4	102.9	2.14	68.3
Clothing Ensemble 1	35.9	0.06	172.4	48.1	0.97	142.2	69.1	1.61	97
Clothing Ensemble 3	71.7	0.61	94	85.4	0.48	86.4	114.8	0.59	61.3
Clothing Ensemble 4	90.2	1.89	76.7	114.8	1.13	65.8	175.6	3.24	41.4

Testing condition: Environment temperature = 35ºC ±0.5ºC; Relative humidity = 50% ±3%; Wind velocity < 0.3 m s^{-1}; Radiant temperature 35.1 ºC; Mean skin temperature = 35ºC ±0.1ºC;

*Nude The nude value for sedentary manikin test included chair; the nude value for supine manikin test included supportive wooden ground

SD = Standard deviation

5.3.1 Relationship between the thermal insulation of standing and sedentary posture

As shown in Table 5-2, without clothing (naked state), the I_t of sedentary posture or surface air insulation is 0.117 °C m^2 W^{-1}, which is about 50% greater than that of standing position (0.078 °C m^2 W^{-1}). Such difference may be resulted from the additional insulation given by the chair and the reduced convection in the sedentary posture as compared with that in the standing postures, as the sedentary posture creates cavity over the almost horizontal knees and thighs (Nielsen, 1985). Furthermore, at sedentary posture, the radiative heat coefficient would be lower than that of standing posture because of the reduction in radiative body-surface area (Nielsen, 1985).

Table 5-4 lists the nude I_t values of different manikins and human subjects. In the standing posture, the nude I_t of this study is the lowest among the collected data. It is because most of the previous tests were conducted at 20 to 24 ºC environment temperature, but, in the present study, the environment temperature was set at 12.5 ºC. The temperature gradient between manikin skin and the environment could affect the thermal insulation in naked condition because of the effect of surface temperature on natural convection. Fan and Keighley (1991) reported that the surface insulation (nude I_t) in "still" air condition decreases by 25 % with the environment temperature decreasing from 20 to -20 ºC. In addition, wind speed is also an important factor. In the present study, the wind speed in climate chamber is about 0.3 ms^{-1}, which is higher than that in Nielsen et al. (1985)'s work (~ 0.05 m s^{-1}), that in Olesen et al. (1982)'s work (~ 0.05 ms^{-1}) and that in Havenith et al. (1990a)'s work (~ 0.1 m s^{-1}) Furthermore, the I_t of nude standing manikin in the present study was measured by the sweating manikin with simultaneous dry heat loss and perspiration. Qian (2006) reported that the thermal insulation measured on a pure dry thermal manikin is about 2 % higher than that measured on the nude sweating manikin at 20 ºC ambient temperature, 50% relative humidity and 0.22 m s^{-1} wind velocity.

In Figure 5-2, the data of Nielsen et al. (1985) and Havenith et al. (1990a) were measured by human subject tests, whereas the data of Olesen et al. (1982) and our present study were measured by manikin tests. The scatter plot of thermal insulation (I_t) of sedentary posture versus I_t of standing posture (Figure 5-2) indicates a generally linear relationship (R^2 = 0.83, P < 0.0001) between I_t of the standing and that of the sedentary. However, two data from Havenith et al. (1990a) have high deviation from the overall regression line. This may be due to the fact that the clothing ensembles were composed of a coverall worn over the other clothing items. As suggested by Havenith et al. (1990a), a coverall would compress the underlying clothing when sitting more than a two-pieces clothing would do. In addition, chair would add addition thermal insulation to clothing and would compensate certain amount of increased heat loss induced by the compression of clothing. Furthermore, the data of Havenith et al. (1990a) were measured with simple stool having very little insulation. For the data of Nielsen et al. (1985) and Olesen (1982), they were measured by net chairs with up to shoulder backrest (the net chair was constructed in form of horizontal fabric strips and gaps existed between the horizontal fabric strips), which provided higher thermal insulation than the simple stool (backless) since the horizontal fabric strips of net chair with backrest covered more area than the simple stoop. As stated in ISO 9920, office chairs would produce an increase in insulation by about 0.0062 to 0.0264 °C m^2 W^{-1}, depending on the height of backrest and thickness. In the present study, the chair was a normal office chair with soft fixed cushion at bottom and backrest. The backrest height is up to the shoulder in sedentary posture and the thickness of chair was about 75 mm. Therefore, at the same thermal insulation level of standing posture, the thermal insulation of sedentary posture of the present study data are higher than that of other reported data shown in Figure 5-2.

At higher thermal insulation, the overall linear regression line has higher prediction error as shown in Figure 5-2. The thick and bulky clothing in sedentary posture would have extrusion and folding upward at chest area. The additional area gap caused by sedentary posture would provide additional insulation.

Table 5-4. Surface air insulation (I_a) or thermal insulation of naked manikins in standing and sedentary posture

Test method	Source	Standing Posture Nude I_t (°C m^2 W^{-1})	Sedentary Posture Included chair I_t (°C m^2 W^{-1})
Manikin Test	TIAX*	0.129	/
Manikin Test	NCTRF*	0.083	/
Manikin Test	ARIEM 1*	0.111	/
Manikin Test	ARIEM 2*	0.102	/
Manikin Test	NCSU*	0.083	/
Manikin Test	KSU*	0.104	/
Manikin Test	HK*	0.101	/
Manikin Test	McCullough et al. 1989	0.112	/
Manikin Test	Olesen et al. 1982	0.112	0.116
Manikin Test	Havenith et al. 1990	0.113	/
Manikin Test	Nilsson et al. 2000	0.085	/
Manikin Test	Parsons et al. 1999	0.111	/
Manikin Test	ISO 9920	0.109	/
Manikin Test	This study	0.078	0.117
Human Subject Test	Nielsen et al. 1985	0.140	0.152

* The data were collected by (Fan, 2006)

