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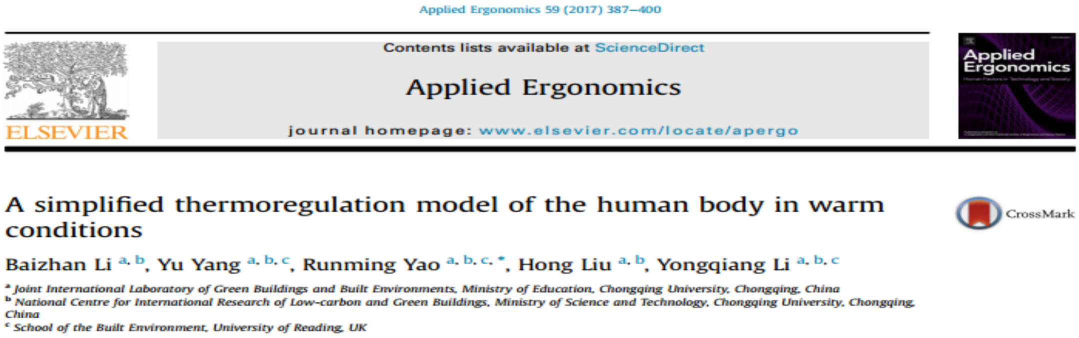
Article

Accepted Version

Li, B., Yang, Y., Yao, R., Liu, H. and Li, Y. (2017) A simplified thermoregulation model of the human body in warm conditions. Applied Ergonomics, 59 (A). pp. 387-400. ISSN 0003-6870 doi: https://doi.org/10.1016/j.apergo.2016.09.010 Available at http://centaur.reading.ac.uk/68981/


Applied Ergonomics 59 (2017) 387–400
Contents lists available at ScienceDirect
Applied Ergonomics
journal homepage: www.elsevier.com/locate/apergo
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Baizhan Li [a, b], Yu Yang [a, b, c], Runming Yao [a, b, c, *], Hong Liu [a, b], Yongqiang Li [a, b, c]
[a] Joint International Laboratory of Green Buildings and Built Environments, Ministry of Education, Chongqing University, Chongqing, China
[b] National Centre for International Research of Low-carbon and Green Buildings, Ministry of Science and Technology, Chongqing University, Chongqing, China
[c] School of the Built Environment, University of Reading, UK

A Simplified Thermoregulation Model of the Human Body in Warm Conditions

Baizan Li [a,b]; Yu Yang [a,b,c]; Runming Yao [a,b,c] *; Hong Liu [a,b]; Yongqiang Li [a,b,c]

[a] Joint International Laboratory of Green Buildings and Built Environments, Ministry of Education; Chongqing University, Chongqing, China;

[b] National Centre for International Research of Low-carbon and Green Buildings, Ministry of Science and Technology; Chongqing University, Chongqing, China;

[c] School of the Built Environment, University of Reading, UK

Highlights

A new simplified thermoregulation model of the human body;

Laboratory experimental data used for model verification;

Prediction of skin temperature in transient thermal processes

Nomenclature			
		RH	Relative humidity (%)
		$r_{s,i}$	external radius of layer I (m)
A	body surface area (m^2)	ST	vasoconstriction signal (l/h)
A_r	effective radiation area of body (m^2)	t	time (s)
BF_i	total blood flow of layer i (l/h)	T'	temperature change rate (℃/s)
c	specific heat [J /(kg•℃)]	T_a	mean air temperature (℃)
C	convective heat losses (W/m^2)	T_b	temperature of blood (℃)

C_{res}	respiratory convective heat flow per body surface area (W/m^2)	T_{cl}	mean temperature of the outer surface of the clothed body (℃)
DL	vasodilation signal (l/h)	T_i	temperature of tissue (℃)
E_{diff}	diffusion evaporative heat loss per body surface area (W/m^2)	T_r	mean radiant temperature (℃)
E_{res}	evaporative heat loss from respiration per body surface area (W/m^2)	$T_{set,c}$	core temperature set point (℃)
Err_c	input signals of core layer (℃)	$T_{set,s}$	skin temperature set point (℃)
Err_s	input signals of skin layer (℃)	T_v	venous temperature (℃)
E_{sw}	evaporative heat loss by sweating per body surface area (W/m^2)	V_a	mean air velocity (m/s)
f_{cl}	clothing area factor	V_i	volume of layer I (m^3)
H	height of human body (cm)	W	weight of human body (kg)
h_c	convective heat transfer coefficient (W/m^2·℃)	$\alpha_{m,i}$	proportion of layer i in weight (%)
I_{cl}	total thermal insulation of clothing (clo)	β	counter-current factor
L	length of cylinder (m)	ε	average emissivity of clothing or body surface
M	total metabolic rate (W/m^2)	λ	heat conductivity coefficient [W/(m·k)]
M_b	total basal metabolic rate (W/m^2)	ρ	density (kg/m^3)
$M_{b,i}$	heat production by basic metabolism per cubic metre (W/m^3)	σ	Stefan-Boltzmann constant[W/(m^2·K^4)]
m_{cl}	weight of the clothing (kg)		
$M_{s,i}$	heat production by shivering per cubic metre (W/m^3)		Subscript
M_{shi}	shivering heat production (W/m^2)	i	layer number
$M_{w,i}$	heat production by activity metabolism per cubic metre (W/m^3)	1	layer of core
P_a	water vapour partial pressure (Pa)	2	layer of muscle
Q_b	total blood flow to cylinder (m^3)	3	layer of fat
Q_i	blood flow per cubic metre of layer i [m^3/(s·m^3)]	4	layer of skin
r	radius of cylinder (m)	b	central blood node
R	radiative heat losses (W/m^2)	cl	clothing node
R_d	dynamic sensitivity of thermoreceptors (s)		

Abstract

Thermoregulation models of the human body have been widely used in thermal comfort studies. The existing models are complicated and not fully verified for application in China. This paper presents a simplified thermoregulation model which has been statistically validated by the predicted and measured mean skin temperature in warm environments, including 21 typical conditions with 400 Chinese subjects. This model comprises three parts: i) the physical model; ii) the controlled system; and iii) the controlling system, and considers three key questions formerly ignored by the existing models including: a) the evaporation efficiency of regulatory sweat; b) the proportional relation of total skin blood flow and total heat loss by regulatory sweating against body surface area; and c) discrepancies in the mean skin temperatures by gender. The developed model has been validated to be within the 95% confidence interval of the population mean skin temperature in three cases.

Keywords:

Thermoregulation Model; Thermal Response; Skin Temperature

1. Introduction

The thermal interaction of the human body with the environment involves two processes: i) the heat transfer between the human body and the thermal environment, simultaneously including radiation, convection, conduction, evaporation and respiration; and ii) the self-regulation function of the human body which responds to varied thermal environments, such as vasoconstriction, vasodilation, shivering and sweating (Cheng *et al*., 2012). Thermoregulation models of the human body are developed to simulate these two processes of interaction and predict the human thermal response under different thermal conditions and have been widely used in the field of physiology or thermal comfort studies (Parsons, 2014). An accurate thermoregulation model will help improve the accuracy of the current thermal comfort prediction models, and provide a basic theoretical analysis of the accuracy of the various models in application (De Giuli *et al*., 2014; Holopainen *et al*., 2014).

The simplified Gagge's 2-node model of thermoregulation (Gagge *et al*., 1971) is one of the most popular models in the field of thermal comfort study. Moreover, various complex thermoregulation models have been further developed by improving the modelling of body segmentation, **particularly for heat insulation** (Arezes *et al*., 2013), thermoregulatory systems and heat transfer (Fiala *et al*., 2001; Munir *et al*., 2009; Stolwijk, 1971; Werner and Webb, 1993; Xu and Werner, 1997), considering individual body characteristics (Takada *et al*., 2009; Zhang *et al*., 2001), and increasing the number of body segments to obtain a higher resolution temperature distribution on the skin surface (Huizenga *et al*., 2001; Tanabe *et al*., 2002).

These models are mostly developed based on European or American populations; however, their accuracy lacks effective validation (Yang *et al*., 2015a). There is little strong evidence in the existing research to show that existing models are applicable to the Chinese population. Thermal comfort prediction for the Chinese people still remains in an early research stage which is largely based on the modification of the traditional models but is still lacking systematic analysis (Zhou *et al*., 2013; Zhou *et al*., 2014). In this context, this paper aims to i) validate the predictive accuracy of the classic Two-Node model for the Chinese population; and ii) develop and validate a new simplified model based on the laboratory experiments.

The mean skin temperature was used for the validation of the developed model. In the existing studies, skin temperature has been demonstrated to be strongly related to the thermal interaction between the human body and the thermal environment, which is also an important indicator of thermal comfort (Parsons, 2014). It has been successfully used to validate increasingly complex and sophisticated predictive models for thermoregulatory responses, and to build thermal sensation models.

The systems predicting the interaction between people and their environment are complex (Andrew Thatcher, 2016). Here, the developed model shows advantages over many other existing models. The individual differences in human thermal responses are caused by some characteristics which can be quantitatively defined (age, height, weight, etc.), but may also contains some of the potential differences which are not so easily described such as the property of each layer of the body including core composition, muscle composition, fat composition and skin composition respectively. The mean basal metabolic rate of the Chinese population is re-measured in this study. It has allowed the simplification of the human body abstraction as a cylinder with its specific geometric dimensions and heat transfer direction, which cannot be provided by simply adjusting the parameters of existing models for the Chinese population. Meanwhile, the introduction of a cylinder model and the development of control plates make it more convenient and accurate in application compared to other models (Yang *et al*., 2015b).

2. Description of the new model

The proposed model consists of three parts: the physical model of the human body, the controlled system and the controlling system.

2.1 Physical model of the human body

In this physical model, the human body is abstracted as a cylinder consisting of four concentric layers: the core, muscle, fat and skin. A central pool of blood delivers the arterial blood to the capillaries and tissues in each layer, and meantime the blood flows back to the central pool through the veins. The schematic diagram of this physical model is shown in Figure 1. Assuming that the physical characteristics in each layer are uniform, the physical parameters of each layer are recalculated from the data of reference (Gordon *et al*., 1976; Stolwijk, 1971) and listed in Table 1.

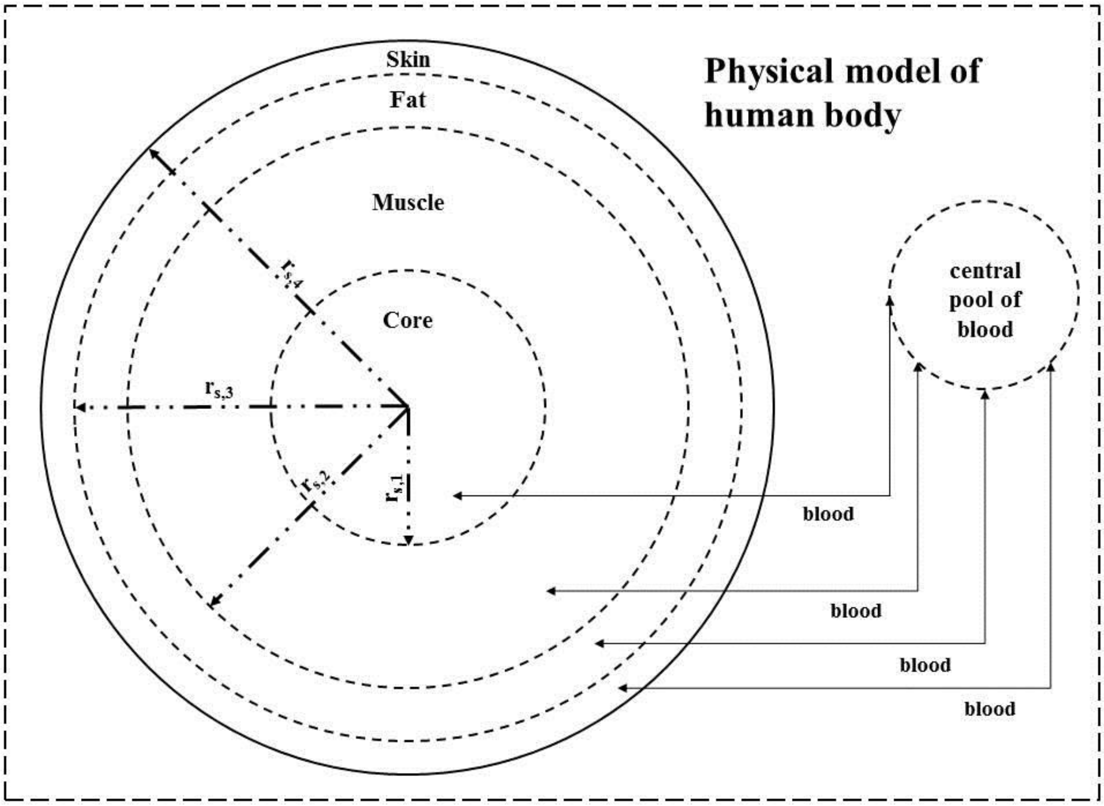


Figure 1. The schematic diagram of the physical model of **the** human body

Table 1. The physical parameters of the layers (Gordon *et al.*, 1976; Stolwijk, 1971)

Layer	Core	Muscle	Fat	Skin
Density (kg/m^3)	ρ_1 =977	ρ_2 =1115	ρ_3 =850	ρ_4 =1000
Specific heat (J /(kg•℃))	c_1 =2968	c_2 =3105	c_3 =2510	c_4 =3760
Heat conductivity coefficient (w/(m•k))	λ_1 =0.42	λ_2 =0.66	λ_3 =0.21	λ_4 =0.21

Considering the size of the physical model, the height dimension is far greater than the radius dimension. In the simulation, heat is only supposed to be transferred in a radial direction. Radial dependency of temperature is calculated in the model. In this paper, abbreviations with subscripts of $i=1,2,3,4$ represent the layers of core, muscle, fat and skin respectively. The subscripts *b* and *cl* represent the central blood and clothing nodes respectively.

