Zhao-Hua Zhang [1,2],
Yunyi Wang [1],
Jun Li [1,3]

Model for Predicting the Effect of an Air Gap on the Heat Transfer of a Clothed Human Body

1) Fashion Institute, Donghua University, Shanghai 200051, China
E-mail: lijun@dhu.edu.cn

2) Changzhou Textile & Garment Institute, Changzhou 213164, China

3) Key Laboratory of Clothing Design & Technology, Ministry of Education, China

Abstract
Considering a clothing system consists of the human body, an air gap layer under the clothing as well as a fabric layer and boundary layer adjacent to the fabric, heat transfer from the skin to the environment is influenced by human body thermoregulation, the air gap, the fabric and environmental conditions. Based on Stolwijk's 25-node thermoregulatory model, a new mathematical model was developed to include the sensible and latent heat transfer through the air gap, fabric layer and boundary layer adjacent to the fabric. To quantify the effect of the air gap on human body heat transfer, a 3D human body scanner was utilised to measure the air gap thickness of five experimental garments of increasing chest circumference. The model can be used to predict the apparent clothing temperature and heat loss from the human body when people are dressed in differently sized clothing.

Key words: *3D scanner, clothing temperature, heat loss, air gap.*

Introduction

Air gaps entrapped between the skin and inner surface of clothing act as a microclimate, influencing the thermal contact feeling of the wearer and thermoregulatory response of the body [1 - 3]. Some researchers have investigated the influence of air gap distributions on the protective performance of thermal protective clothing. Kim (2002) [4] utilised a three-dimensional (3D) whole body digitiser to quantify air gap sizes in single and multilayer clothing systems and investigated the relationship between air gap distributions and burn patterns obtained from full-scale manikin fire tests. Song (2007) [5] examined the relationships between burn patterns measured on a flash fire manikin and manikin-garment air gap sizes measured by a three-dimensional body scanner. He developed a numerical model to predict the dimensions of a skin-clothing air gap for optimum thermal protection. Other researchers have investigated the relationship between air volume and clothing thermal insulation. Lee and Hong (2007) [6] measured the microclimate volume of layered clothing using a 3D scanner and related it to the thermal insulation value of the clothing system by means of a thermal manikin. In the last 40 years, a considerable amount of papers have modelled heat transfer from the human body to the surrounding air [7 - 10]. Although these models are fairly complex, few have concerned the prediction of the apparent clothing temperature and heat loss from differently sized garments. In this study, based on the air gap thickness of differently sized clothing obtained from a 3D scanner, a mathematical model is established to predict the effect of the air gap on the apparent clothing temperature and heat loss of a clothed human body.

Table 1. Fabric specification.

Fabric	Cotton
Weight, g/m^2	126
Thickness, mm	0.312
Warp density, 1/10 cm	585.6
Weft density, 1/10 cm	284
Thermal resistance, clo	0.155

Experimental

Five women's coats (B90; B94; B98; B102; B106) of increasing breast circumference, from 90 cm to 106 cm, were tested as experimental garments. All the garments had the same pattern design and were made of the same cotton fabric, as shown in ***Table 1***. The only difference in the five experimental garments was their gradually increasing breast circumference. 'B90' means that the breast circumference of the experimental garment is 90 cm, and so on.

To investigate the effect of air gap thickness on the heat transfer of a clothed human body in detail, a three-dimensional scanner (BMS from TC2) was applied to quantitatively measure the air gap thickness. Six healthy women aged 23 ± 2 years, of 160 ± 2 cm height, 86 ± 2 cm bust circumference, 70 ± 2 cm waist circumference, and 90 ± 2 cm hip circumference volunteered to participate in the tests. The subjects wore a bra and trousers for the initial scan and then put on the experimental garment for a second scan in the same body pose. Every test was repeated three times to reduce er-