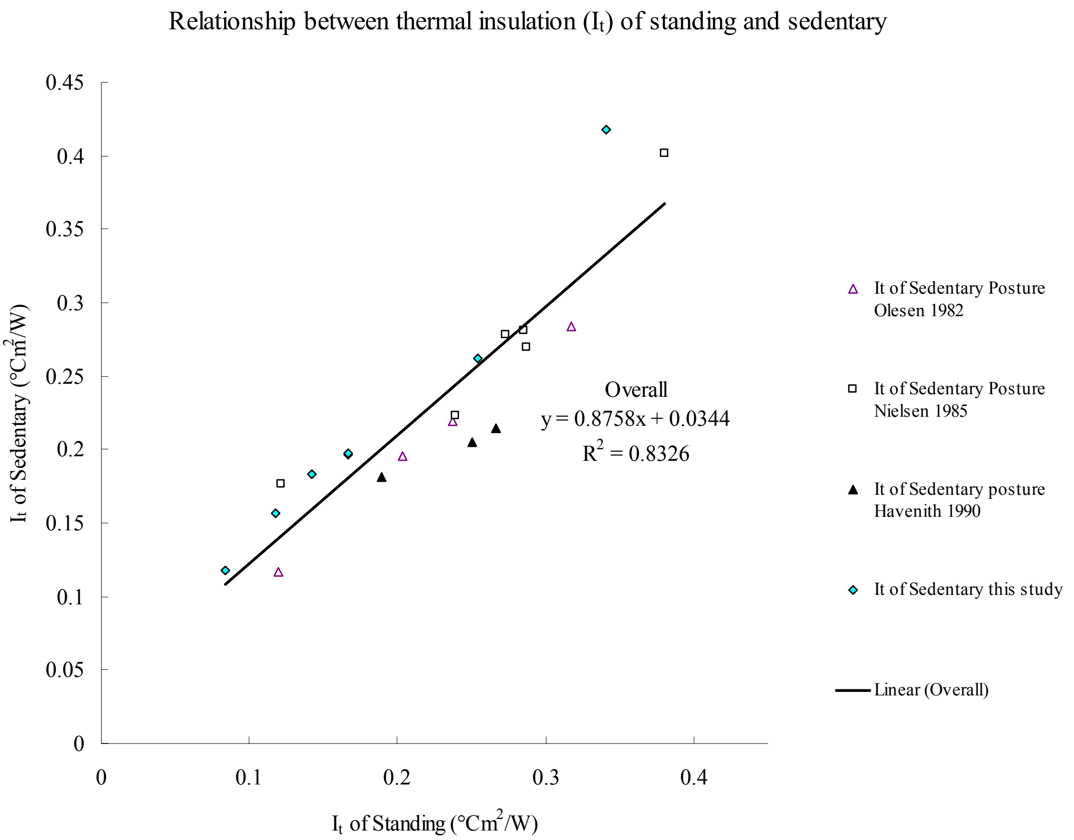


Figure 5-2. Relationship between thermal insulation (I_t) of standing posture and sedentary postures

5.3.2 Relationship between the thermal insulation of standing and supine postures

Figure 5-3 shows the relationship between standing and supine posture in terms of the thermal insulation (I_t). The correlation is high and significant ($R^2 = 0.98$, $P < 0.01$). The relationship can be described by the following linear regression equation:

$$I_t \text{ of supine posture} = 0.0585 + 0.9558 \cdot (I_t \text{ of standing}) \quad (5\text{-}1)$$

From the above regression equation and regression line shown in Figure 5-3, the I_t at supine posture is greater than that at standing posture when the I_t at standing posture is below 0.3 °C m^2 W^{-1}, however the opposite is true when the I_t at standing posture is greater than 0.3 °C m^2 W^{-1}. This is because the wooden frame (or bed) on which the supine posture was laid provides additional insulation, but for thick clothing the reduction of thermal insulation due to compression becomes more dominant.

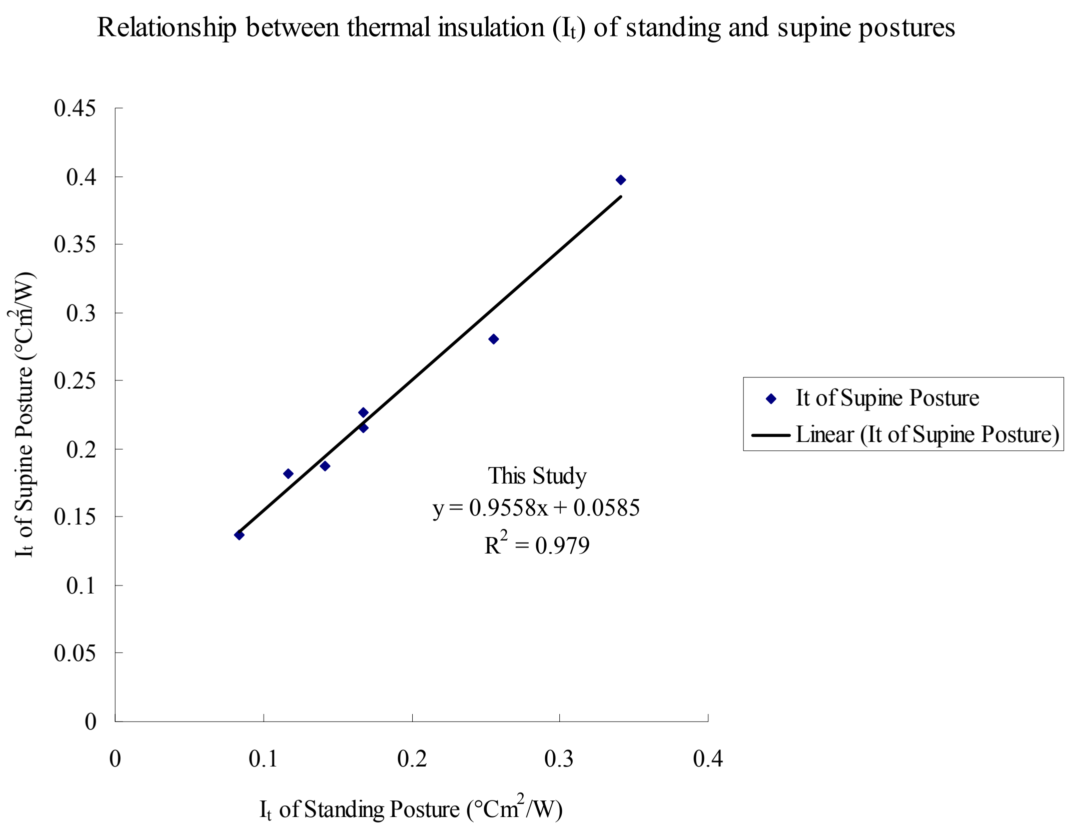


Figure 5-3. Relationship between thermal insulation (I_t) of standing posture and supine posture (°C m^2 W^{-1})

