# Investigation into the Dynamic Heat and Moisture Transfer through Clothing Systems Using a Perspiring Fabric Manikin

**Xianfu WAN**

**Ph.D.**

**The Hong Kong Polytechnic University**

**2008**

**The Hong Kong Polytechnic University**

**Institute of Textiles and Clothing**

# Investigation into the Dynamic Heat and Moisture Transfer through Clothing Systems Using a Perspiring Fabric Manikin

**Xianfu WAN**

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

**11/2007**

# 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.

______________________

**Xianfu WAN**

# Abstract

Clothing thermal comfort is not only important to survival for people in extreme environments, but also important to improve the living condition in every day life. Thermal comfort should be considered in two related aspects: thermal comfort under steady-state conditions and thermal comfort under transient conditions. Considerable research work has been or is being carried out on clothing thermal comfort under steady-state conditions. Comparatively, little work has been reported on the transient heat and moisture transfer through actual clothing ensembles, although some work is reported on the transient heat and moisture transfer through clothing materials or assemblies. Attempts had been made to establish models for estimating thermal transient comfort, these models however included either the steady-state properties of clothing ensembles, viz. clothing thermal insulation and moisture vapour resistance, or the dynamic heat and moisture transfer through layered fabrics, but not the dynamic behaviour of real clothing ensembles. Clothing properties specific to transient conditions should be defined and investigated.

In this study, a new transient thermal model, integrating the dynamic heat and moisture transfer through clothing as well as the two-node human physiological model, is proposed to predict the human physiological responses. The model considered clothing ventilation and moisture accumulation on the surface of the skin and inner surface of the underwear. The numerical results of the model are validated with a set of previously published experimental data and another set of

data obtained from current experimental investigation. Very good agreement was found. The model has also been applied to better understand the complex interaction of the various human, clothing and environmental factors and their effects on the human thermal physiological response.

In order to quantify the dynamic thermal properties of clothing using the sweating fabric manikin-Walter, a novel test method has also been developed and an associated index was proposed in this test method, the sweating manikin was used to simulate human body's experience in the thermal transient changing from resting to exercising. The average changing rate of mean skin temperature of the manikin in the first hour of simulated 'exercise' ($STCR$) was taken as an index to provide a measure of the dynamic thermal properties of clothing ensembles.

Seven clothing ensembles (Five of them consists of sports T-shirts made of different fabrics and the same shorts; one consists of a business suit, long-sleeve underwear, shorts and long trousers; another consists of a coat long-sleeve underwear, shorts and long trousers) were tested repeatedly on the sweating fabric manikin according to the proposed test procedure. The tests showed good precision and reproducibility. The coefficient of variation is generally less than 4%.

It was further found that the index $STCR$ was significantly different among the four clothing ensembles consisting of sports T-shirts made of different fabrics and the same shorts, despite of the fact that the thermal insulation and water vapour resistance of the four clothing ensembles are very close. On the other hand, although the thermal insulation and water vapour resistance of the clothing ensemble with a business suit and a coat are very different from those of the clothing ensemble with two sports T-shirt, their *STCR* values are very close. Through the theoretical analysis of the dynamic heat and moisture transfer within the clothing-manikin-environment system, it becomes clear that *STCR* is an integrated parameter which reflects the dynamic heat and moisture transfer through clothing ensembles during the thermal transients from standing to walking.

Human physiological experiments were also conducted to investigate the relationship between the new index measured from the manikin tests and the physiological responses in terms of changes of body temperature. The present study showed that a test method can be developed based on the sweating fabric manikin-Walter to provide an objective measure of such dynamic properties.

From the present study, it was shown that the changing rate of the mean skin temperature of the clothed manikin-Walter when changing from the “resting” to “exercising” mode is related to the changing rate of the body temperature of a wearer wearing the same type of clothing and undergoing a similar change of body activities, it is therefore reasonable to use the changing rate of the mean skin temperature of the clothed manikin-Walter as an objective index for quantifying the dynamic thermal properties of clothing ensembles. The use of the objective index from tests on the sweating manikin-Walter is clearly advantageous, since tests involving human subjects are time consuming, expensive and poor in reproducibility.

A higher value of the index means faster rate of change of body temperature, and shorter duration before the wearer approaching a dangerous thermo-physiological state. Clothing should therefore be designed to reduce the value of the index.

# Publications arising from the thesis

## Journal Papers

Wan, X., Fan, J., 2008, A transient thermal model of the human body-clothing-environment system, Journal of thermal biology, 33(2), 87-97.

Wan, X., Fan, J., 2008, A novel test method for measuring the thermal properties of clothing ensembles under dynamic conditions, submitted to Measurement Science and Technology, 19(6).

Kar, F., Fan, J., Yu, W., Wan, X., 2007, Effects of thermal and moisture transport properties of T-shirts on wearer's comfort sensations, Fibers and Polymers, 8(5), 537-542.

## Conference Papers

Wan, X., Fan, J., 2005, A human-clothing-environment system model for simulating dynamic thermal process during human exercise, The 9th World Multi-Conferentce on Systemics, Cybernetics and Informatics (WMSI), Orlando, USA.

Wan, X., Fan, J., 2006, A transient thermal model of the human-clothing-environment system, The 3rd European conference on Protective Clothing (ECPC) and NOKOBETEF 8. Gdynia, Poland.

# Acknowledgements

This project was funded by the Research Grant Council of HKSAR through a CERG project awarded to my chief supervisor Prof. Jintu Fan.

I would like to express my deepest gratitude and appreciation to my supervisor, Prof. Jintu Fan, for his excellent guidance and patient support throughout this research. During the progress of this research, I encountered many difficulties which I don't know the way out. Fortunately, every time Prof. Fan patiently encouraged me and provided me creative ideas and professional advice. Without him this project can not possibly be accomplished.

Special thanks are also due to Prof. Xiaoming Qian for his advice and encouragement, to Prof. Hiromi Tokura for his advice in wearer trials.

Sincere appreciation is due to Mr. Yuen Shing John Wu for his help in the maintenance and improvement of the sweating manikin-Walter, to Tai On Machinery Metal Factory for the assistance in the construction of the mechanical parts of the manikin.

Many thanks also to Dr. Ning Du for his advice in mathematic modeling.

Finally, I would like to thank my family and friends for their love and encouragement throughout this research.

# Contents

# List of Figures

# List of Tables

# Nomenclatures

$a$ ratio of counter-current heat exchange

$A$ cross sectional area that the thermal energy or mass passes through (m$^2$)

$A_{Du}$ surface area of whole body (m$^2$)

$A_{Du,i}$ surface area of segment i (m$^2$)

$A_{Du,f}$ total surface area of the covered body parts (m$^2$)

$A_s$ surface area of the clothing assembly (m$^2$)

$BF_{i,j}$ blood flow rate (l h$^{-1}$)

$BFB_{i,j}$ basal blood flow rate (l h$^{-1}$)

$C$ water vapour concentration (Kg m$^{-3}$)

$C^*(T)$ saturated water vapour concentration at temperature $T$ (Kg m$^{-3}$)

$C_a$ moisture vapour concentration of environment (Kg m$^{-3}$)

$C_{ch}$ shivering control coefficient for core layer of head segment (W)

$C_{dl}$ vasodilation control coefficient for core layer of head segment (W ℃$^{-1}$)

$C_{d,i,j}$ thermal conductance between node (i, j) and its neighbor (W ℃$^{-1}$ )

$C_f$ moisture concentration in the fiber (Kg m$^{-3}$)

$C_{mc}$ moisture vapour concentration within the clothing microclimate (Kg m$^{-3}$)

$C_{mc,i}$ water vapour concentration in microclimate (i) (Kg m$^{-3}$)

$C_s$ moisture concentration at the surface (Kg m$^{-3}$)

$C_{st}$ vasoconstriction control coefficient for core layer of head segment (l ℃$^{-1}$)

$C_{sw}$ sweat control coefficient for core layer of head segment (W ℃$^{-1}$)

$C_{\infty}$ moisture concentration at the fluid (Kg m$^{-3}$)

$Chilf_i$ distribution coefficient of individual muscle layer for the shivering heat production

$Cld_{i,j}$ cold signal (℃)

$Clds$ integrated cold signal (℃)

$Cp_{b,h}$ specific heat capacity of human body (J Kg$^{-1}$ ℃$^{-1}$)

$Cp_{b,m}$ specific heat capacity of manikin Walter (J Kg$^{-1}$ ℃$^{-1}$)

$Cp_{blood}$ heat capacity of blood (W h ℃$^{-1}$)

$Cp_{cl,i,k}$ specific heat capacity of fabric layer (i, j) (J Kg$^{-1}$ ℃$^{-1}$)

$Cp_f$ specific heat capacity of the fibers (J Kg$^{-1}$ ℃$^{-1}$)

$Cp_{i,j}$ heat capacity of body node (i, j) (W h ℃$^{-1}$)

$Cp_l$ specific heat capacity of water (J Kg$^{-1}$ ℃$^{-1}$)

$Cv_a$ volume heat capacity of air (J m$^{-3}$ ℃$^{-1}$)

$Cv_{blood}$ volumetric specific heat of blood (W h l$^{-1}$ ℃$^{-1}$)

$D_a$ diffusion coefficient of water vapor in the air (m$^2$ s$^{-1}$)

$D_{eff}$ effective diffusion coefficient of water vapour in the fabric (m$^2$ s$^{-1}$)

$D_f$ diffusion coefficient of moisture in the fiber (m$^2$ s$^{-1}$)

$D_l$ diffusion coefficient of liquid water (m$^2$ s$^{-1}$)

$DL$ vasodilation signal (l h$^{-1}$)

$DTS$ dynamic thermal sensation in Fiala's model

$d_c$ effective radius of the capillaries (m)

$E$ condensation or evaporation coefficient ($5 \times 10^{-3}$)

$E_{\max}$ evaporation rate when the skin completely covered with sweat for the given conditions (W m$^{-2}$)

$ET^*$ effective temperature proposed by Gagge (℃)

$Err_{i,j}$ error signal in body node (i, j) (℃)

$F_1$ thermal sensation of sedentary subjects

$F_2$ thermal sensation of exercising subjects

$F_3$ dynamic components of sensation of cooling caused by skin and core temperature drop

$F_3^{'}$ dynamic components of sensation caused by skin cooling

$F_4$ dynamic components of sensation of warming caused by skin and core temperature rising

$F_4^{'}$ dynamic components of sensation due to skin warming

$f$ fraction by volume of the fabric taken up by fiber

$f_a$ volume fraction of void space in the fabric

$f_{cl}$ clothing area factor

$f_l$ fraction by volume of the fabric taken up by water

$f_{op}$ apparent portion of the surface area $A_s$ that is open to the air-flow

$f_x$ effective fractions of fibers parallel to the direction of heat flow

$f_y$ effective fractions of fibers perpendicular to the direction of heat flow

$H_0$ internal heat production inside the manikin body during the standing period (W $m^{-2}$)

$H_h$ heat production within the human body (W $m^{-2}$)

$H_{h,i,j}$ the rate of internal heat production in body node (i, j) (W)

$H_m$ heat production inside Walter's body, including the heat produced by heaters and pumps (W $m^{-2}$)

$HR$ heart rate (beat $min^{-1}$)

$h$ convection heat transfer coefficient (W $m^{-2}$ ℃$^{-1}$)

$h_c$ convective heat transfer coefficient at the skin surface or the inner surface of the fabric layer (W $m^{-2}$ ℃$^{-1}$)

$h_{coa}$ convective heat transfer coefficient at the outer surface of clothed body (W $m^{-2}$ ℃$^{-1}$)

$h_e$ evaporative heat transfer coefficient at the outer surface of clothed body (W $Pa^{-1}$ $m^{-2}$)

$h_m$ convective mass transfer coefficient at the skin surface or the inner surface of the fabric layer (Kg $Pa^{-1}$ $m^{-2}$ $s^{-1}$)

$h_{moist}$ moisture convective transfer coefficient (m $s^{-1}$)

$h_r$ radiative heat transfer coefficient (W $m^{-2}$ ℃$^{-1}$)

$h_{toa}$ overall heat transfer coefficient at the outer surface of clothed body (W $m^{-2}$ ℃$^{-1}$)

$i_m$ water vapour permeability of clothing

$K$ thermal conductivity (W $m^{-1}$ ℃$^{-1}$)

$K_a$ thermal conductivity of air (W $m^{-1}$ ℃$^{-1}$)

$K_{dry}$ thermal conductivity for dry fabric (W $m^{-1}$ ℃$^{-1}$)

$K_f$ thermal conductivity of fibers (W m$^{-1}$ ℃$^{-1}$)

$K_l$ thermal conductivity of liquid water (W m$^{-1}$ ℃$^{-1}$)

$K_{moist}$ thermal conductivity of the moist fabric (W m$^{-1}$ ℃$^{-1}$)

$K_r$ thermal conductivity due to radiation (W m$^{-1}$ K$^{-1}$)

$KV$ dimensionless coefficient of clothing system for ventilation

$KVI$ constant for calculation of heat taken by ventilation

$KVR$ constant for calculation of moisture taken by ventilation

$LR$ Lewis number

$M_{b,h}$ mass of human body per unit surface area (Kg m$^{-2}$)

$M_{b,m}$ mass of manikin Walter (Kg m$^{-2}$)

$M_{cl}$ mass of clothing (Kg m$^{-2}$)

$M_{cl,i,k}$ mass of fabric (i, k) (Kg m$^{-2}$)

$M_{clw,i,k}$ mass of moisture within fabric (i, k) (Kg m$^{-2}$)

$M_{f,i,k}$ mass of fibers within fabric (i, k) (Kg m$^{-2}$)

$M_{\max,i,k}$ maximum quantity of water per unit fabric area that can be present as vapour in fabric (i, k) (Kg m$^{-2}$)

$M_{swa,i}$ sweat accumulation on the skin per unit body surface area (Kg m$^{-2}$)

$M_w$ molecular mass of the water vapour (1.8015×10-2 Kg mol$^{-1}$)

$Met$ metabolic rate (W m$^{-2}$)

$Met_b$ basal metabolic rate of whole body (W m$^{-2}$)

$Met_{b,i,j}$ basal metabolic rate in body node (i, j) (W)

$Metf_i$ distribution coefficient of musle layer for heat production due to external work

$Met_{shiv}$ metabolic heat energy due to shivering (W $m^{-2}$)

$Met_{shiv,i,j}$ shivering heat production in body note (i, j) (W)

$m$ permeation coefficient of the skin (Kg $Pa^{-1}$ $m^{-2}$ )

$m_c$ condensation/evaporation rate (Kg $s^{-1}$)

$m_{conv}$ rate of moisture convection (Kg $s^{-1}$)

$m_{diff}$ moisture transmitted through the void space of the fabric (Kg $s^{-1}$)

$m_{l,i,k}$ liquid water flux from fabric (i, k) to fabric (i, k+1) (Kg $m^{-2}$ $s^{-1}$)

$m_{rsw,i}$ regulatory sweating per unit body surface area (Kg $m^{-2}$ $s^{-1}$)

$m_s$ mass flux of sweat absorbed from the skin surface by the inside surface of the fabric (Kg $m^{-2}$ $s^{-1}$)

$m_{vent}$ moisture transfer by wind penetration and ventilation (Kg $m^{-2}$ $s^{-1}$)

$m_{vent,i}$ moisture flux taken by ventilation (Kg $m^{-2}$ $s^{-1}$)

$m_w$ moisture flux due to wicking (Kg $m^{-2}$ $s^{-1}$)

$n$ total number of fabric layers

$P_a$ water vapour pressure in environment (Pa)

$P_c$ capillary pressure (Pa)

$P_{ch}$ shivering control coefficient for core layer and skin layer of each segment (W ℃$^{-2}$)

$P_{cl,i,k}$ water vapour pressure in fabric (i, k) (Pa)

$P_{dl}$ vasodilation control coefficient for core layer and skin layer of each segment (l $h^{-1}$ $K^{-2}$)

$P_{mc,i}$ water vapour pressure of microclimate in part (i) (Pa)

$P_s(T)$ saturated vapour pressure at temperature $T$ (Pa)

$P_{sk}$ water vapour pressure at skin surface (Pa)

$P_{sk,i}$ water vapour pressure on the skin surface in body part (i) (Pa)

$P_{st}$ vaconstriction control coefficient for core layer and skin layer of each segment (l $h^{-1}$ $K^{-2}$)

$P_{sw}$ sweat control coefficient for signals from core layer of head segment and skin layer of each segment (W $K^{-2}$)

$PMV$ PMV Predicted Mean Vote in Fanger's PMV model

$PMV^*$ Gagge's PMV* index

$Q_{b,i,j}$ heat exchange rate between central blood compartment and node (i, j) (W)

$Q_c$ heat released in the fabrics by condensation or absorption of water (W $m^{-2}$)

$Q_{cond}$ energy transferred by conduction (W)

$Q_{cond,i,j}$ conductive heat exchange rate with neighboring layer (W)

$Q_{conv}$ convective heat flow (W)

$Q_{diff}$ heat loss by vapour diffusion through skin (W $m^{-2}$)

$Q_{e,h}$ latent heat loss from the skin surface of human body (W $m^{-2}$)

$Q_{e,i}$ latent heat loss from the skin in body part (i) (W)

$Q_{e,m}$ latent heat loss at the skin surface of Walter (W m$^{-2}$)

$Q_{e,res}$ latent respiration heat loss (W m$^{-2}$)

$Q_r$ heat loss by radiation (W m$^{-2}$)

$Q_{res}$ total heat loss from respiration (W m$^{-2}$)

$Q_{res}(2,1)$ heat loss by respiration at core layer of chest segment (W)

$Q_{sw}$ heat loss by evaporation of sweat (W m$^{-2}$)

$Q_{sw,req}$ sweat rate for comfort (W m$^{-2}$)

$Q_{t,h}$ sensible heat loss from the skin surface of human body (W m$^{-2}$)

$Q_{t,i}$ sensible heat loss from skin surface in body part (i) (W)

$Q_{t,m}$ sensible heat loss at the skin surface of Walter (W m$^{-2}$)

$Q_{t,res}$ dry respiration heat loss (W m$^{-2}$)

$Q_{t,conv}$ heat loss by convection from the out surface of the clothed body(W m$^{-2}$)

$Q_{t,rad}$ heat loss by radiation from the outer surface of the clothed body (W m$^{-2}$)

$Q_{vent,i}$ heat taken by ventilation in part (i) (W m$^{-2}$)

$Q_{w,i,j}$ heat production caused by external work in body node (i, j) (W)

$R$ universal gas constant (8.315 J mol-1 K-1)

$R_e$ total water vapour resistance (m$^2$ Pa W$^{-1}$)

$R_{e,0}$ water vapour resistance of clothing during the standing period unit different (m$^2$ Pa W$^{-1}$)

$R_{e,1}$ water vapour resistance of clothing during the walking period (m$^2$ Pa W$^{-1}$)

$R_{ec}$ intrinsic resistance of clothing to vapour transfer (m$^2$ Pa W$^{-1}$)

$R_{eci}$ intrinsic moisture vapour resistance of the inner tight-fitting underwear (m$^2$ Pa W$^{-1}$)

$R_{eco}$ intrinsic moisture vapour resistance of the outer garments (m$^2$ Pa W$^{-1}$)

$R_{e,dyn}$ total clothing moisture vapour resistance when the person is walking in windy conditions (m$^2$ Pa W$^{-1}$)

$R_{e,fabric}$ water vapour resistance of the fabrics in clothing ensemble (m$^2$ Pa W$^{-1}$)

$R_{e,i,k}$ water vapour resistance of fabric (i, k) (m$^2$ Pa W$^{-1}$)

$R_{eoa}$ water vapour resistance of the outer surface air layer (m$^2$ Pa W$^{-1}$)

$R_{esk,h}$ water vapour resistance of the skin (m$^2$ Pa W$^{-1}$)

$R_{esk,m}$ water vapour resistance of Walter's 'skin' (m$^2$ Pa W$^{-1}$)

$R_t$ total thermal insulation(m$^2$ ℃ W$^{-1}$)

$R_{t,0}$ thermal resistance of clothing during the standing period (m$^2$ ℃ W$^{-1}$)

$R_{t,1}$ thermal resistance of clothing during the walking period (m$^2$ ℃ W$^{-1}$)

$R_{tc}$ intrinsic clothing insulation (m$^2$ ℃ W$^{-1}$)

$R_{tci}$ intrinsic thermal insulation of the inner tight-fitting underwear (m$^2$ ℃ W$^{-1}$)

$R_{tco}$ intrinsic thermal insulation of the outer garments (m$^2$ ℃ W$^{-1}$)

$R_{t,dyn}$ total clothing thermal insulation when the person is walking in windy condition (m$^2$ ℃ W$^{-1}$)

$R_{t,fabric}$ thermal insulation of the fabrics in clothing ensemble (m$^2$ ℃ W$^{-1}$)

$R_{t,i,k}$ thermal insulation of fabric (i, k) (m$^2$ ℃ W$^{-1}$)

$RH$ relative humidity of the surroundings

$R_{toa}$ thermal insulation of the outer surface air layer (m$^2$ ℃ W$^{-1}$)

$R_{t,skin}$ thermal insulation of Walter's 'skin' (m$^2$ ℃ W$^{-1}$)

$r$ radial coordinate of a fiber (m)

$r_f$ radius of fibers (m)

$S$ the area enclosed by the curve OB, line AB and OA in the dynamic simulation (℃ hour)

$S_{ch}$ shivering control coefficient for skin layer of each segment (W ℃$^{-1}$)

$S_{cld,core}$ cold signal from core of human body (℃)

$S_{cld,sk}$ cold signal from skin (℃)

$S_{dl}$ vasodilation control coefficient for skin layer of each segment (l h$^{-1}$ ℃$^{-1}$)

$S_{st}$ vasoconstriction control coefficient for skin layer of each segment (l ℃$^{-1}$)

$S_{sw}$ sweat control coefficient for skin layer of each segment (W ℃$^{-1}$)

$SKINC_i$ distribution coefficient of skin layer for vasoconstriction

$SKINR_i$ weighting coefficient of skin layer for integration of sensor signals

$SKINS_i$ distribution coefficient of skin layer for sweat

$SKINV_i$ distribution coefficient of skin layer for vasodilation

$ST$ vasoconstriction signal

$STCR$ dynamic index, the average skin temperature changing rate of the manikin in the "exercise" mode (℃ h$^{-1}$)

$S_{\Delta T,core}$ head core temperature error signal (℃)

$S_{\Delta T,sk}$ skin temperature error signal (℃)

$T$ temperature (℃)

$T_0$ mean skin temperatures of the manikin when the manikin is thermal balanced during standing period in the dynamic simulation (℃)

$T_1$ mean skin temperatures of the manikin when the manikin is thermal balanced during walking in the dynamic simulation (℃)

$T_a$ temperature of environment (℃)

$T_{b,h}$ temperature of human body (℃)

$T_{b,m}$ temperature of Walter's body (℃)

$T_{blood}$ temperature of central blood node (℃)

$T_{cl}$ temperature of clothing (℃)

$T_{cl,i,k}$ temperature of fabric (i, k) (℃)

$T_{core,h}$ head core temperature (℃)

$T_{i,j}$ temperature of body node (i, j) (℃)

$T_m$ mean temperature between heat source and sink (K)

$T_{mc,i}$ temperature of clothing climate in part (i) (℃)

$T_{mrt}$ mean radiant temperature of the environment (℃)

$T_s$ temperature of surface between a solid and a moving fluid (℃)

$T_{set,i,j}$ set point temperature of the node (i, j) (℃)

$T_{s,h}$ surface temperature of clothed body (℃)

$T_{sk,h}$ mean skin temperature of human body (℃)

$T_{sk,h}(i)$ mean skin temperature of subjects at the ith 30th second in exercise period during wearer trials (℃)

$T_{sk,h}'$ average changing rate of mean skin temperature of subjects in exercise period during wearer trials (℃ $h^{-1}$)

$T_{sk,m}$ mean skin temperature of manikin (℃)

$T_{sk,m}(i)$ mean skin temperature of Walter at the ith 5 second during the exercise period in the dynamic simulation (℃)

$T_{sk,m}'$ dynamic Index, the average changing rate of mean skin temperature in the first hour of exercise during the dynamic simulation (℃ $h^{-1}$)

$T_{sk,req}$ mean skin temperature of human body for comfort (℃)

$T_{re,h}$ rectal temperature of subjects (℃)

$T_{\infty}$ fluid temperatures (℃)

$TL$ thermal load (W $m^{-2}$)

TRF temperature regulating factor

$t$ time (s)

$th$ thickness of clothing (m)

$th_{layer,i,k}$ thickness of fabric (i, k) (m)

$U_{vent}$ volume of air ventilation from the clothing system caused by wind penetration and ventilation (m $s^{-1}$)

$V_{ap}$ rate of air penetration through the clothing assembly ($m^3 m^{-2} h^{-1}$)

$V_{mc}$ total clothing climate volume ($m^3$)

$V_{mc,i}$ clothing climate volume in body segment (i) ($m^3$)

$V_{walk}$ walking speed (m $s^{-1}$)

$V_{wind}$ wind velocity of environment (m $s^{-1}$)

$VI$ ventilation index ($m^3$ $s^{-1}$)

$v$ is the wind velocity (m $s^{-1}$)

$v_0$ air speed in the 'still' air condition (m $s^{-1}$)

$W$ external mechanical work (W $m^{-2}$)

$\tilde{W}$ free water content, the ratio of the free water mass to the fibers mass

$\tilde{W}_{i,k}$ free water content in fabric (i, k)

$Wrm_{i,j}$ warm signal(℃)

$Wrms$ integrated warm signal (℃)

$w$ skin wettedness

$w_0$ skin wettedness level for comfort at the given metabolic rate

$x$ X-coordinate

Greek Symbols

$\beta$ average angle of the capillaries in fabrics

$\gamma$ regain proportionality constant

$\Delta H$ increased heat production inside the manikin body during the walking period compared with that during the standing period (W m$^{-2}$)

$\Delta T_{b,h}$ change of body temperature of subjects in the exercise period (℃)

$\varepsilon$ porosity of the fabrics

$\varepsilon_{a,i,k}$ volume fraction of gas phase

$\varepsilon_{bw,i,k}$ volume fraction of the water absorbed within fibers

$\varepsilon_{f,i,k}$ volume fraction of fibers

$\varepsilon_l$ volume fraction of the liquid water

$\varepsilon_{l,i,k}$ volume fraction of liquid phase

$\varepsilon_t$ thermal emissivity

$\varepsilon_\beta$ emissivity of the environment

$\eta$ dynamic viscosity of water (kg m-1s-1)

$\lambda$ latent heat of evaporation of water (J Kg$^{-1}$)

$\lambda_a$ heat of sorption of vapour by fibers (J Kg$^{-1}$)

$\lambda_l$ heat of absorption of liquid water by fibers (J Kg$^{-1}$)

$\rho$ density of the fibers (Kg m$^{-3}$)

$\rho_l$ density of liquid water (Kg m$^{-3}$)

$\sigma$ Stefan-Boltzmann constant ($5.67 \times 10^{-8} W / m^2 K^4$)

$\varsigma$ Surface tension (N m$^{-1}$)

$\tau$ effective tortuosity of the fabric for water vapour diffusion

$\phi$ contact angle

**Indices**

i = segment number of body part (1-16)

j = number of body layer (1-4)

k = number of fabric layer

# Chapter 1 Introduction

## 1.1 Background

Thermal comfort is defined as the condition of mind, which expresses satisfaction with the thermal environment (Fanger 1970). Clothing thermal comfort is the performance of clothing in assisting the human body in maintaining the thermal comfort state (Fan 1989).

Clothing thermal comfort can be evaluated by direct measurements on human subjects or objective simulation tests. Direct measurements on human body are costly and may expose the subjects to danger, and the results tend also to be less accurate and reproducible. Therefore, various forms of objective simulation tests have been developed over the years. The simplest type of the simulation test is the flat plate methods. The frequently used version of this kind is the skin model, which is now an ISO standard (ISO 11092， 1993(E)). To better simulate the human configuration, cylindrical methods, such as the cylindrical Togmeter, were also developed (Fan 1989).

Flat plate and cylindrical methods are very useful for evaluating the thermal and water vapor transmission properties of clothing materials or simple clothing assemblies, but present difficulties in applying the results to actual clothing in wear. The best simulation test is the use of thermal manikins. Many thermal manikins have been developed around the world since the first one segment and dry copper manikin from the USA Army in 1940s. Despite this, simulation of human perspiration remained a challenge. In 2002, Fan and Chen developed a completely new type of perspiring manikin called "Walter". Walter is the first manikin made of mainly water and high strength breathable fabric. Walter has four main features. First, it has a waterproof, but moisture permeable fabric skin. Moisture transmitted from the manikin's insides through tiny pores in the skin. Second, it can be thought of as 'warm-blooded'. Water at body temperature is pumped from the centre of Walter's body to his extremities. Thirdly, it can simultaneously measure the two most important parameters-thermal insulation and moisture vapour resistance. Finally, Walter's skin can be unzipped and interchanged with different versions to simulate different rates of perspiration. Walter has been used to measure the thermal insulation and moisture vapour resistances of clothing ensembles, and demonstrated high accuracy and reproducibility (Fan and Chen 2002).

Thermal comfort should be considered in two related aspects: thermal comfort under steady-state conditions and thermal comfort under transient conditions. Thermal comfort under steady-state conditions can be determined based on the general comfort equation. Provided we know the clothing thermal insulation and moisture vapour resistance, the heat stress of a clothed man, in terms of the required evaporation for thermal equilibrium, required sweat rate and skin wettedness, or the cold stress, in terms of the required insulation for thermal comfort, can be determined. The suitability of clothing ensembles for a range of thermal environments can also be evaluated. The accurate determination of clothing thermal insulation and moisture vapour resistance is therefore critical. Considerable research has been and is being carried out in developing test methods, particularly thermal manikin, for the realistic and accurate measurement of these two parameters. The effects of clothing materials, clothing constructions, as well as environmental factors on these two parameters have also been extensively investigated.

Studies of thermal comfort under steady-state conditions are important to people under long exposure to certain conditions. However, in many situations, people are moving about, changing their activities and clothing, etc, the steady state is not reached. Attempts had been made to establish models for estimating thermal transient comfort， these models however only included the steady-state properties of clothing, viz. clothing thermal insulation and moisture vapour resistance, but not the dynamic behaviour of clothing. Clothing properties specific to transient conditions should be defined and investigated. Vokac et al (1973) proposed a method of evaluating the clothing ventilation index from monitoring the dynamic changes of temperature and humidity at the skin surface at the sudden change of body motion. Birnbaum and Crockford (1978) described a procedure to measure the rate of air exchange between the clothing micro-climate and the environment by using a trace gas. Since these methods were time consuming and involved human subjects, only very limited data were obtained and they are not commonly used.

While little work has been reported on investigation of coupled dynamic heat and moisture transfer through actual clothing ensembles, some work has been done on the dynamic heat and moisture transfer through layered fabrics. Wang and Yasuda (1991) developed an apparatus to simultaneously measure the transient temperature and moisture changes in-between fabric layers under simulated perspiration. Experimental results (Yasuda et al 1992) showed that the accumulation of the moisture content between fabric layers was strongly related to the moisture absorption properties of the fabric. A number of theoretical models (Farnworth 1986, Li & Holcombe 1992) have also been proposed to model the coupled dynamic heat and moisture transfer in fabrics or simple clothing ensembles since the first such work by Henry (1948).

In this research, the perspiring fabric manikin Walter is applied to investigate the dynamic heat and moisture transfer through real clothing ensembles. The study is aimed at establishing an objective method to measure the properties of real clothing ensembles important to thermal transient comfort.

## 1.2 Objectives

(1) To apply the recently developed perspiring fabric manikin-Walter for quantifying and measuring the properties of clothing ensembles important to thermal transient comfort.

(2) To investigate the dynamic heat and moisture transfer through clothing ensembles during the simulated onset and ending of sweating and body movement.

(3) To investigate the relationship between properties of clothing ensembles and thermal transient comfort.

## 1.3 Research Significance

*(1) Contribution towards the knowledge archives of the dynamic interaction between human body, clothing and the environment in terms of heat and moisture exchange*

Although some work was done on the dynamic heat and moisture transfer through layered fabrics, little experimental investigation has been carried out on actual clothing ensembles. With the development of our perspiring fabric manikin-Walter, it is now possible to investigate the dynamic heat and moisture transfer through actual clothing ensembles. The outcome of this research will provide original experimental data and better understanding, which are essential to the advancement of thermal physiology and environmental engineering.

*(2) Objective method for evaluation of clothing thermal transient comfort*

A standard procedure using the perspiring fabric manikin-Walter will be established for measuring the clothing properties related to thermal transient comfort. The performance of clothing in terms of thermal transient comfort can be evaluated based on the relationship between the clothing properties and thermal transient comfort to be established in this study. This objective method will be practically useful for product evaluation and quality control.

*(3) Knowledge and guidelines for functional clothing design and product development*

Based on the understanding of the relationship between clothing design, clothing materials and thermal transient comfort, we can develop insights and practical guidelines for the development of “high-tech” functional clothing for optimal comfort.