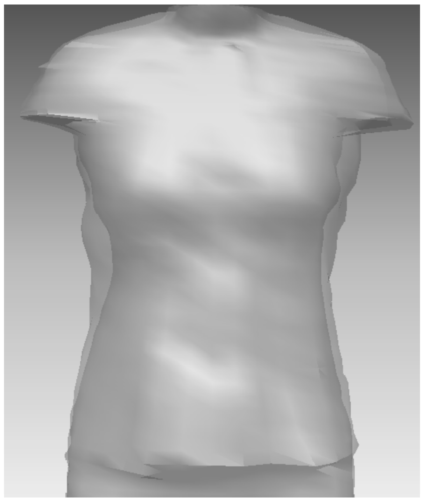

Figure 1. *Air gap distribution under garment B94.*

Table 2. *Average air gap sizes under a human trunk.*

Garment code	B90	B94	B98	B102	B106
Air gap thickness, cm	0.51	0.83	1.12	1.51	1.97
Air gap volume, cm3	2397.5	4003.7	5110.8	7810.9	8484.6

rors caused by human respiration. With Rapidform software (INUS Technology, Inc.), the initial and second scans were overlapped using a region unchanged in both scans. In this study, only the female torso was focused on, hence the head and extremities were deleted during the analysis. ***Figure 1*** shows an overlapping image of garment B94 over the scan of Body 94, as well as the air gap distribution between the human body and clothing. As shown in ***Table 2,*** the air gap thickness and volume of the five experimental garments increased with the garment size.

Mathematical model

Human beings can maintain heat balance with the environment through thermoregulation and behavioural regulation. The temperature of human skin changes dynamically according to human metabolic heat production, the air gap, clothing insulation and environment conditions, which will influence heat loss from a clothed human body. As shown in ***Figure 2,*** the human body, clothing and environment should be integrated into a system for study. To simulate the effect of air gap thickness on heat exchange between the human body and the environment, a mathematical model is developed to include human thermoregulatory as well as dry and evaporative heat transfer from the skin to the environment through clothing. The starting point of the model is Stolwijk's 25-node model of thermoregulation, but with increases in the two layers, viz. the inner layer and outer layer of clothing in this model. Thus the new model has six segments (head, trunk, arms, hands, legs, and feet), each segment of which is composed of six concentric layers (core, muscle, fat, skin, an inner and outer layer of clothing), 37 nodes in total plus the central blood compartment. Heat balance equations for the six layers and central blood compartment can be expressed as follows:

- Core layer:

$$C(i,1)\frac{dT(i,1)}{dt} = Q(i,1) - B(i,1) + - TD(i,1) - RES(i,1) \quad (1)$$

- Muscle layer:

$$C(i,2)\frac{dT(i,2)}{dt} = Q(i,2) - B(i,2) + + TD(i,1) - TD(i,2) \quad (2)$$

- Fat layer:

$$C(i,3)\frac{dT(i,3)}{dt} = Q(i,3) - B(i,3) + + TD(i,2) - TD(i,3) \quad (3)$$

- Skin layer:

$$C(i,4)\frac{dT(i,4)}{dt} = Q(i,4) - B(i,4) + + TD(i,3) - E(i,4) - Q_{mc}(i) \quad (4)$$

- Inner layer of clothing:

$$A_s(i)L_{mc}(i)C_{mc}(i)\frac{dT(i,5)}{dt} = = Q_{mc}(i) - Q_f(i) \quad (5)$$

- Outer layer of clothing:

$$A_{cl}(i)M_f C_f \frac{dT(i,6)}{dt} = Q_f(i) - Q_a(i) \quad (6)$$

- Central blood:

$$C(37)\frac{dT(37)}{dt} = \sum_{i=1}^{6}\sum_{j=1}^{4} B(i,j) \quad (7)$$

Where i (1 - 6) represents the six segments of the body; j (1 - 6) represents the six concentric layers; $C(i, j)$ and $C(37)$ are the heat capacity of the body node and central blood node; $Q(i, j)$ is the total metabolic heat production; $TD(i, j)$ is the thermal conductance between neighboring layers within the same segment; $B(i, j)$ is the convective heat transfer between central blood and the body node; $RES(i,1)$ is the heat loss through respiration; $T(i, j)$ is the temperature of the body and clothing layer; $T(37)$ is the temperature of the central blood node; $E(i,4)$ is the latent heat loss from the skin through clothing to the environment; $Q_{mc}(i)$ is the direct heat transfer from the skin to the inner layer of the fabric for a clothed body segment; $Q_f(i)$ is the direct heat transfer from the inner layer to the outer layer of the fabric; $Q_a(i)$ is the direct heat flux transfer from the fabric outer layer to the environment; $A_s(i)$ and $A_{cl}(i)$ are the surface area of the body and clothing, respectively; $L_{mc}(i)$ is the air gap thickness of segment i; $C_{mc}(i)$ is the volume heat capacity of air; C_f is the specific heat of the fabric, and M_f is the mass of the fabric.

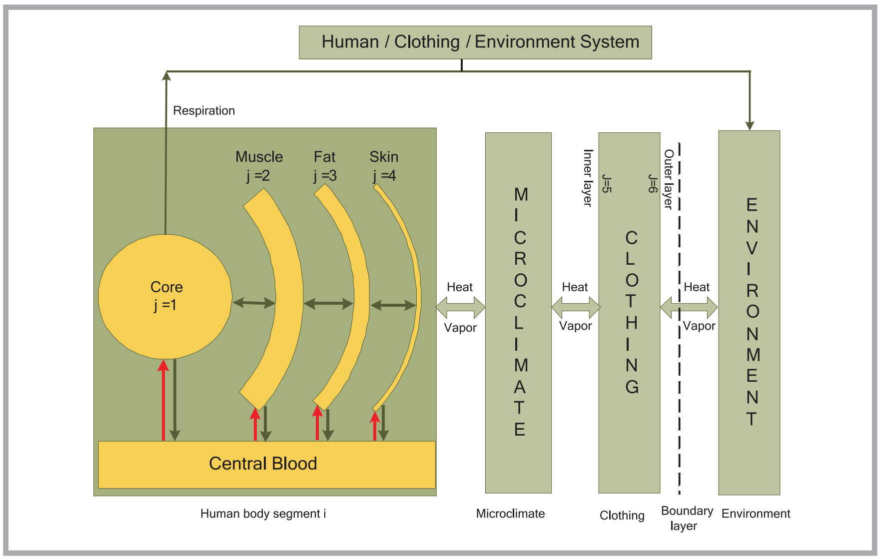

Figure 2*. Human body/clothing/environment system.*

$Q(i, j)$ is the sum of the basal metabolic rate $QB(i, j)$, heat production due to external work $W(i, j)$ and shivering $CH(i, j)$. As the extra work and shivering only occur in the muscle layer (j = 2), and $W(i, j) = CH(i, j) = 0$ for other layers ($j \neq 2$) [9]:

$$Q(i,j) = QB(i,j) + W(i,j) + CH(i,j) \quad (8)$$

$$W(i,2) = 58.2(met - QB)A_s Metf(i) \quad (9)$$

Where, met is the metabolic rate of the whole body, and $Metf(i)$ is the control coefficient of extra heat production.

The shivering heat production $CH(i,2)$ is calculated by:

$$CH(i,2) = \{-CchErr(1,1) + - Sch(Wrms - Clds) + + PchCld(1,1)Clds\} Chilf(i) \quad (10)$$

Where, Cch, Sch and Pch are control coefficients; $Err(i, j)$ is the error signal between the temperature of the node $T(i, j)$ and the set point $T_{set}(i, j)$, and $Wrms$ and $Clds$ are an integrated warm signal and cold signal:

$$Err(i,j) = T(i,j) - T_{set}(i,j) \quad (11)$$

$$Wrms = \sum_{i=1}^{6}(SKINR(i) \times Wrm(i,4)) \quad (12)$$

$$Clds = \sum_{i=1}^{6}(SKINR(i) \times Cld(i,4)) \quad (13)$$

When $Err(i, j) > 0$, $Wrm(i, j) = Err(i, j)$, $Cld(i, j) = 0$; when $Err(i, j) < 0$, $Cld(i, j) = -Err(i, j)$, $Wrm(i, j) = 0$.