5.3.3 Relationship between the evaporative resistance of standing and sedentary postures

As shown in Figure 5-4, there is a high correlation between evaporative resistance (R_e) of standing posture and R_e of sedentary posture ($R^2 = 0.981$, $P < 0.05$). The relationship can be described by the following linear regression equation:

$$R_e \text{ of Sedentary} = 13.338 + 1.0548 \cdot (R_e \text{ of Standing}) \tag{5-2}$$

Havenith et al. (1990b) reported that the evaporative resistance of sedentary posture was about 16%-38% higher than that of standing. Their finding was based on three samples and the evaporative resistance was measured by an indirect method, i.e. trace gas diffusion on human subjects. In this study, based on more accurate direct measurements using standing and sedentary sweating fabric manikin, we showed that the difference is in the range from 20% to 97%.

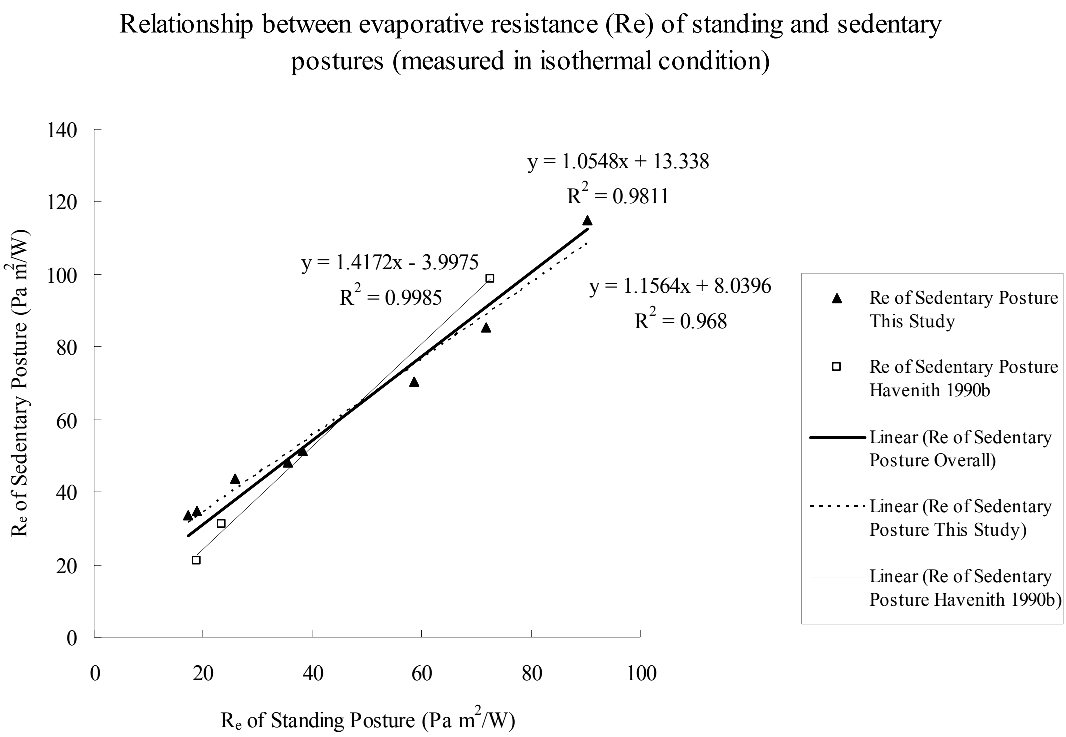


Figure 5-4. Relationship between evaporative resistance (R_e) of standing posture and sedentary posture (Pa m^2 W^{-1})

5.3.4 Relationship between the evaporative resistance of standing and supine postures

The evaporative resistance (R_e) in supine posture has so far not been investigated. Past researches involving a manikin or human subject at supine posture only focused on the condensation effect on thermal insulation (Camenzind et al. 2001, Havenith 2002, Havenith et al. 2004). It is because of the unavoidable huge condensation which made the accurate measurement of evaporative resistance at supine posture extremely difficult. Because of the unique feature of our sweating fabric manikin (i.e. it reduces the perspiration rate with increasing amount of clothing worn), excessive condensation does not occur during testing, which makes accurate measurement of evaporative resistance at supine posture possible. In the present study, seven clothing ensembles were measured in terms of evaporative resistances in isothermal condition. The results are listed in Table 5-3. The nude R_e for supine posture is higher than that of sedentary and standing postures. This is because, in supine posture, around one third of body surface was blocked by the supportive wooden surface with an impermeable layer, which led to substantial increase in evaporative resistance.

The evaporative resistance of supine posture is plotted against that of standing posture in Figure 5-5. Significant linear correlation ($R^2 = 0.946$, $P < 0.05$) can be seen. The relationship can be described by the following linear regression equation:

$$R_e \text{ of Supine} = 13.76 + 1.6232 \cdot (R_e \text{ of Standing}) \qquad (5\text{-}3)$$