## 1.4 Outlines of the thesis

Chapter 1 provides a general introduction including background, objectives and significance of the present study. Chapter 2 reviews the relevant fundamental knowledge as well as the related work done by previous researchers. Chapter 3 is devoted to describe a new theoretical model for the human body-clothing-environment system. Chapter 4 reports on the new test method as well as the new index for quantifying the dynamic clothing thermal properties important to thermal transient comfort. Chapter 5 reports on the wearer trials conducted to investigate the relationship between the new index of dynamic clothing thermal properties and transient thermo-physiological responses. Finally, Chapter 6 gives out general conclusions and suggestions for future work.

# Chapter 2 Literature Review

## 2.1 Thermal Comfort

### 2.1.1 Definition of Thermal Comfort

Thermal comfort is often defined as the condition of mind which expresses satisfaction with the thermal environment. It refers to the subjective state of the observer that can be described using verbal scales for (dis)comfort or (un)pleasantness (Hensel 1982). People often confuse thermal comfort and thermal sensation. In contrast to thermal comfort, thermal sensation is a rational experience that can be characterized as being directed towards an objective state, it is considered to be correlated with the activity of cutaneous thermoreceptors (Ebbecke 1917, 1948). In many cases, however, thermal comfort and thermal sensations correlate with each other. Under normal conditions, thermal sensations and comfort change in a more or less parallel way, in neutral thermal sensations people feel pleasant, whereas cold and hot sensations make unpleasant feeling, and the more intense the cold or warm sensation is, the more unpleasant people would feel.

### 2.1.2 Thermal functions of human body

Human body is a complex organic system, in which food and oxygen go through complex chemical reactions to produce the energy required for keeping its running. This process is commonly referred as metabolism. In fact, human is an inefficient metabolic machine, in which most of his energy intake in the form of fuel is transformed into heat. As a living man, which is known as homeotherm, this metabolism is uninterrupted and the heat should get off the body at a certain rate so that the body core temperature could be maintained as a fairly constant temperature around 37$^{o}$C for comfort. If the rate is too fast or too slow due to the environmental factors, the body temperature will be beyond this range and man will feel substantial discomfort. Therefore, the comfort of human body is the balance between the body heat production and heat dissipation. Human body has physiological mechanism to regulate the heat exchange with the environment for thermal comfort. So it is necessary to understand how the human body performs thermally.

***Heat balance***

Fanger(1970) described the energy balance between the human body and the environment as follows:

$$H_h - Q_{diff} - Q_{sw} - Q_{e,res} - Q_{t,res} = Q_{t,rad} + Q_{t,conv} \tag{2-1}$$

Where $H_h$ is the internal heat production, $Q_{diff}$ is the heat loss by vapour diffusion through skin, $Q_{sw}$ is the heat loss by evaporation of sweat, $Q_{e,res}$ is the latent respiration heat loss, $Q_{t,res}$ is the dry respiration heat loss, $Q_{t,rad}$ is heat loss by radiation from the outer surface of the clothed body and $Q_{t,conv}$ is heat loss by convection from the outer surface of the clothed body.

***Internal heat production***

The internal heat production is related to the activity of the person. In general, oxygen is taken into the body and is transported by the blood to the cells of the body where it is used to burn food. Most of the energy (metabolic rate $Met$) released is converted to internal body heat ($H_h$); some is converted to external mechanical work ($W$) depending upon the activity. So that

$$H_h = Met - W \tag{2-2}$$

Energy for external mechanical work will vary from about zero to no more than 25 percent of total metabolic rate.

The total metabolic heat generation in human body consists of three sources: basal metabolism for life, voluntary metabolism for activity and shivering or involuntary metabolism for thermoregulatory system. Among them only the shivering can be controlled by the thermoregulatory system. When other means, such as vasoconstriction, the basal and voluntary metabolism, etc., are not sufficient to return the core temperature to its normal level, shivering — involuntary muscle contractions—begins to generate heat in muscle tissue. This can increase the rate of heat generation in the human body by several hundred percent. Shivering is a very powerful force to maintain normal body temperature when the body is exposed to extreme cold.

ASHRAE (1993) gives the following equation for calculating additional metabolic heat energy due to shivering ($Met_{shiv}$):

$$Met_{shiv} = 19.4 S_{cld,sk} S_{cld,core}, Wm^{-2} \tag{2-3}$$

where $S_{cld,sk} = (33.7 - T_{sk,h})$ for skin temperature less than 33.7°C (otherwise $S_{cld,sk} = 0$) and $S_{cld,core} = (36.8 - T_{core,h})$ for core temperatures less than 36.8 °C (otherwise $S_{cld,core} = 0$).

***Body respiration system***

The respiratory system plays an important role in the heat transfer between the human body and environment. Approximately, about 15% of total heat generated by the body is transferred to the environment by the respiratory system in moderate environmental condition. Heat and water vapour are transferred to inhaled air by convection and evaporation from the mucosal lining of the respiratory tract. Therefore breathing results in a dry heat loss and latent heat loss from the body. The heat and water vapour exchange in respiration can be looked as ventilation between expired and inspired air. Fanger (1970) derived two equations to calculate the dry and latent heat loss based on this mechanism.

$$Q_{t,res} = 0.0163 Met(34 - T_a) \tag{2-4}$$

$$Q_{e,res} = 2 \times 10^{-5} Met(5866 - P_a) \tag{2-5}$$

where $T_a$ is ambient temperature (℃) and $P_a$ is vapour pressure in ambient air (Pa).

***Body perspiration system***

Water vapour diffusion through the skin is one part of the latent perspiration, a process not subject to thermoregulatory control. The skin is assumed as water vapour barrier. This barrier is provided by the deeper layers of the horny layer of the epidermis. Fanger (1970) proposed the following equation to calculate the heat loss by water vapour diffusion:

$$Q_{diff} = \lambda m \left( P_s(T_{sk,h}) - P_a \right) \tag{2-6}$$

where $\lambda$ is heat of vaporization of water, $m$ is permeation coefficient of the skin, $P_s(T_{sk,h})$ is saturated vapour pressure at skin temperature.

Sweating is another way of perspiration. Different from skin diffusion, sweating is a powerful means of temperature regulation. Evaporation of sweat from the skin surface has a very effective cooling effect due to the great latent heat of evaporation of water. The evaporation of sweat on the skin surface allows large amounts of heat (up to 1300W, which is about 12 times the basal level of heat production) to be dissipated, even in hot environments.

There is two types of sweat gland: apocrine glands are found in the armpit and public regions, are generally vestigial, and are responsible for the distinctive odour in these regions; eccrine glands are distributed about the body (many on the forehead, neck, trunk, back of forearm and hand, and fewer on thighs, soles and palms). It is the eccrine glands that perform the thermoregulatory function.

Sweating is caused by temperature stimulus from the skin and core. Elevating the core temperature by 1 $^{o}$C can produce an increase in sweat rate by a factor of 10-20 times. When the vasodilatation is not sufficient to bring the core temperature back to normal, the anterior hypothalamus in the thermoregulatory system initiates the sweating process by sending sweat-promoting signals to all of the sweat glands of the body through the sympathetic nerves.

Skin becomes wet due to sweat, if the wettedness is beyond a certain range, suppression in sweating will occur. This phenomenon is called Hidromeiosis, which is a reduction in sweat associated with wetting the skin. This decline is exponential and tends towards zero; however, recovery is rapid (Kerslake, 1972).

***Body blood circulatory system***

The transport of thermal energy throughout the tissue is an important function of blood circulatory system. The thermoregulatory system employs the circulatory system as its major controlling mechanism through its intricate network of blood vessels by varying the local caliber of smaller arteries, arterioles, and veins to locally vary the hydraulic resistance and thus control blood flow to whole body. The blood flow is a very important part of thermal regulation of the human body, about 50-80% of heat flow in tissue is carried in or out of the tissue by blood flow. The skin temperature, which is an important determinant of the heat transfer between body and the surroundings, is also controlled by the blood flow in human body.

If the core temperature rises above the normal level, the skin blood vessels are intensely dilated in most areas of the body. Full vasodilation can increase the rate of heat transfer to the skin surface as much as eight-fold. When the vessels are dilated, much of the blood passes near the skin where it may be cooled before it returns to the body core. Therefore, the skin temperature will more closely reflect deep body temperature, and heat loss from the body will increase to a cooler environment due to the high skin temperature. If ambient temperatures are higher than those of the skin, usually, by increasing the skin temperature, less heat will be transferred from the environment to the body. However, in environments where the net loss from the skin is negative, vasodilation is undesirable, since it allows heat from the environment to be transmitted more rapidly to the body core.

When the core temperature is below its normal level, the posterior hypothalamic sympathetic centers in the thermoregulatory system cause the blood vessels of the skin to constrict powerfully. This lessens the flow of warm blood from the internal structures to the skin, decreasing the transfer of heat to the body surface from those organs producing the most heat. When vasoconstriction occurs, the temperature of the skin falls to near the temperature of the surroundings; this causes heat loss to be greatly diminished, allowing the internal body to retain its heat and the core temperature to rise. In addition, because of the constriction of skin blood returning to the heart via the deep veins, the extremities will be heated to some degree by the near arteries. In this way, blood can be supplied to an extremity that may be 10 to 20 degrees colder than the body core, yet the blood that returns to the core may only be cooled 1 or 2 degrees. Thus the temperature of the trunk is maintained while the extremities are allowed to cool. Vasoconstriction does not occur in the head because the blood flow to the brain must be maintained.

***Thermal regulation system***

As mentioned, the human body should maintain a thermal balance between the heat generated by the body and that loss to the environment. In practice, what is achieved is not a steady state but a dynamic equilibrium: as external conditions continually change, so the body responds to regulate the internal body temperature.

Most powerful form of human thermoregulation is behavioural; put on or take off clothes, change posture, move, take shelter, etc. The human body also has physiological system of thermoregulation. Both systems continually interact and respond to changing environments in an attempt to ensure human survival and comfort.

The mechanisms of physiological thermoregulation is when the body becomes hot it loses heat by vasodilation and, if required, sweating. If the body becomes cold then heat is preserved by vasoconstriction and, if necessary, generated by shivering.

### 2.1.3 Physiological State of Thermal Comfort

In cool environments, thermal comfort is best correlated with mean skin temperature and body temperature. However, in warm conditions, it was found that thermal discomfort are related to sweating rather than skin or body temperatures (Winslow et al. 1937, 1939; Gagge et al. 1967, 1969).

In 1970, Hardy described the physiological conditions of general thermal comfort (at low activity levels) have been described as follows:

(1) internal body temperature 36.6 to 37.1 $^{o}$C,

(2) mean skin temperature 33 to 34.5 $^{o}$C for man and 32.5 to 35 $^{o}$C for women,

(3) local skin temperature is variable over the body but generally between 32 and 35.5 $^{o}$C

(4) temperature regulation is completely accomplished by vasomotor control of blood flow to the skin (no sweating/shivering present).

Fanger(1970) also defined three conditions for a person to be in overall thermal comfort:

(1) the body is in heat balance;

(2) sweat rate is within comfort limits;

(3) mean skin temperature is within comfort limits.

The sweat rate and mean skin temperature for comfort $Q_{sw,req}$ and $T_{sk,req}$ was provided by Rohles and Nevins(1971) as follows:

$$T_{sk,req} = 35.7 - 0.0275(Met - W) \tag{2-7}$$

$$Q_{sw,req} = 0.42(Met - W - 58.15) \tag{2-8}$$

Based on heat balance equation and the above thermal comfort conditions, he PMV (Predicted Mean Vote) to predict thermal comfort state of human body. Gagge (1986) found that PMV is not very sensitive to humidity in warm environments, so he introduced PMV* which can characterize and predict warm discomfort better.

As for non-uniform environmental conditions, local comfort is also important A person may feel thermally neutral as a whole but still feel uncomfortable if on or more parts of the body are too warm or too cold (ASHRAE 2001). It was found that the mechanisms which evoke the perception of general and local (dis)comfort are different. The physiological mechanisms governing local perceptive responses were found to be associated with cutaneous thermoreception. Overall perceptive responses reflect an integration of thermal afferents from various sites of the human skin. Local thermal sensation is governed by skin temperature irrespective of the general thermal state of the body. In contrast, local comfort appears to be highly dependent on the state of general comfort.

For transient conditions, the physiological basis is not yet well understood. The dynamic response to transient conditions is correlated to the response of the body's thermal receptor. When condition change, the thermoreceptors send not only the static signal based on skin and core temperature but also a dynamic signal based on the rate of change in both temperatures (Hensel 1982).

## 2.2 Heat and Mass Transfer through Clothing

### 2.2.1 The Human-Clothing-Environment System

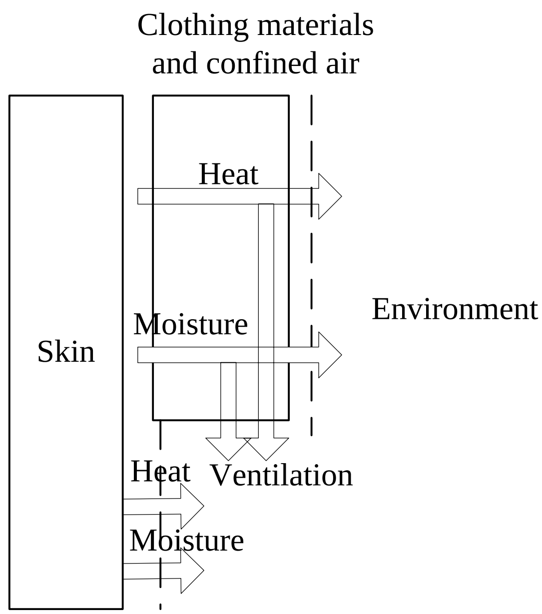



*Figure 2-1 Human-clothing-environment system*

Figure 2-1 illustrates a human-clothing-environment system. Heat and moisture are dissipated from the skin of human body. After that, heat is divided into two parts. One flows directly into environment by convection and radiation from the exposed skin. The other is transferred into the clothing microclimate. In the clothing microclimate, some heat is taken away by ventilation; the remainder goes through clothing materials. Finally heat goes out from the outer surface of clothing ensembles. Moisture has the similar pathway. Nevertheless in the clothing materials, the mechanisms of heat and moisture transfer are very different. It involves very complex processes. Conduction, convection, radiation are the mechanism of heat transfer; diffusion, absorption/desorption, condensation/evaporation and wicking are the mechanism of moisture transfer. Absorption/desorption and condensation/evaporation are accompanied with heat releasing and absorbing. So the moisture transportation is coupled with heat transfer.

### 2.2.2 Heat Transfer through Clothing System

#### 2.2.2.1 Conduction

Conduction is one of the basic mechanisms of heat flow, which occurs by the interaction or collision of adjacent molecules and the transfer of kinetic energy. This type of heat transfer requires a direct physical contact between the interaction objects. The rate of conductive heat transfer is proportional to the temperature difference between them and inversely proportional to the distance over which conduction takes place. According to the Fourier's law, the energy conducted can be expressed as following:

$$Q_{cond} = -KA\frac{dT}{dx} \tag{2-9}$$

Where, $K$ is a proportional coefficient called "thermal conductivity"; A is the cross sectional area that the thermal energy passes through; $T$ is the temperature.

In a fabric the conduction heat loss is determined by the thickness of the fabric and its thermal conductivity. The thermal conductivity for dry fabric is a combination of the conductivity of air $K_a$ and that of the fiber $K_f$. It may be estimated using the following equation (Bogaty et al 1957):

$$K_{dry} = f_x(f_a K_a + f K_f) + f_y K_a K_f /(f_a K_f + f K_a) \qquad (2\text{-}10)$$

Where $f_x$ and $f_y$ are the effective fractions of fibers parallel and perpendicular to the direction of heat flow, respectively, $f$ is the fraction by volume of the fabric taken up by fibers, $f_a$ is the fraction by volume of the fabric taken up by air. The conductivity of air is 0.025 W/mK and that of fibers is about 0.1 W/mK, therefore in fabrics of fiber contents below 10%, the conductivity is effectively that of air.

Hollies and Bogaty (1965) found the thermal conductivity of moist fabrics was proportional to the moisture content, they proposed the following equation to calculate the thermal conductivity for moist fabrics:

$$K_{moist} = (1 - f_l)K_{dry} + f_l K_l \qquad (2\text{-}11)$$

where $K_{moist}$ is the thermal conductivity of the moist fabric, $K_{dry}$ is the overall conductivity of the dry fabric, $K_l$ is the thermal conductivity of water, $f_l$ is the fraction by volume of the fabric taken up by water.

### 2.2.3.2 Convection

Convection is the heat transfer from one place to another within a fluid, gas or liquid, by the mixing of one portion of fluid with another. The rate of convection depends on the motion of the fluid and the temperature gradient. Convection is the most important mechanism for thermal energy transfer between a solid and a moving fluid. Regardless of the particular nature of the convective heat transfer process, the appropriate rate equation is of the form

$$Q_{conv} = -hA(T_s - T_\infty) \tag{2-12}$$

where, $Q_{conv}$ is the convective heat flow which is proportional to the difference between the surface and fluid temperatures, $T_s$ and $T_\infty$, respectively. This expression is known as Newton's law of cooling, and the proportionality constant $h$ is termed the convection heat transfer coefficient. It depends on conditions in the boundary layer, which are influenced by surface geometry, the nature of the fluid motion, and an assortment of fluid thermodynamic and transport properties.

Convective heat transfer may be classified according to the nature of the flow. We speak of forced convection when the flow is caused by external means, such as by a fan, a pump, or atmospheric winds. In contrast, for natural convection the flow is induced by buoyancy forces, which arise from density differences caused by temperature variations in the fluid.

For the sedentary human body under no wind conditions, natural convection is the main mechanism of heat exchange among skin, microclimate, clothing materials and environment. While when there is wind or human body is moving, forced convection takes the place of natural convection and becomes one of the dominative factors in heat transfer among clothing system. There are two kinds of forced convection in clothing system: wind penetration and ventilation by pumping effect.

**Wind penetration**

Air penetration can induce the air exchange. In windy conditions, Stuart and Denby (1983) and Fan and Keighley (1989) stated that air penetration into permeable clothing is a major cause of reduction in thermal insulation and vapor resistance. The air penetration is induced by the air pressure difference between inner surface and outer surface of clothing system. Kerslake (1971) pointed out that the rate of air penetration through the clothing assembly $V_{ap}$ was approximately linearly related to the wind velocity:

$$V_{ap} = 3600 A_s f_{op} v \tag{2-13}$$

where $A_s$ is the surface area of the clothing assembly, $f_{op}$ is the apparent portion of the surface area $A_s$ that is open to the air-flow; $v$ is the wind velocity, or flow velocity of air through the clothing assembly, which is assumed to be equal to the wind velocity.

**Ventilation by pumping effect (Below action)**

Ventilation is one of the most effective mechanisms to remove heat and moisture from the clothed body, therefore, an important determinant of thermal comfort. In a cool climate, clothing insulation may be much less effective at preserving body heat than would be expected if there was an assumption of no clothing ventilation. For active people, clothing insulation can be reduced by 50 percent in the cold conditions (ISO TR 11079 1993).

There were two kinds of research methodology on clothing ventilation: direct measurement and indirect evaluation.

Crockford et al (1972) first developed a direct method to measure the ventilation rate in the clothing ensemble. They used a tracer gas technique by introducing the gas through pipes beneath the clothing on active human subjects and monitoring the return of oxygen concentration. And then the ventilation rate was determined by fitting the curve using an oxygen concentration recovery model. Hollies et al (1973) modified the Crockford et al's method (1972) by measuring half-times to calculate the microclimate air exchange. Birnbaum and Crockford(1978) proposed a Ventilation Index to evaluate the ventilation properties of clothing and developed the measurement method based on two techniques: the measurement of clothing microclimate volumes (Crockford and Rosenblum 1974) and trace gas method to measure the air exchange rate

(Crockford et. al. 1972). Lotens and Havenith (1986,1988) further developed the tracer gas technique, provided a more convenient and effective method. Compared with the Crockford et al.'s method, it omitted the step to measure the microclimate volumes. Reischl et al (1987) further improved the methodology; they developed an advanced sensor to measure the local ventilation values which can provide local design guideline for comfort.

Indirect evaluation method provided another way to study the influence of clothing ventilation. This method assumed that the reduction in the insulation value of the clothing between the wearer being static and being moving is due to the ventilation effect. The insulation can be measured on thermal manikins (Seppanen et. al. 1972, Goldman 1974, Olesen et. al. 1982, Olesen and Madsen 1983， Fan and Chen 2002) or subjects (Belding et. al. 1947, Mitchell and Rensburg 1973, Nishi et. al. 1975, Vogt et. al. 1983 1984, Nielsen et. al. 1985, Bakkevig and Nielsen 1995). By this approach, the relationship between thermal insulation/water vapor resistance and ventilation dominant factors, walking speed and wind velocity, can be established (Holmer et. al. 1999, Nission et. al. 2000, Qian 2005). Qian (2005) established a quasi-physical model to predict the thermal insulation and moisture vapour resistance of the clothing ensemble for clothed human walking in wind. Based on this model, he derived a dimensionless air ventilation coefficient. This ventilation coefficient is dependent on the clothing feature such as garment style, fit and properties of fabrics, but independent of wind velocity and walking speed. It can therefore better represent the ventilation properties of clothing ensemble compared with other indices such as Ventilation Index and air exchange rate.

**2.2.3.3 Radiation**

The heat flow due to radiation is more complex as it is governed by the temperature difference between the heat emitter and the heat absorber. The infra-red radiation only travels a few millimeters into a fabric as it either scattered or absorbed by the fibers. These fibres in turn emit radiation which travels a further short distance to the next fibers and so on until it reaches the far surface. Therefore the radiative heat transfer between the body and the environment is indirect and depends on the absorption and emission properties of the fibers.

Herrington et al. (1949) made a careful assessment of the radiation exchange between the nude human body and the environment and related this to contributions from other avenues of heat exchange. Part of the potential thermal stress arises because much of the body is exposed to direct sunlight and skin is a good absorber of energy over a wide spectral range.

Woodcock et al. (1957) derived an equation to evaluate the radiation heat exchange between clothed man and the environment as follow:

$$Q_{t,rad} = 5.72 \times 10^{-12} [(T_{s,h} + 273.15)^4 - (T_a + 273.15)^4] \varepsilon_\beta A_{Du} f_{cl} \tag{2-14}$$

where $T_{s,h}$ is the surface temperature of clothed body, $T_a$ is the temperature of the environment, $\varepsilon_\beta$ is the emissivity of the environment, $A_{Du}$ is the DuBois surface area and $f_{cl}$ is the ratio of the effective radiating surface to the DuBois surface area.

Fanger (1970) derived a similar equation for the heat loss by radiation from the outer surface of the clothed body.

$$Q_{t,rad} = 3.97 \times 10^{-8} A_{Du} f_{cl} \left[ (T_{cl} + 273)^4 - (T_{mrt} + 273)^4 \right] \qquad (2\text{-}15)$$

where $T_{mrt}$ is mean radiant temperature (℃).

Farnworth (1983) proposed the formula to calculate the conductivity ($K_r$) due to radiation in the centre of a thick specimen as:

$$K_r = \frac{8\sigma T_m{}^3 r_f}{f\varepsilon_t} \qquad (2\text{-}16)$$

where $\sigma$ is Stefan-Boltzmann constant ($5.67 \times 10^{-8} W / m^2 K^4$), $T_m$ is mean temperature between heat source and sink, $\varepsilon_t$ is thermal emissivity, $r_f$ is radius of fibers and $f$ is fractional fiber volume.

### 2.2.3 Moisture Transfer through Clothing System

In order to keep the wearer dry and hence comfortable, clothing that is worn during various activities has to be able to deal with moisture transfer. There are three ways to transmit moisture in clothing system: diffusion, convection and wicking of liquid water.

#### 2.2.3.1 Diffusion

Water vapour diffusion is the basic mechanism of moisture transfer. The rate of water vapour transfer by diffusion is proportional to the gradient of water vapour concentration. According to the Fickian law, the moisture transmitted through the void space of the fabric can be expressed as following:

$$m_{diff} = -D_{eff} A \frac{dC}{dx} \tag{2-17}$$

where, $D_{eff}$ is effective diffusion coefficient of water vapour in the fabric; A is the cross sectional area that the water vapour passes though; $\frac{dC}{dx}$ is the gradient of water vapour concentration in the void space.

$D_{eff}$ is dependent on the volume fraction of water vapour ( $f_a$ ), as the fiber and the liquid water volume fractions increase, there will be less space available in the void space for the diffusion to take place. One may define the effective diffusivity as:

$$D_{eff} = \frac{D_a f_a}{\tau} \tag{2-18}$$

where $\tau$ is the effective tortuosity of the fabric for water vapour diffusion, $D_a$ is the diffusion coefficient of water vapour in air.

#### 2.2.3.2 Convection

According to analogy theory between heat and mass transfer (Cengel, 2003), the rate of moisture convection ( $m_{conv}$ ) can be expressed as the form of Newton's Law of cooling:

$$m_{conv} = h_m A(C_s - C_\infty) \tag{2-19}$$

where $h_m$ is the moisture convective transfer coefficient, $C_s$ and $C_\infty$ is the moisture concentration at the surface and the fluid.

Similar to heat convection in the clothing, both natural and forced moisture convection occurs among skin, microclimate, clothing materials and environment. Wind penetration and ventilation by pumping effect also cause forced convection of moisture. The total moisture transfer by wind penetration and ventilation by pumping effect can be calculated by the following equation (Qian, 2005):

$$m_{vent} = U_{vent}(C_{mc} - C_a) \tag{2-20}$$

where $U_{vent}$ is the volume of air ventilation from the clothing system caused by wind penetration and ventilation, $C_a$ are the moisture vapour concentration of environment and $C_{mc}$ is the mean moisture vapour concentration within the clothing microclimate.

#### 2.2.3.3 Liquid water transport

The main form of liquid water transport in a fabric is wicking. Wicking in fabric is caused by fiber-liquid molecular attraction at the surface of fiber materials, which is determined mainly by surface tension and effective capillary pore distribution and pathways. This effect is also deemed to be driven by capillary pressure (Gibson, 1996). The capillary pressure is often a function of the fraction of the void space occupied by the liquid. Stanish et al. (1986) proposed an empirical equation for capillary pressure ( $P_c$ ):

$$P_c = a\left(\frac{f_l}{f_a}\right)^{-b} \tag{2-21}$$

where $f_l$ is the volume fraction of liquid water, $f_a$ is the volume fraction of void space in the fabric, $a$ and $b$ is constant.

Others considered wicking as liquid diffusion (Fan et al. 2004, Li et al. 2002). Fan et al. (2004) used the following equation for the liquid water flow rate:

$$m_w = D_l \rho (1 - f) \frac{\partial \widetilde{W}}{\partial x} \tag{2-22}$$

where $D_l$ is the diffusion coefficient of liquid water, $\rho$ is the density of the fibers , $f$ is the volume fraction of the fibers and $\widetilde{W}$ is the free water content (the ratio of the free water mass to the fibers mass) .

Li et al. (2001) derived the diffusion coefficient $D_l$ on the basis of Darcy's law and Hagen-Poiseuille's law as follows:

$$D_l(\varepsilon_l) = \frac{\varsigma \cos\phi \sin^2\beta d_c \varepsilon_l^{1/3}}{20\eta\varepsilon^{1/3}} \tag{2-23}$$

where $\varsigma$ is surface tension, $\varepsilon$ is the porosity of the fabrics, $\varepsilon_l$ is the volume fraction of the liquid water, $d_c$ is the effective radius of the capillaries, $\phi$ is contact angle, $\beta$ is the average angle of the capillaries in fabrics and $\eta$ is dynamic viscosity of water.

### 2.2.4 Coupled Heat and Moisture Transfer through Clothing System

Heat and moisture transfers in clothing system are coupled in rather complicated mechanism. There are two kind of moisture transfer phenomenon that occurs accompanied by heat releasing or capturing: sorption/desorption and condensation/evaporation.

#### 2.2.4.1 Moisture Sorption/desorption

Water absorption capacity differs from garment to garment. The factors governing the differences in absorbency of garments are fiber type, yarn type, type of fabric construction and garment construction. Among them, the absorption ability of fiber plays the dominant role. Since the properties of fibers vary with the moisture condition, testing should be done under controlled conditions. For this purpose, a standard temperate atmosphere is defined as $20^{o} \pm 2^{o}$C and 65% r.h. Under the specific conditions the amount of moisture contained in the textiles (Moisture regain or content) is used to evaluate the absorbency of fabrics.

The sorption and desorption of moisture by the fibers were believed to obey the Fickian law (Fan et al. 2000, Li et al. 2002):

$$\frac{\partial C_f}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left( rD_f \frac{\partial C_f}{\partial r} \right) \tag{2-24}$$

where, $C_f$ is the moisture concentration in the fiber, $D_f$ is the diffusion coefficient of moisture in the fiber, and $r$ is the radial coordinate of a fiber.

When a fiber absorbs water, heat is released. The heat of absorption is defined as the heat released when one gram of water is absorbed by an infinite mass of the material at given moisture regain. The water may be absorbed from water vapour, to give a value $\lambda_a$, or from liquid water, to give a value $\lambda_l$. According to the First Law of Thermodynamics,

$$\lambda_a = \lambda_l + \lambda , \tag{2-25}$$

where $\lambda$ is the latent heat of condensation.

$\lambda_l$ can be expressed as a function of the relative humidity ($RH$) (Lotens, 1993):

$$\lambda_l\,(J/kg) = 1.95 \times 10^5 (1 - RH)\left(\frac{1}{0.2 + RH} + \frac{1}{1.05 - RH}\right). \tag{2-26}$$

#### 2.2.4.2 Condensation/evaporation

Condensation is the process by which a gas or vapour changes to a liquid. Condensation occurs when the air is saturated. Reversely, evaporation is the change from a liquid to a gas state. When the relative humidity of the surrounding air is below 100%, the liquid water will evaporate. Along with the physical state of water changing, an enormous quantity of thermal energy is released (for condensation) or captured (for evaporation). This heat is called latent heat. The condensation/evaporation rate is determined by the difference between the saturated water vapour concentration ($C^*(T)$) and water vapour concentration in the air filling the interfiber void spaces ($C_a$). It has the expression of:

$$m_c = h_{moist} A(C^*(T) - C_a) \tag{2-27}$$

where $h_{moist}$ is the mass transfer coefficient, A is the area of liquid-gas interface.

Fan et al. (2004) modeled water condensation and evaporation based on the Hertz-Knuden equation (Jones 1992) as follows:

$$m_c = -E\sqrt{M_w / 2\pi R}(1 - RH)P_s(T) / \sqrt{T + 273.15} \tag{2-28}$$

where $E$ is the condensation or evaporation coefficient ($5 \times 10^{-3}$), $M_w$ is the mass of a water molecule, $R$ is the universal gas constant, RH is relative humidity of the surroundings, $P_s(T)$ is the saturated water vapour pressure and $T$ is temperature.

The heat released or captured can be calculated by:

$$Q_c = \lambda m_c \tag{2-29}$$

where $\lambda$ is latent heat for evaporation.

## 2.3 Modeling the Thermal System of Human Body-Clothing-Environment

### 2.3.1 Comfort Models

For more than 30 years, two comfort models under steady state have been most commonly used to evaluate thermal sensation: Fanger's PMV (Predicted Mean Vote) model (Fanger 1970), and Gagge's PMV* (1986). The two models are very effective for evaluating indoor environments that are uniform, stable, and close to thermal neutrality, and have been extensively used for that purpose.

Fanger's PMV model is based on the heat balance equation and his extensive experiments. Fanger proposed that the degree of discomfort will depend on the thermal load (TL), which is defined as the difference between the internal heat production and the heat loss to the actual environment for a man hypothetically kept at the comfort values of the mean skin temperature and the sweat secretion at the actual activity level. He stated the average thermal sensation or Predicted Mean Vote ( $PMV$ ) is a function of the thermal load( $TL$ ).

$$PMV = \alpha TL \tag{2-30}$$

where

$\alpha = 0.303e^{-0.036Met} + 0.028$, $TL = H_h - Q_{diff} - Q_{sw} - Q_{e,res} - Q_{t,res} - Q_{t,rad} - Q_{t,conv}$.

Gagge et al. (1986) introduced the PMV* index to improve PMV's sensitivity to humidity in warm environments. PMV* is identical to PMV but substituted a new Effective Temperature ($ET^*$) for the operative temperature used in the PMV equation. $ET^*$ is the temperature of an isothermal environment at 50% RH in which a subject, while wearing clothing standardized for the activity concerned, has the same heat stress (skin temperature) and thermoregulatory strain (skin wettedness) as in the actual environment (ASHRAE 2001). At neural and cool temperatures, the slopes of $ET^*$ on a psychrometric chart are similar to air temperature but become more affected by humidity as the temperature increases.