The geometric characteristics of the physical model can be calculated from the basic information of the human body (gender, height, weight and body fat percentage). The surface area A (m^2) of a Chinese human body can be obtained by Equations 1 and 2 for male and female subjects (Wang, 1994). The length of the cylinder L (m) and the external radius of layer i (which is denoted by $r_{s,i}$ (m)) can be calculated by Equations 5 and 6 respectively.

$A = 0.0057H + 0.0121W + 0.0882$ (for males) ………………………..Eq. (1)

$A = 0.0073H + 0.0127W - 0.2106$ (for females) ……………………...Eq. (2)

$m_i = \alpha_{m,i} W$ ……………………………………………………..Eq. (3)

$V_i = m_i / \rho_i$ …………………………………………………………Eq. (4)

$L = A^2 / \left(4\pi \sum_{i=1}^{4} V_i \right)$ ………………………………………………….Eq. (5)

$r_{s,i} = \sqrt{\dfrac{\sum_{i=1}^{4} V_i}{\pi L}}$ ……………………………………………………….Eq. (6)

Where H is the height (cm); W is the weight (kg); $\alpha_{m,i}$ is the proportion of layer i in the weight, which is recalculated by reference to Stolwijk (1971) and shown in Table 2; V_i is the volume of layer i (m^3).

Table 2. The proportions of layers by weight (Stolwijk, 1971)

Core ($\alpha_{m,1}$)	Muscle and Fat ($\alpha_{m,2} + \alpha_{m,3}$)	Skin ($\alpha_{m,4}$)	Total
22%	73%	5%	100%

Therefore, gender, height, weight and body fat percentage can be used as the inputs for the physical model. The default values for Chinese male and female subjects in the model are set as 170cm, 70kg, 20% and 160cm, 55kg, 25% respectively (Yang, 2015).

2.2 Controlled system

The controlled system is used to simulate the internal heat transfer of the body and the heat transfer between the body surface and the thermal environment.

Based on the physical model of the human body, the scheme of thermal interaction for humans with the environment can be seen from Figure 2.

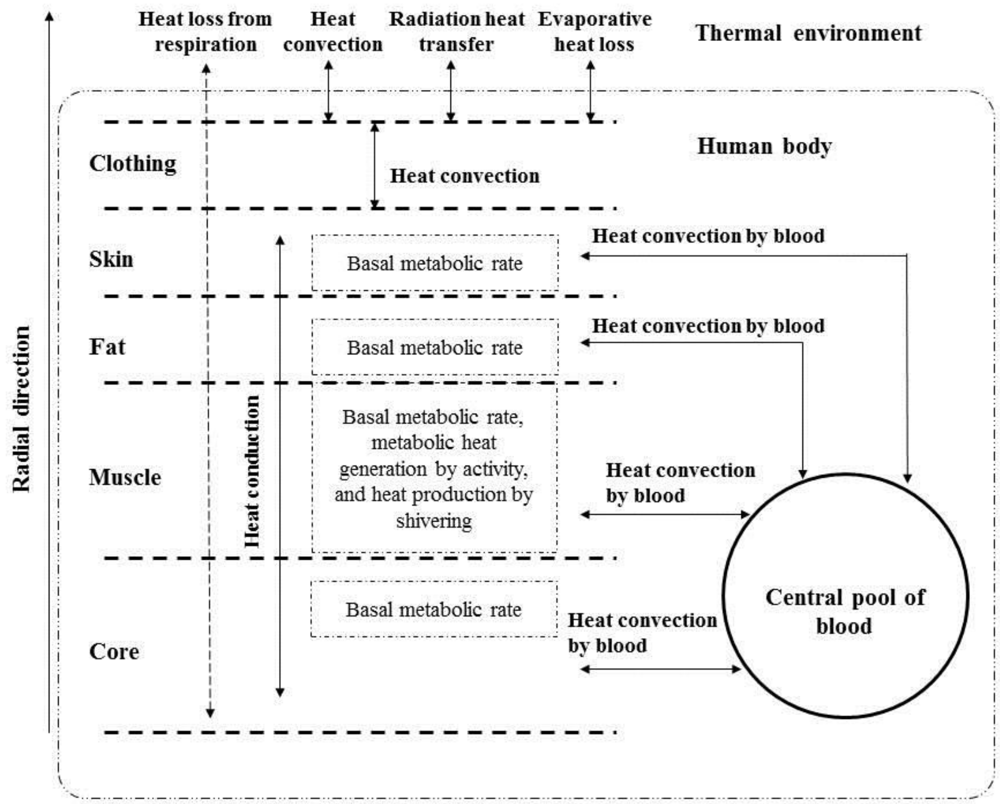


Figure 2. The scheme for the thermal interaction of humans with the environment

2.2.1. Energy equation

The energy equation in a one-dimensional cylindrical coordinate system based on classical heat transfer theory is:

$$\rho_i c_i \frac{\partial T_i}{\partial t} = \lambda_i \left(\frac{\partial^2 T_i}{\partial r^2} + \frac{1}{r}\frac{\partial T_i}{\partial r} \right) + M_{b,i} + M_{w,i} + M_{s,i} + \beta Q_i c_b \rho_b \left(T_b - T_i \right) \quad \text{.......Eq. (7)}$$

Where, $T_i(r,t)$ is the temperature of tissue (℃); $M_{b,i}(r)$ is the heat production by basic metabolism in Watts per cubic metre (W/m^3); $M_{w,i}\left(r,t\right)$ is the heat production by activity metabolism per cubic metre (W/m^3); $M_{s,i}\left(r,t\right)$ is the heat production by shivering per cubic metre (W/m^3); β is the counter-current factor, by which the approximate heat exchange between arterial blood and venous blood is considered. The effect of the counter-current usually takes place in cold conditions and β equals 1 in this paper for warm conditions. $Q_i\left(r,t\right)$ is the blood flow per cubic metre [m^3/(s·m^3)]; c_b is the specific heat of central blood, which equals 3,760 [J /(kg•℃)] ; ρ_b is the density of central blood, which equals 1,000 (kg/m^3); T_b is the temperature of central blood (°C).

Table 3. The mean basal metabolic rate of the Chinese population M_b (W/m^2)(Yao, 2005)

Gender	Age						
	11-15	16-17	18-19	20-30	31-40	41-50	Over 51
Male	54.28	53.69	46.14	43.82	44.05	42.77	41.38
Female	47.88	50.44	42.77	40.68	40.79	39.52	38.47

$M_{b,i}$ can be calculated from the total basal metabolic rate M_b (W/m^2), which is related to gender and age; the data for the Chinese population is shown in Table 3 (Yao, 2005):

$$M_{b,i} = \delta_i M_b A / V_i \quad \text{……Eq. (8)}$$

Where, δ_i is the proportion of the basal metabolic rate taken up by layer *i*.

Gordon *et al*. (1976) gave the reference value as shown in Table 4.

Table 4. The proportion of the basal metabolic rate for each layer of the human body (Gordon *et al*., 1976)

Core (δ_1)	Muscle (δ_2)	Fat (δ_3)	Skin (δ_4)	Total
4.1%	74.9%	0.7%	20.9%	100.0%

Assuming $M_{w,i}$ is only related to the activity level and this energy is produced by the muscle, the following equations are used to describe $M_{w,i}$:

$$M_{w,1} = M_{w,3} = M_{w,4} = 0 \quad \text{..Eq. (9)}$$

$$M_{w,2} = \left(M - M_b\right) A / V_2 \quad \text{...Eq. (10)}$$

Where, M is the metabolic heat generation for a certain activity (W/m^2), which is provided by the international standard (ASHRAE-55, 2004); M_b is assumed to be the basal metabolic rate for the population aged from 20-30.

$M_{s,i}$ and Q_i are variable and controlled by the controlling system.

T_b is considered to be independent of the radius and determined by the energy equation:

$$\rho_b c_b Q_b \frac{dT_b}{dt} = \sum_{i=1}^{4} \int_{r_{s,i-1}}^{r_{s,i}} \beta \rho_b c_b Q_i \left(T_{v,i} - T_b\right) \quad \text{.....................................Eq. (11)}$$

Where, $r_{s,0}$ represents the radius of the cylinder's centre, which is equal to 0; $T_{v,i}\left(r,t\right)$ is the venous temperature (°C), and it is assumed to be equal to the temperature of the adjacent tissue, that is:

$$T_{v,i}\left(r,t\right) = T_i\left(r,t\right) \quad \text{..Eq. (12)}$$

Q_b is the total blood flow to the cylinder (m^3) and is obtained by integration over the volume of a cylinder with length L:

$$Q_b = \sum_{i=1}^{4} 2\pi L \int_{r_{s,i-1}}^{r_{s,i}} Q_i r dr \quad \text{..Eq. (13)}$$

2.2.2. Boundary and initial conditions

The boundary condition at the centre of the cylinder is:

$$\frac{\partial T_i}{\partial r}\Big|_{r=0} = Cres + Eres \quad \text{...Eq. (14)}$$

Where, $Cres$ and $Eres$ are the convective and evaporative heat loss from respiration per body surface area respectively (W/m^2)(Fanger, 1970):

$$C_{res} = 0.0014M\left(34 - T_a\right) \quad \text{......................................Eq. (15)}$$

$$E_{res} = 0.0000173M\left(5867 - P_a\right) \quad \text{..............................Eq. (16)}$$

The continuity of temperature and heat flux at an interface between two layers of different tissues is expressed in Equations 17 and 18.

$$T_i\left(r_{s,i} - 0, t\right) = T_{i+1}\left(r_{s,i} + 0, t\right) \quad (i=1, 2, 3) \text{ ....Eq. (17)}$$

$$\lambda_i\left(\frac{\partial T_i}{\partial r}\right)_{r_{s,i}-0} = \lambda_{i+1}\left(\frac{\partial T_{i+1}}{\partial r}\right)_{r_{s,i}+0} \quad (i=1, 2, 3) \text{ ....Eq. (18)}$$

At the skin surface, the heat brought to the surface by conduction from the deep body is equal to the heat removed from the surface by evaporation and conduction. Therefore, the boundary condition at the skin surface is:

$$\lambda_i \frac{\partial T_i}{\partial r} = -f_{cl}\frac{T_i - T_{cl}}{0.155I_{cl}} - E_{sw} - E_{diff} \quad \left(i = 4, r = r_{s,4}\right) \quad \text{...............Eq. (19)}$$

Where, $I_{cl}\left(t\right)$ is the total thermal insulation of clothing (clo), which can be estimated or calculated by ISO 7730 (ISO-7730, 2005); $E_{sw}\left(t\right)$ is the evaporative heat loss by sweating per body surface area (W/m^2); $E_{diff}\left(t\right)$ is the diffusion evaporative heat loss per body surface area (W/m^2).