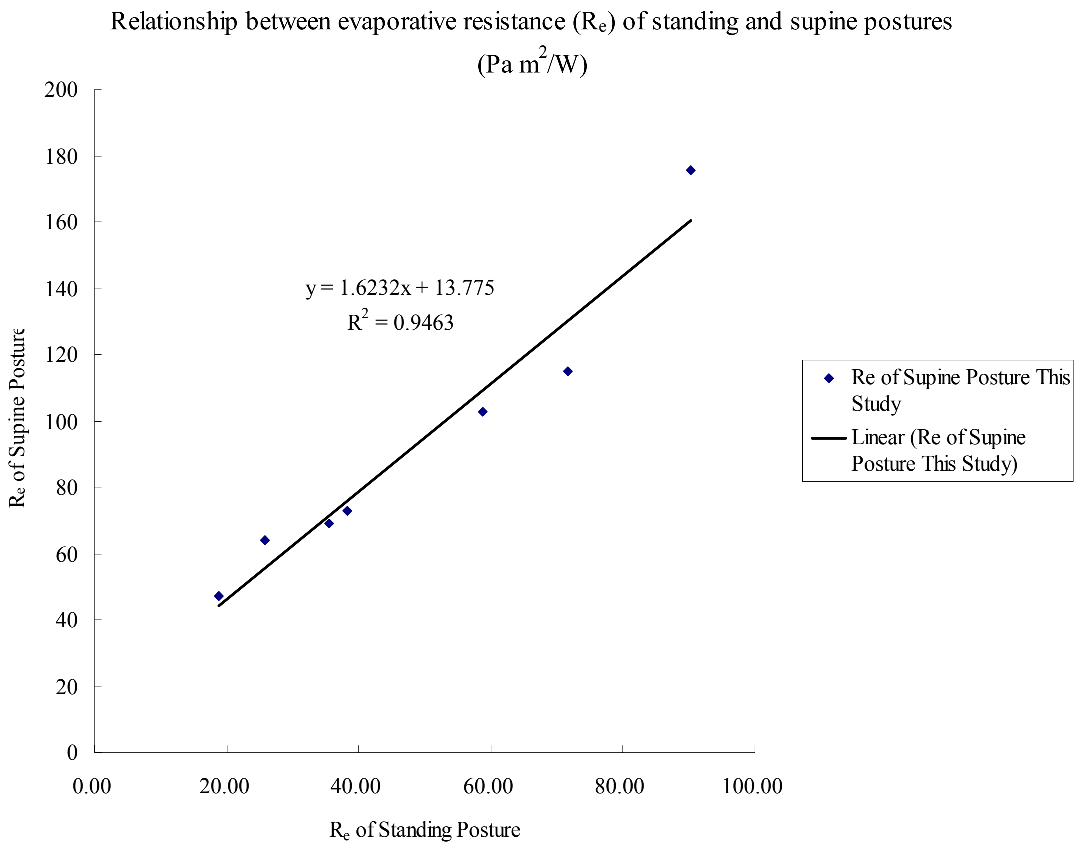


Figure 5-5. Relationship between evaporative resistance (R_e) of standing posture and supine postures (Pa m^2 W^{-1})

5.3.5 Comparison of evaporative resistance measured in isothermal and non-isothermal condition for standing and sedentary posture

Clothing may be worn in non-isothermal conditions, it is therefore necessary to investigate the difference between R_e measured in the isothermal and a non-isothermal condition. Tests were conducted trying to measure the R_e of the 7 clothing ensembles at the environmental temperature of 12.5 °C. However, it was found that it was only possible to measure the R_e of standing and sedentary postures in the non-isothermal condition. Reproducible measurement of R_e at supine posture in the non-isothermal was not possible due to the excessive condensation induced as the back of the supine manikin was in direct contact with the impermeable supportive wooden ground. The results are listed in Table 5-5.

Table 5-5. Evaporative resistance (R_e) of seven clothing ensembles measured in non- isothermal condition (environment temperature = 12.5 °C)

Sample	Standing				Sedentary			
	R_e	SD	Water loss	Moisture vapour accumulation %	R_e	SD	Water loss	Moisture vapour accumulation %
Nude*	9.96	0.26	715.1	-	13.22	0.06	638.7	-
Clothing Ensemble 7	11.45	0.24	646.0	9.68	15.33	0.19	585.0	6.48
Clothing Ensemble 6	18.70	0.49	478.9	12.91	21.14	0.57	467.6	6.88
Clothing Ensemble 2	29.50	0.33	339.4	17.23	28.74	0.56	375.2	8.98
Clothing Ensemble 5	32.38	0.45	318.2	4.09	33.42	0.22	331.8	5.64
Clothing Ensemble 1	24.90	0.14	391.8	14.12	26.45	0.23	399.5	9.93
Clothing Ensemble 3	47.53	0.53	232.1	23.34	44.36	0.33	262.8	30.78
Clothing Ensemble 4	63.49	0.8	181.2	11.85	70.89	0.51	176.6	16.94

Testing condition: Environment temperature = 12ºC ±0.5ºC; Relative humidity = 50% ±3%; Wind velocity < 0.3 m s^{-1}; Radiant temperature 12.1 ºC; Mean skin temperature = 35ºC ±0.1ºC;

*Nude The nude value for sedentary manikin test included chair

Qian and Fan (2006a & 2006b) measured the R_e of 22 clothing ensembles in isothermal and non-isothermal condition using the upright standing manikin and reported that the R_e measured in non-isothermal condition was lower than that in the isothermal condition by 17 to 32%. From the present study, we found that the R_e of standing posture measured in non-isothermal condition was about 30 to 70% lower than that in isothermal condition (See Figure 5-6) and the R_e of sedentary posture measured in non-isothermal condition is about 60 to 150 % lower than that in isothermal condition (See Figure 5-7). The test condition of Qian and Fan (2006a & 2006b) was 20 °C, but the present study was 12.5 °C. A larger temperature gradient caused higher amount of moisture vapour accumulation. In addition, the testing duration of present study was 12 hours, but the testing duration for Qian and Fan (2006a & 2006b) was 5 hours. A longer testing duration would have higher amount of moisture vapour accumulation.

In isothermal condition, the natural convection induced by temperature gradient is much lower than non-isothermal condition. At the same time, the moisture vapour accumulation in isothermal condition is normally very low and close to zero, which is substantially lower than that in non-isothermal condition. In non-isothermal conditions, part of moisture vapour is accumulated in clothing ensemble instead of fully evaporated. It makes the R_e measured in non-isothermal condition apparently lower than that of isothermal condition substantially.