In neutral and cool environments where sweating does not occur PMV and $PMV^*$ values are equal. In warm environments, warm discomfort is linearly proportional to skin wettedness ( $w$ ), $PMV^*$ can be also expressed as a linear function of skin wettedness:

$$PMV^* = \alpha E_{\max}\left(w - w_0\right) \tag{2-31}$$

Where $w_0$ is the skin wettedness level for comfort at the given metabolic rate, $\alpha$ is the same with that in Equation 2-30 for PMV. $E_{\max}$ is the evaporation rate when the skin completely covered with sweat for the given conditions.

In contrast to thermal sensation models for steady state conditions, dynamic thermal sensation models include a derivative that corresponds to sensations experienced in transient conditions. The dynamic response to transient conditions is correlated to the responses of the body's thermal receptors, which respond differently to static and dynamic conditions. Under steady state conditions, the thermoreceptors sense a static signal to the brain; this signal is based on skin temperature and core temperature. When conditions change, the thermoreceptors send not only the static signal based on skin and core temperature but also a dynamic signal based on the rate of change in both temperatures.

Some models have been established to describe the dynamic behaviour of sensation (Hensel 1982, Ring and de Dear 1991, Taniguchi et al. 1992, Fiala 1998, Fiala 2003). These models predict the subjective thermal sensation if skin temperature, skin temperature change rate and core temperature (only required in Fiala's model) are presented.

Fiala's thermal sensation model (2003) was based on statistical analysis of human responses measured in numerous experiments covering a wide range of air temperature (between 5 $^{o}$C and 50 $^{o}$C) and activity levels (between 0.8 met and 10 met) as well as different types of exposure. A group of nonlinear thermal sensation models revealed that the temperature error signals from the skin and the head core and the rate of the change in the mean skin temperature to be the responsible thermophysiological variables that govern the overall sensation of temperature.

For sedentary subjects, Fiala found that thermal sensation correlated better with skin temperature than with other physiological variables, such as internal temperature, sweat rate, or changes in skin blood flow. The response of sedentary subjects ($F_1$) can be calculated by the following equation:

$$F_1 = b_1 S_{\Delta T,sk} \tag{2-32}$$

where $b_1$=0.301 for $S_{\Delta T,sk}$ <0, and $b_1$= 1.078 for $S_{\Delta T,sk}$ >0. $S_{\Delta T,sk}$ is the skin temperature error signal, the difference between mean skin temperature ($T_{sk,h}$) and corresponding reference point ($T_{sk,h,0}$).

$$S_{\Delta T,sk} = T_{sk,h} - T_{sk,h,0}\,. \tag{2-33}$$

For exercising subjects, the thermal sensation ($F_2$) was found to be a function of both the skin temperature error signal ($S_{\Delta T,sk}$) and head core temperature error signal ($S_{\Delta T,core}$):

$$F_2 = \exp\left(\frac{-0.902}{S_{\Delta T,core} + 0.4} + 0.627\right) \cdot \exp\left(\frac{7.612}{S_{\Delta T,sk} + 0.4} + 1.445\right) \tag{2-34}$$

In addition to the above static response, the dynamic response of subject was also predicted in Fiala's model.

The cold sensation ($F_3^{'}$) caused by skin cooling was expressed as:

$$F_3^{'} = 0.114 \frac{dT_{sk,h}^{(-)}}{dt} \tag{2-35}$$

where, $\frac{dT_{sk,h}^{(-)}}{dt}$ is the drop rate of the mean skin temperature.

During skin warming, the response ($F_4^{'}$) was calculated by:

$$F_4^{'} = \frac{dT_{sk,h}^{(+)}}{dt_{\max}} \exp(-0.681t - 1.985)\,. \tag{2-36}$$

where, $\frac{dT_{sk,h}^{(+)}}{dt}_{\max}$ is the maximum positive rate of change of skin temperature, $t$ is the time elapsed since the occurrence of $\frac{dT_{sk,h}^{(+)}}{dt}_{\max}$.

When the effect of internal temperature was taken into account, the cold sensation ( $F_3$ ) can be obtained by $F_3 = F_3^{'}/(1+F_2)$. The warm sensation ( $F_4$ ) can be obtained by $F_4 = F_4^{'}/(1+F_2)$.

Integrating all above response, Fiala derived the complete model for predicting the dynamic thermal sensation (DTS).

$$DTS = 3\times\tanh(F_1 + F_2 + F_3 + F_4) \qquad (2\text{-}37)$$

### 2.3.2 Human Thermal Models

In order to describe the dynamic thermal behaviours of human body, a number of thermal mathematical models were established. Generally a human thermal model can be classified as partial or complete. Partial models are only for one part of the body, while complete ones describe the thermal exchanges in the entire body. The entire-body thermal models evolved from one homogeneous cylinder into multilayered cylinders of various sizes for separate body parts, connected by a circulatory blood flow. The layers are usually deduced from anatomical differences in body tissue: skin, fat, muscle and core. Although the physiologists and engineers who developed those entire-body thermal models employed a variety of approaches, Fu (1995) classified all of them into four categories according to their node number: (1) one-node thermal model; (2) two-node thermal model; (3) multi-node thermal model; (4) multi-element thermal model.

In one-node thermal models, the human body is represented by a node. Givoni and Goldman (1972)'s model is a well known one-node model, in which the time response of rectal temperature and heart rate is predicted from a set of environmental conditions.

Two-node thermal models divide the entire human body into two concentric shells: outer skin layer and a central core. This core represents internal organs, bone, muscle and subcutaneous tissue. The temperature of each shell is assumed to be uniform. In this kind of model, the energy balance are usually established for each node and then solved for the core and skin temperatures and other physiological variables.

Gagge's model (1971, 1986) is a very famous two-node model. In Gagge's model, two energy equations were established for skin and core node respectively. Gagge et. al. developed the thermal control functions for the blood flow rate, the sweat rate, the shivering metabolic rate. All these functions were determined by core and skin temperature signals. Cold skin signal causes vasoconstriction, while vasodilatation is driven by warm skin signal; warm core signal and warm skin signal control sweating, while cold core signal and cold skin signal control shivering. Gagge's model is applicable for moderate levels of activity and uniform environmental conditions.

Multi-node models divide the entire body into more than two concentric shells or nodes and the temperature of each layer is also assumed to be uniform. The same as Gagge's model, in this kind of model, energy balance equations were written for each layer, and the control equations were established.

Stolwijk's model (1966, 1971, 1977) is the one of the most well-known multi-node models. In this model, the human body is divided into five cylindrical body parts for the trunk, arms, hands, legs, and feet and a spherical body part for the head. Each part is consisted of four concentric shells for core, muscle, fat and skin tissue layers. And the blood was assumed to be one node. This model can be used in non-uniform environmental condition, however, it require uniform conditions for each body part.

Multi-element models are the most complicated thermal models. In these models, the human body is divided into several body parts or elements, but unlike multi-node models, no further nodes or layers are employed in each element. The energy and control equations are established for each body element. Wissler' model (1964, 1985), Smith's model (1991) and Fu's model (1995) are typical multi-element ones. These models are so complex that need very powerful computer machines.

### 2.3.3 Clothing Models

The thermal properties of clothing on human body are complex and dynamic, not fully understood, and are difficult to quantify. What is known is mainly derived from theoretical and empirical research. Factors affecting the thermal properties of clothing include heat exchange in clothing materials (conduction, convection, radiation), moisture transportation in clothing materials (moisture absorption, desorption, evaporation, condensation and wicking), heat and moisture exchange between clothing and environment, ventilation, compression, subject posture, fitness, skin surface covered condition and so on.

One approach of assessing the thermal properties of clothing is to establish thermal models of clothing system and attempt to estimate values of quantities required for the thermal models by measurements.

Under steady state, the simplest model is to simplify the clothing system as resistance of heat and moisture transfer. In this model, the whole system is divided into two layers. The clothing materials and confined air is the clothing layer. The outer surface air layer is the second layer. Heat and moisture transfer from skin to environment, via clothing layer first, air layer next.

So in this model, four parameters are used to quantify the thermal properties of clothing system: intrinsic clothing insulation ( $R_{tc}$ ), thermal resistance of outer surface air layer( $R_{toa}$ ), intrinsic resistance of clothing to vapour transfer( $R_{ec}$ ) and resistance of the outer surface air layer to vapour transfer( $R_{eoa}$ ).

Combining $R_{tc}$ and $R_{toa}$, $R_{ec}$ and $R_{eoa}$, total thermal insulation ( $R_t$ ) and total water vapour resistance ( $R_e$ ) can be obtained. These indices synthesize various complex factors such as the influence of clothing materials, ventilation, clothing constructions, clothing style, subject posture and so on.

In order to predict the $R_{tc}$ and $R_{ec}$ during walking in wind, Qian and Fan (2005a, 2005b) developed a new model under steady-state conditions. In Qian and Fan’s model, ventilation through opening and air penetration are involved. The clothing physical characteristics such as clothing style, fit, air permeability of clothing fabrics are put into their model.

Under dynamic conditions, little work has been done to model heat and moisture transfer through the clothing ensembles, although some work was carried out on fabrics and air layers (Henry 1939, David and Nordon 1969, Ogniewicz and Tien 1981, Farnworth 1986, Vafai and Sarkar 1986, Shapiro and Motakef 1990, Fu 1995, Umeno et al. 2001, Li et. al. 2002, 2003, Fan et al. 2000, 2004). In these models, heat loss by ventilation and air penetration was not taken into account.

Their models were not applicable to the situation of walking in wind. Gibson (1996) was the first worker who has contributed the subject through developing a fabric model which considered air penetration through fabric layers based on Darcy’s law. Due to Darcy’s law’s limitation, this model may be not applicable for high air velocity conditions. Ghaddar et al. (2003) also attempted to consider air penetration through clothing materials; however, their model does not consider ventilation through openings.

### 2.3.4 Integrated Models

Numerous thermal mathematical models for thermal comfort, human thermal physiological response and clothing have been developed. Thermal comfort models are combined with human thermal models, although only a few human thermal models include thermal sensation models (Gagge et al. 1986, Wang and Peterson 1991, Fiala 1998, Guan et al. 2003, Rugh et al. 2004). Some models considered the effect of various clothing ensembles on human thermoregulation, but only steady state clothing models were applied in these models (Gagge et. al. 1971, Azer and Hsu 1977, Gagge et. al. 1986, Wang and Peterson 1991, Tanabe et al. 2002).

Some workers attempted to combine the human models with transient clothing models (Jones and Ogawa 1992, Fu 1995, Gibson 1996, Xu and Werner 1997, Umeno et. al. 2001, Ghaddar et. al. 2003, Li et. al. 2004). However, these transient clothing models have not considered ventilation through clothing openings, which is an important heat and moisture transport mechanism in actual clothing ensembles.

## 2.4 Evaluation of Clothing Properties Relevant to Thermal Comfort

### 2.4.1 Parameters for the evaluation

Under steady state conditions, the thermal functions of the clothing system are characterized primarily by two parameters: thermal insulation and water vapour resistance.

The total thermal insulation of a clothing system can be calculated as follows:

$$R_t = \frac{A_{Du}(T_{sk,h} - T_a)}{Q_{t,h}} \tag{2-38}$$

where $Q_{t,h}$ is dry heat transfer through clothing system, $A_{Du}$ surface area of whole body.

The total water vapour resistance can be obtained from the following equation:

$$R_e = \frac{A_{Du}(P_{sk} - P_a)}{Q_{e,h}} \tag{2-39}$$

where $Q_{e,h}$ is the latent heat transfer through a clothing system, $P_{sk}$ is water vapour pressure at skin surface.

$R_t$ and $R_e$ include components due to both the clothing and outer surface air layer. The thermal resistance provided by the outer surface air layer depends upon how environmental conditions affect heat transfer, mainly by convection and radiation.

For a clothed body, the thermal insulation of outer surface air layer is:

$$R_{toa} = \frac{1}{h_{toa}} = \frac{1}{h_r + h_{coa}} \tag{2-40}$$

where $h_{toa}$ is the overall heat transfer coefficient, $h_r$ is radiative heat transfer coefficient and $h_{coa}$ is convective heat transfer coefficient.

Water vapour transfers in the outer surface air layer at a rate depending upon the evaporative heat transfer coefficient $h_e$. The water vapour resistance of the air layer is therefore:

$$R_{eoa} = \frac{1}{h_e} \tag{2-41}$$

$h_e$ can be determined by:

$$h_e = h_{coa} LR \tag{2-42}$$

where, $LR$ is the Lewis number. The value of $LR$ will vary slightly with temperature, but it is typically equal to $0.0165 K / Pa$.

The intrinsic resistance of clothing is the resistance between the skin and the clothing surface. It is determined by subtracting the resistance of the outer surface layer from the total resistance of clothing as follows:

$$R_{tc} = R_t - R_{toa} / f_{cl} \tag{2-43}$$

$$R_{ec} = R_e - R_{eoa} / f_{cl} \tag{2-44}$$

where, $f_{cl}$ is ratio of the clothed surface area of the body to the nude surface area of the body.

Gagge et al. (1941) introduced the *Clo* unit to replace the rather physical unit of $m^{2o}C/W$ with something easily visualized and related to clothing worn on the human body. One *Clo* means that the thermal insulation required to keep a sedentary person comfortable at 21 $^oC$, less 50% RH and with wind speed no more than 0.1 m/s, the body metabolic rate of around 58Watts/$m^2$. It is said to have an average value of 0.155 $m^{2o}C/W$ and is representative of the insulation of a typical business suit.

Woodcock (1962) introduced a parameter under stead state conditions $i_m$ (Moisture Permeability index) to denote the water vapour permeability of clothing. $i_m$ is defined as

$$i_m = \frac{R_t / R_e}{R_{toa} / R_{eoa}} \tag{2-45}$$

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

$$i_m = \frac{R_t}{0.0165 \times R_e} = 60.6 \times \frac{R_t}{R_e} \tag{2-46}$$

The permeability index $i_m$ takes the form of an efficiency factor. Since the ratio $R_t/R_e$ is always less than the ratio $R_{toa}/R_{eoa}$. It has a theoretical range from zero (for the completely impermeable clothing system) to one (for the ideally permeable one).

Crockford and Rosenblum (1974) proposed ventilation index (VI) to evaluate the ventilation properties of clothing under steady state conditions. It is determined by:

$$VI = V_{mc} \times \text{Air exchange rate} \tag{2-47}$$

where $V_{mc}$ is total clothing climate volume. This index is a quantitative representation of total micro-environment air exchange for clothing ensemble under a specified set of conditions.

Although the clothing ventilation index is a quantitative, relatively inexpensive, fast, reliable and repeatable measure, it varies not only with the clothing features but also with wind velocity and walking speed. Qian (2005) derived clothing ventilation index as follows:

$$VI = KV \times A_{du} \times \left(V_{wind} + 2V_{walk} - 0.22\right) \tag{2-48}$$

$KV$ is a dimensionless coefficient of clothing system independent of wind velocity and walking speed, only determined by the clothing features such as garment style, fit and properties of garment fabrics. So $KV$ is a better parameter for the evaluation of the ventilation properties of clothing system than ventilation index.

All the above parameters are applicable for steady state conditions. Because of the complexity for the heat and moisture transfer under dynamic conditions, little work was reported on the evaluation of dynamic thermal performance of fabric. Barbara Pause (1995) proposed the concept of dynamic thermal insulation to measure the transient effect of PCM fabrics, he assumed that the total insulation of PCM fabrics is consisted of a basic insulation and a dynamic thermal insulation which is determined from the duration of the temperature variation during the phase change. By comparing the time for achieving the end temperature of the phase change range of the samples with and without PCM and with reference to the basic thermal insulation of the samples, the dynamic thermal insulation can be calculated. Hittle and Andre (2002) firstly proposed the index called temperature regulating factor (TRF) to indicate the dynamic thermal properties of PCM fabrics. It is based on two assumptions: the thermal conductivity, the density and the specific heat are constant; a constant and comparably large heat capacity is a reasonable approximation for the phase change process occurring in the PCM fabric. Based on this research, ASTM published a standard D7024 (2004) for test method for the determination of TRF.

TRF can be obtained by dividing the amplitude of the temperature variation of the hot plate by the product of the amplitude of the hot plate flux variation and the steady state thermal resistance of fabric. In 2004, Ying et al. proposed three indices to characterize the dynamic properties of PCM fabrics: the static thermal insulation, the thermal regulating capability and the thermal psychosensory intensity.

There is no parameter proposed to describe the dynamic thermal properties of clothing ensembles up to now, although some work attempted to measure the effect of transient thermal properties using thermal manikins. De Dear et al. (1989) applied a non-sweating thermal manikin to investigate the thermal effect of absorption of clothing by changing the environmental humidity. From the manikin's heat loss, the effect of absorption can be observed. ASTM standard F2371 (2005) reported a test method for measuring the thermal effect of Personal Cooling Systems (PCS) using a sweating thermal manikin. This method assesses the effectiveness of PCS by subtracting the time-average power input value and the baseline power value. The baseline power is the power input to the manikin when wearing the turned off PCS (or without the PCS, if it can not be turned off), needed to maintain the skin temperature at $35 \pm 0.5$ $^{o}$C. This method is only applicable to PCS, the dynamic thermal properties of non-PCS clothing can not be evaluated by it.

### 2.4.2 Developments in Instrumentation

Clothing thermal comfort can be evaluated by direct measurements on human subjects or objective simulation tests. Direct measurements on human body are costly and may expose the subjects to danger, and the results tend also to be less accurate and reproducible. Therefore, various forms of objective simulation tests have been developed over the years. The simplest type of the simulation test is the flat plate methods. The frequently used version of this kind is the skin model, which is now an ISO standard (ISO 11092， 1993(E)). To better simulate the human configuration, cylindrical method were also developed (Fan 1989).

Flat plate and cylindrical methods are very useful for evaluating the thermal and water vapor transmission properties of clothing materials or simple clothing assemblies, but present difficulties in applying the results to actual clothing in wear. So many thermal manikins have been developed and applied to measure actual clothing ensembles. In the following sections, the developments of the different instrumentations for measurement of clothing thermal properties are reviewed.

***Flat plate methods***

Lees and Chorlton (1896) developed the first version of flat plate method. This apparatus consisted of a flat cylindrical vessel, a plate at the bottom of the vessel, and a plate hung below the vessel. The temperature within the flat vessel was controlled at 100℃ by passing steam through it. Samples were sandwiched between the upper and lower plates. Temperatures at the lower surface of the upper plate and the upper surface of the lower plate were measured with thermometers. Lees (1898) improved this method, and developed the well known Lee's disc method to evaluate the thermal conductivities of various materials.

Rood (1921) noted the contact thermal insulation between the fabric and the discs and the pressure applied on the fabrics could affect the final results. And He tackled it by using multiple fabric layer techniques and specifying the pressure applied on the fabrics.

Sale (Marsh 1931) developed a new disc method with a guard ring on it. His method employed only on single hot plate, the sample was exposed to the conditioned air and the temperature of the hot plate was controlled at the body temperature. This arrangement is a better simulation of actual clothing in use.

Until 1941, methods that allow simultaneous dry and latent heat transfer were developed. Rees developed a sweating, guarded hot-plate in which the fabrics were placed on a hot, porous plate which was covering on a water dish. Other versions of this kind were developed throughout the world (Mecheels & Umbach 1977, Blyth 1984, Farnworth 1986).

ISO 11092 is the standard test methods on clothing comfort based on the sweating guarded hotplate established in 1993. This standard is intended to simulate the heat and mass transfer process that occur next to human skin and specifies methods for the measurement of the thermal resistance and water vapour resistance of clothing materials under steady-state conditions.

***Cylindrical methods***

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

Since the 1930s, due to the improvement in control techniques, most cylindrical methods have used the constant temperature technique, in which the temperature of the cylindrical body was controlled at a constant level similar to the human body temperature, and the heat supplied to maintain the constant temperature was measured. These methods were used by Marsh in 1931 and Niven & Babbitt in 1938.

Mak (1980) took the advantage of the disc Togmeter design, and applied it in the development of a cylindrical Togmeter. This cylindrical apparatus had an internally heated cylinder and an enclosing layer of known thermal conductivity on which the specimen was covered. The thermal insulation of the specimen as a function of the angular position could be evaluated. This apparatus was especially useful for studies in windy conditions. The criticism to Mak's cylindrical Togmeter was that the size was still too small and heat loss from the ends of the cylindrical apparatus was not prevented. This method was improved by Fan (1989).

In order to study the latent heat transfer, sweating cylindrical apparatus were also developed (Mattle 1999).

***Manikin methods***

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

The first generation were standing (not walk-able) and non-perspiring ones (Kerslake 1963, Fonseca 1975, McCullough et al 1989). The second were movable (walk-able), but non-perspiring ones such as the copper manikin 'Charlie' in Germany (Mecheels and Umbach 1977) and those in Denmark (Olesen et al 1982) and Japan (Hanada 1979).

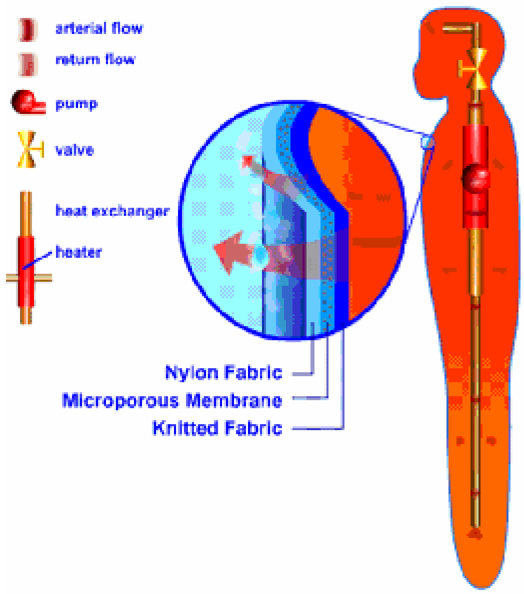
To simulate sweating on non-perspiring manikins, many workers put underwear made of highly absorbent fabrics on the manikin, and supplied water to the underwear by sprinkling or water pipes, so two steps of measurement were necessary as Woodcock and other workers suggested by using these kinds of manikins. The first Step was to measure the dry clothing thermal resistance on a dry manikin and then took the second step, by dressing an underwear made of hydrophilic material on the manikin as its new sweating skin, then spraying water on it, and putting the clothing on the manikin again to measure the evaporative resistance. Under this situation, the evaporative heat can be calculated by subtracting the dry heat loss from the total heat loss. This two-steps method can result in a serious underestimate of the maximum heat loss through clothing, because of the interaction between heat and moisture transfer, the increased heat and moisture transfer through damp clothing, the buffering action of hygroscopic clothing (Spencer-Smith 1976) and the prolonged (more than 12 hours) moisture accumulation (Fan and Chen 2002).

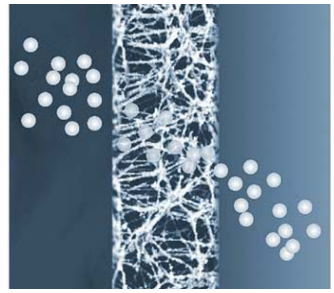
The third generation manikins, that can simulate true perspiration and body motion, are still very rare in the world. The perspiring manikins developed in Japan (Yasuhiko et al 1992) cannot simulate movement. Out of more than 80 manikins in use worldwide, there are a few movable and perspiring manikins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

***Walter***

Many thermal manikins have been developed around the world since the first one segment and dry manikin from the US Army in 1940s. Despite of this, simulation of human perspiration remained to be a big challenge. Fan and Chen (2002) developed a completely new type of perspiring manikin called “Walter”. Fan et. al. further improved it in terms of hardware and software(Fan et. al. 2003, Qian 2005).

Walter is the first perspiring fabric manikin in the world, which is made of mainly water and high strength breathable fabric. Walter has four main features. First, it has a waterproof but moisture permeable fabric ‘skin’ that simulates the evaporation of sweat (Figure 2-2). Second, it has “blood circulation system”. Water at body temperature is pumped from the centre of manikin’s body to his extremities. So he achieves a body temperature distribution similar to a real person. Thirdly, it has metabolic rate. The heater exchangers in its body provide the internal heat production. Fourthly, Walter’s arms and legs are motorized, allowing the simulation of “walking”. Finally, unlike most existing manikins, Walter takes only one step to measure the two most important parameters- thermal insulation and moisture vapour resistance.



Moisture pass through membrane

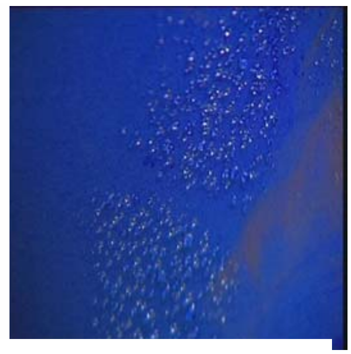


Image of sweating on skin

*Figure 2-2 Simulating the evaporation of sweat by Walter*

The entire measurement and control system is illustrated as Figure 2-3.

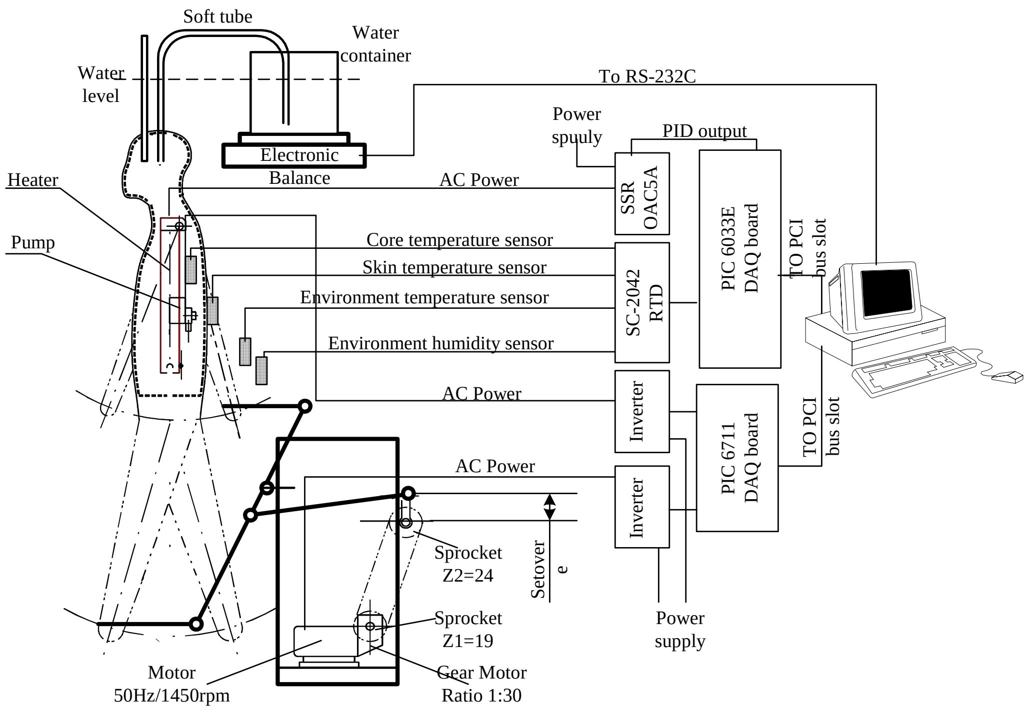



*Figure 2-3 The measurement system of walk-able fabric sweating manikin*

In this present research, Walter is to be applied to simulate transient procedure from standing at rest to walking for a long period so as to measure the thermal properties of clothing ensemble under transient conditions.

## 2.5 Concluding remarks

A lot of studies have been carried on human thermal comfort, human thermal physiological mechanisms and the thermal functions of the clothing system. A number of models were developed to simulate their behaviors. In order to characterize the thermal properties of the clothing system, people proposed some parameters and developed kinds of methods to measure these parameters.

However, the following problems still remain:

(1) Little work has been done to investigate the coupled dynamic heat and moisture transfer through the clothing ensembles, although some work was carried out on the dynamic heat and moisture transfer through layered fabrics.

(2) Some dynamic human-clothing-environment models have been developed to investigate the influence of the thermal properties of the clothing system on human physiological response. However, these models have not considered ventilation through clothing openings, which is an important heat and moisture transport mechanism in actual clothing ensembles.

(3) Dynamic parameters and the measurement method have not been established to evaluate the transient thermal behaviors of entire clothing systems.

# Chapter 3 Transient Thermal Model of the Human Body-Clothing-Environment System

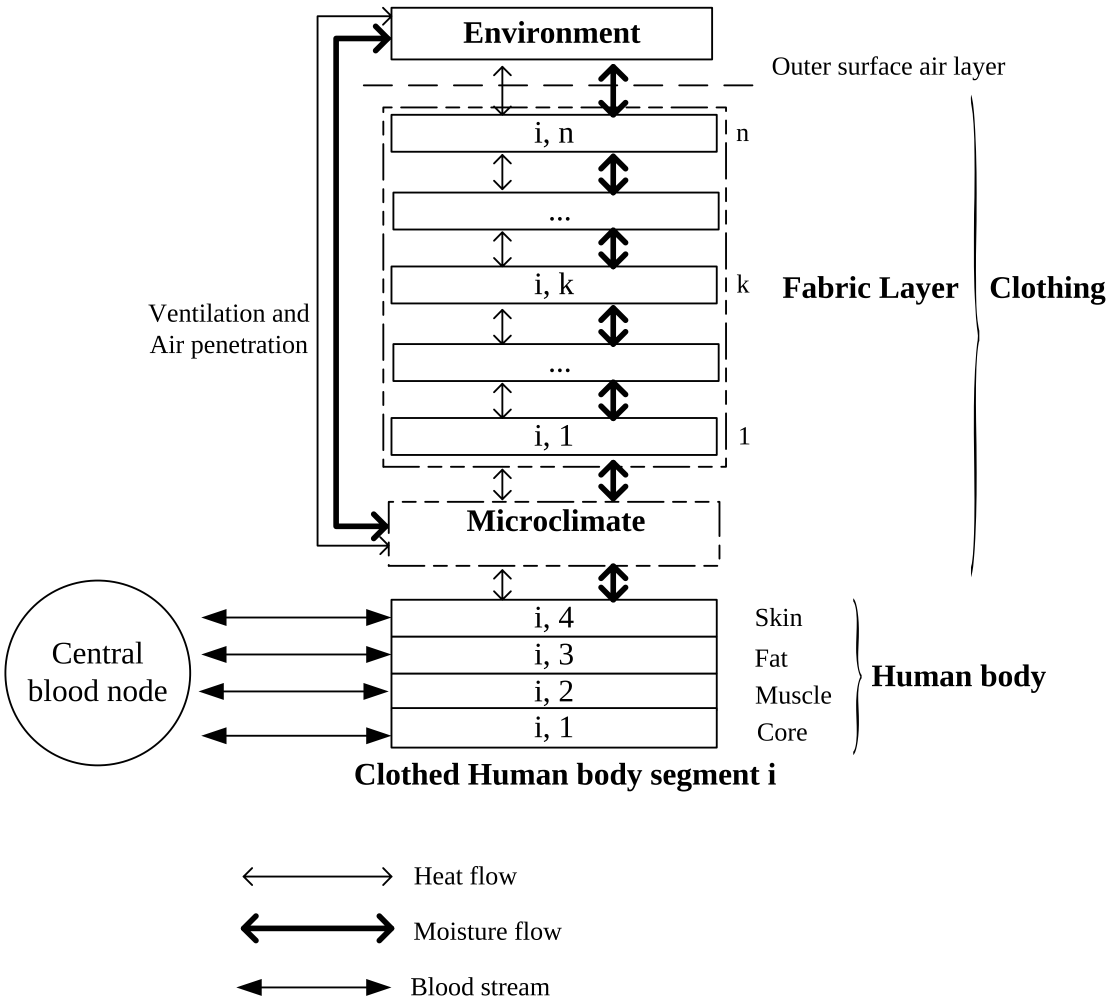
## 3.1 Introduction

Human beings are exposed to a transient thermal environment. Within a limit, human body can regulate the heat exchange with the environment to maintain heat balance. However, when exceeding the environmental limit, such as too hot, too cold or too windy, the regulation ability would be insufficient to maintain the heat balance with the environment. As a behavioural response, human put on clothing to assist his body in adapting the environment.