$f_{cl}\left(t\right)$ is the clothing area factor, which can be roughly estimated by Equation 20 (McCullough *et al*., 1985):

$$f_{cl} = 1.0 + 0.3I_{cl} \text{ .... Eq. (20)}$$

E_{sw} is regulated by the thermoregulatory controlling system; E_{diff} can be calculated from Equation 21 (Fanger, 1970).

$$E_{diff}(t)=0.00305\left(256T\left(r_{s,4},t\right)-3373-P_a\right)\ldots\ldots\ldots\ldots\ldots\ldots\text{Eq. (21)}$$

Considering the fact that people are usually in light clothing in warm conditions, the clothing node is simplified as follows:

$$m_{cl}c_{cl}\frac{dT_{cl}}{dt}=A\frac{T_i-T_{cl}}{0.155I_{cl}}-A\left(C+R\right)\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Eq. (22)}$$

Where, m_{cl} is the weight of the clothing (kg), the default value is set as 0.2 kg in warm conditions; c_{cl} is the specific heat of clothing (*J /(kg• ℃)*), Yi *et al*. (2004) provide the data for some common materials, the value for cotton is 1,210.

$C(t)$ and $R(t)$ are the convective and radiative heat losses from the outer surface of a clothed body, both of which are related to the difference between the mean temperature of the outer surface of the clothed body T_{cl} (℃) and the mean air temperature T_a (℃), as shown in Equation 23.

$$C=f_{cl}h_c\left(T_{cl}-T_a\right)\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Eq. (23)}$$

Where, h_c is the convective heat transfer coefficient (*W /m^2· ℃*); Equations for estimating h_c are expressed as (Fanger, 1970):

$$h_c=2.38\left(T_{cl}-T_a\right)^{0.25}\ \left(\text{when } 2.38\left(T_{cl}-T_a\right)^{0.25}>12.1\sqrt{V_a}\right)\ \ldots\ldots\text{Eq. (24)}$$

$$h_c=12.1\sqrt{V_a}\ \left(\text{when } 12.1\sqrt{V_a}\geq 2.38\left(T_{cl}-T_a\right)^{0.25}\right)\ldots\ldots\ldots\ldots\ \text{Eq. (25)}$$

$$R=f_{cl}\varepsilon\sigma\frac{A_r}{A}\left[\left(T_{cl}+273\right)^4-\left(T_r+273\right)^4\right]\ \ldots\ldots\ldots\ldots\ldots\ldots\text{Eq. (26)}$$

Where,

ε = average emissivity of clothing or body surface, (dimensionless).

σ = Stefan-Boltzmann constant, 5.67×10^{-8} W/ *(m^2·K^4).*

A_r = effective radiation area of body, m^2.

T_r = mean radiant temperature, ℃

The ratio A_r/A is 0.70 for a sitting person and 0.73 for a standing person (Fanger, 1970). Emissivity ε is close to unity (typically 0.95), unless special reflective materials are used or high-temperature sources are involved.

The mean radiant temperature T_r can be determined by the measurement of the black globe temperature (T_g) and the air temperature and air velocity at the level of this globe (ISO-7726, 2001).

1) In the case of natural convection:

$$T_r = \left[\left(T_g + 273\right)^4 + \frac{0.25\times10^8}{\varepsilon_g} \left(\frac{\left|T_g - T_a\right|}{D} \right)^{1/4} \times \left(T_g - T_a\right) \right]^{1/4} - 273 \text{ .... Eq. (27)}$$

Where, ε_g is the emissivity of the black globe (dimensionless); D is the diameter of the globe (m).

For the standard globe D=0.15 m, $\varepsilon_g = 0.95$ (matt black paint) and Equation 27 becomes:

$$T_r = \left[\left(T_g + 273\right)^4 + 0.4\times10^8 \left|T_g - T_a\right|^{1/4} \times \left(T_g - T_a\right) \right]^{1/4} - 273 \text{ ....Eq. (28)}$$

2) In the case of forced convection:

$$T_r = \left[\left(T_g + 273\right)^4 + \frac{1.1\times10^8 \times V_a^{0.6}}{\varepsilon_g \times D^{0.4}} \left(T_g - T_a\right) \right]^{1/4} - 273 \text{ ....Eq. (29)}$$

For the standard globe：

$$T_r = \left[\left(T_g + 273\right)^4 + 2.5\times10^8 \times V_a^{0.6} \left(T_g - T_a\right) \right]^{1/4} - 273 \text{ ....Eq. (30)}$$

The initial conditions which specify the values of all dependent variables at time zero should be provided. The initial values may be equilibrium values which are obtained from a previous steady-state calculation (denoted as $T_a\big|_{t=0}$, $T_r\big|_{t=0}$, $v_a\big|_{t=0}$, $RH_a\big|_{t=0}$, $I_{cl}\big|_{t=0}$, $M\big|_{t=0}$), or they may be non-equilibrium values which result from a previous transient process. In either case, they consist of body temperature specifications at the instant the transient process begins, which are denoted as $T_i\big|_{t=0}$.

2.3 Controlling system

The controlling system is used to simulate the thermoregulatory control mechanisms in the human body. It includes the regulation of blood flow, sweating and shivering. The proposed controlling system is based on the traditional controlling system provided in Stolwijk (1971) and further improved by an empirical formula.

2.3.1. Signal input

The input for the controlling system consists of two signals collected from the core layer and skin layer respectively. These signals are integrated temperatures formed by the hypothalamus temperature and the skin temperature, which can be expressed as:

$$Err_c = T\left(r_{s,0}\right) - T_{set,c} + R_d \times T'\left(r_{s,0}\right)$$ ………………………..Eq. (31)

$$Err_s = T\left(r_{s,4}\right) - T_{set,s} + R_d \times T'\left(r_{s,4}\right)$$ ………………………..Eq. (32)

Where, Err_c are the input signals of the core layer (°C) and Err_s are the input signals of skin layer (°C); $T\left(r_{s,0}\right)$ represents the temperature of the thermoreceptor in the hypothalamus and $T\left(r_{s,4}\right)$ represents the temperature of the thermoreceptor under the skin; $T_{set,c}$ and $T_{set,s}$ are the temperature set points for the core and skin respectively

(°C); R_d is the dynamic sensitivity of the thermoreceptor and T' represents the temperature change rate (°C/s).

The set point temperatures ($T_{set,c}$ and $T_{set,s}$) can be acquired by simulating the body under a thermally neutral condition with no work and no regulatory control. The experiment was designed to show the body's adaptation in a neutral thermal environment. The human body was in a steady state at the end of the exposure stage when the change rate of the body's average skin temperature was <0.01°C/min. The steady neutral environmental parameters and human body temperature set points are recorded in Tables 5 and 6. Parameters for male and female subjects to achieve thermal neutrality were obtained by the previous experimental study and these two sets are listed in Table 5. The calculated set point temperatures are different for each gender and results are shown in Table 6.

Table 2. Parameters for a thermally neutral condition

Parameters	T_a(°C)	RH(%)	V_a(m/s)	T_g(°C)	M(W/m^2)	I_{cl}(clo)
Male	26	74.11	0.05	26.47	58.15	0.4
Female	26.2	73.55	0.06	26.42	55.15	0.4

Table 6. The set point temperatures of the human body

Temperature set points (℃)	$T_{set,c}$	$T_{set,s}$
Male	36.94	34.16
Female	36.67	33.8

The value or the quantitative analysis for R_d is not totally revealed according to the existing references (Kobayashi and Tanabe, 2013; Tanabe *et al*., 2002), it represents the human sensitivity to the change of the ambient temperature. Here we chose empirical values for the prediction accuracy of the model: when $T' > 0$, R_d=0(0); when $T' < 0$, R_d=0 (s) for males, and R_d=1800 (s) for females (Yang, 2015).

2.3.1.1. Vasomotion

The total blood flow for layers BF_i (l/h) is calculated by Equations 33 to 36. The blood flow for core and fat tissue remains constant. For muscle compartments, a blood flow of 1.0 l/h was required for 1.16W metabolic heat production (Tanabe *et al*., 2002). The skin blood flow is controlled by the effect of vasodilation or vasoconstriction in the thermoregulation system, which is assumed to be proportional to the body surface *A*.

BF_1=255 ……………………………………………………….Eq. (33)

BF_2=$14.74+\left(M_{w,2}+M_{shi}\right)\times A/1.16$ ………………………...…Eq. (34)

BF_3=3.5 ……………………………………………………….Eq. (35)

$BF_4=\frac{11.89+DL}{1+ST}\times 2^{Err_s/10}\times\frac{A}{1.89}$ ……………Eq. (36)

$DL=117Err_c+7.5Err_s$ (if DL <0, then DL =0)……………..Eq. (37)

$ST=-0.63Err_c-0.63Err_s$ (if ST <0, then ST =0) …………Eq. (38)

Therefore:

Q_i=$0.278\times 10^{-6}\,\mathrm{BF}_i/V_i$ ……………………………….…………Eq. (39)

2.3.1.2. Sweating

The heat loss by regulatory sweating per body surface area E_{sw} (W/m^2) is calculated by Equations 40 and 41:

For males,

$$E_{sw} = \left(223Err_c + 20Err_s\right) 2^{Err_s/10} / 1.89 \text{ ………………….……… Eq. (40)}$$

For females,

$$E_{sw} = \left(111Err_c + 10Err_s\right) 2^{Err_s/10} / 1.89 \text{ ……………………..………Eq. (41)}$$

E_{sw} shows differences according to gender, the value for females is smaller than that for males under the same conditions. The total heat loss by regulatory sweating is also proportional to the body surface area A.

2.3.1.3. Shivering heat production

The shivering heat production per body surface area (W/m^2) is calculated by Equation 42:

$$M_{shi} = 24.4Err_c Err_s / A \text{ (if } Err_c > 0 \text{ or } Err_s > 0\text{, then } M_{shi} = 0\text{) …………..Eq. (42)}$$

2.4 Numerical solution and computer programming

The numerical solution for solving the thermoregulation model is an explicit method with **centred** finite difference. The spatial grid is radially divided with the spacing $\Delta r = 0.002m$. The time increment is set as 1s.

The simulation program is written in Matlab 2010 and the programming flow chart is shown in Figure 3. It consists of five parts: INPUT, PHYSICAL, CONTROLLING, CONTROLLED and OUTPUT. Their functions are shown Table 7 below:

Table. 7. Model structure distribution

Model Structure	Definition and Coverage
Human body model	Build physical model of human body and calculate the

	geometric, physiological and physical parameters of the model.
Controlling system	Calculate the parameters of the controlling system based on the human thermal physiological responses and thermal adaptability.
Controlled system	Calculate the body temperature according to the equations in a controlled system based on the application of classical heat transfer theory between the human body and the dynamic thermal environment.
Input parameters	Environment parameters
	Mean air temperature, Mean radiant temperature, Mean air velocity, Relative humidity, Metabolic rate, Thermal insulation of clothing.
	Human body parameters
	Gender, age, height, weight, body fat percentage.
Output parameters	Body temperature in any transient of the thermal process.