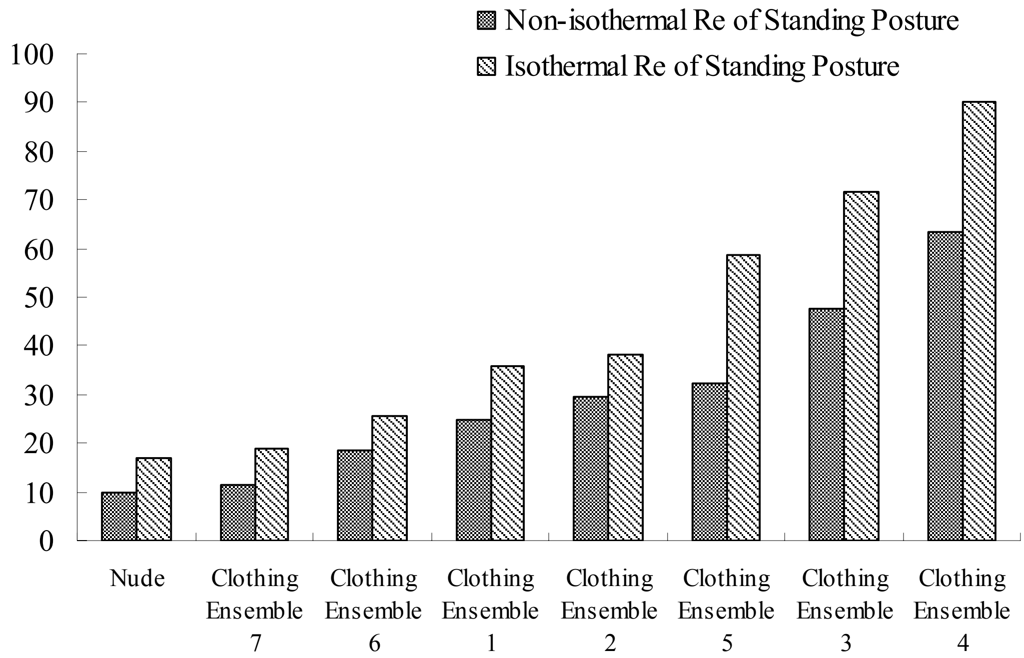


Figure 5-6. Comparison between non-isothermal and isothermal evaporative resistance (R_e) of clothing ensemble in standing posture

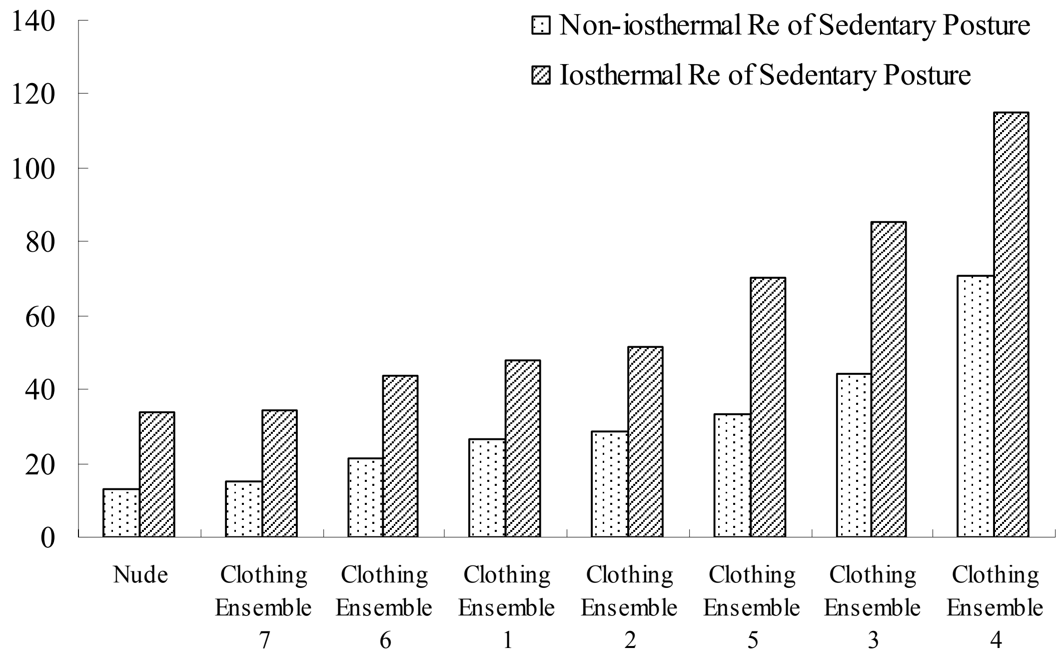


Figure 5-7. Comparison between non-isothermal and isothermal evaporative resistance (R_e) of clothing ensemble in sedentary posture

5.3.6 Comparison of moisture permeability index measured in isothermal and non-isothermal condition for standing and sedentary posture

Table 5-6 compares the moisture permeability indices (i_m) calculated based on the evaporated resistance measured in the isothermal condition and those in the non-isothermal condition. As can be seen, the i_m of standing and sedentary postures measured in non-isothermal condition are greater than those of isothermal condition by 22-56%. Such differences are obviously due to the differences in moisture vapour resistance (R_e) measured in the non-isothermal and isothermal condition, which have been discussed in previous section. The differences are greater for the sedentary posture, as the chair not only leads to an increase in evaporated resistance (R_e), but also induces a significant greater increase in moisture accumulation or condensation in non-isothermal condition.

Table 5-6. Moisture permeability indices of standing, sedentary and supine postures for the seven clothing ensembles calculated from the R_e measured in isothermal condition

	Isothermal Condition		**Non-isothermal Condition**	
sample	**i_m of standing posture (35 °C)**	**i_m of sedentary posture (35 °C)**	**i_m of standing posture (12 °C)**	**i_m of sedentary posture (12.5 °C)**
Clothing Ensemble 7	0.270	0.207	0.446	0.467
Clothing Ensemble 6	0.276	0.217	0.380	0.450
Clothing Ensemble 2	0.264	0.231	0.343	0.414
Clothing Ensemble 5	0.172	0.170	0.313	0.359
Clothing Ensemble 1	0.240	0.231	0.346	0.420
Clothing Ensemble 3	0.215	0.186	0.324	0.359
Clothing Ensemble 4	0.229	0.221	0.325	0.357

Testing condition: (Isothermal Condition) environment temperature = 35 ºC ±0.5ºC;
(Non-isothermal Condition) = 12.5 ºC ±0.5ºC;
Relative humidity = 50% ±3%; Wind velocity < 0.3 m s^{-1}; Mean skin temperature = 35ºC ±0.1ºC;

SD = Standard deviation

Figure 5-8 is the comparison of i_m of standing posture and sedentary posture in isothermal condition, and Figure 5-9 is the comparison of i_m of standing posture and sedentary posture in non-isothermal condition.