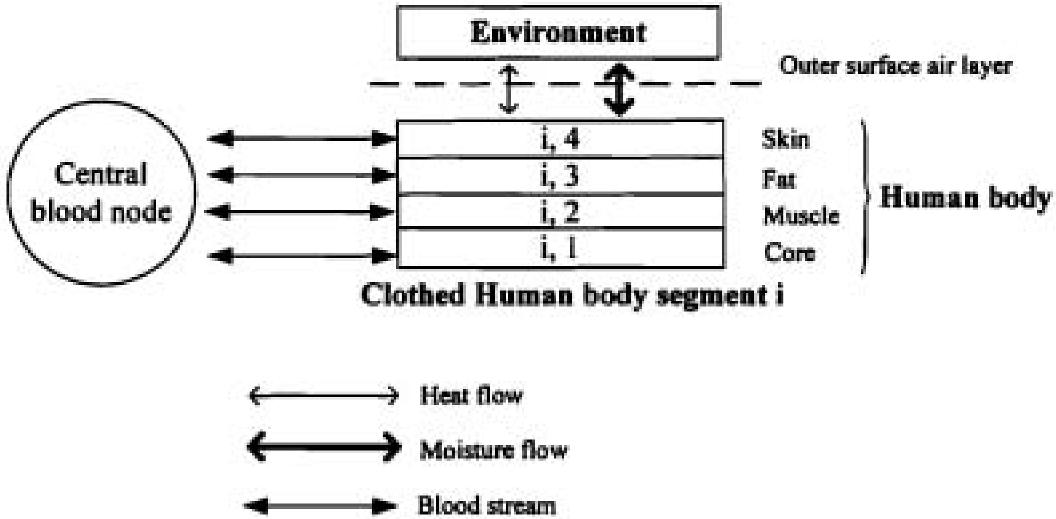
When a person is dressed with clothing, the process of heat exchange between human body and the environment becomes very complex. Heat and moisture transfer through clothing are dissipated from the skin of human body. After that, they are divided into two parts. One flows directly into the environment by convection and radiation from the exposed skin. The other is transferred into the clothing microclimate. In the clothing microclimate, some is taken away by ventilation; the remainder goes through clothing materials. Finally, it goes out from the outer surface of clothing ensembles. In the clothing materials, conduction, convection, radiation are the mechanisms of heat transfer, while diffusion, absorption/desorption, condensation/evaporation and wicking are the forms of liquid water/moisture transfer. Heat and moisture transfer are coupled since that absorption/desorption and condensation/evaporation are accompanied with heat release and absorption.

The understanding of the dynamic heat and moisture transfer through the human-clothing-environment system and its effect on the transient physiological response is important to not only the well-being of human body, but also the design of better clothing and environmental engineering. Many researchers (Wissler, 1964; Stolwijk and Hardy, 1966; Gagge et al., 1971, 1986; Smith, 1991; Jones and Ogawa, 1992, Huizenga et al., 2001; Tanabe et al., 2002) have contributed to the modeling of the physiological regulatory responses of human body during thermal transients. However, most of these models focused on the dynamic physiological behaviour of human body by simplifying clothing as static resistances of heat and moisture transfer. Although some researchers did consider some dynamic properties of fabrics (Xu and Werner, 1997; Li and Holcombe, 1998; Fu, 1995; Umeno et al., 2001; Li et al., 2004), none of these studies has considered the effect of clothing ventilation, which can cause up to 50% reduction in thermal insulation and up to 88% reduction in evaporative resistance (Havenith et al., 1990) depending on the level of activity.

In this chapter, a new transient thermal model, which incorporates Tanabe et al (2002)’s 16 body segments thermoregulatory model as well as the dynamic heat and moisture transfer through clothing including liquid water transport and clothing ventilation, is reported on. The numerical results of the model are compared with two sets of experimental data.




(a) for covered body segments




(b) for uncovered body segments.

*Figure 3-1 Human body-Clothing-Environment System*

### 3.2 Model Description

In this work, the human body is assumed to consist of 16 segments, viz. head, chest, back, pelvis, left shoulder, right shoulder, left arm, right arm, left hand, right hand, left thigh, right thigh, left leg, right leg, left foot and right foot, and each of the segments is composed of four concentric layers of core, muscle, fat and skin. This assumption is in accordance with that of Tanabe et al (2002)'s human thermoregulatory model, which is an extension of the widely recognized Stolwijk (1966)'s thermoregulatory model. Out of the totally 16 segments, some segments are uncovered by clothing and the remaining segments are covered by clothing. For a particular clothed body segment, the clothing is considered as consisting of n layers. The model for the clothed and unclothed segments is illustrated in Figure 3-1(a) and 3-1(b), respectively.

### 3.2.1 Heat transfer within the human body

According to Tanabe et al. (2002)'s thermoregulatory model, all of the blood circulation in the human body is represented by a central blood node. The central blood node is connected to all of the tissue segments by a network of blood vessels which somehow represents the whole-body blood circulation. Heat is transferred through the tissues within individual segment by conduction. The central blood node only exchanges heat energy with other tissue segments by means of convection. Consequently, we have the heat balance equation for each body node (viz. the core, muscle, fat and skin layer in each human body segment) and for the central blood node as follows:

Core layer: $$Cp_{i,1}\frac{dT_{i,1}}{dt} = H_{h,i,1} - Q_{b,i,1} - Q_{cond,i,1} - Q_{res,i,1} \tag{3-1}$$

Muscle layer: $$Cp_{i,2}\frac{dT_{i,2}}{dt} = H_{h,i,2} - Q_{b,i,2} + Q_{cond,i,1} - Q_{cond,i,2} \tag{3-2}$$

Fat layer: $$Cp_{i,3}\frac{dT_{i,3}}{dt} = H_{h,i,3} - Q_{b,i,3} + Q_{cond,i,2} - Q_{cond,i,3} \tag{3-3}$$

Skin layer: $$Cp_{i,4}\frac{dT_{i,4}}{dt} = H_{h,i,4} - Q_{b,i,4} + Q_{cond,i,3} - Q_{t,i} - Q_{e,i} \tag{3-4}$$

Central blood: $$Cp_{blood}\frac{dT_{blood}}{dt} = \sum_{i=1}^{16}\sum_{j=1}^{4} Q_{b,i,j} \tag{3-5}$$

where $Cp_{i,j}$ and $Cp_{blood}$ are heat capacity of body node (i, j) and central blood node, respectively, calculated from the specific heat of tissues that constitute each node; $T_{i,j}$ and $T_{blood}$ are the temperature of body node (i, j) and central blood node; $H_{h,i,j}$ is the rate of internal heat production; $Q_{b,i,j}$ is the heat exchange between each body node and central blood node; $Q_{cond,i,j}$ is the heat transmitted by conduction to neighboring layer of the same segment; $Q_{res,i,1}$ is the heat loss by respiration; $Q_{t,i}$ and $Q_{e,i}$ are sensible and latent heat loss from the skin, respectively.

$H_{h,i,j}$ is the sum of basal metabolic rate $Met_{b,i,j}$, heat production caused by external work $Q_{w,i,j}$ and shivering heat production $Met_{shiv,i,j}$, viz:

$$H_{i,j} = Met_{b,i,j} + Q_{w,i,j} + Met_{shiv,i,j} \tag{3-6}$$

Shivering heat production is one of the thermoregulatory mechanisms of man against cold, it is an increase of heat production during cold exposure due to increased contractile activity of skeletal muscles. Heat production caused by external work and shivering heat production only occurs in muscle layer (j=2), so for other layers ( $j \neq 2$ ) $Q_{w,i,j} = 0$, $Met_{shiv,i,j} = 0$.

In the muscle layer (j=2), they are expressed by Equation 3-7 and Equation 3-8, respectively.

$$Q_{w,i,2} = (Met - Met_b - W) A_{Du} Metf_i \tag{3-7}$$

where, $W$ is the total external work performed by the human body. $Metf_i$ is the distribution coefficient of heat production, due to external work, assigned to the various muscle nodes ,

$$Met_{shiv,i,j} = \{-C_{ch}Err_{1,1} - S_{ch}(Wrms - Clds) + P_{ch}Cld_{1,1}Clds\}Chilf_i \tag{3-8}$$

where, $C_{ch}$ , $S_{ch}$ and $P_{ch}$ are control coefficients, $Err_{i,j}$ is the error signal which is the difference between the temperature of the node $T_{i,j}$ and the set point temperature of the node $T_{set,i,j}$ . $Wrm_{i,j}$ and $Cld_{i,j}$ are warm and cold signal of the warm and cold receptors, respectively. When

$Err_{i,j} > 0$ ,$Wrm_{i,j} = Err_{i,j}$ ,$Cld_{i,j} = 0$; when $Err_{i,j} < 0$, $Cld_{i,j} = Err_{i,j}$ ,$Wrm_{i,j} = 0$.

$Wrms$ and $Clds$ are integrated sensor signals from skin thermoreceptors. They are defined by the following equations. $SKINR_i$ is the weighting coefficient for integration.

$$Wrms = \sum_{i=1}^{16}\left(SKINR_i \times Wrm_{i,4}\right) \tag{3-9}$$

$$Clds = \sum_{i=1}^{16}\left(SKINR_i \times Cld_{i,4}\right) \tag{3-10}$$

$Chilf_i$ is the distribution coefficient of individual muscle layer for the shivering heat production.

$Q_{b,i,j}$ mainly depends on the blood flow rate $BF_{i,j}$ and the temperature difference between each node and central blood node. It may be calculated by:

$$Q_{b,i,j} = aCv_{Blood}BF_{i,j}\left(T_{i,j} - T_{Blood}\right) \tag{3-11}$$

$a$ is the ratio of counter-current heat exchange. $Cv_{Blood}$ is the volumetric specific heat of blood.

In the muscle layer (j=2), the blood flow rate is the sum of basal blood flow $BFB_{i,j}$ and the blood flow caused by external work and shriving. It is assumed that the blood flow of 1 Liter per hour is required for 1.16 W heat production (Tanabe et al 2002), thus

$$BF_{i,j} = BFB_{i,j} + \frac{Q_{w,i,j} + Met_{shiv,i,j}}{1.16} \tag{3-12}$$

In the skin layer (j=4), blood flow rate is regulated by vasodilation and vasoconstriction. It is determined by

$$BF_{i,j} = \frac{BFB_{i,j} + SKINV_i \times DL}{1 + SKINC_i \times ST} \times 2^{Err_{i,4}/10} \tag{3-13}$$

where, $SKINV_i$ and $SKINC_i$ are fractional distribution over the skin area for vasodilation and vasoconstriction, respectively. $DL$ and $ST$ are signals for vasodilation and vasoconstriction, respectively.

$$DL = C_{dl} Err_{1,1} + S_{dl}(Wrms - Clds) + P_{dl} Wrm_{1,1} Wrms\,; \tag{3-14}$$

$$ST = -C_{st} Err_{1,1} - S_{st}(Wrms - Clds) + P_{st} Cld_{1,1} Clds \tag{3-15}$$

$C_{dl}$, $S_{dl}$, $P_{dl}$, $C_{st}$, $S_{st}$ and $P_{st}$ are control coefficients.

For other layers (j=1,3 ), $BF_{i,j} = BFB_{i,j}$.

The heat transmitted by conduction to neighboring layer of the same segment can be calculated by:

$$Q_{cond,i,j} = C_{d,i,j}\left(T_{i,j} - T_{i,j+1}\right) \tag{3-16}$$

where $C_{d,i,j}$ is thermal conductance between the node and it neighbor.

Heat loss by respiration is supposed to occur only in the core layer of the chest segment (i=2, j=1). It is a function of ambient air temperature, vapour pressure and the ventilation volume. Since the ventilation volume is closely related to the metabolic rate, it may be expressed as:

$$Q_{res,2,1} = \{1.4 \times 10^{-3} \times (34 - T_a) + 1.7 \times 10^{-5} \times (5867 - P_a)\} \sum_{i=1}^{16} \sum_{j=1}^{4} H_{h,i,j} \qquad (3\text{-}17)$$

where $T_a$ is ambient air temperature, $P_a$ is ambient vapour pressure.

For other body nodes ($i \neq 2, j \neq 1$), $Q_{res,i,j}$ =0.

For Equations 3-1 to 3-17, the control coefficients for an average male have been determined and can be found from Tanabe et al (2002)'s work.

With equations 3-1 to 3-4, provided we know $Q_{t,i}$ and $Q_{e,i}$ (viz. direct and evaporative heat loss from the skin), we can determine the transient responses of core and skin temperature.

For the clothed body segments, we have:

$$Q_{t,i} = h_c (T_{i,4} - T_{mc,i}) \qquad (3\text{-}18)$$

$$Q_{e,i} = \lambda h_m (P_{sk,i} - P_{mc,i}) \qquad (3\text{-}19)$$

where, $\lambda$ is latent heat of evaporation of water, and $h_c$ and $h_m$ are the convective heat and moisture transfer coefficient between the skin and the microclimate, respectively; $T_{mc,i}$ and $P_{mc,i}$ are temperature and water vapour pressure within the clothing microclimate. These parameters are dependent on the heat and moisture transfer through the clothing system, which will be discussed in the following sections.

For the unclothed body segments, we have:

$$Q_{t,i} = \frac{T_{i,4} - T_a}{R_{toa}} \tag{3-20}$$

$$Q_{e,i} = \frac{P_{sk,i} - P_a}{R_{eoa}} \tag{3-21}$$

where $R_{toa}$ and $R_{eoa}$ are the heat and water vapour resistance of the outer surface air layer. They can be calculated by (Qian and Fan, 2006):

$$R_{toa} = \frac{1}{h_r + 8.3 \times \sqrt{0.11 + 0.45V_{walk} + V_{wind}}} \tag{3-22}$$

$$R_{eoa} = \frac{1}{0.137 \times \sqrt{0.11 + 0.45V_{walk} + V_{wind}}} \tag{3-23}$$

where, $h_r$ is radiative heat transfer coefficient, $h_r = 5.0Wm^{-2}K^{-1}$.

### 3.2.2 Sweat secretion and accumulation on the skin surface

To determine the evaporative heat loss from the skin, it is necessary to model the sweat secretion and accumulation on the skin surface as well as sweat evaporation from the skin and liquid sweat transport through the clothing layers.

Sweating secretion rate is calculated by (Tanabe et al 2002):

$$m_{rsw,i} = \{C_{sw}Err_{1,1} + S_{sw}(Wrms - Clds) + P_{sw}Wrm_{1,1}Wrms\}SKINS_i\, 2^{Err_{i,4}/10} \big/ \lambda \quad (3\text{-}24)$$

where, $SKINS_i$ is fractional distribution over the skin area for sweat. $C_{sw}$, $S_{sw}$ and $P_{sw}$ are control coefficients.

With regard to sweat accumulation on the skin surface, we adapt Umeno et al (2001)'s proposal that the amount of sweat accumulated on the skin surface does not exceed a limit of $35\, g/m^2$. The excess amount of sweat is either absorbed by the inner layer of the clothing at clothed body parts or dripped down at unclothed body parts.

When the sweat accumulation is less than 35 g/m$^2$, sweat accumulation is determined from the difference between the sweat rate plus skin diffusion and the evaporation from the skin (Jones and Ogawa 1992). For the clothed body segments, we have

$$\frac{dM_{swa,i}}{dt} = m_{rsw,i} + \frac{P_s(T_{i,4}) - P_{sk,i}}{\lambda R_{esk,h}} - h_m(P_{sk,i} - P_{mc,i}) \quad (3\text{-}25).$$

When there is sweat accumulation on the skin, the water vapour pressure $P_{sk,i}$ on the surface is saturated; before sweat accumulation takes place, $P_{sk,i}$ is determined by the moisture equilibrium of Equation 3-25, viz.:

$$P_{sk,i} = \begin{cases} P_s(T_{i,4}) & M_{swa,i} > 0 \\ \dfrac{m_{rsw,i}\lambda R_{esk,h} + P_s(T_{i,4}) + P_{mc,i}\lambda R_{esk,h} h_m}{h_m \lambda R_{esk,h} + 1} & M_{swa,i} = 0 \end{cases} \quad (3\text{-}26)$$

In the same way, for the unclothed body segments, we have

$$\frac{dM_{swa,i}}{dt} = m_{rsw,i} + \frac{P_s(T_{i,4}) - P_{sk,i}}{\lambda R_{esk,h}} - \frac{P_{sk,i} - P_a}{\lambda R_{eoa}} \tag{3-27}$$

$$P_{sk,i} = \begin{cases} P_s(T_{i,4}) & M_{swa,i} > 0 \\ \dfrac{\lambda m_{rsw,i} R_{esk,h} R_{eoa} + P_s(T_{i,4}) R_{eoa} + P_a R_{esk,h}}{R_{esk,h} + R_{eoa}} & M_{swa,i} = 0 \end{cases} \tag{3-28}$$

### 3.2.3 Direct and evaporative heat loss from clothed body segments

For the body parts covered by the clothing, heat and moisture transfer from the covered skin to the environment through the clothing microclimate, the fabric layers and the outer surface air layer of the clothing.

#### 3.2.3.1 Heat balance equations

Assume the convective heat transfer coefficient between the skin and the microclimate and that between the microclimate and the inner layer of clothing is the same at different body segments, the heat balance equations of the clothing microclimate between the human body and clothing can be expressed as:

$$V_{mc,i} C v_a \frac{dT_{mc,i}}{dt} = h_c\left(T_{i,4} - T_{mc,i}\right) - h_c\left(T_{mc,i} - T_{cl,i,1}\right) - Q_{vent,i} \tag{3-29}$$

where, $V_{mc,i}$ is the volume of microclimate in body segment $i$. Here we assume the volume of the microclimate is uniformly distributed around the clothed skin surface, so we have

$$V_{mc,i} = V_{mc} \times \frac{A_{Du,i}}{A_{Du,f}} \tag{3-30}$$

In Equation 3-29, $Q_{vent,i}$ is the heat loss from the microclimate due to ventilation and air penetration and $h_c$ is the convective heat transfer coefficient between the skin and the microclimate or that between the microclimate and the inner layer of clothing, the determination of these two parameters will be explained in Section 3.2.3.3 and 3.2.3.4.

In establishing the heat balance equations of the clothing, we assume it consists of n (k=1,n) discretized fabric layers. The heat balance equation of the innermost layer (k=1) is:

$$M_{cl,i,1} Cp_{cl,i,1} \frac{dT_{cl,i,1}}{dt} = h_c \left(T_{mc,i} - T_{cl,i,1}\right) - \frac{T_{cl,i,1} - T_{cl,i,2}}{R_{t,i,1}} + Q_{c,i,1} \tag{3-31}$$

The heat balance equations of the inner fabric layers are:

$$M_{cl,i,k} Cp_{cl,i,k} \frac{dT_{cl,i,k}}{dt} = \frac{T_{cl,i,k-1} - T_{cl,i,k}}{R_{t,i,k-1}} - \frac{T_{cl,i,k} - T_{cl,i,k+1}}{R_{t,i,k}} + Q_{c,i,k} \tag{3-32}$$

The heat balance equation of the outside layer (k=n) can be expressed as:

$$M_{cl,i,n} Cp_{cl,i,n} \frac{dT_{cl,i,n}}{dt} = \frac{T_{cl,i,n-1} - T_{cl,i,n}}{R_{t,i,n-1}} - \frac{T_{cl,i,n} - T_a}{R_{toa}} + Q_{c,i,n} \tag{3-33}.$$

In Equation 3-31 to 3-33, the thermal capacity of the fabric layer, $Cp_{cl,i,k}$, can be calculated from that of the component fibers and water content in the fabric, viz.:

$$Cp_{cl,i,k} = \frac{M_{f,i,k} Cp_f + M_{clw,i,k} Cp_l}{M_{cl,i,k}} \quad (3\text{-}34),$$

$R_{t,i,k}$ is thermal insulation of fabric layer, which is dependent on the thickness and the effective thermal conductivity. It can be calculated by

$$R_{t,i,k} = \frac{th_{layer,i,k}}{\varepsilon_{a,i,k} K_a + \varepsilon_{l,i,k} K_l + \varepsilon_{f,i,k} K_f + \varepsilon_{bw,i,k} K_l} \quad (3\text{-}35),$$

$Q_{c,i,k}$ is heat released by condensation or absorption, the determination of this parameter will be explained in Section 3.2.3.2.

### 3.2.3.2 Moisture Balance Equations

We assume the convective moisture transfer coefficient between the skin and the microclimate and that between the microclimate and the inner layer of clothing is the same at different body segments, the moisture balance equation for the clothing microclimate can thus be described as

$$V_{mc,i} \frac{dC_{mc,i}}{dt} = h_m \left(P_{sk,i} - P_{mc,i}\right) - h_m \left(P_{mc,i} - P_{cl,i,1}\right) - m_{vent,i} \quad (3\text{-}36)$$

where, $m_{vent,i}$ is the moisture loss from the microclimate due to ventilation and air penetration and $h_m$ is the convective moisture transfer coefficient between the skin and the microclimate or that between the microclimate and the inner layer of clothing. The determination of these two parameters will be explained in Section 3.2.3.3 and 3.2.3.4.

The balance of moisture in the innermost fabric layer (k=1) can be expressed as follows.

$$\frac{dM_{clw,i,1}}{dt} = h_m\left(P_{mc,i} - P_{cl,i,1}\right) - \frac{P_{cl,i,1} - P_{cl,i,2}}{\lambda R_{e,i,1}} + m_{s,i} - m_{l,i,1} \qquad (3\text{-}37)$$

where $m_{s,i}$ is the excess sweat captured by the inside surface. It is assumed that, in the clothed body parts, the amount of sweat in excess of the limit of 35 g/m$^2$ in the interface between the skin and inner layer of clothing is fully absorbed by the inner layer of fabric (Umeno et al 2001).

The balance of moisture in the inner fabric layer can be expressed as

$$\frac{dM_{clw,i,k}}{dt} = \frac{P_{cl,i,k-1} - P_{cl,i,k}}{\lambda R_{e,i,k-1}} - \frac{P_{cl,i,k} - P_{cl,i,k+1}}{\lambda R_{e,i,k}} + m_{l,i,k-1} - m_{l,i,k} \qquad (3\text{-}38)$$

The balance of moisture in the outer fabric layer (k=n) can be expressed as

$$\frac{dM_{clw,i,n}}{dt} = \frac{P_{cl,i,n-1} - P_{cl,i,n}}{\lambda R_{e,i,n-1}} - \frac{P_{cl,i,n} - P_a}{\lambda R_{eoa}} + m_{l,i,n-1} \qquad (3\text{-}39)$$

In Equation 3-37 to 3-39, $R_{e,i,k}$ is water vapour resistance of the fabric layer, which can be calculated by

$$R_{e,i,k} = \frac{\tau R(T_{cl,i,k} + 273.15) th_{layer,i,k}}{\lambda D_a \varepsilon_{a,i,k} M_w} \qquad (3\text{-}40)$$

In this work, we adapt Farnworth (1986)'s assumption that three forms of water, vapour, liquid and absorbed water, reach equilibrium locally with each other very rapidly; and the regain of fabric is directly proportional to the surrounding relative humidity, the constant of proportionality being derived from measured value at 20℃ and 65%RH. Then as Farnworth (1986) explained by, $P_{cl,i,k}$ can be calculated by:

$$P_{cl,i,k} = \begin{cases} P_s(T_{cl,i,k}) & M_{clw,i,k} \geq M_{\max,i,k} \\ \dfrac{M_{clw,i,k}}{\dfrac{th_{layer,i,k}(1-\varepsilon_{f,i,k})M_w}{R(T_{cl,i,k}+273.15)} + \dfrac{\gamma M_{f,i,k}}{P_s(T_{cl,i,k})}} & M_{clw,i,k} < M_{\max,i,k} \end{cases} \quad (3\text{-}41)$$

$M_{\max,i,k}$ is the maximum quantity of water per unit fabric area that can be present as vapour, beyond this value condensation will occur,

$$M_{\max,i,k} = \frac{th_{layer,i,k}(1-\varepsilon_{f,i,k})M_w P_s(T_{cl,i,k})}{R(T_{cl,i,k}+273.15)} + \gamma M_{f,i,k} \quad (3\text{-}42)$$

Heat released by condensation or absorption $Q_{c,i,j}$ may be expressed as:

$$Q_{c,i,k} = \begin{cases} \dfrac{P_{cl,i,k-1} - P_{cl,i,k}}{R_{e,i,j-1}} - \dfrac{P_{cl,i,k} - P_{cl,i,k+1}}{R_{e,i,j}} & M_{clw,i,k} \geq M_{\max,i,k} \\ \dfrac{\lambda_a\left(\dfrac{P_{cl,i,k-1} - P_{cl,i,k}}{\lambda R_{e,i,k-1}} - \dfrac{P_{cl,i,k} - P_{cl,i,k+1}}{\lambda R_{e,i,k}}\right) + \lambda_l\left(m_{w,i,k-1} - m_{w,i,k}\right)}{1 + \dfrac{th_{layer,i,k}(1-\varepsilon_{f,i,k})M_w P_s(T_{cl,i,k})}{R(T_{cl,i,k}+273.15)\gamma M_{f,i,k}}} & M_{clw,i,k} < M_{\max,i,k} \end{cases}$$

(3-43)

where $\lambda_a$ is heat released during moisture absorption by the fibers, $\lambda_l$ is heat of absorption of liquid water by the fibers.

$m_{l,i,k}$ is the liquid water flow rate from the k$^{th}$ fabric layer to the k+1$^{th}$ one caused by wicking action, the actual process of wicking action within the fabric is rather complicated, depending on many factors such as fiber geometry, fiber surface tension, porosity, etc. With reference to Fan et al.'s work (2004), here the process is simplified as liquid water diffusion and modeled by:

$$m_{l,i,k} = D_l \rho_l \left(1 - \varepsilon_{f,i,k}\right) \frac{\tilde{W}_{i,k} - \tilde{W}_{i,k+1}}{th_{layer,i,k}} \tag{3-44}$$

where $D_l$ is diffusion coefficient of liquid water, $\rho_l$ is density of liquid water; $\tilde{W}_{i,k}$ is the free water content, defined as the mass of free water divided by the mass of the fibers, which can be calculated from the total water mass minus the water absorbed within the fiber. Based on the presumption of local moisture equilibrium, we have:

$$\tilde{W}_{i,k} = \begin{cases} \dfrac{M_{clw,i,k} - M_{\max,i,k}}{M_{f,i,k}} & M_{clw,i,k} > M_{\max,i,k} \\ 0 & M_{clw,i,k} \le M_{\max,i,k} \end{cases} \tag{3-45}$$

#### 3.2.3.3 Ventilation and air penetration

The heat and moisture loss from the clothing microclimate due to ventilation and air penetration, $Q_{vent,i}$, is related to body motion, wind velocity and temperature differences between the microclimate and the environment. Based on extensive analysis of experimental data, Qian (2005) proposed the following empirical formulas to calculate the ventilative heat loss:

$$Q_{vent,i} = KVI\left(V_{wind} + 2V_{walk} - v_0\right)\left(T_{mc,i} - T_a\right) \tag{3-46}$$

$$m_{vent,i} = \frac{KVR}{\lambda}\left(V_{wind} + 2V_{walk} - v_0\right)\left(P_{mc,i} - P_a\right) \tag{3-47}$$

where, $KVI$ and $KVR$ are constants depending on garment fitting, styles of design and construction of clothing ensemble, $V_{wind}$ is the velocity of wind blowing towards a person, $V_{walk}$ is the walking speed, $v_0$ is a reference air velocity, denoting the air speed of the so called "still air" condition ($v_0 = 0.22 m/s$). The value of $KVI$ typically ranges from 0.6 for a person wearing loose fitting T-shirt and a pant up to 2.0 for someone wearing an underwear, a jacket and a pant. The value of $KVR$ typically ranges from 0.005 for a person wearing loose fitting T-shirt and a pant up to 0.015 for someone wearing an underwear, a jacket and a pant.

For a specific clothing system, $KVI$ and $KVR$ may be determined from the clothing thermal insulation when the wearer is standing in the still air condition and that when the wearer is walking in a windy condition (Qian 2005) by:

$$KVI = \frac{\dfrac{1}{R_{t,dyn} - R_{tci}} - \dfrac{1}{R_{tco} + R_{toa} / f_{cl}}}{V_{wind} + 2V_{walk} - v_0} \qquad (3\text{-}48)$$

$$KVR = \frac{\dfrac{1}{R_{e,dyn} - R_{eci}} - \dfrac{1}{R_{eco} + R_{eoa} / f_{cl}}}{V_{wind} + 2V_{walk} - v_0} \qquad (3\text{-}49)$$

where, $f_{cl}$ is the clothing area factor of the outer garments (viz. the ratio of the outer surface area of the clothing over the surface area of the human body); $R_{t,dyn}$, $R_{tci}$, and $R_{tco}$ are the total clothing thermal insulation when the person is walking in windy conditions, the intrinsic thermal insulation of the inner tight-fitting underwear, the intrinsic thermal insulation of the outer garments, respectively. $R_{e,dyn}$, $R_{eci}$, and $R_{eco}$ are the total clothing moisture vapour resistance when the person is walking in windy conditions, the intrinsic moisture vapour resistance of the inner tight-fitting underwear, the intrinsic moisture vapour resistance of the outer garments, respectively. They can be determined by testing the garment on a thermal manikin. For a range of clothing ensembles investigated, Qian (2005) also proposed empirical formulae to estimate the value of $KVI$ and $KVR$.

### 3.2.3.4 Convective coefficients of heat and moisture transfer

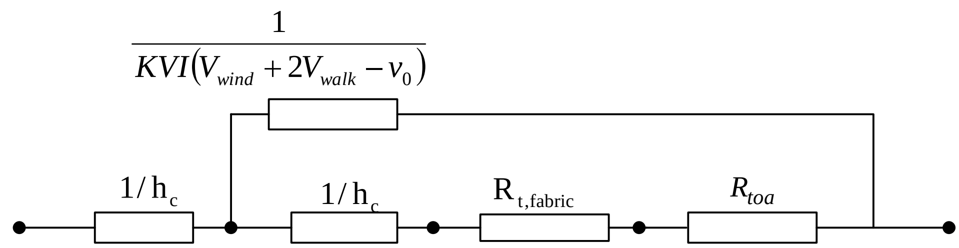



*Figure 3-2 Steady state model of clothing System*

By considering the clothing system in analogy to an electric circuit shown Figure 3-2, the convective heat transfer coefficient between skin and microclimate or between microclimate and inner surface of fabric $h_c$ can be calculated by:

$$1/h_c + \frac{1}{KVI(V_{wind} + 2V_{walk} - v_0) + \dfrac{1}{1/h_c + R_{t,fabric} + R_{toa}}} = R_t \qquad (3\text{-}50)$$

In the same way, $h_m$ can be calculated by:

$$\frac{1}{\lambda h_m}+\frac{1}{KVR(V_{wind}+2V_{walk}-v_0)+\dfrac{1}{1/(\lambda h_m)+R_{e,fabric}+R_{eoa}}}=R_e \tag{3-51}$$

## 3.3 Comparison of model prediction and experimental results

In order to validate the model, the model has been used to predict the transient physiological responses of human subjects in two experiments, and the prediction results are compared with the experimental measurements.

### 3.3.1 Case 1: comparison with the experimental results by Kwon et al.

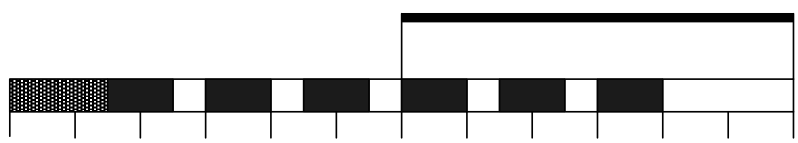


*Figure 3-3 Wearer Trial Procedure in Kwon et al.'s Work*

In 1998, Kwon et al. conducted a number of wearer trials to investigate the physiological effects of hydrophilicity and moisture absorption properties of the clothing fabrics. Figure 3-3 illustrates the procedure of the wearer trials. The experiments had two periods, each of which took one hour. The first period was under almost no wind with an air velocity of 0.14 m/s. The second period was under a wind velocity of 1.5 m/s, blowing towards the subject. During the whole period, the climate chamber was controlled at 30 ℃ and 50%RH. Clothing was stabilized in the environment of 20 ℃ and 30%RH before the experiment. The subjects put on a clothing ensemble and then enter the climate chamber for the experiment. After a 15-min rest, the subjects were asked to repeat 10-min sessions of exercise on a cycle ergometer, followed by 5-min rest six times. Based on the reported pulse rate during exercise (about 125 beats/min) and during rest (about 95 beats/min), and according to ISO 8996, i.e.

$$Met = 4HR - 255 \qquad (3\text{-}52),$$

the metabolic rate during exercise was estimated to be 245 w/m2, and that during resting was 125 w/m2.