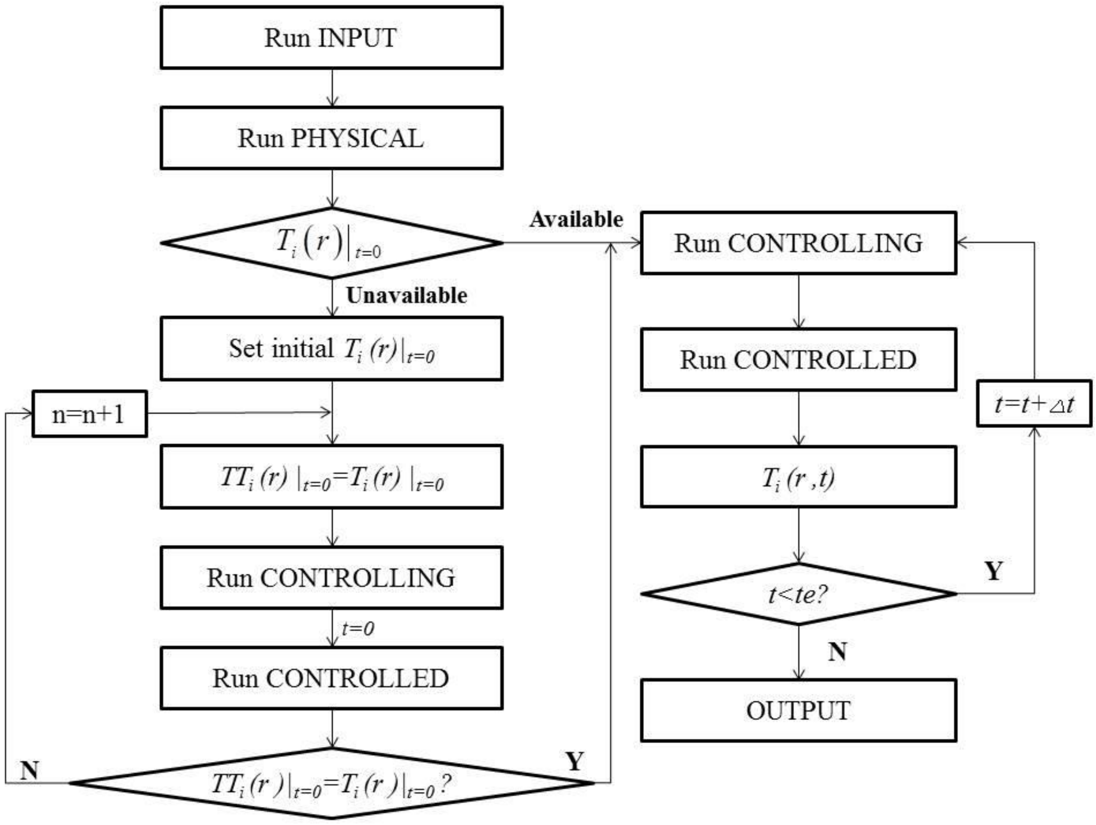


Figure 3. Flow chart of the simulation program.

(n: calculated numbers; t: calculated time; $\triangle$t :time step; te: simulation time)

3. Validation of the models

A model is by definition simpler than the system it attempts to represent. Thus, validation by comparing the model prediction with the experimental data from human subjects is necessary. Not only does this process identify the prediction accuracy of the model, but it also helps to define the range of conditions in which the model is applicable.

Skin temperature is strongly related to the thermal interaction between the human body and the thermal environment (Gagge *et al.*, 1971; Stolwijk, 1971), which is also an important indicator of thermal comfort (Cheng *et al.*, 2012; Fanger, 1970). It has been successfully used to validate increasingly complex and sophisticated predictive models for thermoregulatory responses (Munir *et al.*, 2009; Yi *et al.*, 2004; Zolfaghari and

Maerefat, 2010), and to build thermal sensation models (Lomas *et al*., 2003; Wang, 1994). Therefore, in this paper we choose the mean skin temperature to validate the accuracy of the models.

The method for the model validation can be found in Yang *et al*. (2015a). According to this approach, the accuracy of the model has been primarily examined by inferential statistical analysis, and then assessed through the Bland-Altman method (Bland, J.M. and Altman, D.G., 1986) if necessary. By the validation, the accuracy of the model can be classified into three levels: Ⅰ—The model's prediction is sufficiently statistically accurate; Ⅱ—The model's prediction is sufficiently accurate to be used in applications; Ⅲ—The model's prediction is not sufficiently accurate.

Three series of experimental data from human subjects under the typical warm conditions have been obtained, they are:

Case 1: clothed subjects in step-changing environments (26℃ to 28℃/29℃/30℃/32℃/34℃, then back to 26℃).

Case 2: nude subjects in step-changing environments (28℃ to 32℃/35℃).

Case 3: clothed subjects in typical warm, steady state, environments.

The proposed model has been validated by all the three sets of experiments with a total of 400 subjects. For comparison purposes, the existing Two-Node model, which is regarded as one of the most classic simplified thermoregulation models in thermal comfort studies, has also been validated by comparing its predictions with the experimental data of Case 1.

3.1 Case 1

A temperature step-changing experiment was carried out to validate the performance of the models under transient conditions. Ten male and ten female healthy subjects were recruited randomly to participate in the experiment. During the experiment, all the subjects were required to wear uniform clothing including light long-sleeve cotton shirts and trousers, and light shoes with a total clothing insulation level of 0.4clo (1clo equals 0.155 m^2·K/W). Five environment conditions were designed in this experiment. In each condition, the subjects firstly experienced a step-change thermal process from a neutral environment (Environment Ⅰ) to a typical warm environment (Environment Ⅱ), and then stayed in Environment Ⅱ for 1,800 seconds. The subjects then returned to the neutral condition (Environment Ⅲ) for another 1,800 seconds. The basic information of the subjects and the environment conditions in Case 1 are listed in Tables 8 and 9 respectively.

Table 8. Subjects' information in Case 1 (mean ± standard deviation)

Subjects	Male	Female
Age	24±1	24±1
Height (m)	170±7	159±6
Weight (kg)	58±5	51±8
Body fat percentage (%)	16.9±2.97	25.6±5.3
Clothing insulation (clo)	0.4±0	0.4±0
Activity level (met)	1.0±0	1.0±0

Table 9. Thermal conditions of the experiment in Case 1 (mean ± standard deviation)

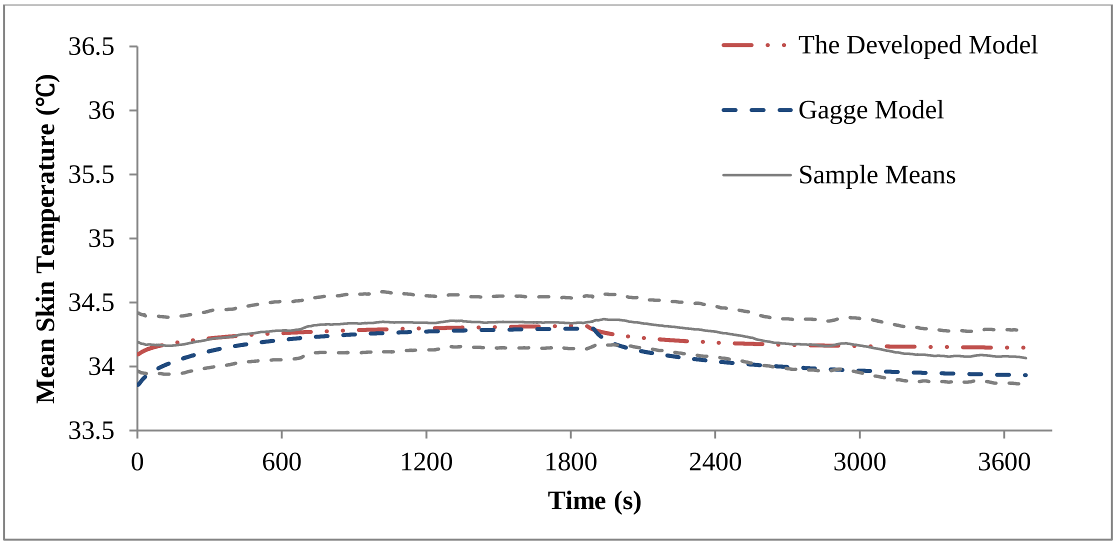
Case 1		Air Temperature (℃)	Relative Humidity (%)	Air Velocity (m/s)	Globe Temperature (℃)
Condition 1	Environment Ⅰ	26.0±0.2	71.9±3.0	0.05±0.00	26.4±0.2
	Environment Ⅱ	28.2±0.1	54.6±0.2	0.18±0.04	28.4±0.1
	Environment Ⅲ	26.0±0.2	70.5±3	0.06±0.01	26.5±0.2

	Environment Ⅰ	26.1±0.1	77.3±2.8	0.05±0.01	26.5±0.1
Condition 2	Environment Ⅱ	29.0±0.1	54.7±0.8	0.17±0.07	29.3±0.1
	Environment Ⅲ	26.2±0.2	75.9±2.5	0.05±0.01	26.6±0.1
	Environment Ⅰ	26.1±0.2	71.5±3.9	0.06±0.01	26.5±0.3
Condition 3	Environment Ⅱ	30.3±0.2	58.1±3.3	0.14±0.09	30.4±0.2
	Environment Ⅲ	26.0±0.3	71.0±3.6	0.06±0.02	26.5±0.3
	Environment Ⅰ	26.5±0.3	70.8±3.7	0.18±0.04	26.5±0.3
Condition 4	Environment Ⅱ	32.0±0.1	53.9±3.9	0.20±0.03	32.0±0.1
	Environment Ⅲ	26.8±0.3	69.6±4.9	0.08±0.02	26.8±0.3
	Environment Ⅰ	26.0±0.1	77.2±1.1	0.05±0.01	26.3±0.2
Condition 5	Environment Ⅱ	33.8±0.1	56.1±0.7	0.20±0.04	33.9±0.0
	Environment Ⅲ	26.2±0.1	75.4±2.5	0.06±0.01	26.5±0.1

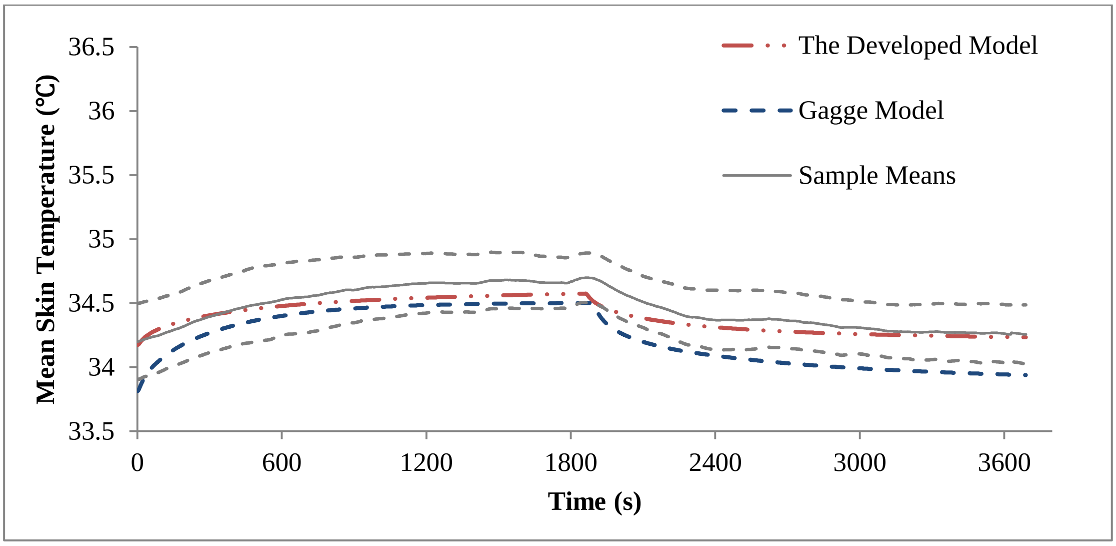
During the experiment, skin temperature measurements at 13 locations on the body including the forehead, chest, back, upper arm (right and left), lower arm (right and left), dorsal hand (right and left), calf (right and left), and thigh (right and left) were performed automatically with a frequency of 0.5 Hz. The 8-point weighted method (Gagge and Nishi, 2011) was adopted to calculate the body mean skin temperature (T_{sk}) as represented by Equation (43):

$$T_{sk} = 0.07T_{forehead} + 0.175T_{chest} + 0.175T_{back} + 0.07T_{upper\ arm} + 0.07T_{lower\ arm} + 0.05T_{hand} + 0.19T_{thigh} + 0.20T_{calf} \quad \text{Eq. (43)}$$