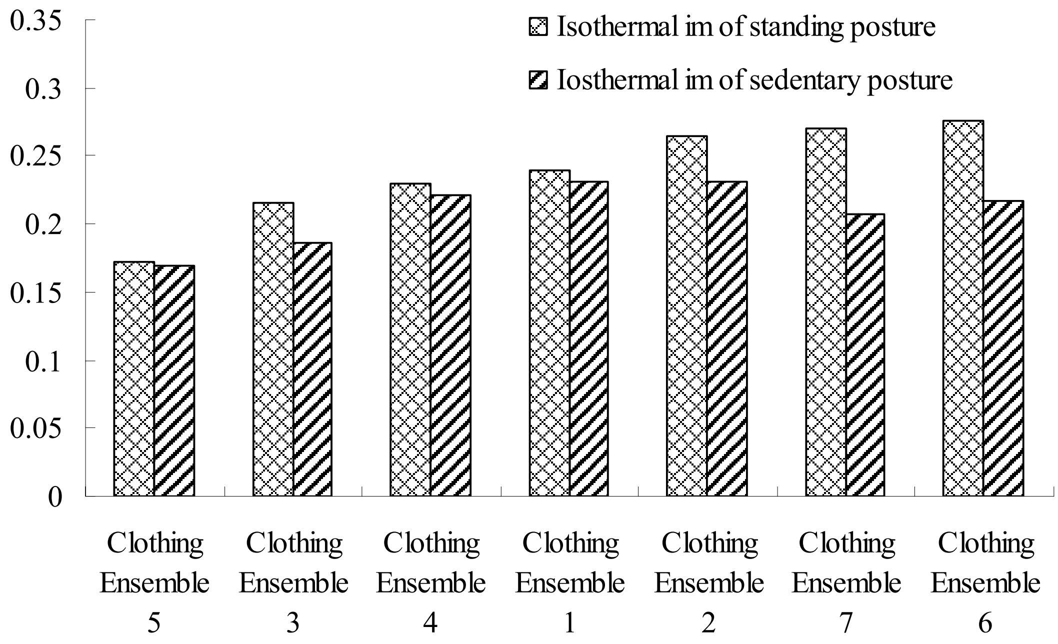


Figure 5-8. Comparison of moisture permeability index (i_m) of standing and sedentary posture in isothermal condition

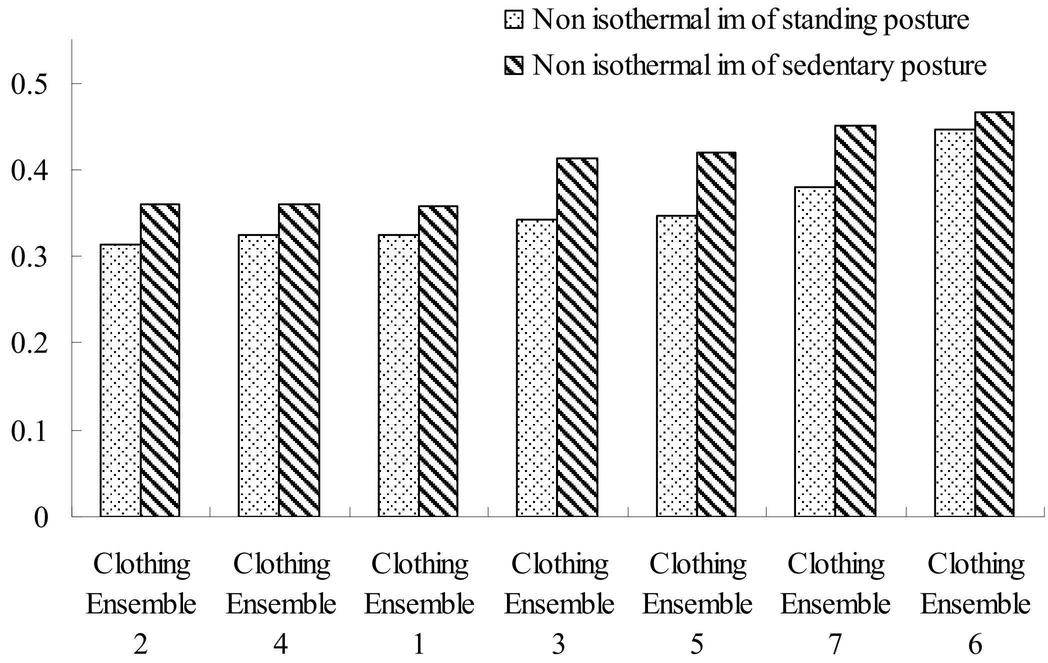


Figure 5-9. Comparison of moisture permeability index (i_m) of standing and sedentary posture in non-isothermal condition

5.3.7 Comparison of heat loss and mass loss methods

The data reported in the previous sections are measured using the mass loss method, i.e. the evaporative heat loss was calculated from the water loss multiplying the heat of evaporation. However, actual evaporative heat loss may be slightly different due to the moisture accumulation within clothing as a result of moisture absorption or condensation. Figure 5-10 and 5-11 plot the typical weight changes of clothing (due to moisture accumulation) for a light weight and heavy weight clothing ensemble, respectively, under the non-isothermal condition (12.5ºC ±0.5ºC; Relative humidity =

50% ±3%). As can been seen, the weight increase of clothing (or moisture accumulation) is the highest at the beginning and then become more gradual. For light weight and permeable garments, moisture accumulation rate after 6 hours stabilized at about 0.2% of water loss per hour. For heavy clothing in non-isothermal condition, as shown in Figure 5-11, moisture accumulation rate after 8 hours stabilized at about 6% of water loss per hour.