*Table 3-1 Physical properties of clothing in Case 1*

| **Parameters** | **Symbol** | **Unit** | **Clothing Ensemble B** | **Clothing Ensemble C** | **Source** |
|---|---|---|---|---|---|
| *KVI* | *KVI* | - | 0.75 | 0.75 | Qian, 2005 |
| *KVR* | *KVR* | - | 0.0081 | 0.0081 | Qian, 2005 |
| Total volume of microclimate | $V_{mc}$ | $m^3$ | 0.033 | 0.033 | |
| Mass | $M_{cl}$ | $kgm^{-2}$ | 0.1252 | 0.1272 | Kwon et al., 1998 |
| Thickness | $th$ | m | $4.9 \times 10^{-4}$ | $4.1 \times 10^{-4}$ | Kwon et al., 1998 |
| Thermal conductivity of fibers | $K_f$ | $Wm^{-2}K^{-1}$ | 0.461 | 0.14 | Rae and Bruce, 1973 |
| Regain proportionality constant | $\gamma$ | - | 0.105 | 0.006 | Kwon et al., 1998 |
| Diffusion coefficient of liquid water | $D_l$ | $m^2s^{-1}$ | $5.4 \times 10^{-11}$ | $1.0 \times 10^{-13}$ | Fan et al., 2004 |
| Heat capacity of fibers | $Cp_f$ | $JKg^{-1}K^{-1}$ | 1210 | 1340 | Morton and Hearle, 1993 |

*Table 3-2 Thermal Insulation and Water Vapour Resistance of Clothing Ensembles in Case 1*

| Conditions | Thermal Insulation $R_t$ ($Km^2W^{-1}$) | Moisture Vapour Resistance $R_e$ ( $m^2PaW^{-1}$) |
|---|---|---|
| No Wind, Resting | 0.197 | 33.6 |
| No Wind, Walking | 0.155 | 24.7 |
| Wind, Resting | 0.140 | 21.6 |
| Wind, Walking | 0.137 | 20.7 |

Three kinds of clothing ensembles in the same style (long-sleeved shirts and full trousers), made of three types of fabrics (labeled as A, B and C) with very similar thickness and permeability, but different moisture absorbency, were tested. Fabric A was a blend of wool and cotton, Fabric B a cotton and Fabric C a polyester. Since the blend ratio of fibers in Fabric A is not provided in Kwon et al.'s paper, we only compared the model prediction for clothing made of Fabric B and C. The clothing properties for the computation are derived, as far as possible, from the information given in Kwon et al's work, and where not possible, from the past publications or handbooks for similar materials or clothing. Table 3-1 and Table 3-2 lists the values of these clothing properties and the sources based on which these values are derived from or estimated.

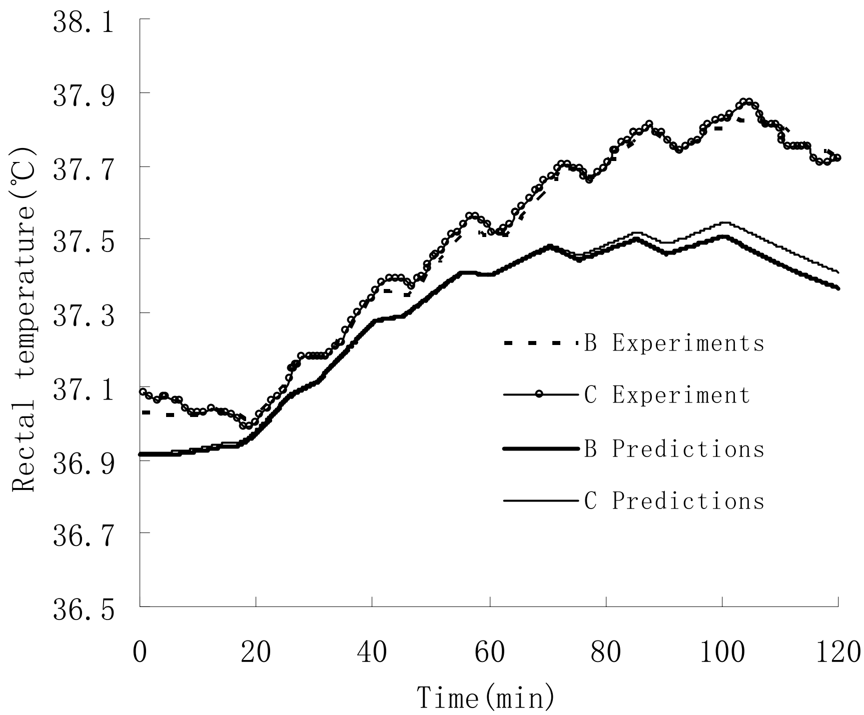



*Figure 3-4 Comparison of rectal temperature prediction of subjects in clothing B and C with experiments in Case1*

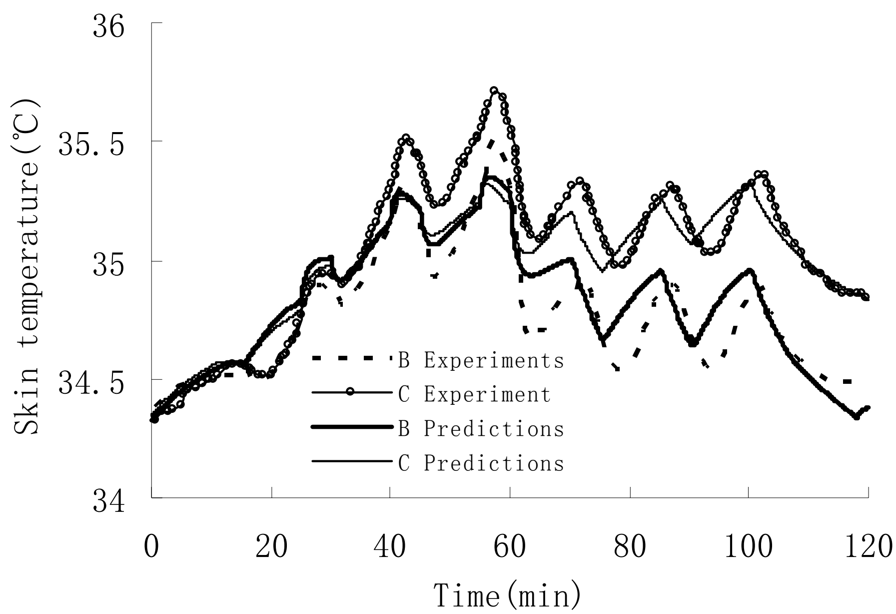



*Figure 3-5 Comparison of mean skin temperature prediction of subjects in clothing B and C with experiments in Case 1*

Figure 3-4 and 3-5 compares the rectal (temperature of the core layer in Pelvis (i=4,j=1)) and mean skin temperature (viz. surface area weighted mean skin temperature) computed by the present model and those measured in Kwon et al. (1998)'s experiments, respectively. As can be seen, the trends predicted by the model are in very good agreements with those measured from the experiments, except that the predicted rectal temperature is relatively lower. The difference between the predicted and measured rectal temperatures may be due to the fact that the model used the control coefficients of an average man as determined by Tanabe et al (2002), but the female human subjects in Kwon et al's experiments had somewhat different physiology from the average man. Both of the results show that $T_{re,h}$ increased gradually on the whole with a greater rise during exercise and a small fall during rest; $T_{sk,h}$ rose during exercise and fell during rest, but generally increased with time during the entire no wind period. When the wind started, $T_{sk,h}$ dropped abruptly to a lower level. The validity of the agreements in terms of absolute values may be arguable, as a number of clothing properties and the exact values of human subjects' control coefficients were not known and estimations had to be made in the computation. However, it is clear that the model has captured the key mechanisms of transient thermal physical responses. Particularly, the model is able to predict the differences of Fabric B and C in terms of body rectal temperature and mean skin temperature during windy conditions, as was observed in the experiments.

### 3.3.2 Case 2: comparison with our own experimental results

*Table 3-3 Physical data of subjects in Case 2*

| **Subject** | **Height** (m) | **Weight** (kg) | **$A_{Du}$** ($m^2$) |
|---|---|---|---|
| 1 | 1.64 | 57.6 | 1.62 |
| 2 | 1.69 | 56.0 | 1.63 |
| 3 | 1.76 | 65.0 | 1.79 |

*Table 3-4 Physical properties of clothing in Case 2*

| **Parameters** | **Symbol** | **Unit** | **Clothing Ensemble** | **Source** |
|---|---|---|---|---|
| *KVI* | *KVI* | - | 0.639 | |
| *KVR* | *KVR* | - | 0.0026 | |
| Total Volume of microclimate | $V_{mc}$ | $m^3$ | 0.019 | |
| Mass | $M_{cl}$ | $kgm^{-2}$ | 0.15093 | |
| Thickness | *th* | m | $5.56\times10^{-4}$ | |
| Thermal conductivity of fibers | $K_f$ | $Wm^{-2}K^{-1}$ | 0.461 | Rae and Bruce, 1973 |
| Regain proportionality constant | $\gamma$ | - | 0.106 | |
| Diffusion coefficient of liquid water | $D_l$ | $m^2s^{-1}$ | $5.4\times10^{-11}$ | Fan et al., 2004 |
| Heat capacity of fibers | $Cp_f$ | $JKg^{-1}K^{-1}$ | 1210 | Morton and Hearle, 1993 |

*Table 3-5 Thermal Insulation and Water Vapour Resistance of Clothing Ensembles in Case 2*

| Conditions | Thermal Insulation $R_t$ ($Km^2W^{-1}$) | Moisture Vapour Resistance $R_e$ ( $m^2PaW^{-1}$) |
|---|---|---|
| No wind, Resting | 0. 171 | 21.0 |
| No wind, Walking | 0. 111 | 14.1 |

We have conducted experiments employing three male subjects wearing cotton T-shirts and shorts to run in a climatic chamber of 20℃, 55%RH and at air velocity of 0.2 m/s (no apparel wind). The heights, body weights and surface area of the three subjects are listed in Table 3-3. The properties of the T-shirts and sorts are listed in Table 3-4 and Table 3-5. Subjects exercised on a running machine at a speed of 1.67 $ms^{-1}$ for 30 min and then had a 10 min rest. The metabolic rate was estimated from the rate of heat beats to be 230 $Wm^{-2}$ during exercise and 100 $Wm^{-2}$ during resting. Skin temperatures were measured with RTD sensors patched at six sites: hand, chest, upper back, lower back, shin and calf. The mean skin temperature $T_{sk,h}$ was calculated by the following equation (Olesen 1984):

$$T_{sk,h} = 0.143T_{hand} + 0.218T_{chest} + 0.181T_{upper\cdot back} + 0.150T_{Lower\cdot back} + 0.167T_{shin} + 0.142T_{calf} \tag{3-53}$$

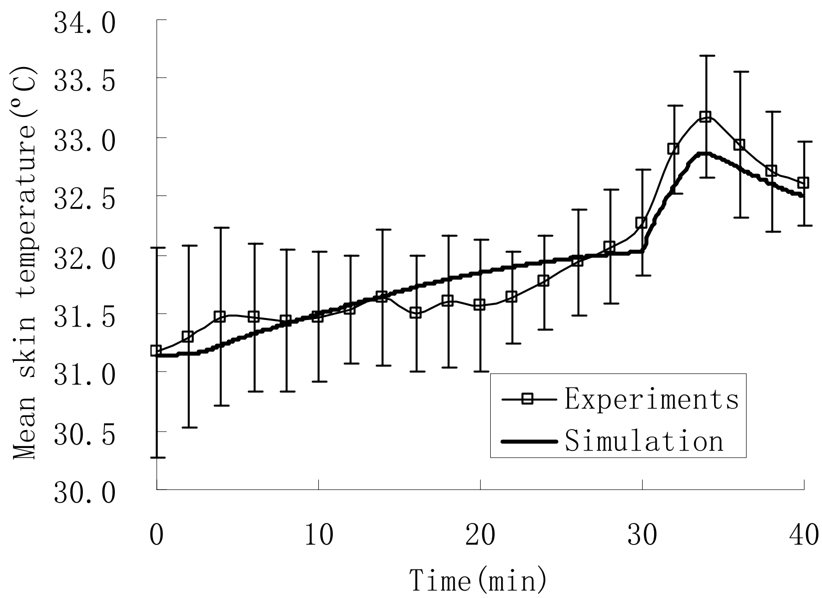



*Figure 3-6 Comparison of mean skin temperature prediction of subjects with experiments in Case 2*

Figure 3-6 plots the comparison of the computed and experimentally measured mean skin temperature $T_{sk,h}$ of the three subjects. In this case, the control coefficients of the human body used in the computation were the same as those published in Tanabe et al's work without adjustment, despite of the fact that the male subjects in our experiments are thinner. As can be seen from the graph, there is a large variation in the measured mean skin temperature, probably due to the large differences of the three male subjects which also vary from time to time. Nevertheless, the trend is clear that $T_{sk,h}$ increased gradually during exercise period, rose sharply at the beginning of the rest period, and reached the peak approximately at the 34$^{th}$ minute. After that, it began to decrease. The computational results had a very good agreement with the experimental ones.

## 3.4 Conclusions

In this chapter, a novel transient thermal model of the Human body-Clothing-Environment system is presented. The model integrated the human thermoregulation and heat and moisture transfer through clothing including ventilation induced by body motion, liquid sweat movement and the coupling effects of heat and moisture transfer. From the comparison between the computational and experimental results, it is convinced that the model has captured the main mechanisms involved in the human-clothing-environment system. The model can be applied for elucidating the effects of the various human, clothing and environmental factors on the human thermal physiological response.

# Chapter 4 Test method for measuring the dynamic thermal properties of clothing

## 4.1 Introduction

Clothing thermal comfort is important not only to survival in extreme environmental conditions, but also to better living in everyday life. Clothing thermal comfort should not only be studied under steady state conditions corresponding to people exposed to certain conditions for a long period of time, but also under transient conditions, since in many situations, people are moving about, changing their activities and clothing, etc, and hence the steady state is not reached. Attempts had been made to establish models for predicting thermal transient comfort (Wang & Peterson 1992 and Jones & Ogawa 1992), these models however only included the steady-state properties of clothing, viz. clothing thermal insulation and moisture vapour resistance, but not the dynamic behaviour of clothing. It is therefore essential to define and quantify the dynamic thermal properties of clothing.

Vokac et al (1973) proposed a method of evaluating the clothing ventilation index from monitoring the dynamic changes of temperature and humidity at the skin surface at the sudden change of body motion. Birnbaum and Crockford (1978) described a procedure to measure the rate of air exchange between the clothing micro-climate and the environment by using a trace gas. Since these methods were time consuming and involved human subjects, they are not widely used and only very limited data were available.

While little work has been reported on the dynamic thermal properties of actual clothing ensembles, some work has been carried on the dynamic thermal properties of layered fabrics. Wang and Yasuda (1991) developed an apparatus to simultaneously measure the transient temperature and moisture changes in-between fabric layers under simulated perspiration. Experimental results (Yasuda et al 1992) showed that the accumulation of the moisture content between fabric layers was strongly related to the moisture absorption properties of the fabric. A number of theoretical models (Farnworth 1986, Li & Holcombe 1992, Fan et al 2000, Fan & Wen 2002) have also been proposed to model the coupled dynamic heat and moisture transfer in fabrics or simple clothing items since the first such work by Henry (1948).

In this chapter, a novel objective method for measuring the dynamic thermal properties of clothing ensembles is reported on. The method is based on the tests on sweating fabric manikin-Walter. A new index is also proposed to quantify the transient properties of clothing ensembles when the dressed human body experiences the thermal transient of changing from resting to exercising state.

## 4.2 A New Index to Measure the Dynamic Thermal Properties of Clothing ensembles

When a person changes from "resting" to "exercising" state, his metabolic heat production and heart rate are increased immediately to the levels corresponding to the intensity of the activity. As a result, his body temperature increases. The slower the increase in body temperature the better, as high body temperature imposes thermal stress to the person and even expose him to danger in life. A clothing ensemble which facilitates the heat loss and slows down the increase in body temperature is hence desirable. Therefore, the changing rate of body temperature of a clothed person is a measure of the dynamic thermal properties of clothing ensembles important to the transient thermal comfort.

Since tests involving human subjects tend to be less reproducible, time consuming and expensive. They may expose human subjects to danger. It is obviously desirable to measure the dynamic thermal properties of clothing ensembles by objective simulation tests. The physiological responses of a person changing from "resting" to "exercising" can be simulated to some extent by using the recently sweating fabric manikin-Walter (Fan and Chen 2002). The manikin-Walter may be set in the "standing" position with an appropriate power input and pumping rate (for water circulation inside the manikin) until it reaches a steady state. The manikin is then set to simulate "walking" motion with a corresponding higher power input and higher pumping rate. The change of the mean skin temperature of the manikin is an indicator of the dynamic properties of clothing ensembles relevant to transient thermal comfort.

Figure 4-1.illustrates a typical change of mean skin temperature, pumping rate for water circulation inside the manikin and power input, when the sweating manikin changes from "standing" to "walking" mode.

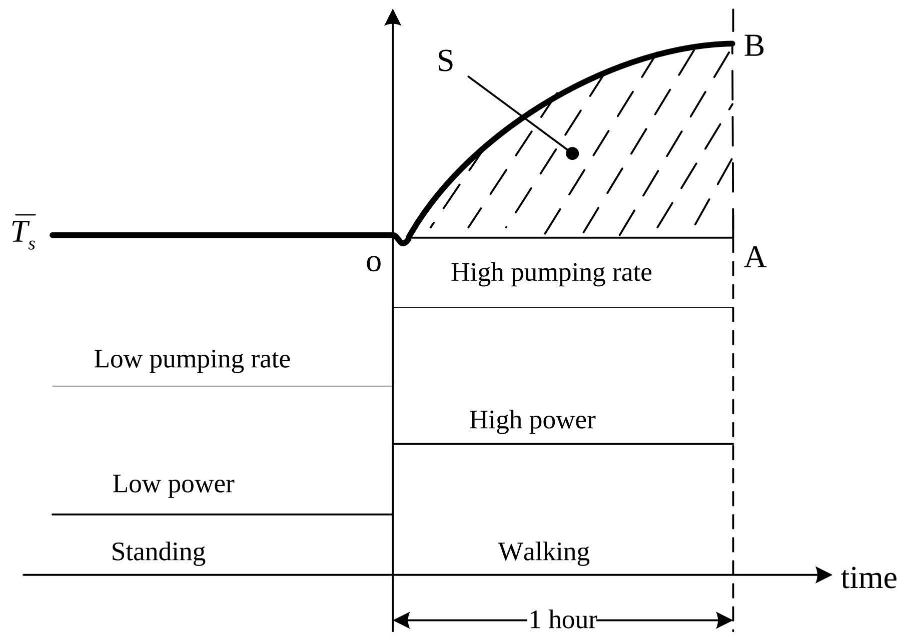



*Figure 4-1 Typical profile of mean skin temperature, pumping rate for water circulation inside the manikin and power input, when the sweating manikin changes from "standing" to "walking" mode.*

As can be seen, the mean skin temperature typically drops a little bit for a very short duration (about 2 minutes) before rising, when the manikin starts to “walk”. This is because the start of “walking” motion immediately increased heat loss by ventilation, but it takes a little time for the increased heat production (from the increased power input) to be transferred to the surface of the manikin. As will be shown in the subsequent experiments involving human subjects, this phenomenon is also apparent in humans.

We use the average skin temperature changing rate ($STCR$) of the manikin in the first hour of “walking” exercise as a measure of the dynamic thermal properties of the clothing ensemble on the manikin. It can be calculated by

$$STCR = \frac{2S}{(|OA|)^2} \tag{4-1}$$

where, $S$ is the area enclosed by the curve OB, line AB and OA. OA is the duration of the “walking” exercise under consideration (OA =1 hour in our study).

## 4.3 Objective Measurements on Sweating Fabric Manikin-Walter

### 4.3.1 Test Procedure

In developing the procedure for the objective measurements using the sweating fabric manikin-Walter, the limitation of the thermoregulatory function of the manikin in comparison with a real person is taken into consideration. For a clothed person changing from “resting” to “exercising” mode, his mean skin temperature may typical change from about 33 $^{o}$C to 36 $^{o}$C with increased perspiration rate to release extra heat. However, in the case of sweating fabric manikin-Walter, if the power input similar to the heat production of a “resting” person is set for the manikin to simulate the “resting” mode, the mean skin temperature would be much lower than 33 $^{o}$C, as the perspiration rate of the manikin is normally greater than that of a real person; on the other hand, if the power input similar to the heat production of an “exercising” person is set for the manikin to simulate the “exercising” mode, the mean skin temperature may be much greater than 36 $^{o}$C, as the perspiration rate of the manikin may be less than the perspiration rate of a real person during exercise. In order to standardize the tests, we control the mean skin temperature of manikin at 31 $^{o}$C when simulating the “resting” mode. When simulating the “exercising” mode, we set the power input of the manikin at 150W/m$^2$ plus the power input required in the “resting” mode.

The detailed measurement procedure is as follows:

Step 1: Set up the sweating manikin-Walter in a controlled environment. Patch 15 temperature sensors at 15 points disturbed on the different parts of skin surface, viz. head, chest, back, tummy, hip, left upper arm, right upper arm, left lower arm, right lower arm, left front thigh, right front thigh, left back thigh, right back thigh, left calf and right calf, as shown in Figure 4-2.

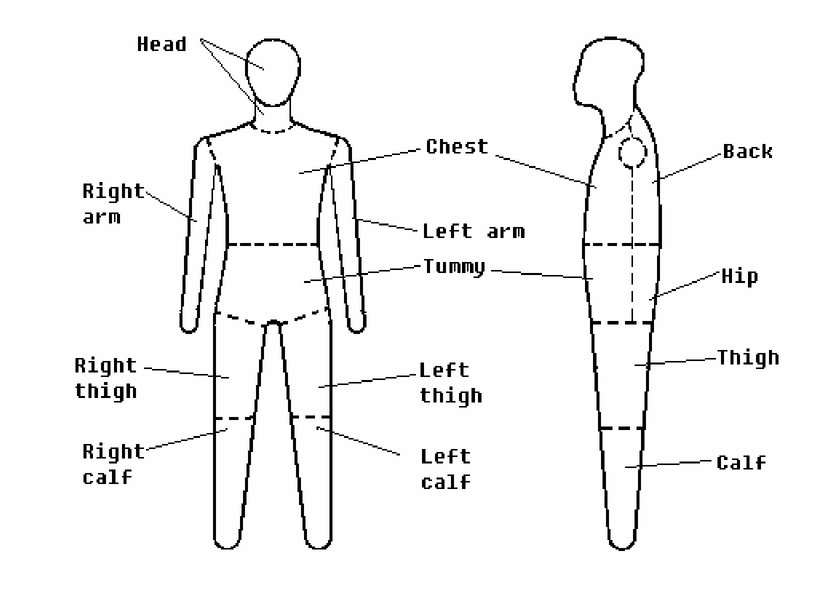



*Figure 4-2 Position of skin temperature sensors*

Step 2: Dress the manikin with the clothing ensemble to be tested.

Step 3: Set the controlled point of skin temperature to be 31 $^{o}$C.

Step 4: Open the files to save the real-time measurement data and some calculation results.

Step 5: Run the system and wait until the manikin stabilizes its skin temperature at 31 $^{o}$C.

Step 6: Keep the system stabilized for at least three hours. During the stable state, record the mean total power inputs of the heaters every hour.

Step 7: Average the values of the total power inputs in all the stable hours to obtain the average power input when the manikin is “standing”.

Step 8: Set the total output of the heaters of the manikin to the “average power input” derived at Step 7.

Step 9: Set the pumping rate of the pumps in manikin's body at a low level of 11W (The minimum output of the pumps) to simulate vasoconstriction at "standing" mode.

Step 10: Wait (for about one hour) until the system reaches stabilization, viz. the manikins' skin temperature is stabilized.

Step 11: Increase the power of the manikin (total output of the heaters) by 150W/m$^2$ (watts per unit area of manikin's skin surface) to simulate the heat production of a person undergoing physical activity; at the same time, start the simulation of "walking" motion at the walking speed of 1.04 km/hr and set the pumping rate of the pumps to the maximum level (The maximum power of the pumps is 24W) to simulate vasodilatation.

Step 12: Record the measurements in real time for at least one hour while the manikin is in "walking" mode.

Step 13: Repeat the Steps 8 to 12 so as to get repeated measurements.

Step 14: End the tests.

### 4.3.2 Calculation of Mean Skin Temperature

During the measurement, the mean skin temperature is calculated as the area-weighted mean skin temperature according to the following equation (Qian 2005):

$$\begin{aligned} T_{sk,m} &= 0.120T_{head} + 0.091T_{chest} + 0.095T_{back} + 0.060T_{tummy} + 0.064T_{hip} \\ &+ 0.049(T_{right.upper.arm} + T_{left.upper.arm}) + 0.033(T_{right.lower.arm} + T_{left.lower.arm}) \\ &+ 0.070(T_{right.front.thigh} + T_{left.front.thigh}) + 0.070(T_{right.back.thigh} + T_{left.back.thigh}) \\ &+ 0.063(T_{right.calf} + T_{left.calf}) \end{aligned} \tag{4-2}$$

### 4.3.3 Samples of Clothing Ensembles

Seven clothing ensembles were tested following the measurement procedure described above. Table 4-1 lists the detailed descriptions of the clothing ensembles and the measured thermal insulation and water vapour resistance when "standing" and "walking". Clothing ensemble No. 1 to No. 5 consists of the same short pants, but T-shirts made of different fabrics. Consequently, the steady state properties (i.e. thermal insulation and water vapour resistance) of Samples no. 1 to 5 are very close. The characteristics of the five T-shirt fabrics are listed in Table 4-2.

*Table 4-1 Details of Clothing Ensembles Tested and Their Properties*

| Clothing ensemble | Description | *STCR* (Mean±SE) | Thermal insulation ($m^2$ K $W^{-1}$) | | Water vapour resistance ($m^2$ Pa $W^{-1}$) | |
|---|---|---|---|---|---|---|
| | | | Standing | Walking at 1.04 km/hr | Standing | Walking at 1.04 km/hr |
| No.1 | Long-sleeve T-shirt made of Fabric No.1 With Short pants | 2.25±0.03 | 0.185 | 0.153 | 22.6 | 18.1 |
| No.2 | Long-sleeve T-shirt made of Fabric No.2 With Short pants | 2.34±0.02 | 0.193 | 0.162 | 20.9 | 17.5 |

| | | | | | | |
|---|---|---|---|---|---|---|
| No.3 | Long-sleeve T-shirt made of Fabric No.3 With Short pants | 2.44±0.03 | 0.192 | 0.161 | 22.7 | 20.7 |
| No.4 | Long-sleeve T-shirt made of Fabric No.4 With Short pants | 2.69±0.02 | 0.194 | 0.166 | 20.7 | 19.1 |
| No.5 | Long-sleeve T-shirt made of Fabric No.5 With Short pants | 2.73±0.03 | 0.185 | 0.148 | 21.2 | 19.4 |
| No.6 | Business suit made of 100% wool, long-sleeve underwear, shorts and long trousers | 2.71±0.04 | 0.285 | 0.227 | 34.8 | 29.5 |
| No.7 | Coat made of 100% polyester, long-sleeve underwear, shorts and long trousers | 2.71±0.06 | 0.258 | 0.237 | 36.6 | 30.3 |

Note: Thermal insulation and water vapour resistance was measured by sweating manikin 'Walter' in the condition of 21 ± 1°C, 70 ± 2 % RH and wind speed of 0.22 m/s.

*Table 4-2 Details of T-shirt Fabrics*

| Fabric Number | Brand Name | Description | Thickness (mm) | Mass (g/m²) |
|---|---|---|---|---|
| No. 1 | Meryl® | 93% Nylon 7% Spandex | 0.61 | 229.7 |
| No. 2 | Nike® | 60% Cotton 40% Polyester | 0.63 | 192.0 |
| No. 3 | Tactel® | 62% Combed Cotton 31% Nylon 7% Lycra | 0.83 | 284.2 |
| No. 4 | Akwatek® | 100% Polyester | 0.64 | 193.4 |
| No. 5 | / | 100% Cotton | 0.56 | 150.9 |

### 4.3.4 Environmental conditions

The experiments were conducted in a climate chamber with the controlled temperature of 21 ± 1 °C, relative humidity of 70 ± 2 % and air velocity of 0.22

m/s.

### 4.4 Results from Manikin Tests

From the measurements on the sweating fabric manikin-Walter, we can obtain the profile of the change of mean skin temperature of Walter (A typical skin temperature profile of Walter is shown in Figure 4-3. From this profile, we can obtain the dynamic index using Equation 4-1.

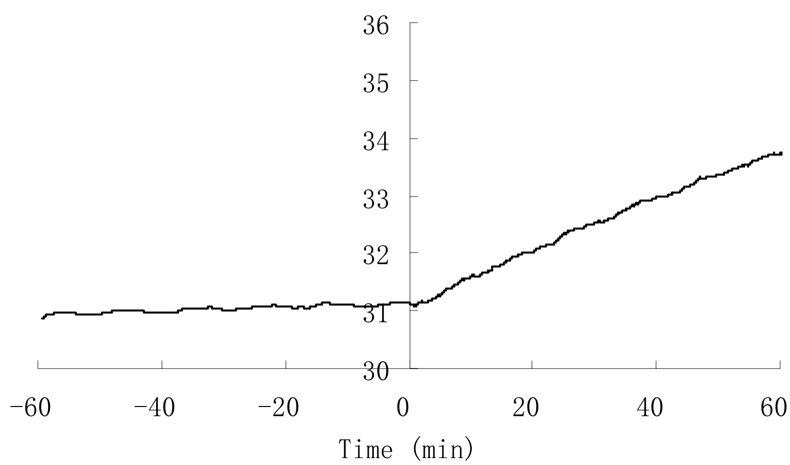



*Figure 4-3 Change of mean skin temperature of Walter when clothed with Clothing Ensemble No.5*

The dynamic index *STCR* of the seven clothing ensembles tested is listed in Table 4-1. The value of the index ranges from 2.25 to 2.71. The standard error of mean ranges from 0.02 to 0.06, the coefficient of variation is less than 4%. This means this measurement method has good precision and reproducibility. From this table, it can be seen that there are significant differences in the values of $STCR$ among Clothing Ensemble No.1, No.2, No.3 and No.4, although their values of thermal resistance and water vapour resistance are very close. But for Ensemble No.4, No.5, No.6 and No.7, the values of $STCR$ have no significant difference, although Ensemble No.6 and No.7 are much thicker and warmer than Ensemble No.4 and No.5. This means the dynamic index $STCR$ is not entirely dependent on the steady state thermal properties of clothing ensembles.

## 4.5 Discussion

The interesting results that $STCR$ of clothing ensembles having similar steady thermal properties may be significant different, while those ensembles with significant different steady thermal properties may have the similar $STCR$. This can be explained by the following theoretical analysis.

Firstly, let's analyze the heat and moisture transfer of the clothing-manikin system. Figure 4-4 illustrates the manikin-clothing system. 'Walter' can be divided into two concentric shells: an outer fabric 'skin' layer and a central core mainly consisted of water. This fabric 'skin' is water vapour permeable but water proof, its water vapour resistance is 8.6 Pam$^2$/W. Heaters in its body provide the internal heat production. This energy is allocated into three ways: heat storage, heat loss by water vapour diffusion through the fabric skin and dry heat loss from the fabric skin.

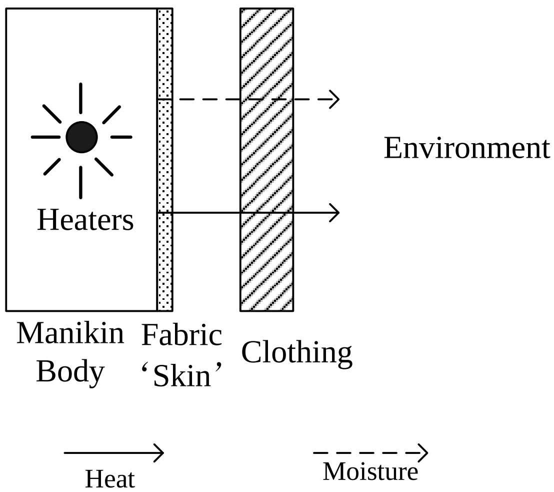



*Figure 4-4 Manikin-Clothing-Environment System*

Hence, we can establish the heat balance equation for the manikin:

$$M_{b,m} Cp_{b,m} \frac{dT_{b,m}}{dt} = H_m - Q_{t,m} - Q_{e,m} \quad (4\text{-}3)$$

where, $M_{b,m}$ is the mass of Walter; $Cp_{b,m}$ is the thermal capacity of Walter; $T_{b,m}$ is the temperature of Walter's body; $H_m$ is the heat production inside Walter's body, including the heat produced by heaters and pumps; $Q_{t,m}$ is the sensible heat loss at the skin surface; $Q_{e,m}$ is the latent heat loss at the skin surface; $t$ is time.