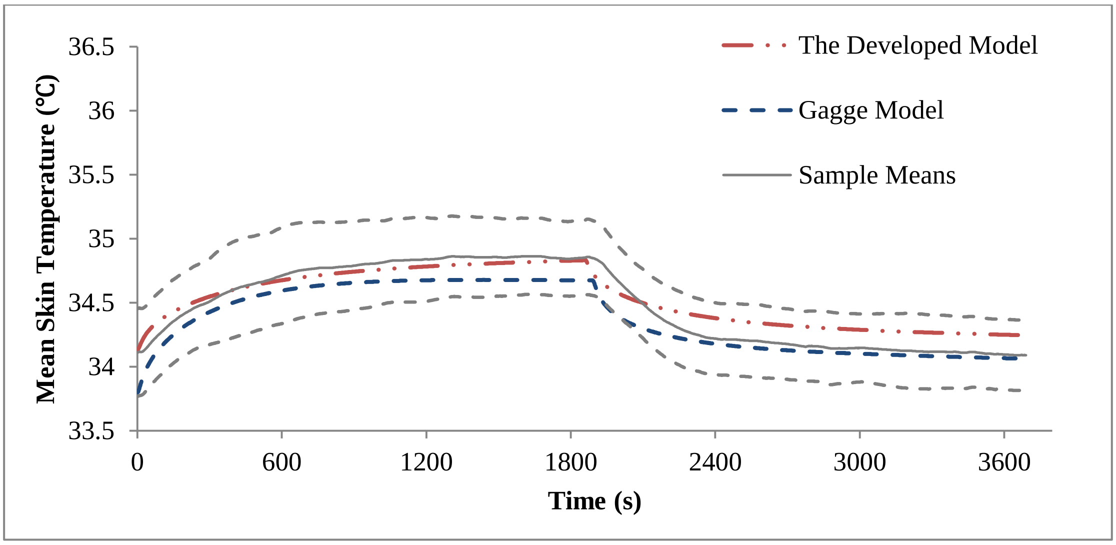
In order to validate and compare the performance of the new model and the classic Two-Node Gagge Model (Gagge *et al*., 1971), the two models were operated to simulate the above thermal process. The predicted and measured skin temperatures during the 3,600 seconds in the experiments of Case 1 are shown in Figure 4 and Figure 5 for male and female subjects respectively. According to the model evaluation method (Yang *et al.*, 2015a), statistical validation is conducted by comparing model predictions with the confidence intervals of the population means. For the model, all the predictions lie within the 95% confidence interval of the population means, indicating no statistically significant difference between the population means and the predictions of the model. The accuracy of the new model in predicting the transient responses for subjects with light clothing is evaluated as Level Ⅰ. However, for the Gagge Model, significant differences were found between the model predictions and the measured data, especially in high-temperature conditions (Conditions 4 and 5). The Gagge Model cannot be statistically validated in this case. Further empirical validation for the Gagge Model is carried out by the Bland-Altman method (Bland, J.M. and Altman, D.G., 1986; Yang *et al.*, 2015a). The 'limit of agreement' of the predictions of the Gagge Model and population means are calculated as [-0.49, 0.09] and [-0.52, 0.19] for males and females respectively, which suggests the predictions of the Gagge Model may be 0.49℃ below or 0.09℃ above the measured sample means for male subjects (similarly 0.52℃ below or 0.19℃ above for female subjects). The Gagge Model is unacceptable if we regard the accuracy requirement for the skin temperature in thermal comfort studies as ‘the difference between the model prediction and the sample mean in most cases must be less than 0.3℃’, and it should be evaluated as Level Ⅲ. Therefore, predictions from our new model are superior to the Gagge model in case 1.



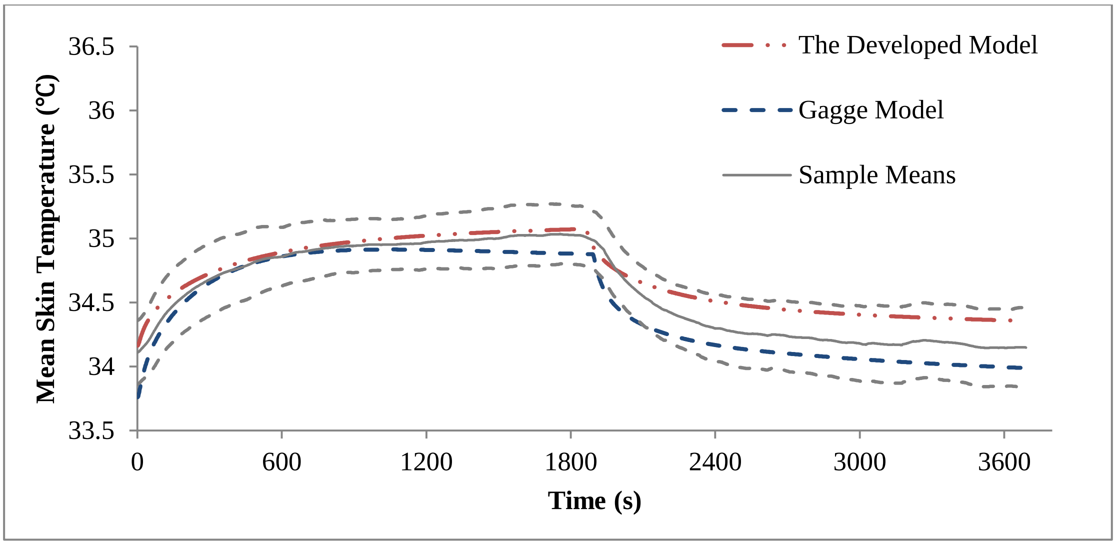
(a) Condition 1



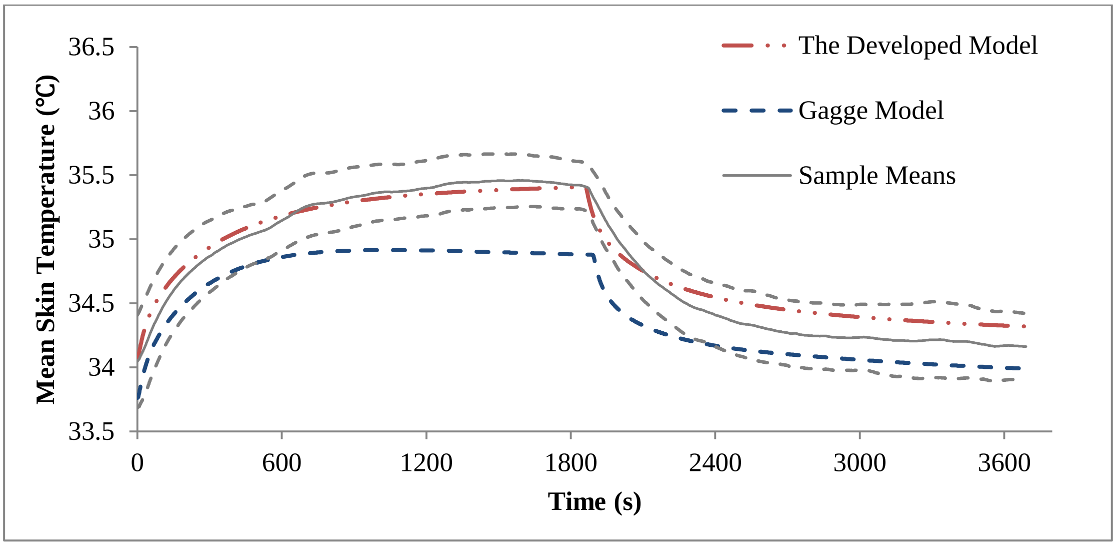
(b) Condition 2



(c) Condition 3

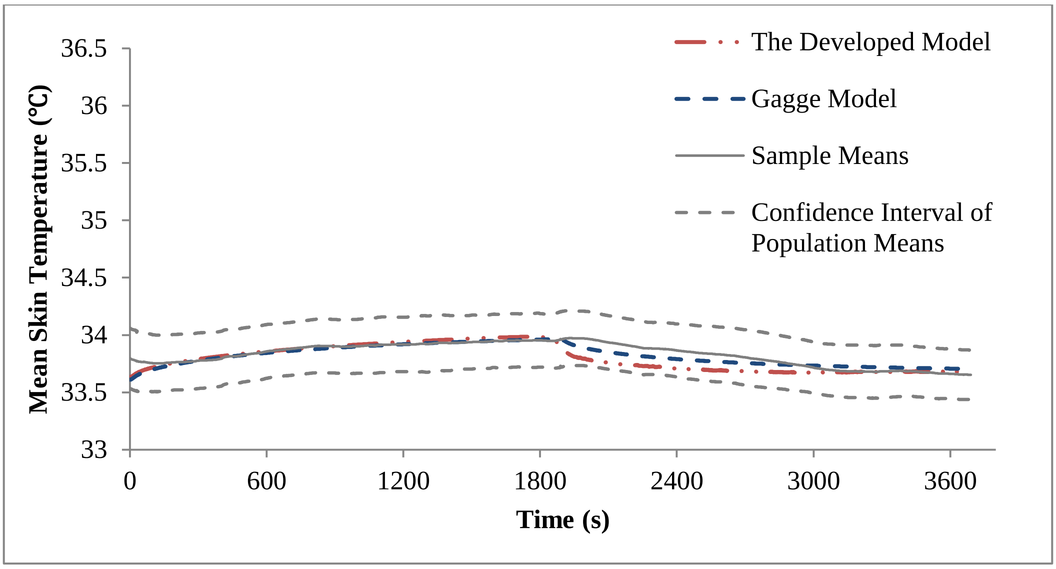


(d) Condition 4

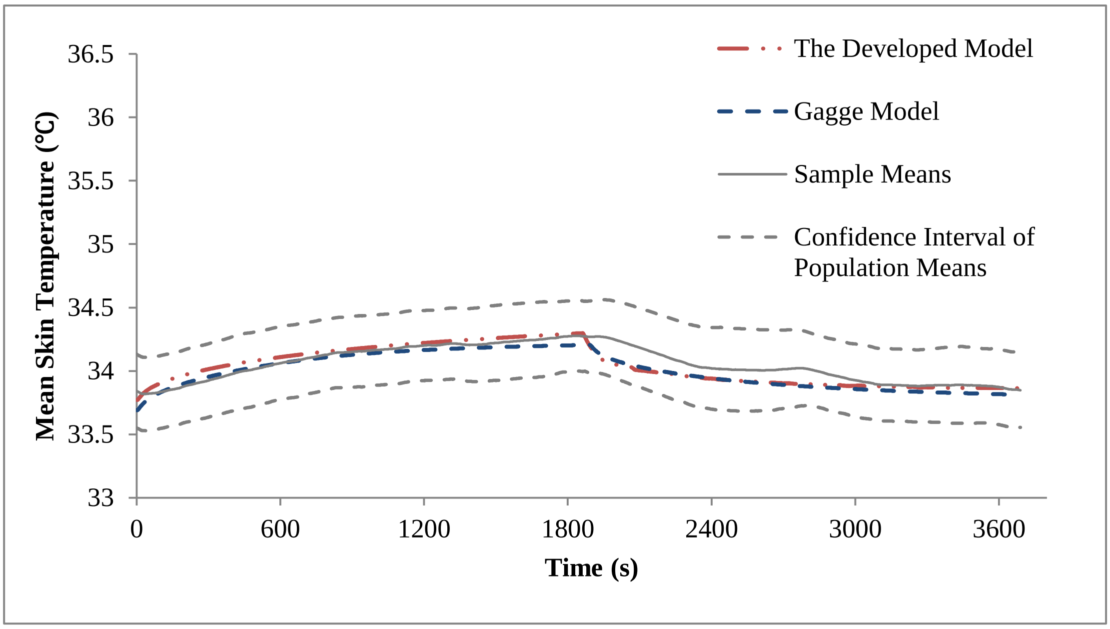


(e) Condition 5

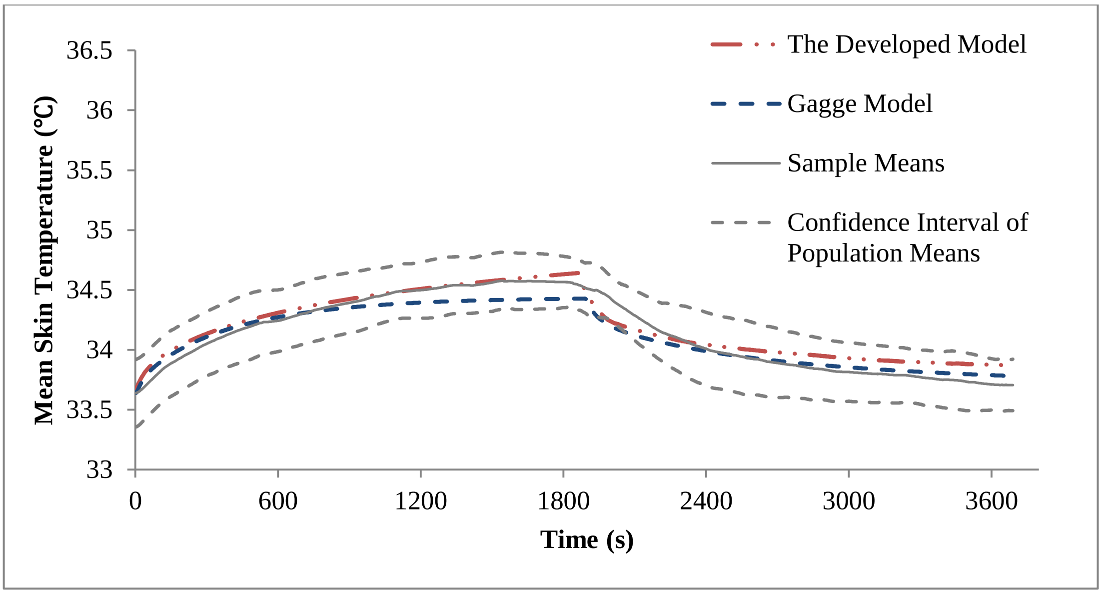
Figure 4. Model validation for Case 1 (male subjects)