To obtain accurate results, it is therefore essential to take the measurements under the condition that minimum moisture absorption or condensation takes place and after a sufficient stabilization period. In this work, the rate of mass loss was only measured after 12 hours of stabilization in an isothermal condition (viz. 35 ºC ±0.5ºC; 50% ±3% RH).

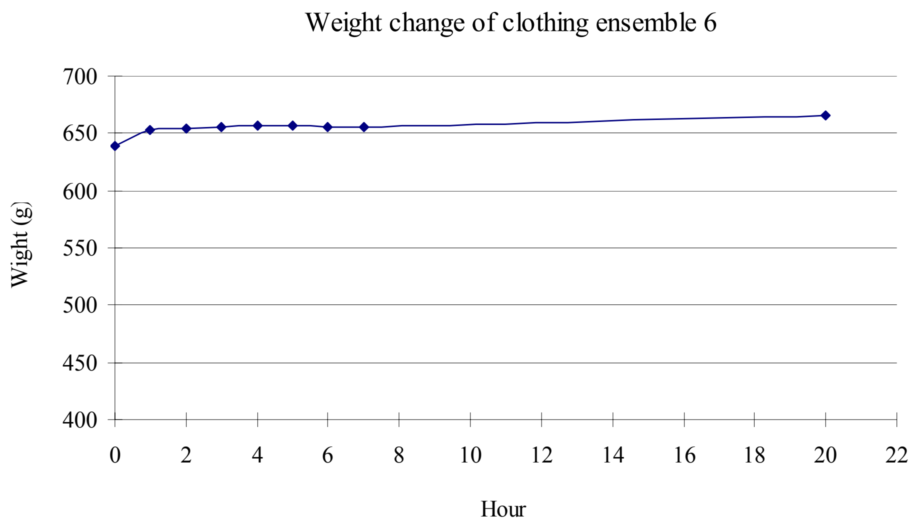


Figure 5-10. Weight change of light weight garment

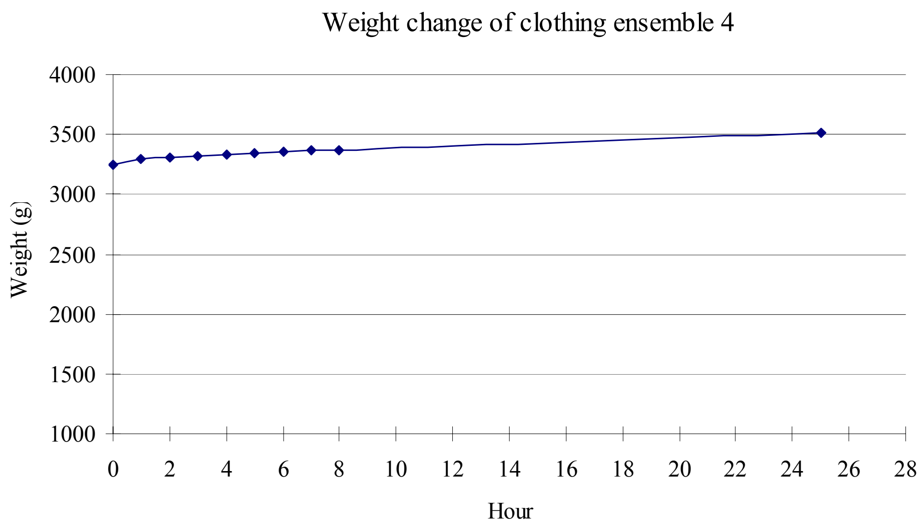


Figure 5-11. Weight change of heavy weight garment

Many other manikins measure the evaporative resistance based on the heat loss method. The heat loss method also has its inherent problem as the heat released from the moisture absorption and condensation can influence the measured evaporative heat. However, it is useful to compare the evaporative resistance measured by the two methods. Table 5-7 and 5-8 list the evaporative resistance values of 7 clothing ensembles measured by the two methods at standing and sedentary posture, respectively, under the isothermal condition. As can be seen, at the standing posture, the difference is very small and even negligible for light weight, thin and permeable clothing (clothing ensemble 7, 6 and 1). However, for heavy and thick clothing (clothing ensemble 4), the difference is up to 11.8%. For the heavy, thick or highly impermeable garment, moisture vapour adsorption (or condensation) would take place even in isothermal condition. Since part of water loss from manikin was adsorbed by the garment instead of released to environment, the evaporative heat loss measured by mass loss method would be higher than the heat loss method and this is consistent with the finding of the past work by Havenith et al. (2008a), who concluded that mass loss method can lead to overestimate of evaporative heat loss in hot environment.

For sedentary posture, as shown in Table 10, the evaporative resistance measured by mass loss method is lower than that measured by heat loss method for all the samples.

The difference is there even for light weight, thin and permeable clothing such as clothing ensemble 7, 6 and 1, it is because the chair not only serves as an additional barrier, but also adsorbs certain amount of moisture vapour. Havenith et al. (2008a) reported that mass loss method can lead to large underestimation of evaporative heat loss in cold environment. The difference ranged from +30% to -38%. For impermeable garments, Havenith et al. (2008b) reported that the difference between mass loss and heat loss method could be more than 100 % in low temperature environment. Since Havenith et al (2008b)'s tests did not have a prolonged stabilization period, the clothing may not be fully saturated with moisture vapour, the difference found by Havenith et al (2008b) would be greater than ours. In this research, the testing duration was more than 12 hours, which can allow the clothing ensemble fully saturated with moisture vapour.