$B(i, j)$ is the product of the blood flow rate $BF(i, j)$ and temperature difference between the body node and central blood node.

$$B(i,j) = \rho CBF(i,j)(T(i,j) - T(37)) \quad (14)$$

Where, ρ and C represent the density and specific heat of blood. The blood flow to the core and fat compartments remains at the basal value; the muscle compartment, on the other hand, is influenced by external work and shivering. The skin blood flow is highly dependent on vasodilatation and vasoconstriction, thus:

$$BF(i,1) = BFB(i,1) \quad (15)$$

$$BF(i,2) = BFB(i,2) + \frac{W(i,2) + CH(i,2)}{1.16} \quad (16)$$

$$BF(i,3) = BFB(i,3) \quad (17)$$

$$BF(i,4) = = \frac{BFB(i,4) + SKINV(i) \times DL}{1 + SKINC(i) \times ST} \times 2^{Err(i,4)/10} \quad (18)$$

Where, $BFB(i, j)$ is the basal blood flow rate, which is set as the input constant; $SKINV(i)$ and $SKINC(i)$ are control coefficients, and DL and ST are the signals for vasodilatation and vasoconstriction, calculated by:

$$DL = CdlErr(1,1) + + Sdl(Wrms - Clds) + + PdlWrm(1,1)Wrms \quad (19)$$

$$ST = -CstErr(1,1) + - Sst(Wrms - Clds) + + PstCld(1,1)Clds \quad (20)$$

Where, Cdl, Sdl, Pdl, Cst, Sst, Pst are control coefficients.

$TD(i, j)$ is expressed by the product of the temperature difference and thermal conductance $TC(i, j)$ between the node and its neighbour:

$$TD(i,j) = TC(i,j)(T(i,j) - T(i,j+1)) \quad (21)$$

Heat loss by respiration only occurs at the core layer of the chest segment i.e. node (2, 1), for other body nodes ($i \neq 2, j \neq 1$), $RES(i, j) = 0$.

$$RES(2,1) = \{0.0014(34 - T_a) + + 0.017(5.867 - P_a)\} \sum_{i=1}^{6}\sum_{j=1}^{4} Q(i,j) \quad (22)$$

Where, T_a and P_a are the temperature and water vapour pressure of the environment.

Sensible heat loss from skin

The heat loss from skin to the environment $Q_{mc}(i)$ is different for clothed and unclothed body segments. For the body parts covered by clothing, heat transfer takes place from the skin through the air gap under the clothing, the fabric layer and outer surface air layer of the clothing into the environment, whereas for the unclothed body segments, heat transfer occurs through the boundary air layer of naked skin and is directly dissipated into the environment by natural convection and radiation.

Heat is transferred from the skin to the inner layer of clothing by conduction or convection through the air gap layer, as well as by way of the radiation between the skin and inner surface of clothing. According to Catton's theory [11], for air in a vertical enclosure of thickness δ, heat transfers by conduction when Ra is less than 1000; when the value is more, natural convection will take place. The Nusselt number Nu_δ can be expressed as ***Equation 23***.

Then the heat transfer coefficient through the air gap $h_{mc}(i)$ can be deduced from ***Equation 24***. Where, Ra is the Rayleigh number; Pr is the Prandtl number; $H(i)$ is the height of the body segment i; k_a is the thermal conductivity of air; g is the gravitational acceleration; β is the thermal coefficient of volume expansion; α is the thermal diffusivity, and υ is the kinematic viscosity.

Then the total sensible heat transfer from the skin to the inner layer of clothing can be expressed as ***Equation 25***. Where the first term on the right side represents the thermal conduction or natural convection through the air gap, the second term - the radiant heat transfer between the skin and inner layer of clothing; σ is the Stefan-Boltzman constant; e_s is the emissivity of skin, and e_f is the emissivity of the fabric.