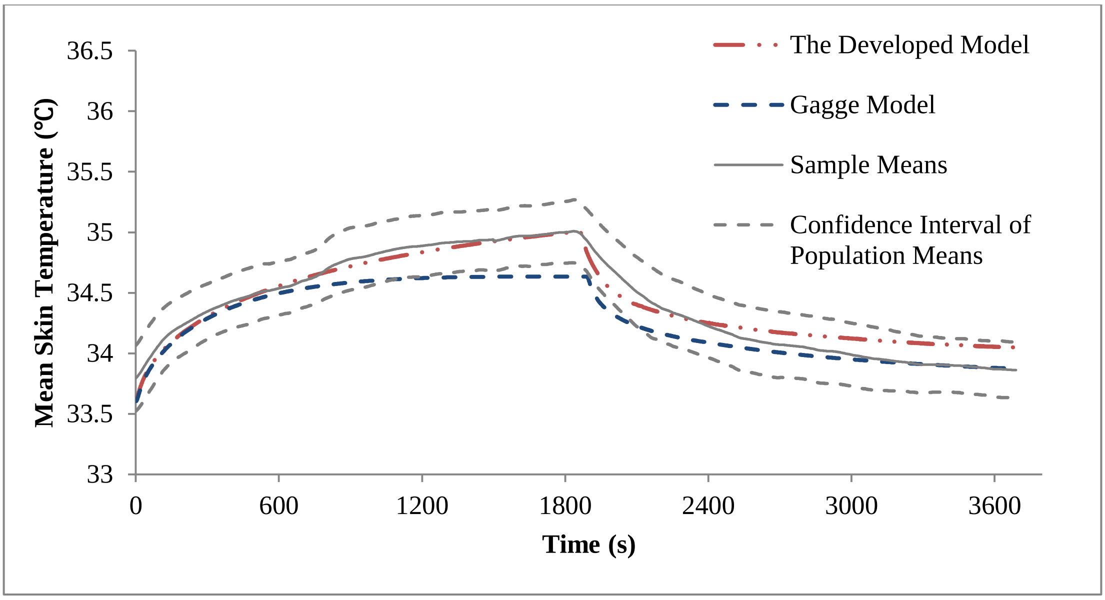
(a) Condition 1



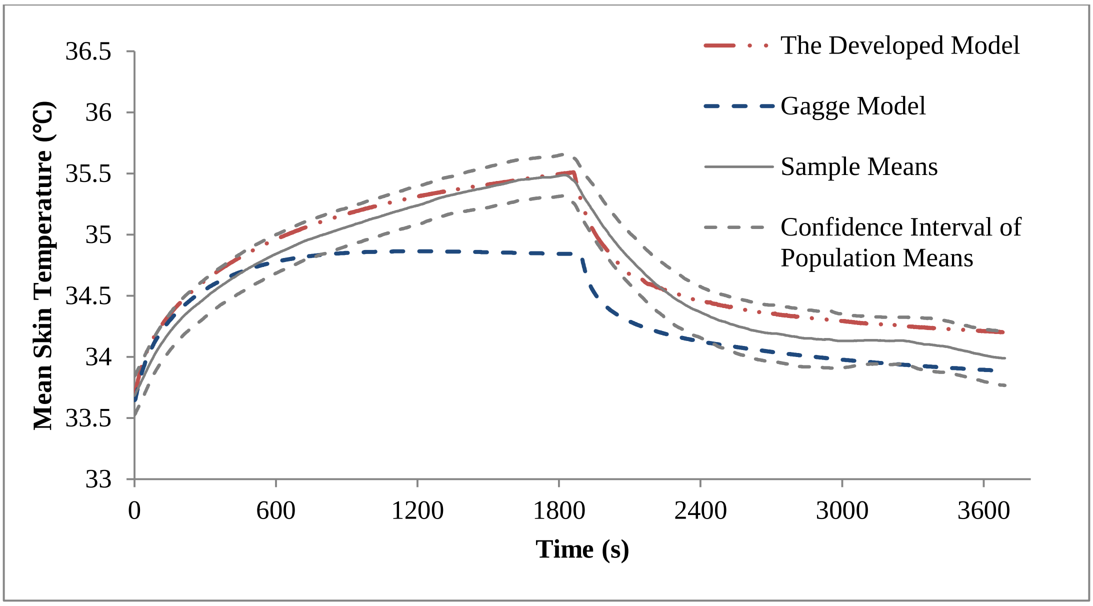
(b) Condition 2



(c) Condition 3



(d) Condition 4



(e) Condition 5

Figure 5. Model validation for Case 1 (female subjects)

3.2 Case 2

A further experiment was set up for nude subjects to validate the new simplified model. Ten half-naked healthy male students were randomly recruited as subjects and each participated in one of two condition sets in this experiment. In both conditions, the subjects experienced a temperature step-change process from a neutral environment (Environment Ⅰ) to a typical warm environment (Environment Ⅱ) and then stayed in Environment Ⅱ for a period of 3,600 seconds. The data for the subjects and the thermal conditions in Case 2 are listed in Tables 10 and 11 respectively. Skin temperatures were collected as in Case 1.

Table 10. Subjects' information in Case 2 (mean ± standard deviation)

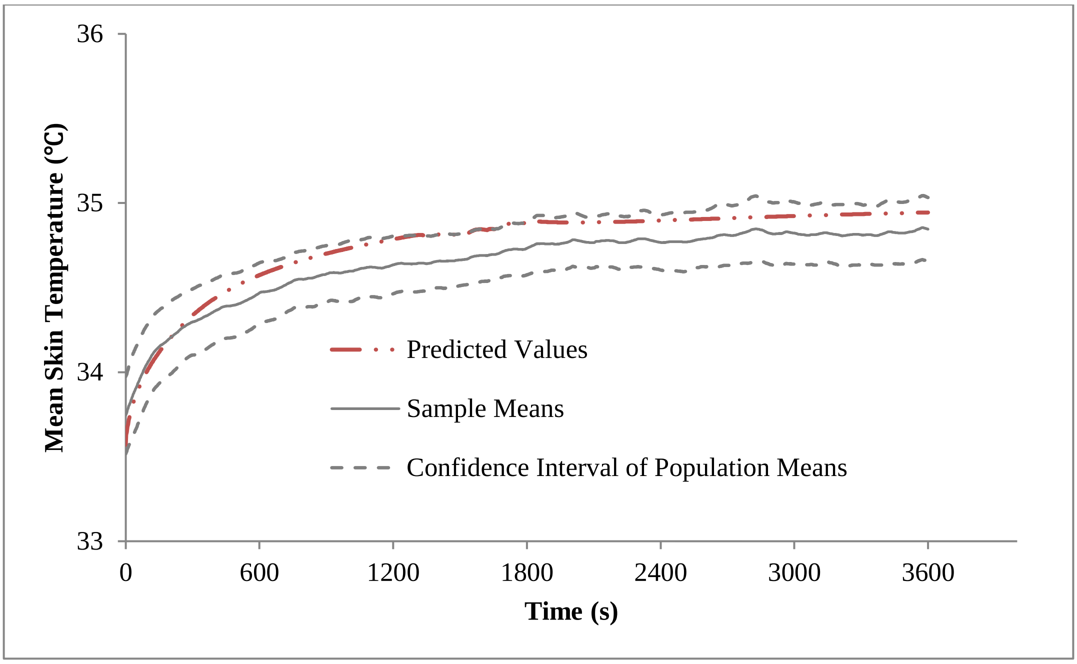
Age	24±1
Height (m)	174±6
Weight (kg)	60±7
Body fat percentage (%)	15.8±2.5

Clothing insulation (clo)	0.03±0
Activity level (met)	1.0±0

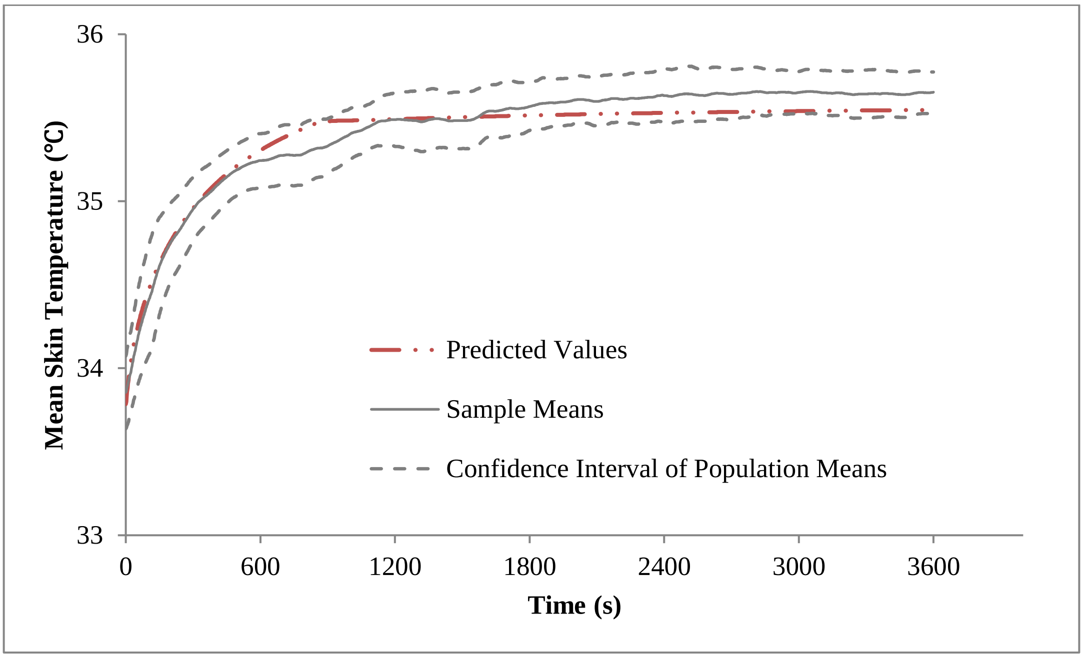
Table 11. Thermal conditions of the experiment in Case 2 (mean ± standard deviation)

Case 2		Air Temperature (℃)	Relative Humidity (%)	Air Velocity (m/s)	Globe Temperature (℃)
Condition 1	Environment Ⅰ	28.0±0.2	61.7±5.2	0.06±0.01	28.1±0.3
	Environment Ⅱ	31.9±0.1	55.1±0.3	0.09±0.02	32.0±0.1
Condition 2	Environment Ⅰ	28.2±0.1	60.4±2.8	0.06±0.01	28.3±0.2
	Environment Ⅱ	34.7±0.1	55.8±0.3	0.18±0.04	34.7±0.1

The predicted values of the new model and experimental results of body skin temperature are shown in Figure 6. For all the conditions, no significant difference was found between the model prediction and the target population. According to the model validation method (Yang *et al*., 2015a), the accuracy of the model is evaluated as Level I, which means that the new model is statistically accurate to simulate the transient mean skin temperature for the nude population under typical warm conditions.



(a) Condition 1



(b) Condition 2

Figure 6. Validation of the Developed Model for Case 2

3.3 Case 3

Steady-state experiments were conducted to validate the new model's accuracy in various typical warm environments. The warm environments include the variation of temperature, humidity and air velocity. Three series of human exposure experiments with fourteen conditions in total were carried out in a climate chamber. In each series, ten male and ten female healthy subjects were recruited. During the experiment, subjects were required to wear uniform clothing including short-sleeve shirts, shorts and lightweight shoes with an insulation level of 0.26clo (1clo equal to 0.155m^2·K/W). In each of the conditions, subjects were given sedentary office activities and 120 minutes exposure was provided for subjects to reach a steady state. At the end of the exposure, skin temperatures at 13 locations on the body were recorded as illustrated in Case 1. The data on the subjects and the thermal conditions in Case 3 are listed in Tables 12 and 13 respectively. The default body fat percentages are set as 15% and 25% for male and female subjects respectively.