If the clothing is simplified as the resistance of heat and water vapour transfer, the above equation can be written as:

$$M_{b,m}Cp_{b,m}\frac{dT_{b,m}}{dt}=H_m-\frac{T_{sk,m}-T_a}{R_t}-\frac{P_s(T_{sk,m})-P_a}{R_{esk,m}+R_e} \tag{4-4}$$

where $T_{sk,m}$ is the mean skin temperature of manikin; $T_a$ is the air temperature in environment; $R_t$ is the thermal resistance of clothing ensemble; $P_s(T_{sk,m})$ is the water vapour pressure on the inner surface of the 'skin', it is saturated water pressure at the skin temperature; $P_a$ is the water vapour pressure in environment; $R_{esk,m}$ is the moisture vapour resistance of the 'skin' and $R_e$ is the moisture resistance of clothing ensemble.

$$\Theta\ T_{sk,m}=-\frac{T_{b,m}-T_a}{R_{t,skin}+R_t}\times R_{t,skin}+T_{b,m}=\frac{R_t}{R_{t,skin}+R_t}\times T_{s,m}+\frac{R_{t,skin}}{R_{t,skin}+R_t}T_a \tag{4-5}$$

$$\therefore M_{b,m}Cp_{b,m}\frac{dT_{b,m}}{dt}=M_{b,m}Cp_{b,m}\frac{R_t}{R_{t,skin}+R_t}\frac{dT_{sk,m}}{dt}=H_m-\frac{T_{sk,m}-T_a}{R_t}-\frac{P_s(T_{sk,m})-P_a}{R_{esk,m}+R_e} \tag{4-6}$$

When air temperature ranges from 30 to 37 ℃, the saturated water vapour pressure can be looked as linear with the air temperature. We regressed with the Arden Buck Equation (Buck 1996) using a linear function, and obtained the following equation:

$$P_s(T)=290.24T-4517 \quad (30\le T\le 37) \quad (R^2=0.998) \tag{4-7}$$

So we have:

$$P_s(T_{sk,m})=290.24T_{sk,m}-4517 \tag{4-8}$$

Substitute Equation 4-8 into Equation 4-7:

$$M_{b,m}Cp_{b,m}\frac{R_t}{R_{t,skin}+R_t}\frac{dT_{sk,m}}{dt}=H_m-\frac{T_{sk,m}-T_a}{R_t}-\frac{290.24T_{sk,m}-4517-P_a}{R_{esk,m}+R_e} \qquad (4\text{-}9)$$

Solve this equation, we have:

$$T_{sk,m}=-(T_1-T_0)\exp(-t/\tau)+T_1 \qquad (4\text{-}10)$$

where $\tau=\dfrac{M_{b,m}Cp_{b,m}\dfrac{R_t}{R_{t,skin}+R_t}}{\dfrac{1}{R_t}+\dfrac{290.24}{R_{esk,m}+R_e}}$, (4-11)

$T_0$ and $T_1$ are the mean skin temperatures of the manikin when the manikin is thermal balanced during standing and during walking, respectively.

So $T_{sk,m}$ is an exponential function of time when the clothing is simplified as resistance of heat and moisture transfer. As plotted in figure 4-5, $T_{sk,m}$ increases with time as an exponential curve, and infinitely approaches the new balance point $T_1$.

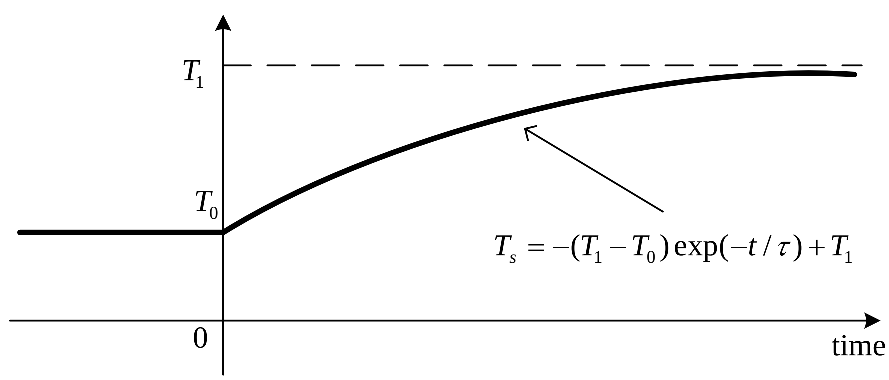



*Figure 4-5 Mean skin temperature of manikin 'Walter' during thermal transients*

*if the clothing is simplified as resistance of heat and moisture transfer*

$T_0$ and $T_1$ can be calculated from the heat balance equations:

$$T_0 = \frac{H_0 + \dfrac{T_a}{R_{t,0}} + \dfrac{4517 + P_a}{R_{esk,m} + R_{e,0}}}{\dfrac{1}{R_{t,0}} + \dfrac{290.24}{R_{esk,m} + R_{e,0}}} \tag{4-12}$$

where $H_0$ is the internal heat production inside the manikin body during the standing period, $R_{t,0}$ and $R_{e,0}$ are thermal resistance and water vapour resistance of clothing during the standing period, respectively.

$$T_1 = \frac{H_0 + \Delta H + \dfrac{T_a}{R_{t,1}} + \dfrac{4517 + P_a}{R_{esk,m} + R_{e,1}}}{\dfrac{1}{R_{t,1}} + \dfrac{290.24}{R_{esk,m} + R_{e,1}}} \tag{4-13}$$

where $\Delta H$ is the increased heat production inside the manikin body during the walking period compared with that during the standing period, it is used to simulate the heat production caused by 'exercise' of human body; $R_{t,1}$ and $R_{e,1}$ are thermal resistance and water vapour resistance of clothing during the walking period, respectively.

Average changing rate of mean skin temperature in the first hour of exercise $STCR$ can be derived as the following:

$$S = \int_0^1 T_{sk,m} dt = (T_1 - T_0)(1 + \tau \exp(-1/\tau) - \tau) \tag{4-14}$$

$$STCR = \frac{2S}{(1hour)^2} = 2(T_1 - T_0)(1 + \tau\exp(-1/\tau) - \tau) \tag{4-15}$$

In our experiments, $T_0$ is set to be 31 ℃, and $\Delta H$ was specified to be 157.2 w/m2, therefore $STCR$ can be determined by $R_{t,0}$, $R_{e,0}$, $R_{t,1}$ and $R_{e,1}$.

In reality, however, the heat and moisture transfer in clothing ensemble is much more complicated, heat release/ absorption is usually accompanied by water vapour sorption/desorption and water vapour evaporation/condensation, or phase changing of Phase Changing Materials (PCM) if there is PCM in the clothing ensemble. Except for the above coupled phenomena, heat and moisture storage also makes the clothing improper to be looked as resistance under thermal transients. Heat release may make the manikin increases its temperature faster, resulting a higher value of $STCR$ than that predicted from Equation 4-15. On the contrary, heat absorption may make $STCR$ smaller than that calculated from Equation 4-15. $STCR$ is an integrated parameter which can reflect the dynamic heat and moisture transfer properties of clothing ensemble under test during the thermal transients from standing to walking.

## 4.5 Conclusions

In this chapter, a new test method for measuring the thermal properties of clothing ensembles under dynamic conditions is described. A new dynamic index to evaluate the properties of clothing when the wearer experiences thermal transients from standing to exercising is also proposed. Good precision and reproducibility are shown in the results. The use of the objective index from tests on the sweating manikin-Walter is clearly advantageous, since tests involving human subjects are time consuming, expensive and poor in reproducibility.

# Chapter 5 Experiments on Human Subjects and Comparisons with results from Sweating Manikin

## 5.1 Introduction

Human physiological responses are greatly influenced by the properties of clothing ensemble. From literature review, we know human body's thermoregulation is dependent upon the balance of heat production together with heat gain from the environment and loss to the environment through the transfer of heat by conduction, convection, radiation and evaporation. Clothing system, as an interactive barrier, greatly affects thermal balance, so as to influence human physiological responses.

The interaction of clothing system is derived from the physical properties of the clothing materials and ventilation effect. In order to better understand the influence of clothing system on the physiological and subjective sensations, many workers conducted experiments on subjects wearing different clothing under different conditions (Vokac 1976, Holmer 1985, Nielsen and Endrusick 1990, Ha and Tokura 1995, Kwon et. al. 1998, Ha et. al. 1999, Gavin et. al. 2001, Zhang and Gong 2002, Zhang et. al. 2003, Lee and Choi 2004, Shin-ya et. al. 2005).

In Chapter 3, by numerical simulation, the effect of the heat absorption or release of clothing and ventilation on physiological and subjective responses has been studied. In Chapter 4, a new index of clothing ensembles for representing the transient properties of clothing ensembles is described. In order to better understand the effect of this index on physiological reactions, wearer trials were carried out and results are analyzed and discussed in this chapter.

## 5.2 Wearer trials

In order to evaluate whether the dynamic index *STCR* (viz. the average changing rate of the mean skin temperature) is related to transient thermal comfort, Physiological wearer trials involving human subjects wearing these clothing ensembles were conducted.

In the first set of wearer trials, four male subjects wearing one of the sample clothing ensembles were asked to jog on a motorized treadmill. The skin temperatures of the human subjects were monitored. Since it was later observed that there were considerable fluctuations in the skin temperature measurement probably due to the interference of the electro-magnetic waves of the treadmill motor, it was considered that the mean body temperature may be a more stable measure of the thermal physiological responses of the human subjects, and hence another set of wearer trials was conducted. In the second set of wearer trials, one male subject wearing each of the sample clothing ensembles was asked to exercise on a cycle ergometer. Both rectal and skin temperatures were measured during these experiments. The measurements for each clothing ensemble were repeated three times.

### 5.2.1 First Set of Wearer Trials on a Motorized Treadmill

Four young male subjects participated in this study. They were 1.67 ± 0.08m of height, 62.95 ± 7.88 kg of weight. Experiments were conducted in a climate chamber at air temperature of 20 ℃, relative humidity of 55% and air velocity of 0.22 m/s. The clothing ensembles were stored in the conditioned climate chamber for at least 2 hours before experiment.

After the human subject entered the climate chamber, he was asked to wear the clothing ensemble for testing, and have the skin sensors attached. As Figure 5-1 illustrates, the wearer first rest for 10 minutes, then ran on a treadmill for 30 minutes at a speed of 1.67m/s. After exercise, the wearers took rest in the chamber for another 10 minutes. The skin temperatures at different locations of the body surface were recorded in every 30 seconds.

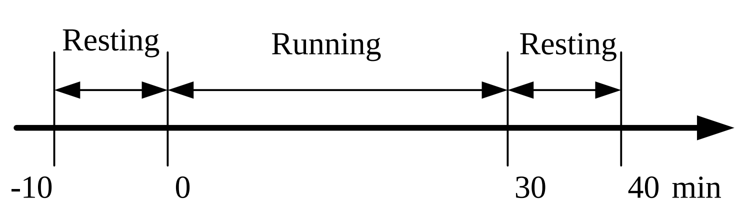



*Figure 5-1 Procedure of exercise on a motorized treadmill*

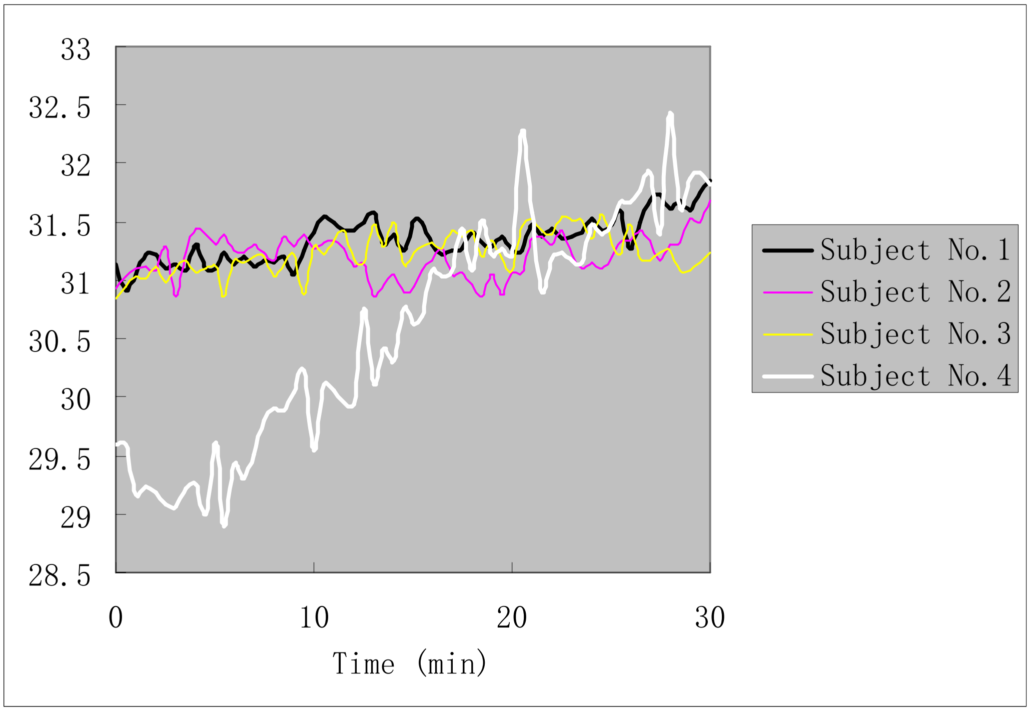



*Figure 5-2 Skin temperature of subjects for clothing ensemble No.1 in the first set of wear trials*

The temperature profiles of the four human subjects wearing the same clothing ensemble No.1 are shown in Figure 5-2. As can be seen, for any single subject, the skin temperature fluctuates as much as 0.5 ℃. This was found to be was caused by the interference of the electro-magnetic waves of the treadmill motor. Furthermore, there is huge difference in the temperature profile between the four subjects, even they wear the same clothing ensemble, probably due to the physiological differences between the subjects and differences in garment fitting.

### 5.2.2 Second Set of Wearer Trials on a Cycle Ergometer

#### 5.2.2.1 Subject.

One young male subject participated in this study. He was 1.57m of height, and 56kg of weight. Measurement was repeated 3 times for each clothing ensemble.

#### 5.2.2.2 Clothing ensembles.

The clothing ensembles in Chapter 4 were measured in the wearer trials.

#### 5.2.2.3 Procedure.

Experiments were conducted in a climate chamber at air temperature of 25 ℃, a relative humidity of 55% and air velocity of 0.22 m/s. The clothing was stored in the conditioned climate chamber for at least 2h before experiment.

After entered the climate chamber, the subject wore the test clothing ensemble. First of all, a rectal temperature sensor was inserted into the rectum by the subject himself, and skin temperature sensors were attached on six sites: forehead, chest, back, upper arm, thigh and hand. Then he sat on a cycle ergometer (Model SPIRIT 1335, JKEXER®, Jih Kao Co., Taiwan). As shown in

Figure 5-3, first of all, the subject took rest for 60 minutes. Then he exercised on a cycle ergometer for 30 minutes. The cycling speed was 20 km/hour. After exercise, the subject took rest on for 10 minutes. At the end of the experiment, the subject took off the clothing ensemble.

At the beginning of exercise, the system started to record the skin temperatures and the rectal temperature every 5 second.

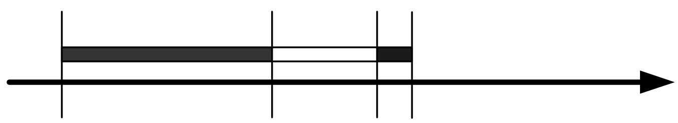


*Figure 5-3 Procedure of exercise on a cycle ergometer*

### 5.2.2.4 Calculation and statistical analysis

The mean skin temperature of the subject was calculated by the following equation (Palmes and Park 1947):

$$T_{sk,h} = 0.14T_{head} + 0.19T_{chest} + 0.19T_{back} + 0.11T_{arm} + 0.05T_{hand} + 0.32T_{thigh} \qquad (5\text{-}1)$$

Mean body temperature was calculated as follows (Kwon et al., 1998):

$$T_{b,h} = 0.8T_{re,h} + 0.2T_{sk,h} \qquad (5\text{-}2)$$

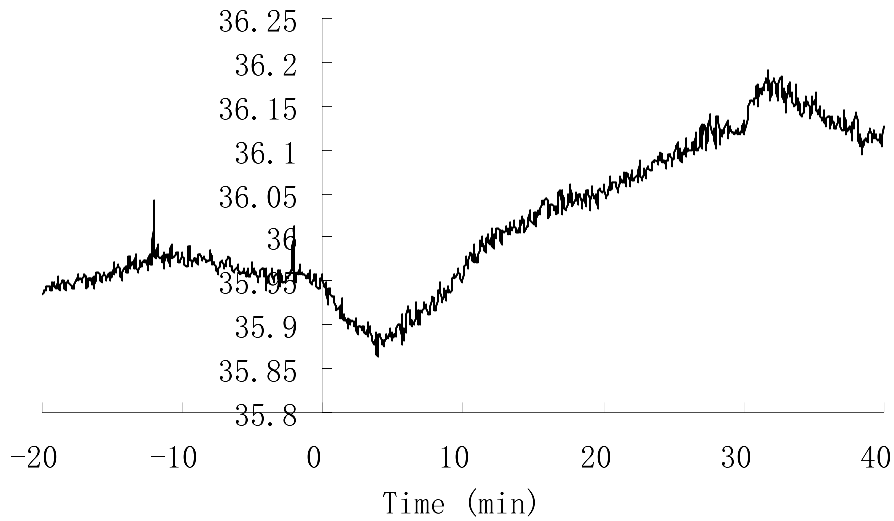



*Figure 5-4 Body temperature of the subject for Ensemble No.5*

Figure 5-4 shows a typical body temperature profile obtained when the subject worn Clothing Ensemble No. 5. As can be seen, before the cycling exercise, the body temperature was almost stabilized at 35.95±0.05 $^{o}$C, after the wearer started cycling, the body temperature initially dropped from about 35.95 $^{o}$C to about 35.87 $^{o}$C before rising gradually up to 36.12 $^{o}$C at the end of the cycling. After stopping the cycling, the temperature continued to rise a bit before decreasing gradually. The initial drop of body temperature was induced because heat loss from the body increased immediately as a result of ventilation, whereas it takes a short while for the body to increase heat generation owing to increased activity level.

From the body temperature profiles of the human subject, the average changing rate of body temperature $T_{b,h}^{'}$ of the subject during exercise period can be calculated. Since $T_{b,h}$ was monitored every five seconds, we have

$$T_{b,h}{}' = \frac{2 \times \sum_{i=1}^{360} \left(T_{b,h}(i) - T_{b,h}(0)\right) \times \frac{5s}{3600s/hour}}{(0.5hour)^2} = \frac{1}{90} \times \sum_{i=1}^{60} \left(T_{b,h}(i) - T_{b,h}(0)\right) \qquad (5\text{-}3)$$

where $T_{b,h}(i)$ is body temperature at the ith 5 second during the exercise period. $T_{b,h}(0)$ is the body temperature at the beginning of the exercise, because $T_{b,h}$ may fluctuate at the start of the exercise period, $T_{b,h}(0)$ was determined by averaging values of $T_{b,h}$ just before (i.e. 2 minutes before) the start of the exercise and just after (i.e. 2 minutes after) the start of the exercise.

The statistical significances between the means were compared by using a one-way repeated measures analysis of variance (ANOVA) with Bonferroni post-hoc test for the clothing ensembles during exercise. The P-value less than 0.05 was considered statistically significant.

## 5.3 Results

*Table 5-1 ANOVA Result*

Tbody

| | Sum of Squares | Df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | 24.678 | 6 | 4.113 | 479.231 | .000 |
| Within Groups | 5.527 | 644 | .009 | | |
| Total | 30.206 | 650 | | | |

*Table 5-2 Result of Comparisons between any two of the clothing ensembles*

**Multiple Comparisons**

Dependent Variable: Tbody
Bonferroni

| (I) ClothingNo | (J) ClothingNo | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| 1 | 2 | -.13432(*) | .01359 | .000 | -.1758 | -.0929 |
| | 3 | .49505(*) | .01359 | .000 | .4536 | .5365 |
| | 4 | .21006(*) | .01359 | .000 | .1686 | .2515 |
| | 5 | .20486(*) | .01359 | .000 | .1634 | .2463 |
| | 6 | .14024(*) | .01359 | .000 | .0988 | .1817 |
| | 7 | -.05312(*) | .01359 | .002 | -.0946 | -.0117 |
| 2 | 1 | .13432(*) | .01359 | .000 | .0929 | .1758 |
| | 3 | .62937(*) | .01359 | .000 | .5879 | .6708 |
| | 4 | .34439(*) | .01359 | .000 | .3029 | .3858 |
| | 5 | .33918(*) | .01359 | .000 | .2977 | .3806 |
| | 6 | .27456(*) | .01359 | .000 | .2331 | .3160 |
| | 7 | .08120(*) | .01359 | .000 | .0398 | .1226 |
| 3 | 1 | -.49505(*) | .01359 | .000 | -.5365 | -.4536 |
| | 2 | -.62937(*) | .01359 | .000 | -.6708 | -.5879 |
| | 4 | -.28498(*) | .01359 | .000 | -.3264 | -.2435 |
| | 5 | -.29019(*) | .01359 | .000 | -.3316 | -.2487 |
| | 6 | -.35481(*) | .01359 | .000 | -.3962 | -.3134 |
| | 7 | -.54817(*) | .01359 | .000 | -.5896 | -.5067 |
| 4 | 1 | -.21006(*) | .01359 | .000 | -.2515 | -.1686 |
| | 2 | -.34439(*) | .01359 | .000 | -.3858 | -.3029 |
| | 3 | .28498(*) | .01359 | .000 | .2435 | .3264 |
| | 5 | -.00520 | .01359 | 1.000 | -.0466 | .0362 |
| | 6 | -.06983(*) | .01359 | .000 | -.1113 | -.0284 |
| | 7 | -.26318(*) | .01359 | .000 | -.3046 | -.2217 |
| 5 | 1 | -.20486(*) | .01359 | .000 | -.2463 | -.1634 |
| | 2 | -.33918(*) | .01359 | .000 | -.3806 | -.2977 |
| | 3 | .29019(*) | .01359 | .000 | .2487 | .3316 |
| | 4 | .00520 | .01359 | 1.000 | -.0362 | .0466 |
| | 6 | -.06462(*) | .01359 | .000 | -.1061 | -.0232 |
| | 7 | -.25798(*) | .01359 | .000 | -.2994 | -.2165 |
| 6 | 1 | -.14024(*) | .01359 | .000 | -.1817 | -.0988 |
| | 2 | -.27456(*) | .01359 | .000 | -.3160 | -.2331 |
| | 3 | .35481(*) | .01359 | .000 | .3134 | .3962 |
| | 4 | .06983(*) | .01359 | .000 | .0284 | .1113 |
| | 5 | .06462(*) | .01359 | .000 | .0232 | .1061 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 7 | -.19335(*) | .01359 | .000 | -.2348 | -.1519 |
| 7 | 1 | .05312(*) | .01359 | .002 | .0117 | .0946 |
| | 2 | -.08120(*) | .01359 | .000 | -.1226 | -.0398 |
| | 3 | .54817(*) | .01359 | .000 | .5067 | .5896 |
| | 4 | .26318(*) | .01359 | .000 | .2217 | .3046 |
| | 5 | .25798(*) | .01359 | .000 | .2165 | .2994 |
| | 6 | .19335(*) | .01359 | .000 | .1519 | .2348 |

* The mean difference is significant at the .05 level.

Table 5-1 shows the ANOVA results, Table 5-2 shows the result of comparisons between any two of the clothing ensembles. It can be seen that the differences among body temperature for the seven clothing ensembles were significant (F=479.23, P<0.01), except that clothing ensemble No. 4 and No. 5 have no significant in the body temperature.

Table 5-3 lists the mean values, standard deviations of the means of three repeated measurements of $T_{b,h}^{'}$ for the seven clothing ensembles tested. As can be seen, the standard deviations of the means of $T_{b,h}^{'}$ are generally high, indicating the difficulty in obtaining the reproducible measurements from human subjects. This is because the change of body temperature from resting to exercising is generally quite small (e.g. 0.25 $^{o}$C), while the inherent variability of the human subject can be close to that magnitude.

*Table 5-3 The changing rate of body temperature $T'_{b,h}$ of the subject in wearer trials*

| Clothing Ensemble | $T'_{b,h}$ (℃/hour) | |
|---|---|---|
| | Mean | Standard Error of Mean |
| No.1 | 0.114 | 0.022 |
| No.2 | 0.160 | 0.016 |
| No.3 | 0.101 | 0.018 |
| No.4 | 0.178 | 0.062 |
| No.5 | 0.241 | 0.040 |
| No.6 | 0.245 | 0.091 |
| No.7 | 0.252 | 0.081 |

## 5.4 Results Analysis and Discussion

Despite of the huge variability of the subjective results, there is a definite trend of body temperature increase when exercise starts, it would be interesting to see how the change rate of body temperature relates to the change rate of manikin's skin temperature $STCR$. Figure 5-5 shows the correlation between the dynamic index $STCR$ and the $T'_{b,h}$ obtained from subjective wearer trials. As can be seen, a positive linear relationship exists.

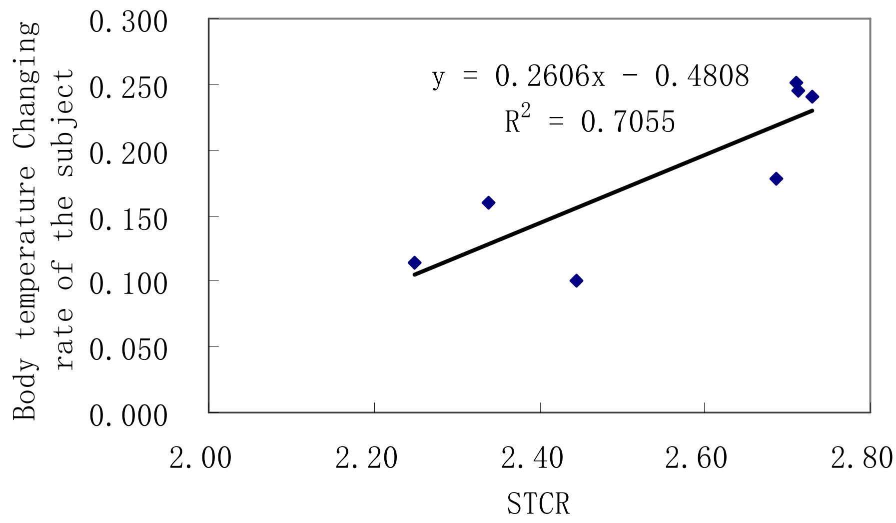



*Figure 5-5 Correlation between the dynamic index $STCR$ of clothing ensembles and the changing rate of mean body temperature of the subject*

The correlation and difference between the dynamic index *STCR* of clothing ensembles and the changing rate of mean body temperature of the subject can be better understood by the following analysis.

Consider the human body-clothing-environment system, the heat balance of the system can be expressed by

$$M_{b,h}Cp_{b.h}\frac{dT_{b,h}}{dt} = H_h - Q_{res} - Q_{t,h} - Q_{e,h} \tag{5-4}$$

where, $M_{b,h}$ is the mass of human body per unit surface area; $Cp_{b,h}$ is the specific heat capacity of human body; $T_{b,h}$ is the temperature of human body; $H_h$ is heat production within the human body corresponding to the level of activity; $Q_{res}$ is the heat loss from respiration. $Q_{t,h}$ is the sensible heat loss from the skin surface and $Q_{e,h}$ is the latent heat loss from the skin surface, $t$ is time.

Consider the manikin-clothing-environment system, the heat balance of the system can be expressed by

$$M_{b,m}Cp_{b,m}\frac{dT_{b,m}}{dt} = H_m - Q_{t,m} - Q_{e,m} \qquad (5\text{-}5)$$

where, $M_{b,m}$ is the mass of the manikin-Walter; $Cp_{b,m}$ is the thermal capacity of Walter; $T_{b,m}$ is the temperature of Walter's body; $H_m$ is the heat production inside Walter's body, including the heat produced by heaters and pumps; $Q_{t,m}$ is the sensible heat loss at the skin surface; $Q_{e,m}$ is the latent heat loss at the skin surface.

Comparing Equation (5-4) and (5-5), they similarity can be easily observed. As a result, the change of the body temperature of the manikin would be equivalent to the change of the temperature of the human body, if the heat production inside the manikin could simulate the heat production inside the human body minus the heat loss by respiratory, viz.

$$H_m = H_h - Q_{res} \qquad (5\text{-}6)$$

and if the sensible and insensible heat loss from the manikin are the same as those from the human body, viz.

$$Q_{t,m} = Q_{t,h}; \qquad (5\text{-}7)$$

$$Q_{e,m} = Q_{e,h}\,; \tag{5-8}$$

However, the conditions expressed by Equations (5-7) and (5-8) are difficult to achieve even though the environment, which the manikin is exposed to, and the physical activity that the manikin performs, are similar to those exposed or performed by the human subject. This is because the human body has a powerful thermoregulatory system, whereas the manikin can simulate little of such function.

Human body can regulate the thermal resistance of the skin through vasodilation/vasoconstriction and regulate perspiration rate so as to change the sensible and insensible heat loss. On the other hand, the manikin has no such function. Furthermore, the regulation of the perspiration rate of the manikin is very much limited in comparison with that of the human body. The perspiration rate in a human body can increase dramatically as the level of activity increases or when he is exposed to higher temperature environments, etc. On the other hand, the perspiration rate of the manikin-Walter can only be regulated slightly by the change of skin temperature through the alteration of the pumping rate of the inner pumps, which results in a change in the difference of the water vapour pressure at the skin surface and that in the environment.

The difference in the thermoregulatory function of the human body and manikin is the reason why the measured skin temperature change (equivalent to the body temperature change of the manikin) in the manikin is much greater than the change of the body temperature in the human body.

## 5.5 Conclusions

In this chapter, in order to validate the significance of the method developed in Chapter 4, physiological experiments were conducted to investigate the effect of the new index on the physiological responses. From the present study, it was shown that the changing rate of the mean skin temperature of the clothed manikin-Walter when changing from the “resting” to “exercising” mode is related to the changing rate of the body temperature of a wearer wearing the same type of clothing and undergoing a similar change of body activities, it is therefore reasonable to use the changing rate of the mean skin temperature of the clothed manikin-Walter as an objective index for quantifying the dynamic thermal properties of clothing ensembles.

A higher value of the index means faster rate of change of body temperature, and shorter duration before the wearer approaching a dangerous thermo-physiological state. Clothing should therefore be designed to reduce the value of the index.

Since the subjective wearer trials are very time consuming, only limited number of subjective wearer trials have been carried out in this study to validate the correlation between the proposed index and the changes of body temperature in actual use. Further work in this respect is required.

# Chapter 6 Conclusions and Suggestions for Future Research

## 6.1 Conclusions

Under most of the environmental conditions, clothing is essential for people's survival, as human body's own ability to adapt itself to the wide range of thermal environments is very much limited. Clothing properties relevant to thermal comfort are therefore important criteria for people to select clothing for different end uses.

Because of the importance of clothing thermal comfort, much research work has been carried out in this field, particularly on clothing thermal comfort under steady state. Comparatively, however, little work has been reported on the transient thermal comfort of actual clothing ensembles, although some work has been done on the dynamic heat and moisture transfer through fabrics. This is perhaps due to the complexity of clothing thermal comfort under transient conditions.

People rarely live in constant environments. They usually experience thermal transients even within a controlled climate chamber, where some temperature fluctuation may exist. So, the significance of the investigation into clothing thermal comfort under transient conditions is obvious.

The dynamic heat and moisture transfer through clothing systems and its effect on thermal transient comfort should be better understood; evaluation and test methods for the dynamic thermal properties of clothing ensembles should be established. In the present work, many efforts have therefore been directed to investigate the dynamic heat and moisture transfer through clothing systems, and to develop a test procedure and index to quantify the dynamic properties of clothing ensembles important to thermal transient comfort.

First of all, a new theoretical model for the human-clothing-environment system to better understand the mechanism of the dynamic heat and moisture transfer through the clothing system has been established in the present study. Different from other models, the new model not only takes into account the dynamic heat and moisture transfer through clothing fabrics, but also clothing ventilation. Integrated with a human thermoregulation model, the new model was used to predict the physiological responses under the influence of dynamic thermal properties of clothing system during different thermal transients. The numerical results of the model agreed well with experimental results from two set of separate experiments

In the present study, a novel test method has also been developed and an associated index proposed for quantifying the dynamic thermal properties of clothing using the sweating fabric manikin-Walter. In this test method, the sweating manikin was used to simulate human body's experience in the thermal transient changing from resting to exercising. The average changing rate of mean skin temperature of the manikin in the first hour of simulated 'exercise' *STCR* was taken as an index to provide a measure of the dynamic thermal properties of clothing ensembles.

Seven clothing ensembles (Five of them consists of sports T-shirts made of different fabrics and the same shorts; one consists of a business suit, long-sleeve underwear, shorts and long trousers; another consists of a coat long-sleeve underwear, shorts and long trousers) were tested repeatedly on the sweating fabric manikin according to the proposed test procedure. The tests showed good precision and reproducibility. The coefficient of variation is generally less than 4%.

It was further found that the index *STCR* was significantly different among the four clothing ensembles consisting of sports T-shirts made of different fabrics and the same shorts, despite of the fact that the thermal insulation and water vapour resistance of the four clothing ensembles are very close. On the other hand, although the thermal insulation and water vapour resistance of the clothing ensemble with a business suit and a coat are very different from those of the clothing ensemble with two sports T-shirt, their *STCR* values are very close. Through the theoretical analysis of the dynamic heat and moisture transfer within the clothing-manikin-environment system, it becomes clear that *STCR* is an integrated parameter which reflects the dynamic heat and moisture transfer through clothing ensembles during the thermal transients from standing to walking.

Human physiological experiments were also conducted to investigate the relationship between the new index measured from the manikin tests and the physiological responses in terms of changes of body temperature. The present study showed that a test method can be developed based on the sweating fabric manikin-Walter to provide an objective measure of such dynamic properties.

From the present study, it was shown that the changing rate of the mean skin temperature of the clothed manikin-Walter when changing from the “resting” to “exercising” mode is related to the changing rate of the body temperature of a wearer wearing the same type of clothing and undergoing a similar change of body activities, it is therefore reasonable to use the changing rate of the mean skin temperature of the clothed manikin-Walter as an objective index for quantifying the dynamic thermal properties of clothing ensembles. The use of the objective index from tests on the sweating manikin-Walter is clearly advantageous, since tests involving human subjects are time consuming, expensive and poor in reproducibility.