Influenced by the intrinsic thermal insulation of fabric R_f, the dry heat transfer through fabric is determined by:

$$Q_f(i) = A_{cl}(i)\frac{T(i,5) - T(i,6)}{R_f} \quad (26)$$

The dry heat transfer from the outer layer of fabric to the environment is composed of convective and radiant heat:

$$Q_a(i) = A_{cl}(i)h_a(i)(T(i,6) - T_a) + + \sigma e_f(T^4(i,6) - T_a^4) \quad (27)$$

Where the first term represents natural convection from the outer layer of clothing to the environment, the second term - radiant heat transfer, and $h_a(i)$ is the natural convective heat transfer coefficient, which can be calculated using Kyunghoon's theory [12]:

$$Nu_\delta = \begin{cases} 1 & Ra \le 10^3 \\ 0.22\left(\frac{\text{Pr}}{0.2 + \text{Pr}} Ra\right)^{0.28}\left(\frac{H}{\delta}\right)^{-1/4} & 10^3 < Ra < 10^{10} \end{cases} \quad (23)$$

$$h_{mc}(i) = Nu_\delta \frac{k_a}{L_{mc}(i)} = 0.22\left(\frac{\text{Pr}}{0.2 + \text{Pr}} \frac{g\beta T((i,4) - T(i,5))H(i)^3}{\alpha\upsilon}\right)^{0.28}\left(\frac{H(i)}{L_{mc}(i)}\right)^{-1/4}\frac{k_a}{L_{mc}(i)} \quad (24)$$

$$Q_{mc}(i) = A_s(i)\left\{h_{mc}(i)(T(i,4) - T(i,5)) + \frac{\sigma(T^4(i,4) - T^4(i,5))}{1/e_s + 1/e_f - 1}\right\} \quad (25)$$

Equations 23, 24, 25.

$$Nu = \frac{h_a(i)H(i)}{k_a} = $$

$$= 0.518\left(\frac{C_p\rho^2 g\beta(T(i,6)-T_a)H^3(i)}{k_a\mu}\right)^{1/4} \qquad (28)$$

$$h_a(i) =$$

$$= 0.518\left(\frac{C_p\rho^2 g\beta(T(i,6)-T_a)H^3(i)}{k_a\mu}\right)^{1/4} \qquad (29)$$

Where C_p is the heat capacity at constant pressure, ρ - the density, and μ is the viscosity.

Based on the energy conversation law, we establish heat balance equations for the inner layer and outer layer of clothing.

- Inner layer:

$$A_s(i)L_{mc}(i)C_{mc}(i)\frac{dT(i,5)}{dt} = Q_{mc}(i) - Q_f(i)$$

- Outer layer:

$$A_{cl}(i)M_f C_f \frac{dT(i,6)}{dt} = Q_f(i) - Q_a(i)$$

For unclothed body segments, $Q_{mc}(i)$ is the direct heat loss from naked skin to the environment by natural convection and radiation. Similarly, the convective heat transfer coefficient of unclothed body segments is:

$$h_a(i) =$$

$$= 0.518\left(\frac{C_p k_a^3\rho^2 g\beta(T(i,4)-T_a)}{\mu H(i)}\right)^{1/4} \qquad (30)$$

The total sensible heat of unclothed body segments is then expressed as:

$$Q_{mc}(i) = A_s(i)[h_a(i)(T(i,4)-T_a) + \sigma e_s(T^4(i,4)-T_a^4)] \qquad (31)$$

The latent heat loss from skin

$E(i, 4)$ is the evaporative heat loss from the surface of skin through clothing to the environment, calculated by:

$$E(i, 4) = EB(i, 4) + SKINS(i) \times$$
$$\times\ SWEAT \times 2^{(T(i,4)-T_{set}(i,4))/4} \qquad (32)$$

Where, $EB(i, 4)$ is the heat loss through skin by water vapour diffusion, which is given as a constant in Stowijk's model; $SKINS(i)$ is the control coefficient, and $SWEAT$ is the sweating control signal, which can be determined by:

$$SWEAT = Csw \times Err(1, 1) +$$
$$+\ Ssw \times (Wrms - Clds) + \qquad (33)$$
$$+\ Psw \times Wrm(1, 1) \times Wrms$$

Csw, *Ssw*, *Psw* are control coefficients.