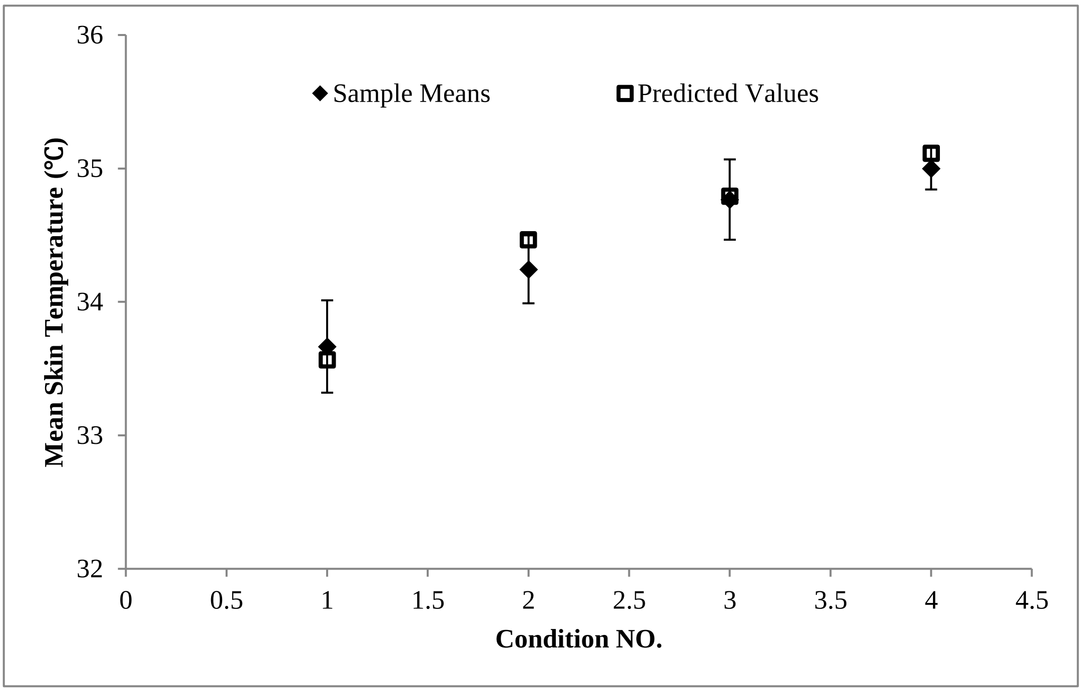
Table 12. Subjects' information in Case 3 (mean ± standard deviation)

Series	A		B		C	
Subjects	Male	Female	Male	Female	Male	Female
Age	24±1	24±1	23±1	24±1	23±1	24±1
Height (m)	173±5	160±7	175±5	159±4	172±6	160±3
Weight (kg)	61±4	50±6	67±10	46±4	63±9	48±5
Clothing insulation (clo)	0.26±0	0.26±0	0.26±0	0.26±0	0.26±0	0.26±0
Activity level (met)	1.2±0	1.2±0	1.2±0	1.2±0	1.2±0	1.2±0

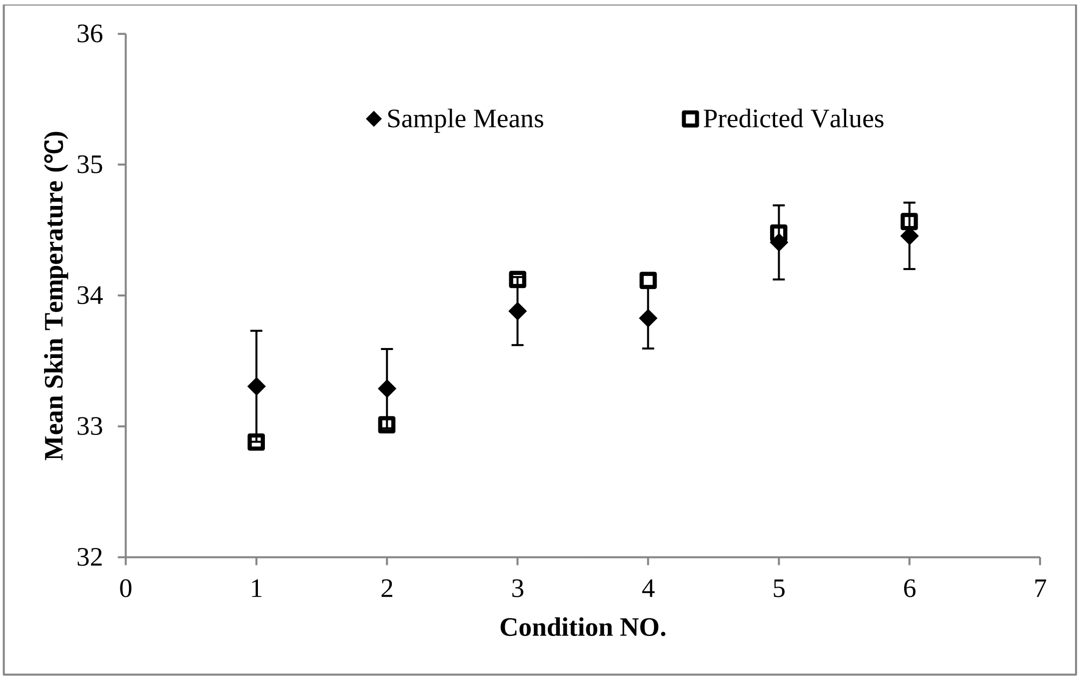
Table 13. Thermal conditions of the experiment in Case 3 (mean ± standard deviation)

Case 3		Ambient Temperature (℃)	Relative	Velocity(m/s)	Black-bulb
Series	Conditions				
A	1	26.9±0.2	54±4	0.11±0.02	26.6±0.1

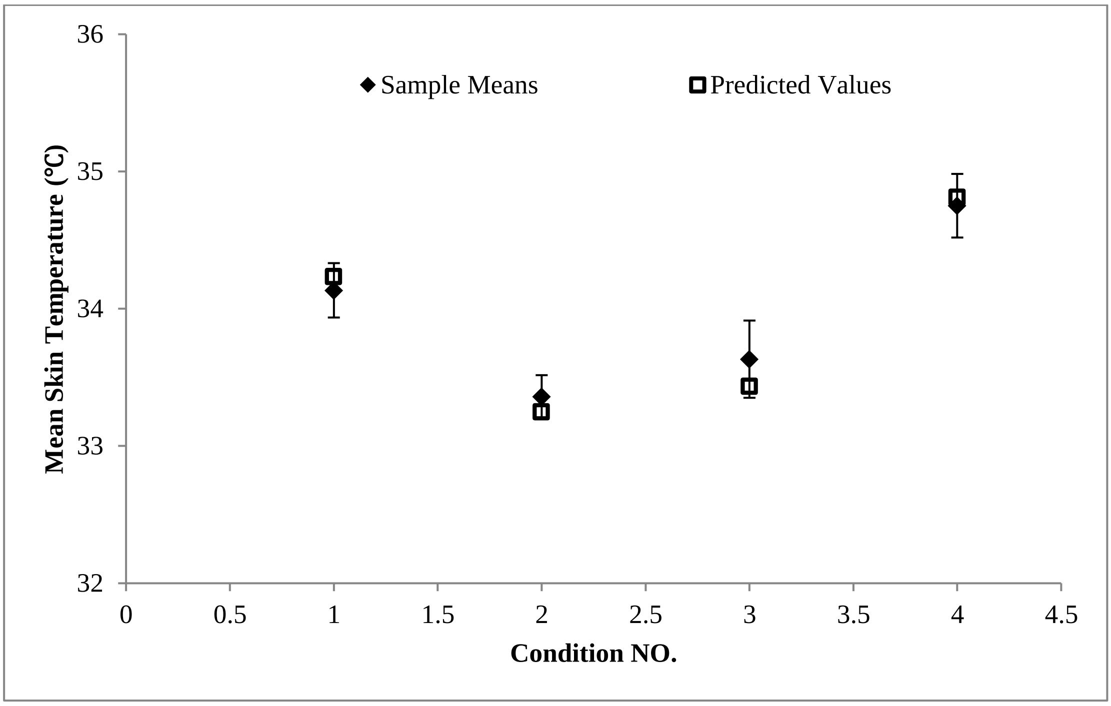
	2	28.9±0.2	55±7	0.11±0.04	28.5±0.2
	3	31.0±0.2	51±7	0.14±0.04	30.4±0.1
	4	32.9±0.2	54±5	0.12±0.02	32.3±0.1
B	1	25.6±0.1	41±1	0.08±0.05	25.6±0.1
	2	25.9±0.1	60±1	0.1±0.06	25.6±0.1
	3	28.0±0.1	40±2	0.07±0.01	27.6±0.1
	4	27.9±0.1	60±1	0.09±0.03	27.6±0.2
	5	29.8±0.1	42±2	0.1±0.02	29.4±0.2
	6	29.9±0.1	60±1	0.09±0.03	29.4±0.1
C	1	28.0±0.1	90±1	0.6±0.03	28.0±0.1
	2	28.1±0.2	90±1	0.79±0.04	28.0±0.2
	3	30.0±0.2	80±1	0.81±0.04	29.8±0.2
	4	32.0±0.2	80±1	0.79±0.03	31.9±0.2