A higher value of the index means faster rate of change of body temperature, and shorter duration before the wearer approaching a dangerous thermo-physiological state. Clothing should therefore be designed to reduce the value of the index.

## 6.2 Suggestions for future work

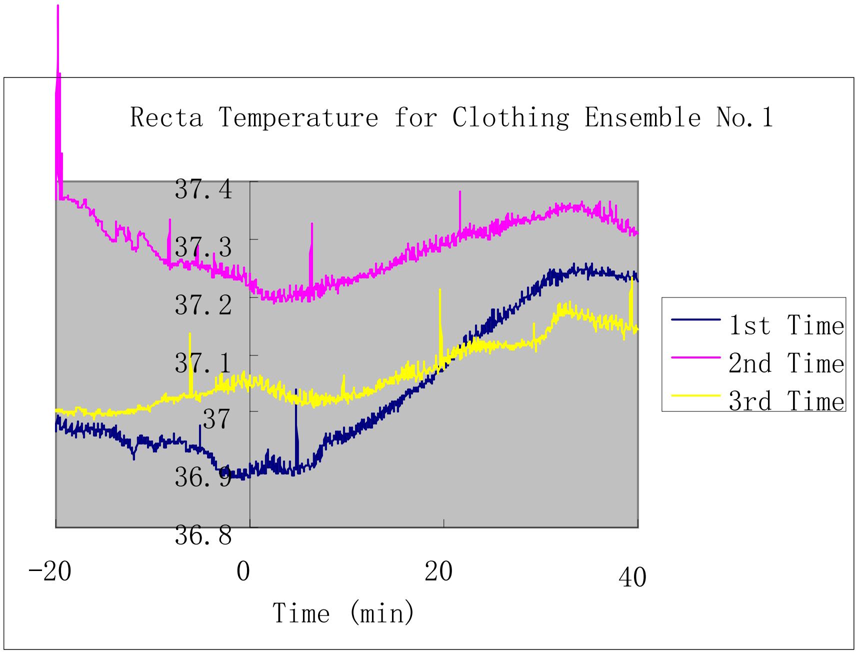
Since wearer trials involving human subjects are time-consuming and expensive, in this project, only limited such experiments were conducted due to time and funding constraints. In future, it is recommended to conduct wearer trials involving more human subjects and more clothing ensembles. This will make the findings more convincing.

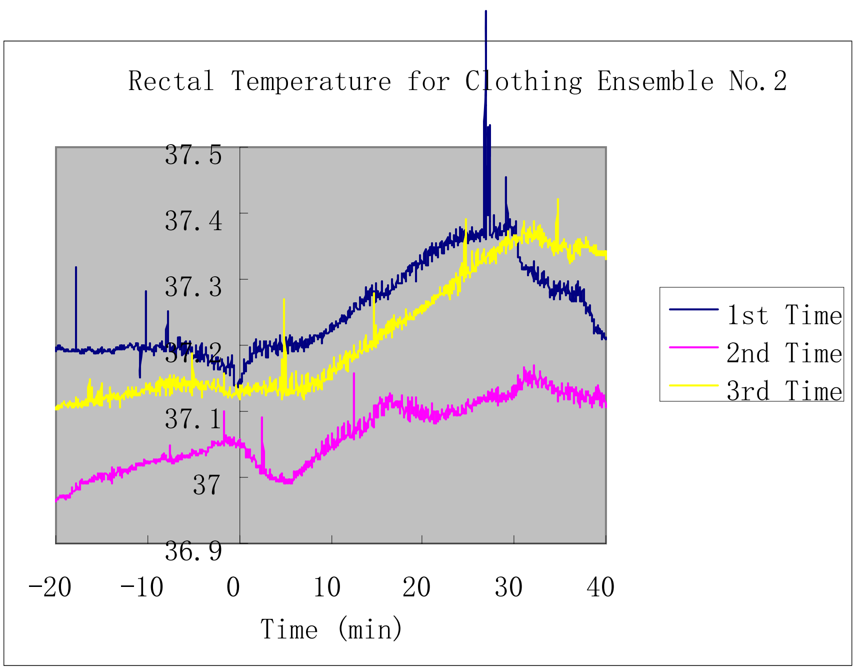
Although the sweating fabric manikin-Walter can simulate some aspects of human thermoregulation, the simulation is limited. Walter's skin can not change its water vapour permeability for different clothing ensembles and the perspiration rate is only regulated by the change of mean skin temperature which in turn changes the water vapour pressure at the skin. On the other hand, human body can regulate its perspiration rate to a much great extent when he changes from "rest" to "exercising". Future work should be directed to improve the thermoregulation of Walter to make it much closer to a real person.

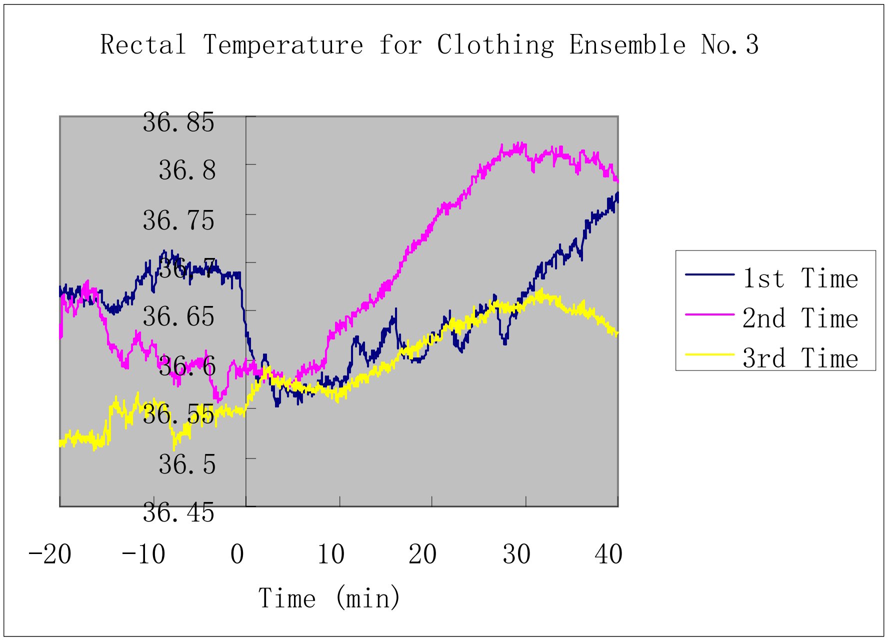
In this project, an index for measuring the dynamic thermal properties of clothing ensembles is proposed. However, how clothing and fabric parameters affect the index have not been investigated. Future work is needed to investigate the relationship between the index and the clothing factors. This would provide guidelines to the optimum function design of clothing.

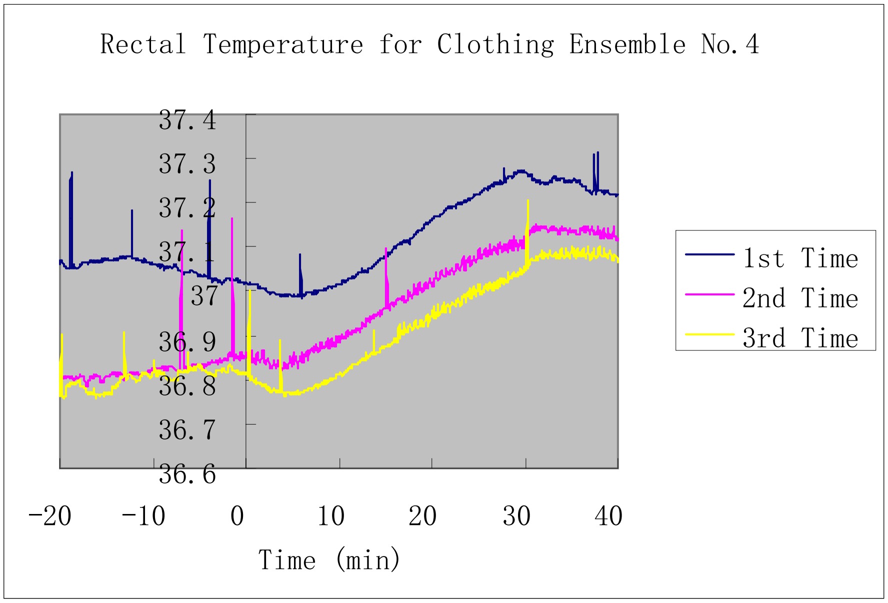
# Appendices

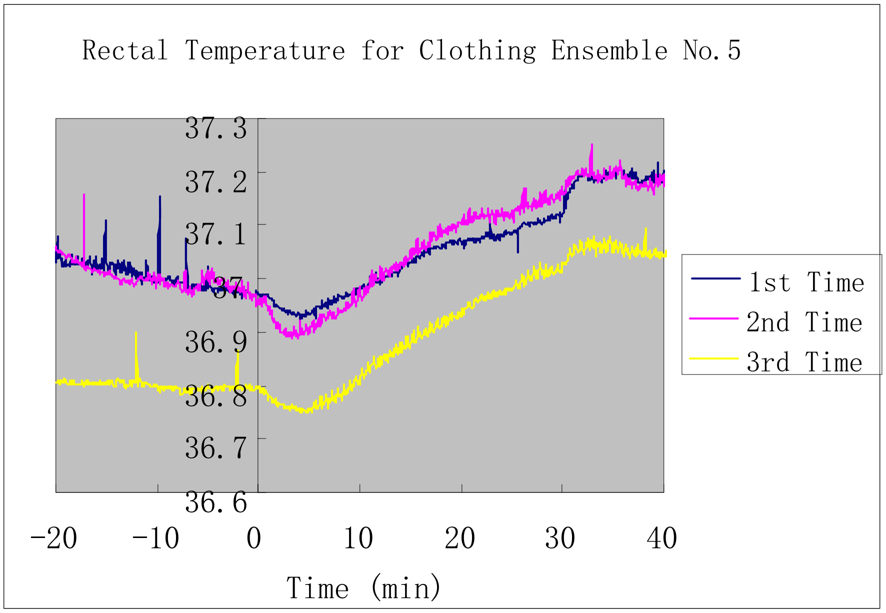
## Appendix A: Rectal Temperature of the Subject in Wearer Trials

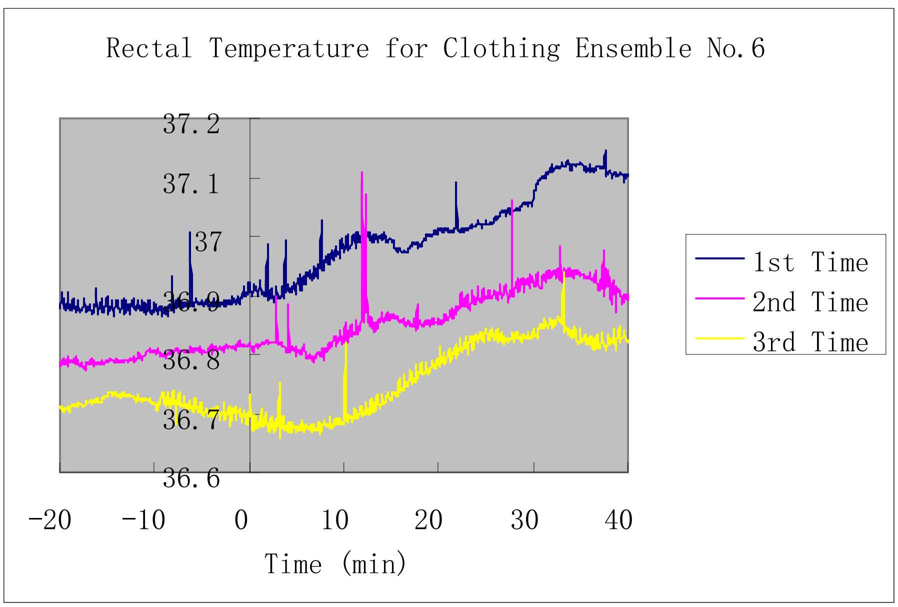


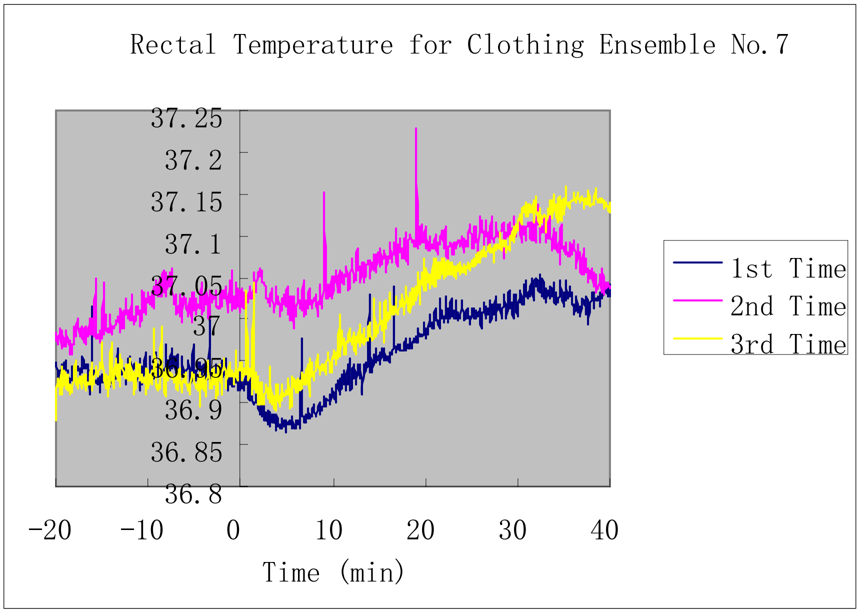




Rectal Temperature for Clothing Ensemble No.3
36.85
36.8
36.75
36.7
36.65
36.6
36.55
36.5
36.45
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time

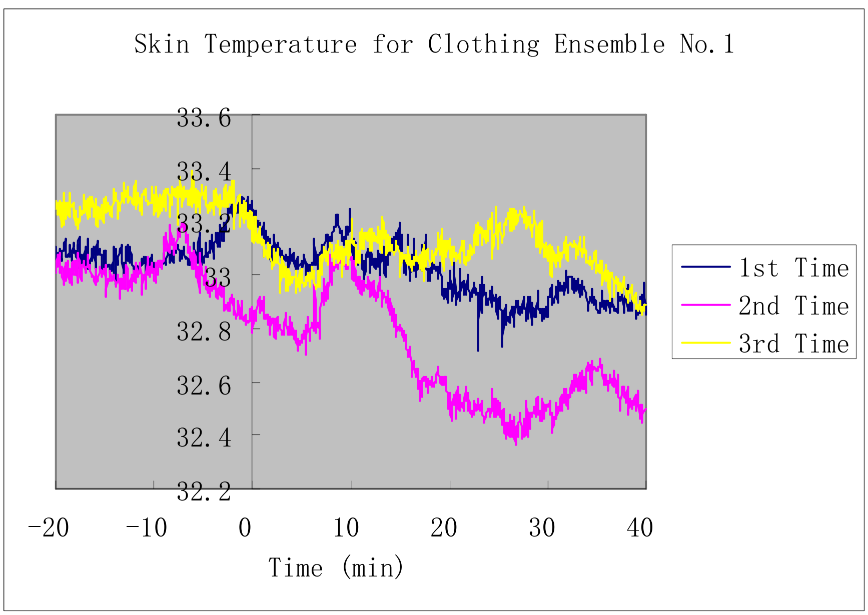

Rectal Temperature for Clothing Ensemble No.4
37.4
37.3
37.2
37.1
37
36.9
36.8
36.7
36.6
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time

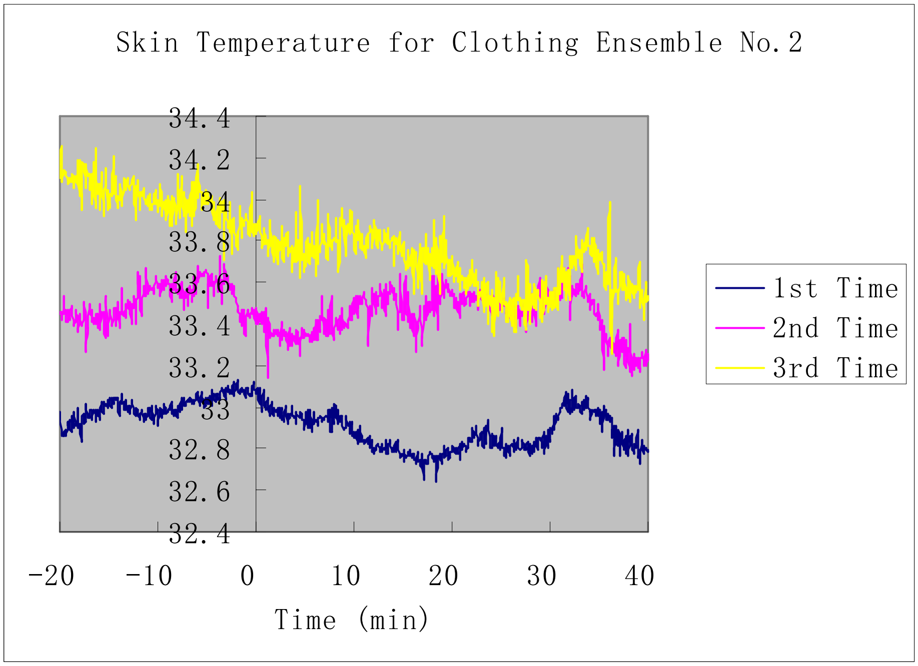

Rectal Temperature for Clothing Ensemble No.5
37.3
37.2
37.1
37
36.9
36.8
36.7
36.6
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time

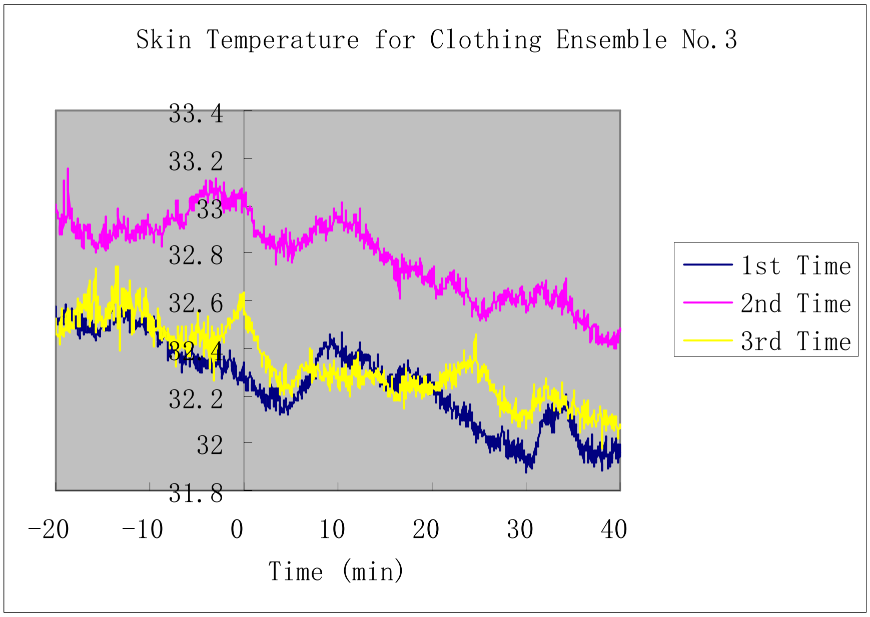

Rectal Temperature for Clothing Ensemble No.6
37.2
37.1
37
36.9
36.8
36.7
36.6
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time

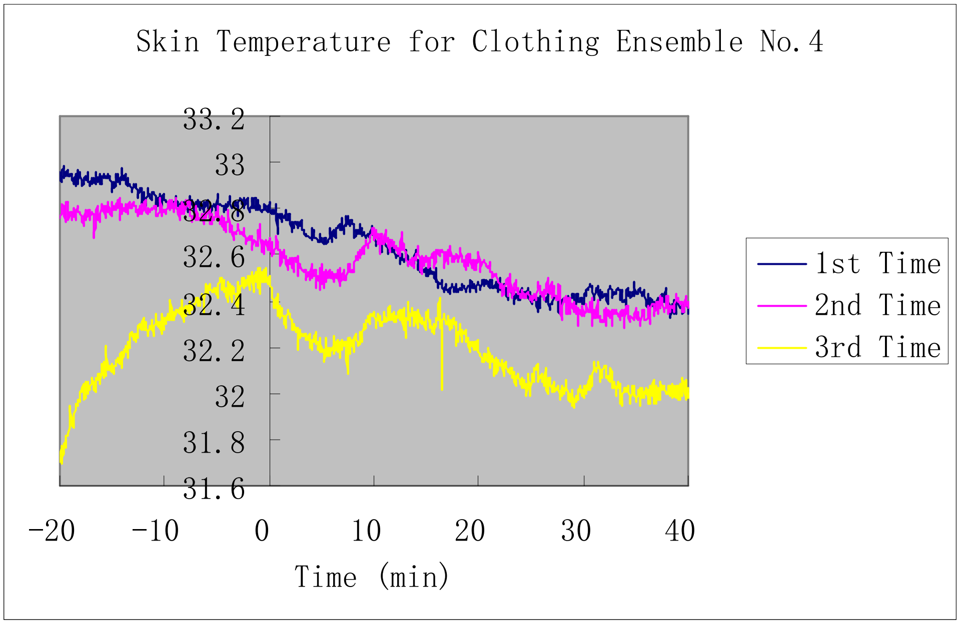


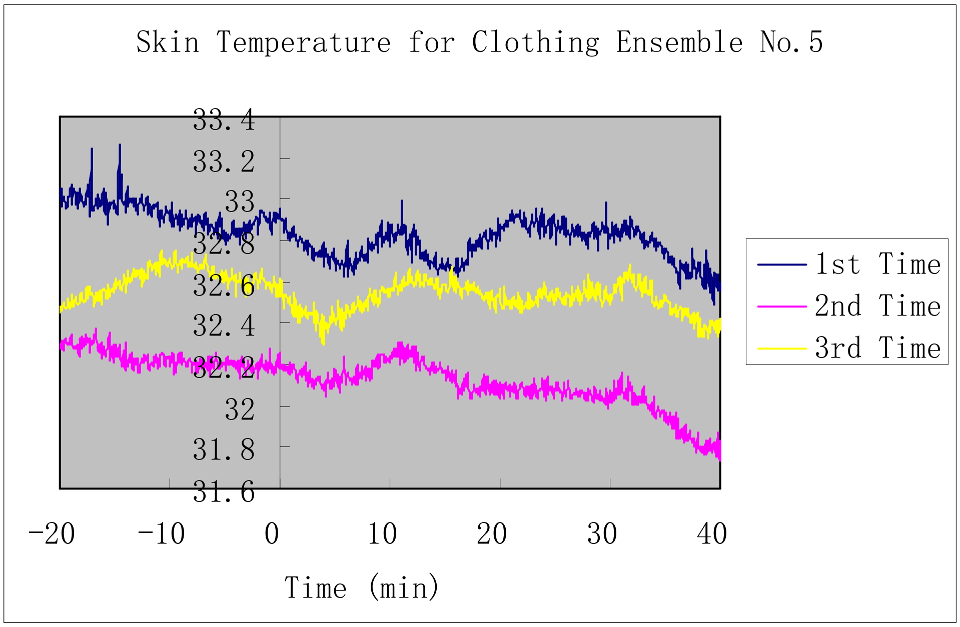

## Appendix B: Skin Temperature of the Subject in Wearer Trials

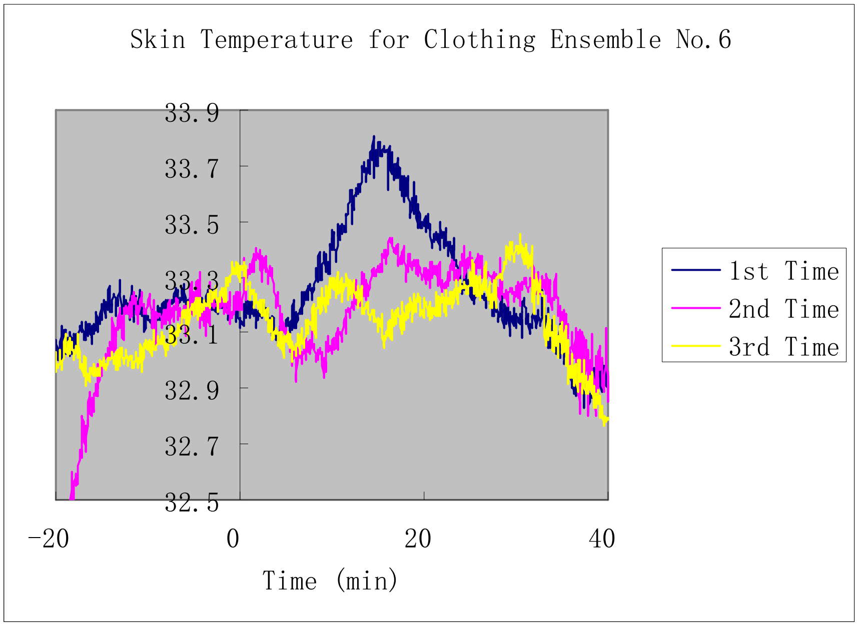


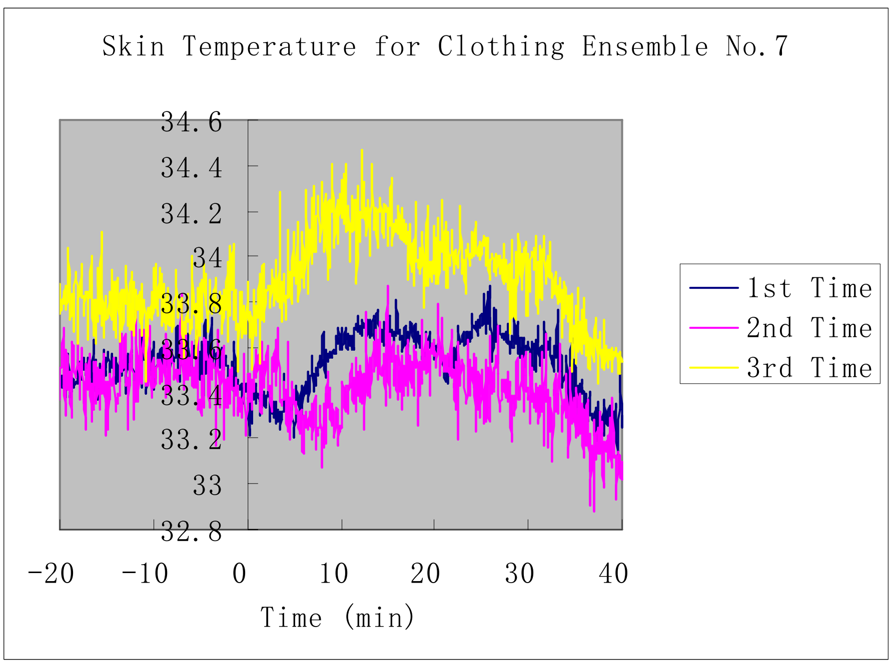

Skin Temperature for Clothing Ensemble No.2
34.4
34.2
34
33.8
33.6
33.4
33.2
33
32.8
32.6
32.4
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time


Skin Temperature for Clothing Ensemble No.3
33.4
33.2
33
32.8
32.6
32.4
32.2
32
31.8
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time

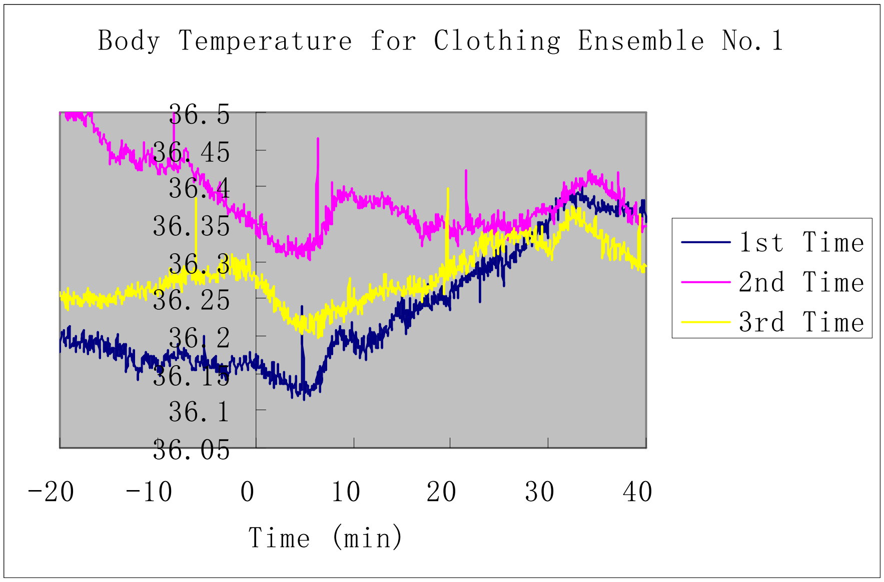

Skin Temperature for Clothing Ensemble No.4
33.2
33
32.8
32.6
32.4
32.2
32
31.8
31.6
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time

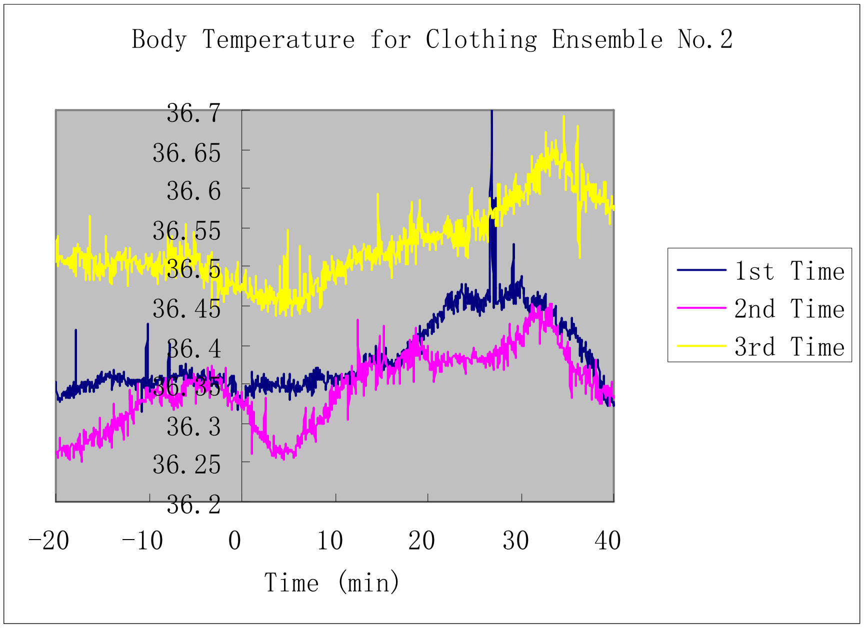

Skin Temperature for Clothing Ensemble No.5
33.4
33.2
33
32.8
32.6
32.4
32.2
32
31.8
31.6
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time

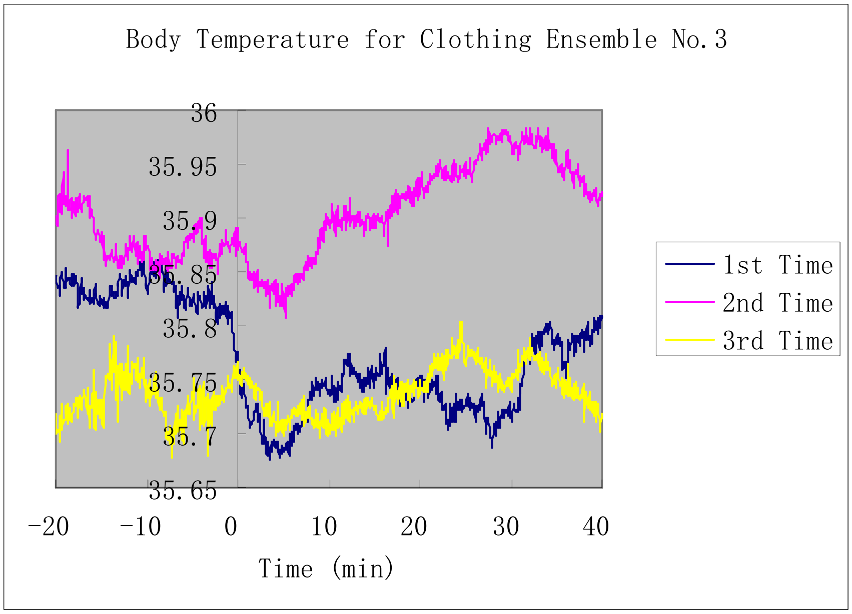

Skin Temperature for Clothing Ensemble No.6
33.9
33.7
33.5
33.3
33.1
32.9
32.7
32.5
-20
0
20
40
Time (min)
1st Time
2nd Time
3rd Time