The maximum evaporative heat loss $EMAX(i)$ happens when the skin is completely covered by sweat and the vapour pressure next to the skin equals the saturation pressure of water at skin temperature, thus:

$$EMAX(i) = h_e(i)(Pskin(i) - P_a)A_s(i) \qquad (34)$$

Where $EMAX(i)$ is the maximum evaporative heat loss, $Pskin(i)$ - the saturated vapour pressure at skin temperature, and $h_e(i)$ is the convective mass transfer coefficient, which can be calculated by:

$$h_e(i) = LR \cdot h_c(i) \qquad (35)$$

Where LR is the Lewis ratio, and $H_c(i)$ is the convective heat transfer coefficient from the skin through clothing to the environment, expressed as:

$$H_c(i) = \frac{1}{L_{mc}(i)/k_a + R_f + 1/h_a(i)} \qquad (36)$$

***Table** 3. Reference set of simulated condition.*

Fabric type	Cotton
Thermal resistance, (m2·K)/W	0.036
Mass, kg/m2	0.125
Specific heat of cotton [13], J/(kg·K)	1210
Environment temperature, K	298
Relative humidity, %	50
Air velocity, m/s	0.1

If any evaporative heat in $E(i, 4)$ exceeds its corresponding max value, then it must be reduced to $EMAX(i)$.

The control coefficients and constants in the above equations, from 1 to 36, can be found in Stolwijk's work [7].

Results and discussion

By solving the heat balance equations of the human body and clothing (***Equation 1** - **Equation** 7*), the effects of the air gap on human body heat transfer, as well as the interaction between the human, clothing and the environment can be predicted. The major parameters of the mathematical model are the air gap thickness, kind of fabric, environmental temperature and humidity, and metabolic heat production. The reference condition for parametric studies is listed in ***Table 3***.

Effect of air gap thickness

For a standing human body, the metabolic heat production is suggested as 1.7Met (100.4 W/m2) [14]. Based on the measured air gap thickness of five experimental garments, the heat loss from a clothed human body under the reference condition is simulated. The apparent clothing temperatures after a thirty-minute simu-

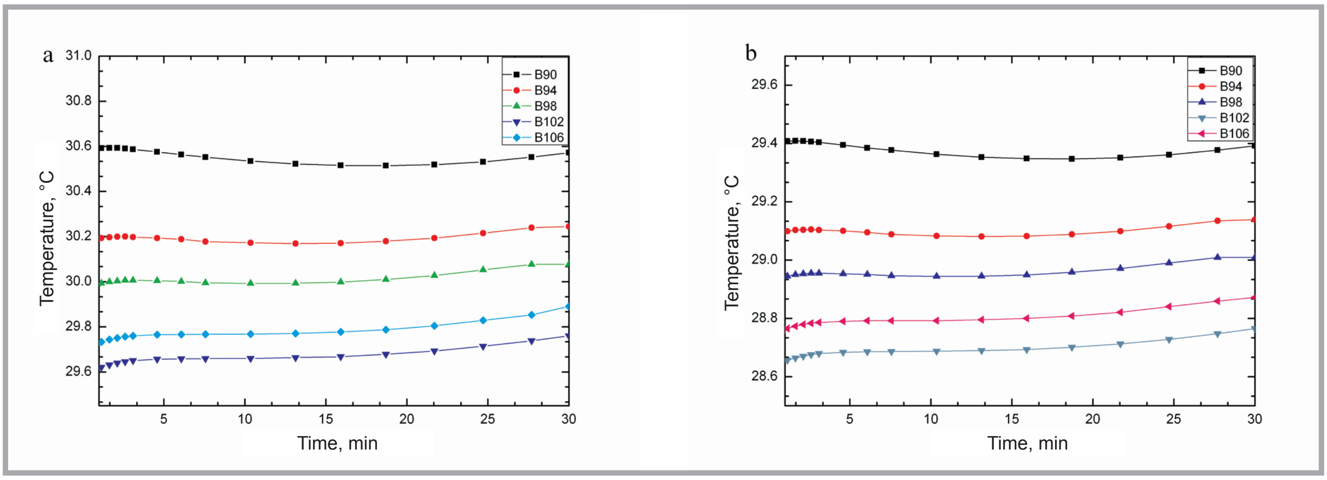

***Figure 3.** (a) Inner layer temperature of five experimental garments (b) Outer layer temperature of five experimental garments.*