Table 5-7. Heat loss and mass lost methods in isothermal condition for standing posture

Standing manikin	R_e (Pa m^2 W^{-1}) Isothermal test heat loss method	R_e (Pa m^2 W^{-1}) Isothermal test mass loss method	I_t (m^2 °C W^{-1}) (non-sweating manikin)	i_m heat loss method	i_m mass loss method
Clothing ensemble 7	18.71	18.9	0.089	0.289	0.270
Clothing ensemble 6	25.57	25.7	0.119	0.281	0.276
Clothing ensemble 2	39.54	38.3	0.181	0.278	0.264
Clothing ensemble 5	60.24	58.7	0.184	0.185	0.172
Clothing ensemble 1	35.76	35.9	0.163	0.276	0.240
Clothing ensemble 3	68.69	71.7	0.263	0.232	0.215
Clothing ensemble 4	100.81	90.2	0.381	0.229	0.229

Table 5-8. Heat loss and mass lost methods in isothermal condition for sedentary posture

Sedentary posture	R_e (Pa m^2 W^{-1}) Isothermal test heat loss method	R_e (Pa m^2 W^{-1}) Isothermal test mass loss method	I_t (m^2 °C W^{-1}) (non-sweating manikin)
Clothing ensemble 7	37.932	34.6	0.130
Clothing ensemble 6	45.971	43.9	0.163
Clothing ensemble 2	55.411	51.4	0.207
Clothing ensemble 5	71.861	70.5	0.213
Clothing ensemble 1	51.167	48.1	0.189
Clothing ensemble 3	85.892	85.4	0.284
Clothing ensemble 4	125.48	114.8	0.393

5.4 Concluding remarks

This chapter presents original data on the effect of postures on the evaporative resistance of clothing, thermal insulation and permeability index, based on the measurements under three postures, viz. standing, sedentary and supine. Regression models are also established to predict the evaporative resistance and thermal insulation of clothing under sedentary and supine postures from those under standing posture with high coefficients of correlations. In addition, this study further showed that the apparent evaporated resistances of standing and sedentary posture measured in non-isothermal condition are much lower than those in the isothermal condition because of greater condensation in non-isothermal condition, and the apparent evaporative resistances measured using the mass loss method are generally lower than those measured using the heat loss method due to moisture absorption or condensation within clothing.

Chapter 6

Conclusions and Recommendations for Further Work

6.1 Conclusions

6.1.1 Uniqueness of sweating rate measurement

In this study, a unique direct sweating measuring system was developed (Figure 3-8 in Chapter 3). The system can monitor the sweating quantity in real time manner. It avoided the needs of measuring the total weight of manikin such as the Coppelius method mentioned in Chapter 2.1.4.1.

6.1.2 Uniqueness of sweating fabric skins of supine and sedentary manikins

In this study, two unique water vapour permeable fabric skins were developed to simulate sweating and for the formation of supine and sedentary postures by changing sweating fabric skins. This research filled the technological gap by developed a sweating fabric manikin with supine and sedentary postures with high reproducibility for thermal insulation and evaporative resistance measurements. .

6.1.3 Testing protocol for the measurement of evaporative resistance of sleeping bags

In this study, a testing protocol for the measurement of evaporative resistance of sleeping bags was established. The isothermal testing method was adopted because it can avoid excessive condensation. From experiments, it was found that measurements should be taken after covering the manikin with the sleeping bag for at least 7 h to allow sufficient time for the sleeping bag to reach saturation in moisture absorption. The details of testing protocol are shown in Chapter 4 section 4.2.4.

6.1.4 Effect of material properties on the thermal insulation and evaporative resistance of sleeping bag tests

This study showed that, while thermal insulation may be highly related to the mass of the sleeping bags for the same design and same type of filling materials, the evaporative resistances of the sleeping bags are only weakly related to their mass. Evaporative resistance of the sleeping bag is highly related to the water vapour permeability of the shell fabrics and the overall thickness of sleeping bags. This study further showed that the moisture permeability index of sleeping bags are between 0.1

and 0.2, much smaller than those of clothing worn at the upright position, probably because the impermeable supporting ground creates additional evaporative resistance.

6.1.5 The effect of posture positions on clothing thermal insulation and evaporative resistance

In this study, the influence of postures on the evaporative resistance and thermal insulation are quantified by regression models. They are useful for predicting the thermal insulation and evaporative resistance in supine and sedentary posture by the results of standing posture. They are also useful for researchers to verify their thermal comfort modeling in difference postures.

The present study also showed that the apparent evaporated resistances (R_e) of standing and sedentary posture in non-isothermal condition are much lower than those in the isothermal condition. This is mainly caused by the greater moisture accumulation or condensation in non-isothermal condition.

6.2 Recommendations for further work

Firstly, human subject test for sleeping bag would be an important and interesting topic for further work in future. In the existing EN 13537 standard, the temperature labels for extreme, comfort and limit are based on human subject tests and non-sweating manikin measurements. Evaporative resistance measurement using sweating supine manikin is not considered in the standard. Therefore, human subject test and sweating supine manikin measurement can help to improve the existing EN 13537 sleeping bag standard.

Secondly, modeling of dry and wet heat exchange in different postures also would be a useful and interesting topic for further work. Havenith et al. (2008) investigated the differences between mass loss and power loss method for calculating evaporative heat loss in standing posture and showed a model for illustrating the differences. However, there is still room for development of models in supine and sedentary postures.

Thirdly, it is also very interesting and meaningful in the future to investigate the difference between heat loss and mass loss methods during initial moisture adsorption and saturated period at subzero, mild and hot environment temperature.

Fourthly, for the thermal comfort evaluation of sleeping bag, the effect of the construction techniques of sleeping bags is not investigated in this study. Sleeping bag construction techniques such as quilted through, box baffling and edged-stabilized method would affect the evaporative resistance of sleeping bag to a certain extent. It would an interesting topic for research in future.

Fifthly, for manikin skin area measurement, this study used area to weight method to calculate the total surface area of manikin and the area of different parts by measuring the weight of patterns pieces. Because of lack of resources and equipment, this study cannot use three-dimensional laser scanner to measure the surface area of manikin. In future, it is recommended to use three-dimensional laser scanner to measure the surface area of manikin for further verification of the measurement of manikin surface area.

Sixthly, in terms of sweating simulation, this study focused on the uniform sweating over whole manikin body. In future, non-uniform sweating simulation over manikin body would be an interesting research topic for simulating realistic human sweating distribution.

Lastly, the evaporative resistance of supine manikin in non-isothermal condition is not investigated in this study. This is because there is excessive condensation in non isothermal condition, which makes measurement difficult. It is interesting in the future to study the heat and mass transfer in a more realistic non isothermal condition (such as subzero ambient temperature). It would be preferable to develop a manikin skin simulating insensible perspiration, which would allow direct measurement of heat loss and mass loss.

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