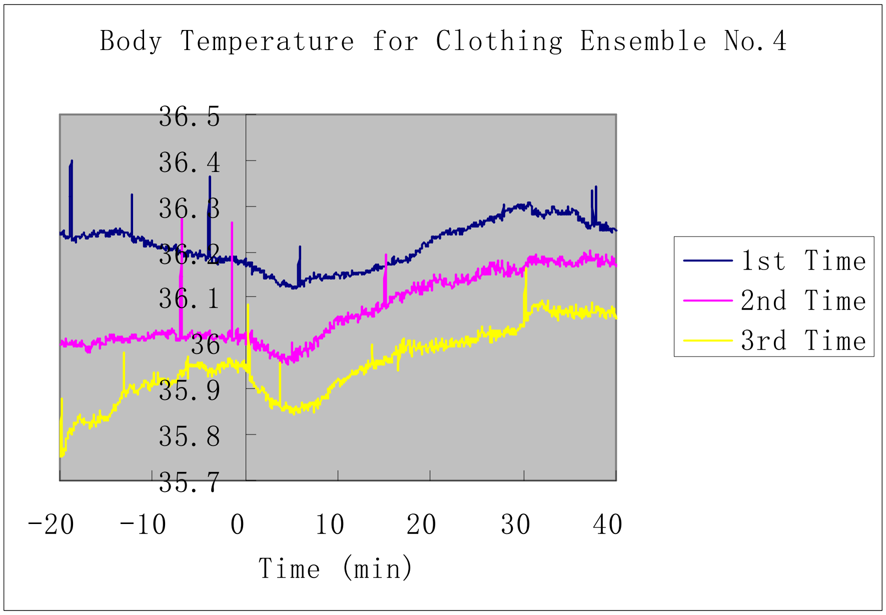

Skin Temperature for Clothing Ensemble No.7
34.6
34.4
34.2
34
33.8
33.6
33.4
33.2
33
32.8
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time

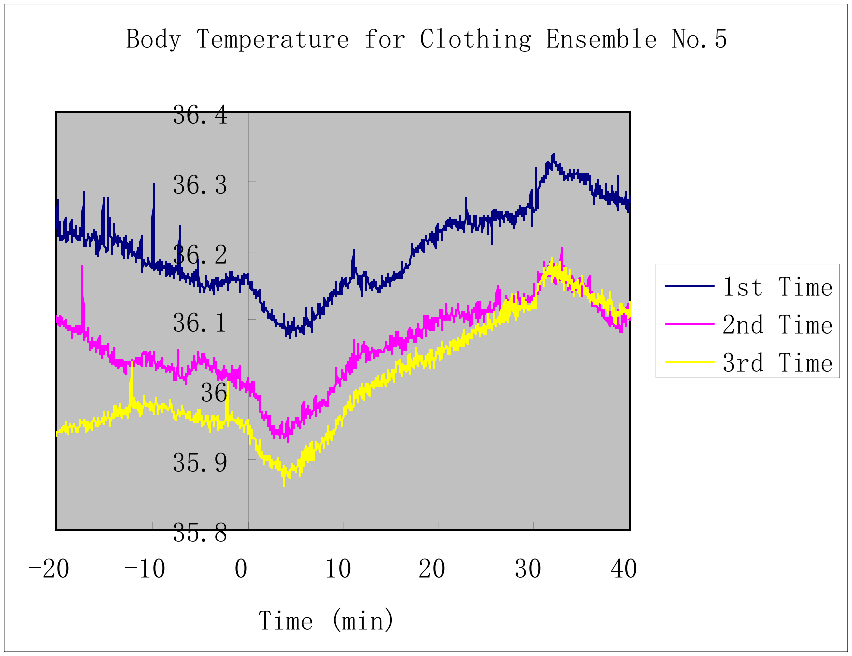
## Appendix C: Body Temperature of the Subject in Wearer Trials

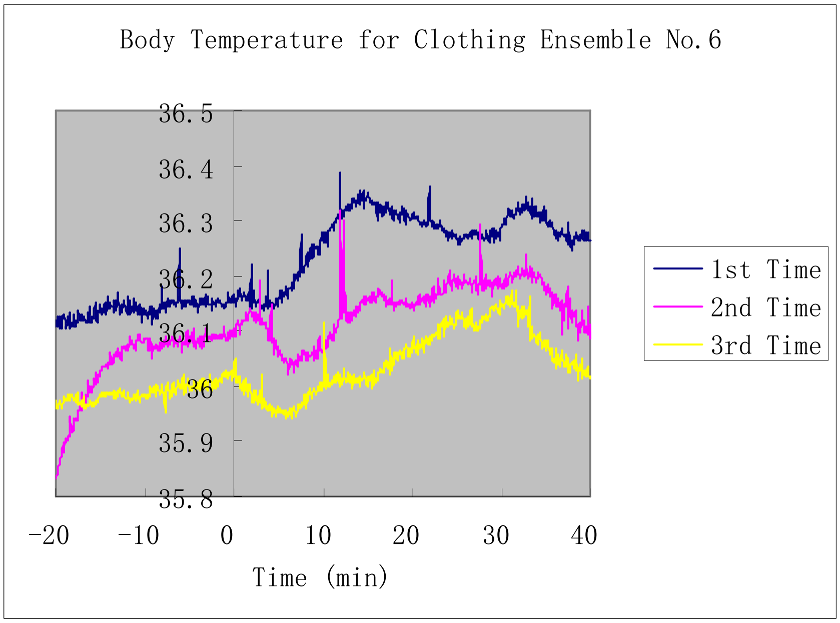


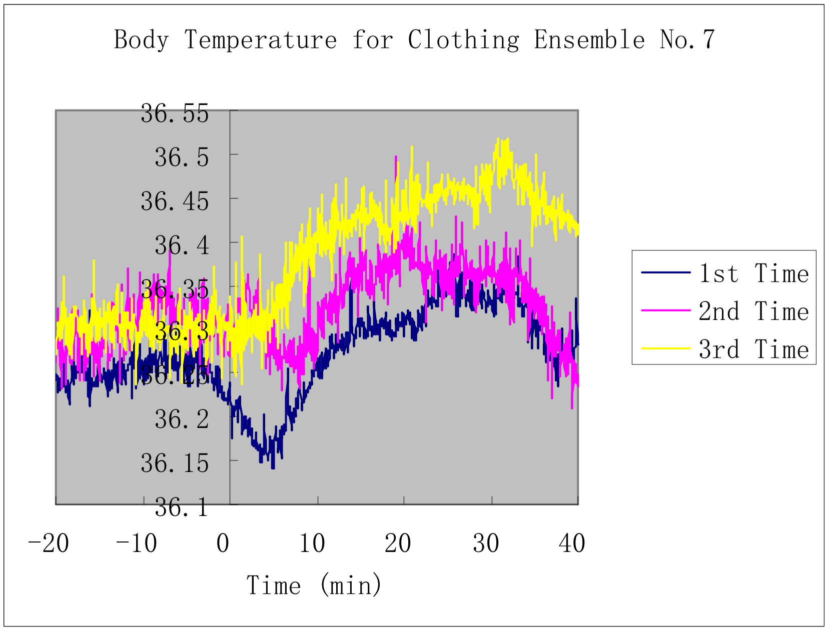




Body Temperature for Clothing Ensemble No.3
36
35.95
35.9
35.85
35.8
35.75
35.7
35.65
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time


Body Temperature for Clothing Ensemble No.4
36.5
36.4
36.3
36.2
36.1
36
35.9
35.8
35.7
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time


Body Temperature for Clothing Ensemble No.5
36.4
36.3
36.2
36.1
36
35.9
35.8
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time


Body Temperature for Clothing Ensemble No.6
36.5
36.4
36.3
36.2
36.1
36
35.9
35.8
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time


Body Temperature for Clothing Ensemble No.7
36.55
36.5
36.45
36.4
36.35
36.3
36.25
36.2
36.15
36.1
-20
-10
0
10
20
30
40
Time (min)
1st Time
2nd Time
3rd Time

## References


ASHRAE, 1993, Physiological principles and thermal comfort, ASHRAE Handbook of Fundamentals, Chapter 8, Atlanta, USA.

ASHARE, 2001, Thermal comfort, ASHRAE Handbook of Fundamentals, Chapter 8, Atlanta, USA.

ASTM D7024-04, 2004, Standard test method for steady state and dynamic thermal performance of textile materials, West Conshohocken, USA

ASTM F2371-05, 2005, Standard test method for measuring the heat removal rate of personal cooling systems using a sweating heated manikin, West Conshohocken, USA.

Azer, N.Z. and Hsu, S., 1977, The prediction of thermal sensation from a simple model of human physiological regulatory response, ASHRAE Transactions, 83(1), pp.88-102.

Bachmann, V.P., 1928, Ueber die Bestimmung des Warmehaltungsvermometers, Deut. Med. Woch., 54, pp.146-147.

Bakkevig, M.K. and Nielsen, R., 1995, The impact of activity level on sweat accumulation and thermal comfort using different underwear, Ergonomics, 38, pp.926-939.

Belding, H.S., Russel, H.D., Darling, R.C. and Folk, G.E., 1947, Analysis of factors concerned in maintaining energy balance for dressed men in extreme cold; effects of activity on the protective value and comfort of an arctic uniform, American Journal of Physiology, 149, pp.223-239.

Birnbaum, R.R. and Crockford.G.W., 1978, Measurement of the clothing ventilation index, Applied Ergonomics, 9(4), pp.194-200.

Blyth, G., 1984, Heat and vapour transfer properties of knitted fabrics, Ph.D Thesis, The University of Leeds.

Bogaty, H., Hollies, N. R. S., and Harris, M., 1957, Some thermal properties of fabrics: Part I, The effect of fiber arrangement, Textile Res, J., 27, 445-449.

Buck, A. L. 1996, Buck Research Manuals.

Cengel, Y.A., 2003, Heat transfer: a practical approach, McGraw-Hill Book Company, New York.

Crockford, G.W., Crowder, M. and Prestidage, S.P., 1972, A trace gas technique for measuring clothing microclimate air exchange rates, Brit.J.Industr.Med., 29, pp.378-386.

Crockford, G.W. and Rosenblum.H.A., 1974, The measurement of clothing microclimate volumes, Clothing research journal, 2, pp.109-114.

David, H. G.. and Nordon, P., 1969, Case studies of coupled heat and moisture diffusion in wool beds, Textile Res. J., 39, pp.166-172.

De Dear, R. J., Knudsen, H. N., Fanger, P. O., 1989, Impact of air humidity on thermal comfort during step changes, ASHRAE Transactions, 95(part 2), pp.336-350.

Ebbecke, U. , 1917, Über die Temperaturempfindungen in ihrer Abhängigkeit von der Hautdurchblutung und von den Reflexzentren, Pflügers Arch Ges Physiol, 169, pp. 395-462.

Ebbecke, U., 1948, Schüttelfrost in Kälte, Fieber und Affekt, Klin Wschr, 26, pp. 609-613.

Fan, J., 1989, A study of heat transfer through clothing assemblies, Doctoral dissertation Thesis, The University of Leeds.

Fan, J. and Keighley, J.H., 1989, A theoretical and experimental study of the thermal insulation of clothing in windy conditions, IJCST, 1(1), pp.21-29.

Fan, J., Lou, Z. and Li, Y., 2000, Heat and moisture transfer with sorption and condensation in porous clothing assemblies and numerical simulation, International Journal of Heat and Mass Transfer, 43, pp.2989-3000.

Fan, J. and Chen, Y.S., 2002, Measurement of clothing thermal insulation and moisture vapour permeability using a novel perspiring fabric thermal manikin, Measurement Science and Technology, 13, pp.1115-1123.

Fan, J. and Wen, X. 2002, Modeling heat and moisture transfer through fibrous insulation with phase change and mobile condensates, International Journal of Heat and Mass Transfer, 45, pp.4045-4055

Fan, J., Qian, X. and Newton, E., 2003, Recent developments of sweating fabric manikin "Walter", Proceedings of the 2nd European Conference on Protective Clothing(ECPC), Montreux,Switzerland, May,2003.

Fan, J., Cheng, X., Wen, X. and Sun, W., 2004, An improved model of heat and moisture transfer with phase change and mobile condensates in fibrous insulation and comparison with experimental results, Int. J. Heat Mass Transfer, 47, pp.2443-2352.

Fan, J. and Qian, X., 2004, New functions and applications of Walter, the sweating fabric manikin, Eur J Appl Physiol, 92, pp.641-644

Fanger, P.O., 1970, Thermal comfort, Danish Technical Press, Copenhagen.

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

Farnworth, B., 1983, Mechanism of heat flow through clothing insulation, Tex. Res. J., 53(12), pp.717-725.

Farnworth, B., 1986, A numerical model of the combined diffusion of heat and water vapor through clothing, Tex.Res.J., 56, pp.653-665.

Fiala, D., 1998, Dynamic simulation of human heat transfer and thermal comfort, Ph.D Thesis, De Montfort University, Leicester.

Fiala, D., 2002, First principles modeling of thermal sensation responses in steady state and transient conditions, ASHRAE Transactions, 109, pp.179-186.

Fiala, D., Lomas, K.J. and Stohrer, M., 2003, First principles modeling of thermal sensation responses in steady-state and transient conditions, ASHRAE Transactions, 109, pp.179-186.

Fonseca, G.F., 1975, Sectional dry heat transfer properties of clothing in wind, Tex. Res. J., 45, pp.30-34.

Fu, G., 1995, A transient,3-D mathematical thermal model for the clothed human, Ph.D Thesis, Kansas State University, Manhattan, Kansas.

Gagge, A.P. and Burton, H.C.A., 1941, Practical system of units for the description of the heat exchange of man with his environment, Science, pp.428-430.

Gagge, A., P., Stolwijk, J.A.J. and Nishi, Y., 1971, An effective temperature scale based on a simple model of human physiological regulatory response, ASHRAE Transactions, 77,Pt.1, pp.247-262.

Gagge, A., P., Fobelets, A.P. and Berglund, L.G., 1986, A standard predictive index of human response to the thermal environment, ASHRAE Transactions, 92, pp.709-731.

Gavin, T.P., et al., 2001, Clothing fabric does not affect thermoregulation during exercise in moderate heat, Med.Sci.Sports.Exerc., 33(12), pp.2124-2130.

Ghaddar, N., Ghali, K. and Jones, B., 2003, Integrated human-clothing system model for estimating the effect of walking on clothing insulation, International Journal of Thermal Sciences, 42, pp.605-619.

Gibson, P.W., 1996, Multiphase heat and mass transfer through hygroscopic porous media with applications to clothing materials, Thesis, University of Massachusetts Lowell, Lowell.

Gibson, P.W., Kendrick, C., Rivin, D., Sicuranza, L. and Charmchi, M., 1995, An automated water vapor diffusion test method for fabrics, Laminates, and films, Journal of Coated Fabrics, 24, pp.322-345.

Givoni, B. and Goldman, R.F., 1972, Predicting rectal temperature response to work,environment, and clothing, J.Appl.Physiol., 32, pp.812-822.

Goldman, R.F., 1974, Clothing design for comfort and performance in extreme thermal environment, Transaction of the New York Academy of Sciences, 36, pp.531-544.

Guan, Y., Jones, B.W., Hosni, M.H. and Gielda, T.P., 2003, Investigation of human thermal comfort under highly transient conditions for automotive applications-part1: experimental design and human subject testing implementation, ASHRAE Transactions, 109, pp.885-897.

Ha, M. and Tokura, H., 1995, Effects of two kinds of clothing made from hydrophobic and hydrophilic fabrics on local sweating rates at an ambient temperature of 37 oC, Ergonomics, 38(7), pp.1445-1455.

Ha, M., Tokura, H., Yanai, Y., Moriyama, T. and Tsuchiya, N., 1999, Combined effects of fabric air permeability and moisture absorption on clothing microclimate and subjective sensation during intermitten exercise at 27℃, Ergonomics, 42(7), pp.964-979.

Hardy, J. D. , 1970, Thermal comfort: Skin temperature and Physiological thermoregulation, Physiological and Behavioral Temperature Regulation, Springfield, Illinois, Thomas, pp.856-873

Hanada, K., 1979, Studies on the regional thermal resistance of clothing system, Part I, J.Japen.Res.Assoc.For Text.End-Uses 20.

Havenith, G., et al., 1990, Resultant clothing insulation: a function of body movement, posture, wind, clothing fit and ensemble thickness, Ergonomics 33, pp. 67-84.

Henry, P. S. H., 1939, Diffusion in Absorbing Media, Proc. R. Soc. 171A, pp.215-241.

Hensel, H., 1982, Thermal sensation and thermoreceptors in man, Charles C Thomas.

Hittle, D. C., Andre, T. L., 2002, A new test instrument and procedure for evaluation of fabrics containing phase-change material, ASHRAE Transactions, 108.

Hollies, N.R.S., L.Fourt, G.Arnold and N.Custer, 1973, Use type tests for comfort and effectiveness of firemen's turnout coats, U.S.Department of Commerce, Contract No.NBS 2-35929, COM-74-11075/OGI, pp.18-26.

Holmer, I. 1984, Required clothing insulation (IREG) as an analytical index of cold stress, ASHRAE Transactions, 90, pp.1116 -1128.

Holmer, I., 1985, Heat exchange and thermal insulation compared in woolen and nylon garments during wear trials, Tex.Res. J., 55, pp.511-518.

Holmer, I. 1999, Thermal manikins in research and standards, Proc. Of 3th int. meeting on thermal manikin testing, pp.1-7, Sweden, October, 1999.

Holmer, I., Nilsson, H., Havenith, G. and Parsons, K., 1999, Clothing convective heat exchange, Ann. Occup. Hyg., 43(5), pp.329-337.

Holmer, I., Parson, K. Alfano, G. and Griefahn, B. 2001, Development and validation of the predicted heat strain model, Ann. Occup. Hyg., 45(2), pp. 123-135

Houghton, F.C. and Yaglou, C.P., 1923a, Determining lines of equal comfort, ASHRAE Transactions, 29, pp.163.

Houghton, F.C. and Yaglou, C.P., 1923b, Determining lines of equal comfort, ASHRAE Transactions, 29, pp.363.

Huizenga, C., et al., 2001, A model of human physiology and comfort for assessing complex thermal environments, Build. Environ. 36, pp.691-699.

ISO 11092, 1993, Textiles - Physiological effects - Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test), International Standards Organization, Geneva.

ISO 7933, 1989, Hot environments – Analytical determination and interpretation of thermal stress using calculation of required sweating rate, International Standards Organization, Geneva.

ISO 8996, 1990, Ergonomics – Determination of metabolic heat production, International Standards Organization, Geneva.

Jones, B.W. and Ogawa, Y., 1992, Transient interaction between the human and the thermal environment, ASHRAE Transactions, 98(1), pp.189-195.

Jones, F.E., 1992, Evapoation of Water-with Emphasis on Application and Measurements, Lewis Publishers, MI, USA.

Kerslake, D.M., 1963, A heated manikin for studies of ventilated clothing, MOD London, FPRC Memo No 214.

Kerslake, D.M., 1971, Physiological aspects of comfort, 3th Shirley International Seminar,"Textiles and Comfort", Shirley Institute,Manchester.

Kerslake, D.M., 1972, The stress of hot environment, Monographs of the Physiological Society, 29.

Kwon, A., Kato, M., Kawamura, H., Yanai, Y. and Tokura, H., 1998, Physiological significance of hydrophilic and hydrophobic textile materials during intermittent exercise in humans under the influence of warm ambient temperature with and without win, Eur.J.Appl.Phsiol., 78, pp.487-493.

Lee, J.Y. and Choi, J.W., 2004, Influences of clothing types on metabolic, thermal and subjective response in a cool environment, Journal of Thermal Biology, 29, pp.221-229.

Lees, C.H., 1898, On the thermal comductivity of single and mixed solid and liquid and their variation with temperature, Phil. Trans., A191, pp.399-440.

Lees, C.H. and Chorlton, J.D., 1896, On a simple apparatus for determining the thermal conductivity of cements and other substances used in arts, Phil. Mag., 41, pp.495-503.

Li, Y. and Holcombe, B.V., 1992a, A two stage sorption model of the coupled diffusion of moisture and heat in wool fabric, Tex.Res. J., 62(4), pp.211-217.

Li, Y. and Holcombe, B. V. 1992b, Transient interaction between the human and the thermal environment, ASHARE Trans., 98, Part I, pp.189-195.

Li, Y., Holcombe, B., 1998, Mathematical simulation of heat and mass transfer in a human-clothing-environment, Text. Res. J., 68, pp389-397.

Li, Y., Zhu, Q.Y. and Luo, Z.X., 2001, Numerical simulation of heat transfer coupled with porous textiles, Preceedings of the 6th Asian Textile Conference, Hong Kong, August 22-24.

Li, Y., Zhu, Q.Y. and Yeung, K.W., 2002, Influence of thickness and porosity on coupled heat and liquid moisture transfer in porous textiles, Tex. Res. J., 72(5), pp.435-446.

Li, Y., Li, F., Liu, Y. and Lou, Z., 2004, An integrated model for simulating interactive thermal processes in human-clothing system, Journal of Thermal Biology, 29, pp.567-575.

Lotens, W.A. and Havenith, G., 1986, Ventilation of garments, Annals of physiology and anthropology, 5(3), pp.139-140.

Lotens, W.A. and Havenith, G., 1988, Ventilation of rainwear determined by a trace gas method, Taylor & Francis, New York.

Lotens, W., 1993, Heat transfer from humans wearing clothing, Ph.d Thesis, TNO Institute for Perception, Soesterberg, The Netherlands.

Malchaire, J. Piette, A., Kampmann, B., Mehnert, P., Gebhardt, H., Havenith, G., Den Hartog, E., Holmer, I., Parson, K., Alfano, G. and Griefahn, B., 2001, Development and validation of the predicted heat strain model, Ann. Occup. Hyg., 45(2), pp. 123-135

Mak, K.H., 1980, A study of thermal properties of some textile fabrics, Ph.d Thesis, The University of Leeds.

Marsh, M.C., 1931, The thermal insulatio properties of fabrics, J.Text.Inst., 22, pp.T245.

Marsh, M.C., 1931, The thermal insulation properties of fabrisc, J.Text.Inst., 22, pp.T245.

Mattle, N., 1999, Use sweating articulated manikin SAM for thermophysiological assessment of complete garments, Proceedings of the Third International Meeting on Thermal Manikin Testing, at the National Institute for working life, Stockholm,Sweden, Oct,1999, pp.100-101.

McCullough, E.A., Jones, B.W. and Tamura, T., 1989, A data base for determining the evaporative resistance of clothing, ASHRAE Transactions, 95(2), pp.316-328.

Mecheels, J. and Umbach, K.H., 1977, Thermo-physiological properties of clothing system, Melliand Textilberichte, 57, pp.1029-1032.

Meinander, H., 1999, Extraction of data from sweating manikin tests, Proc.3rd Int.Meeting on Thermal Manikin Testing(3IMM), Stockholm,Sweden, Oct,1999, pp.95-99.

Meinander, H., et al., 2003, Thermal insulation measurement of cold protective clothing using thermal manikins(Report 4), Tempere University of Technology, pp.ISSN 1459-3734.

Mitchell, D. and Rensburg, A.J.V., 1973, Assessment of clothing insulation: the problem and its solution using direct calorimetry on exercising men, Archives des Sciences Physiologiques, 27, pp.A149-A162.

Morton, W. E., Hearle, J. W. S., 1993, Physical Properties of Textile Fibres, The Textile Institute, Manchester.

Nielsen, R. and Endrusick, T.L., 1990, Thermoregulatory responses to intermittent exercise are influenced by knit structure of underwear, Eur.J.Appl.Phsiol., 60, pp.15-25.

Nielsen, R., Olesen, B.W. and Fanger, P.O., 1985, Effect of physical activity and air velocity on the thermal insulation of clothing, Ergonomics, 28(12), pp.1617-1631.

Nilsson, H.O., Anttonen, H. and Holmer, I., 2000, New algorithms for prediction of wind effects on cold protective clothing, Ergonomics of protective clothing, Arbete och halsa, August,2000, pp.17-20.

Nishi, Y., Gonzales, R., R, and Gagge, A., P., 1975, Direct measurement of clothing heat transfer properties during sensible and insensible heat exchange with thermal environment, ASHRAE Transactions, 81, pp.183-199.

Niven, C.D. and Babbitt, J.D., 1938, On the heat transmission of textile fabrics, J. Text. Inst, 29, pp.T161.

Ogniewicz, Y. and Tein, C. L., 1995, Analysis of condensation in porous insulation slab bounded on one side by a cold surface, Int. J. Heat Mass Trans. 38(17), pp. 3253-3262

Olesen, B.W., 1984, How many sites are necessary to estimate a mean skin temperature?, New York.

Olesen, B.W. and Madsen, T.L., 1983, Measurements of the thermal insulation of clothings by a movable manikin, International Congress of 'Medical and Biophysical Aspects of Protective Clothing', Lyon, July,1983.

Olesen, B.W., Slivinska, E., Madsen, T.L. and Fanger, P.O., 1982, Effect of body posture and activity on the insulation of clothing.Measurements by a movable thermal manikin, ASHRAE Transactions, 88(183), pp.791-805.

Palmes, E. D. and Park, C. R., 1947, Report 2-17-1, Us Army Medical Dept Field Research Lab., Fort Knox, Kentucky.

Parsons, K. C. 1995, International heat stress standards: a review, Ergonomics, 38(1), pp. 6-22

Pause, B., 1995, Development of heat and cold insulating membrane structures with phase change material, Journal of Coated Fabric, 25, pp59-68

Qian, X., 2005, Prediction of clothing thermal insulation and moisture vapour resistance, Ph.D Thesis, The Hong Kong Polytechnic University, Hong Kong.

Qian, X. and Fan, J., 2005a, A quasi-physical model for predicting the clothing thermal insulation and moisture vapour resistance, Part I: building the model, Submitted to Annals of Occupational Hygiene.

Qian, X. and Fan, J., 2005b, A quasi-physical model for predicting the clothing thermal insulation and moisture vapour resistance, Part II: Validation and comparison of the models, Submitted to Annals of Occupational Hygiene.

Qian, X. and Fan J. 2006, Interactions of the surface heat and moisture transfer from the human body under varying climatic conditions and walking speeds, Applied Ergonomics, 37(6), pp.685-693.

Rae, A., Bruce, R. 1973, The Wira Textile Data Book, Wira, Leeds.

Reishl, U., Spaul, W.A., Dukes-Dobos, F.N. and Hall, E.G., 1987, Ventilation analysis of industrial protective clothing, Trends in Ergonomics/Human Factors IV, Holland.

Ring, J.W. and de Dear, R.J., 1991, Temperature transients: a model for heat diffusion through the skin, thermoreceptor response and thermal sensation, Indoor Air, 1(4), pp.448-456.

Rohles, F.H. and Nevins, R.G., 1971, The nature of thermal comfort for sedentary man, ASHRAE Transactions, 77(1), pp.239-246.

Rood, E.S., 1921, Thermal conductivity of some wearing materials, Phy.Rev., 18, pp.356-361.

Rugh, 2004, Predicting human thermal comfort in a transient nonuniform thermal environment, Eur.J.Appl.Phsiol., 92, pp.721-727.

Seppanen, O., Mcnall, P.E., Munson, D.M. and Sprague, C.H., 1972, Thermal insulating values for typical clothing ensembles, ASHRAE Transactions, 78(1), pp.120-130.

Shapiro, A. P., Motakef, S., Unsteady heat and mass transfer with phase change in porous slab: analytical solutions and experimental results, J. Heat Mass Transfer, 33, pp. 163-173.

Shin-ya, H., Nakai, S., Yoshida, T. and Takahashi, E., 2005, Effects of sportswear on thermoregulatory responses during exercise in a hot environment, Environmental Ergonomics, 3(65-69).

Smith, C.E., 1991, A transient, Three-Dimensional model of the human thermal system, Ph.D Thesis, Kansas State University.

Spencer-smith, J.L., 1976, The physical basis of clothing comfort, Part 1, Clothing research journal, 4(3), pp.126-138.

Stanish, e.a., 1986, A mathematical model of drying for hygroscopic porous media, AIChe Journal, 32(8), pp.1301-1311.

Stolwijk, J. A. J., Hardy, J. D., 1966, Temperature regulation in man – a theoretical study, Pflugers Archiv., 291, pp.129-162.

Stolwijk, A.J., 1971, A mathematical model of physiological temperature regulation in man, NASA Technical Report, No.NASA CR-1855.

Stolwijk, A.J. and Hardy, J.D., 1977, Control of Body temperature, Handbook of Physiology-Reaction to Environmental Agents, pp.45-67.

Stolwijk, J.A.J. and Hardy, J.D., 1966, Temperature regulation in man - a theoretical study, Pflugers Arch, 291, pp.129-162.

Stuart, M.I.a.D., E.F., 1983, Wind induced transfer of water vapor and heat through clothing, Tex. Res. J., 11, pp.655-660.

Tanabe, S., Kobayashi, K., Nakano, J., Ozeki, Y. and Konishi, M., 2002, Evaluation of thermal comfort using combined multi-node thermoregulation (65M) and radiation models and computational fluid dynamics (CFD), Energy and Building, 34, pp.637-646.

Taniguchi, Y., Aoki, H. and Fujikake, K., 1992, Study on car air conditioning system controlled by car occupants' skin temperatures - part1: research on a method of quantitative evaluation of car occupants' thermal sensations by skin temperatures, SAE PAPER-920169, pp.13-19.

Umeno, T., Hokoi, S. and Takada, S., 2001, Prediction of skin and clothing temperatures under thermal transient considering moisture accumulation in clothing, ASHRAE Transactions, 107, pp.71-81.

Vafai, K., Sarka, S., 1986, Condensation effects in a fibrous insulation slab, J. Heat Transfer, 108, pp.667-675.

Vogt, J.J., Meryer, J.P., Candas, V., Libert, J.P. and Sagot, J.C., 1983, Pumping effect on thermal insulation of clothing worn by human subjects, Ergonomics, 26, pp.963-974.

Vogt, J.J., Sagot, J.C., Meryer, J.P. and Candas, V., 1984, Basic, effective and resultant clothing insulations, ASHRAE Transactions, 90, pp.1091-1098.

Vokac, Z., Kopke, V. and Keul, P., 1973, Assessment and analysis of the bellows ventilation of clothing, Tex. Res. J., 43(8), pp.474-482.

Vokac, Z., Kopke, V. and Keul, P., 1976, Physiological responses and thermal, humidity, and comfort sensations in wear trials with cotton and polypropylene vests, Tex.Res. J., 46, pp.30-38.

Wang, J.H. and Yasuda, H., 1991, Dynamic water vapour and heat transport through layered fabrics, part 1: effect of surface modification, Tex. Res. J., 61(1), pp.10-20.

Wang, X. L. and Peterson, F.H. 1992. Estimating thermal transient comfort, ASHRAE Trans., 98, Part I, pp.182-188.

Winslow, C.E.A., Herrington, L.P. and Gagge, A., P., 1937, Relations between atmospheric conditions, physiological reactions and sensations of pleasantness, American Journal of Hygiene, 26(1), pp.103-115.

Winslow, C.E.A., Herrington, L.P. and Gagge, A., P., 1938a, The reactions of the clothed human body to variations in atmospheric humidity, American Journal of Physiology, 124(3), pp.692-703.

Winslow, C.E.A., Herrington, L.P. and Gagge, A., P., 1938b, The reactions of the clothed human body to variations in atmospheric humidity, American Journal of Physiology, 124(3), pp.692-703.

Winslow, C.E.A., Herrington, L.P. and Gagge, A., P., 1939, Physiological reactions and sensations of pleasantness under varying atmospheric conditions., ASHRAE Transactions, 44, pp.179-194.

Wissler, E.H., 1964, A mathematical model of the human thermal system, Bull.Math.Biophy., 26(2), pp.147-166.

Wissler, E.H., 1985, Mathematical simulation of human thermal behavior using whole body models, Heat Transfer in Medicine and Biology, pp.325-373.

Woodcock, A.H., 1962, Moisture transfer in textile systems , part 1, Tex. Res. J., 32, pp.628-719.

Xu, X. and Werner, J., 1997, A dynamic model of the human/clothing/environment-system, Appl. Human Sci., 16(2), pp.61-75.

Yasuda, T., Miyama, M. and Yasuda, H., 1992, Dynamic water vapour and heat transport through layered fabrics, part2: effect of the chemical nature of fibers, Tex.Res.J., 62(4), pp.227-235.

Yasuhiko, D., et al., 1992, A model of sweating thermal manikin, J.Tex.Mach.Soc.Jan., 37, pp.101-112.

Ying, B., Kwok, Y., Li, Y., Zhu, Q., Yeung, C., 2004, Test method assessing the performance of textiles incorporating phase change materials, Polymer Testing, 23, pp. 541-549

Zhang, H., 2003, Human thermal sensation and comfort in transient and non-uniform thermal environments, Thesis, University of California, Berkeley.

Zhang, P. and Gong, R.H., 2002, Effects of clothing material on thermoregulatory responses, Tex.Res. J., 72(1), pp.83-89.