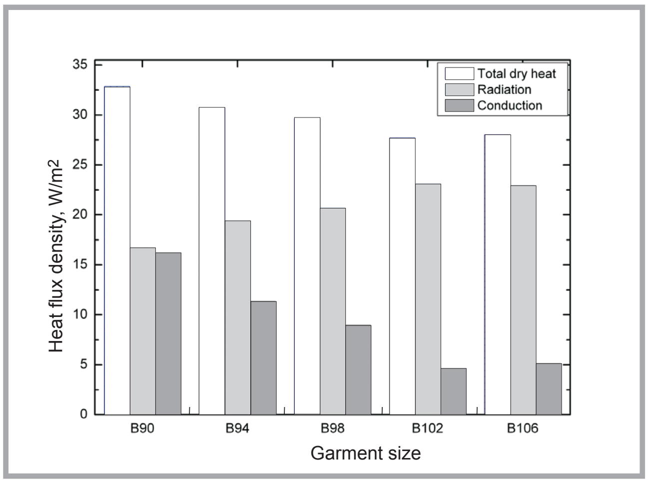

***Figure 4.** Dry heat loss of the five garments.*

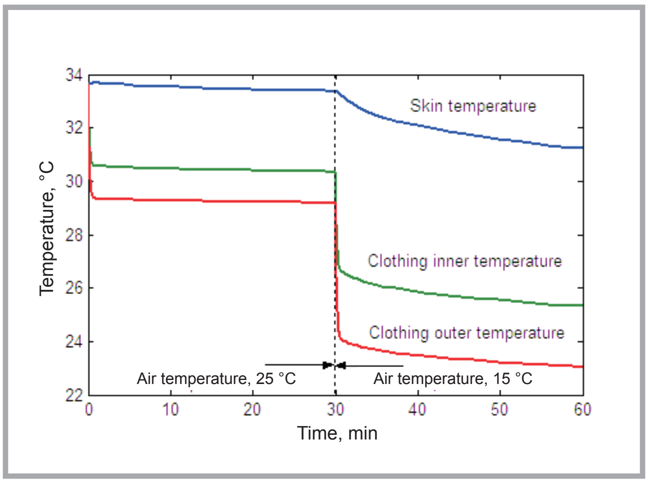

***Figure 5.** Apparent skin and clothing temperatures in a changing environment.*

lation are shown in ***Figure 3***. The temperature at the inner and outer clothing surface decreases with the air gap thickness when the garment size is smaller than B102, as the air gap behaves like insulating material, blocking heat transfer from the skin to the clothing surface. However, the temperature goes up when the garment size reaches B106 with an air gap thickness of 1.97 cm. From the simulated results it can be observed that natural convection appears when the air gap thickness is bigger than 15 mm. The onset of natural convection increases heat transfer from the skin to the inner layer of clothing, elevating the apparent temperature of garment B106.

The effect of air gap thickness on sensible heat loss through the air gap is shown in ***Figure 4***. It can be seen that the total dry heat flux densities from skin decrease until the garment size is larger than B102, among which the conductive component decreases from 49% to 17% of the total sensible heat flux densities, while the radiant heat increases from 51% to 83%. Since the radiation is independent of the air gap thickness, the radiant heat loss through the air gap increases with an increase in the temperature difference between the skin and clothing surface. A large rate of reduction in the conductive component leads to a decrease in the total heat gain. The total and conductive heat flux of garment B106 increase due to natural convection, consequently the radiant component decreases. It seems that the air gap thickness increases linearly with the garment size, from tight to loose, whereas heat transfer from the human body to the environment occurs irregularly. The air gap under garment B102 can efficiently block heat loss from the human body, creating the lowest apparent temperature of clothing.

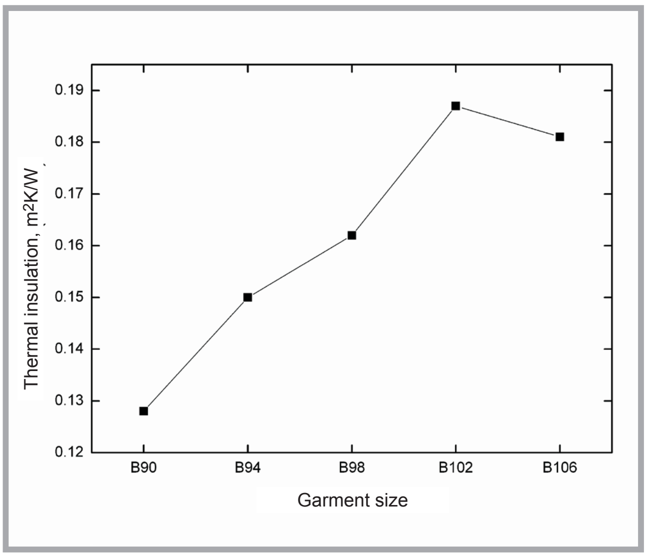

***Figure 6**. Thermal insulation of the five garments.*

Effect of environment temperature

The numerical solution simulates a person wearing clothing B90 standing in an initial warm atmospheric condition for thirty minutes and then moving to a cold environment. The initial warm atmospheric condition is 25 °C and 50% RH, and the cold condition is assumed to be 15 °C and 50% RH. The simulated skin, inner clothing surface and outer clothing surface temperature of the human trunk are shown in ***Figure 5***. When coming into a cold environment, skin temperature declines not as sharply as apparent clothing temperatures, which is because the specific heat of human skin is 3760 J/(kg·K), nearly three times larger than that of cotton fabric. The temperature of the outer clothing surface and inner surface declines by about 6 °C and 4.5 °C respectively, when the environmental temperature decreases from 25 °C to 15 °C. The higher decrease in temperature at the outer clothing surface is a result of basic fabric insulation, which makes the inner clothing surface less sensitive than the outer one.

Thermal insulation estimation

The usual way to assess the transport of heat and moisture through clothing ensembles is using a thermal manikin [15 - 17]. However, a thermal manikin is expensive, complicated, and not available everywhere. A substitute method is to build a mathematical model for estimating the thermal insulation of a clothing system. In this study, the total sensible heat flux and apparent clothing temperature can be derived from mathematical model above. Hence the effective thermal insulation of a clothing system can be calculated by:

$$R_t = \frac{T(i,4) - T(i,6)}{q_{mc}(i)} = \frac{T(i,4) - T(i,6)}{q_f(i)} = \frac{T(i,4) - T(i,6)}{q_a(i)} \quad (37)$$

The relationship between the thermal insulation calculated and air gap thickness is shown in ***Figure 6.*** Although the air gap thickness of the five experimental garments increases from 5.1 mm to 19.7 mm, the thermal insulation of the five garments does not increase linearly. Garment B102 has the highest thermal insulation of the five experimental garments, showing that the tolerance between the body and garment is helpful to enhance the thermal insulation of a garment; however, this should be controlled within reason.

Conclusions

Air gaps entrapped between the human body and a garment influence heat loss from skin to the environment. In this paper, we have presented a transient thermal model of the human body/clothing/environment system, which can be used to predict the apparent temperature and heat loss of differently sized garments. The difference in clothing and skin temperatures from segment to segment is the result of the uneven distribution of air layers under garments. This research sheds light on the effect of the air gap on the heat transfer of a clothed human body. A thorough examination with experiments remains as future work, for example, a thermal manikin and infrared thermal camera can be used to measure the heat loss and apparent temperature of a clothed human body.

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