(a) Series A



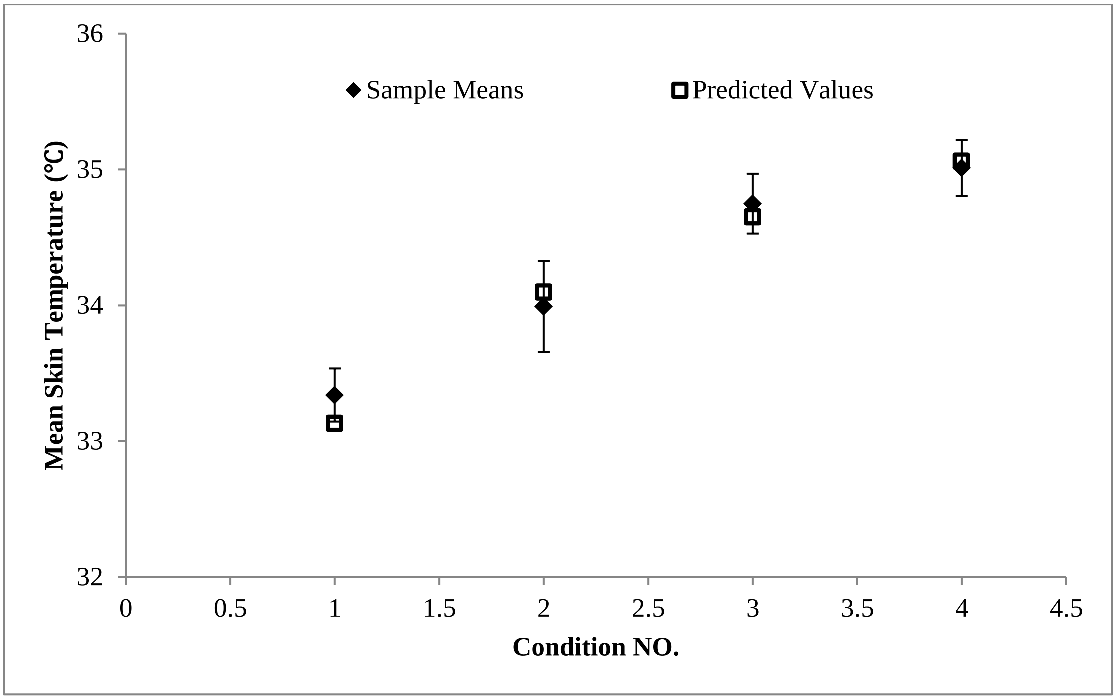
(b) Series B



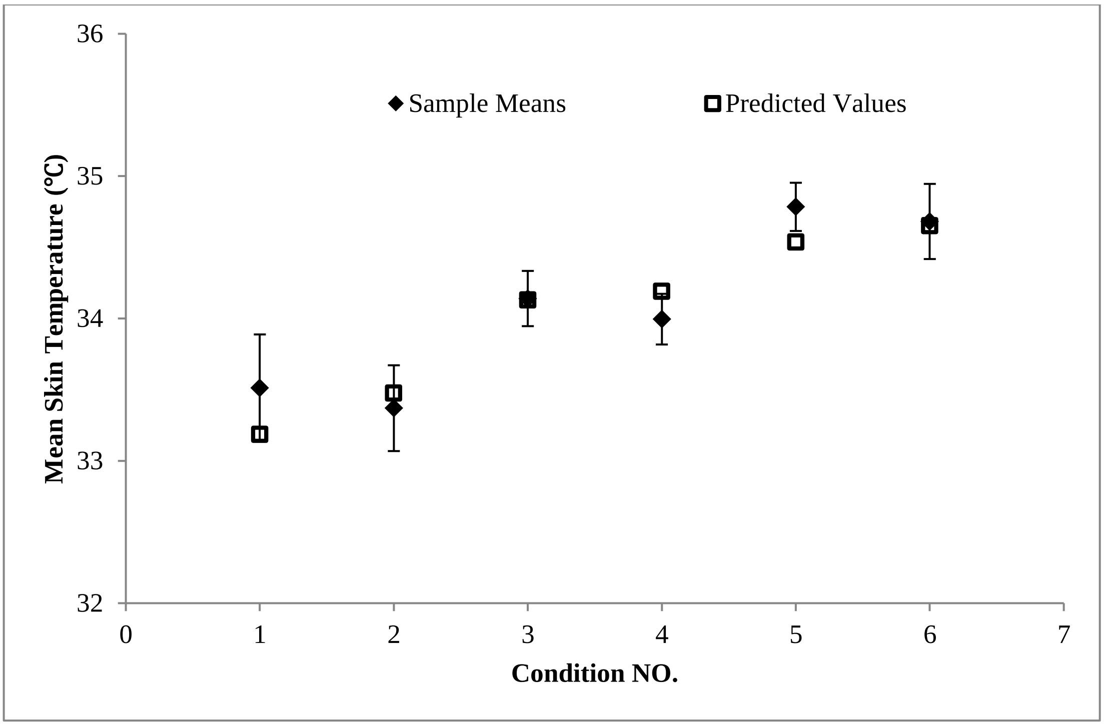
(c) Series C

Figure 7. Validation of the Developed Model for Case 3 (male subjects)

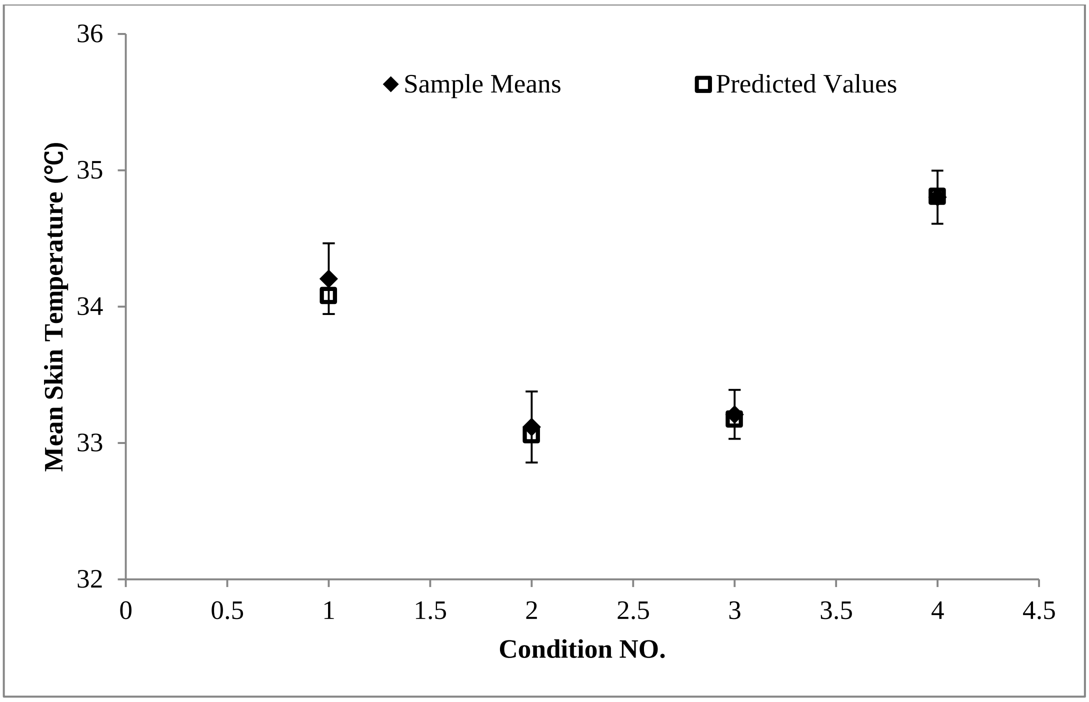
(The error bars represent the 95% confidence interval for the population means)



(a) Series A



(b) Series B



(c) Series C

Figure 8. Validation of the Developed Model for Case 3 (female subjects)

(The error bars represent the 95% confidence interval for the population means)

The predicted values of the new model and experimental results of the body skin temperature under different conditions are shown in Figure 7 and Figure 8 for male and female subjects respectively. The skin temperature for both males and females can be accurately predicted by the developed model. The performance of the new model in the steady state condition is evaluated as Level Ⅰ.

4. Discussion

A thermoregulation model of the human body has been presented. The new model is simplified compared to most existing models (e.g. (Fiala *et al.*, 2001; Huizenga *et al.*, 2001; Wan and Fan, 2008) etc.). Nevertheless, the model is statistically accurate in estimating the transient skin temperature of the human body as discussed in the next section. The model has been validated by comparing its simulation with experimental results from responses by a total of 400 subjects under typical warm conditions, as shown in Table 14. The advantage of this simplified model is that it can be more practical in application and yet further optimization of the empirical parameters can be more easily achieved.

Table 14. Accuracy level in Case validation

Case study	Working conditions	The accuracy of the model
Case 1	Transient response for subjects with light clothing	Level Ⅰ
Case 2	Transient response for the nude population	Level Ⅰ
Case 3	Steady state	Level Ⅰ

In contrast with the existing models, the major contribution of this newly developed model is to point out three questions neglected in thermoregulation modelling and optimize them. They involve a) the evaporation efficiency of regulatory sweat; b) the effect of body surface area on thermoregulatory calculations; c) the gender difference. The developed model establishes its advantages over current models as shown in Table 15.

Table 15. Advantages and development of the new model over existing models

Advantages	Development compared with the existing models
Differences between races	1) Physical parameters of the physical abstract model. 2) Metabolic heat production in the controlled system. 3) Parameter selection and optimization in the controlling system.
Differences between individuals	1) Height, weight, body fat rate. 2) Age Factor. 3) Gender factor.
Simplicity and accuracy	1) Simplicity: physical structure, the input parameters. 2) Accuracy: model validation, accuracy level.

4.1 Evaporation efficiency of regulatory sweating

In the new model, the calculation of heat loss by regulatory sweating is optimized based on the empirical formula in Stolwijk (1971). The value of E_{sw} calculated from the new model is obviously lower than that obtained from the model in Stolwijk (1971) under the same conditions. The original empirical formula for calculating E_{sw} (Stolwijk, 1971) was based on a common assumption that all the sweating can be evaporated directly. However, the reality is that considerable sweating will adhere to the body surface, clothing or drop down from the body rather than evaporating instantly as heat loss. Thus, the original calculation for E_{sw} overestimates the evaporation heat loss and modified empirical formulas considering the ‘evaporation efficiency’ are employed as Equation 40 and Equation 41. In order to illustrate the optimization of evaporation by sweating, the study applied the original and modified equations for E_{sw} respectively to simulate male subjects’ skin temperature in the thermal process of Condition 5 in Case 1, the results for the initial 1,800 seconds are shown in Figure 9. It is obvious that when applying the original calculation for E_{sw}, the predicted skin temperature is significantly lower than the measured value, which is the result of the overestimation of E_{sw}. This optimization of E_{sw} has also been validated in all the high temperature conditions in our experiments. As the assumption that the sweating can be evaporated away completely is quite common in the existing models (e.g. (Gagge *et al.*, 1971; Munir *et al.*, 2009; Tanabe *et al.*, 2002)), the question of sweating evaporation efficiency should be worthy of attention in further models.

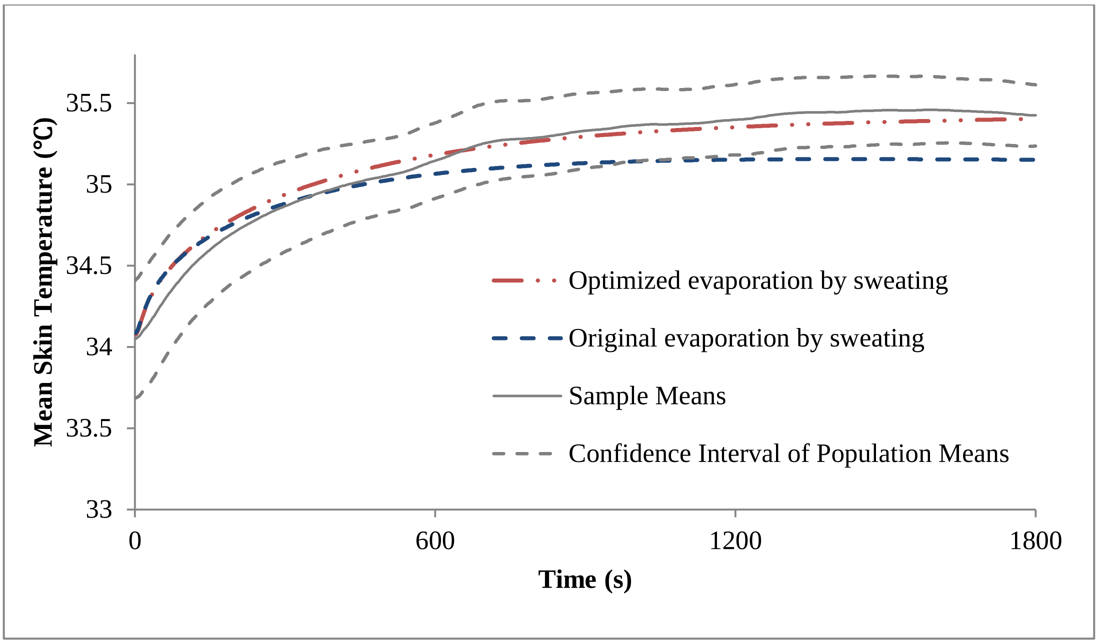


Figure 9. Example to illustrate the optimization of evaporation by sweating

4.2 Effect of body surface area on thermoregulatory calculation

The body surface area (*A*) decides the heat transfer at the skin surface thereby further influencing the body temperature. However, in most existing models (e.g. (Gagge *et al*., 1971; Stolwijk, 1971; Tanabe *et al*., 2002)), the effect of *A* is ignored when calculating the value of total heat loss by regulatory sweating or total skin blood flow, both of which should be theoretically proportional to *A*. As a modification, the new model introduces the **variable *A*** into the formula when estimating the total heat loss by regulatory sweating and total skin blood flow. Figure 10 shows the results of the model with (Equation 36 and Equation 43) or without (Equation 44 and Equation 45) consideration of *A* respectively when predicting the first 1,800 seconds of Condition 5 in Case 1 for females. According to the model evaluation method, the model's performance is improved from Level Ⅱ to Level Ⅰ by introducing *A* into the calculation of total heat loss by regulatory sweating and total skin blood flow. The effect of *A* on the simulation results is usually insignificant for populations with similar physiques; however, when populations have significantly different values of *A*, e.g. the value is calculated as 1.6m^2 for Chinese females compared with the 1.89m^2 (Stolwijk, 1971) for an American or European 'standard man', the effect of *A* should not be ignored. This optimization, based on the effect of *A*, takes into account the different physiques of populations, which makes the model more reasonable and reliable.

$$BF_4 = \frac{11.89 + DL}{1 + ST} \times 2^{Err_s/10} \quad \text{Eq. (44)}$$

$$E_{sw} = (111Err_c + 10Err_s)2^{Err_s/10} / A \quad \text{Eq. (45)}$$

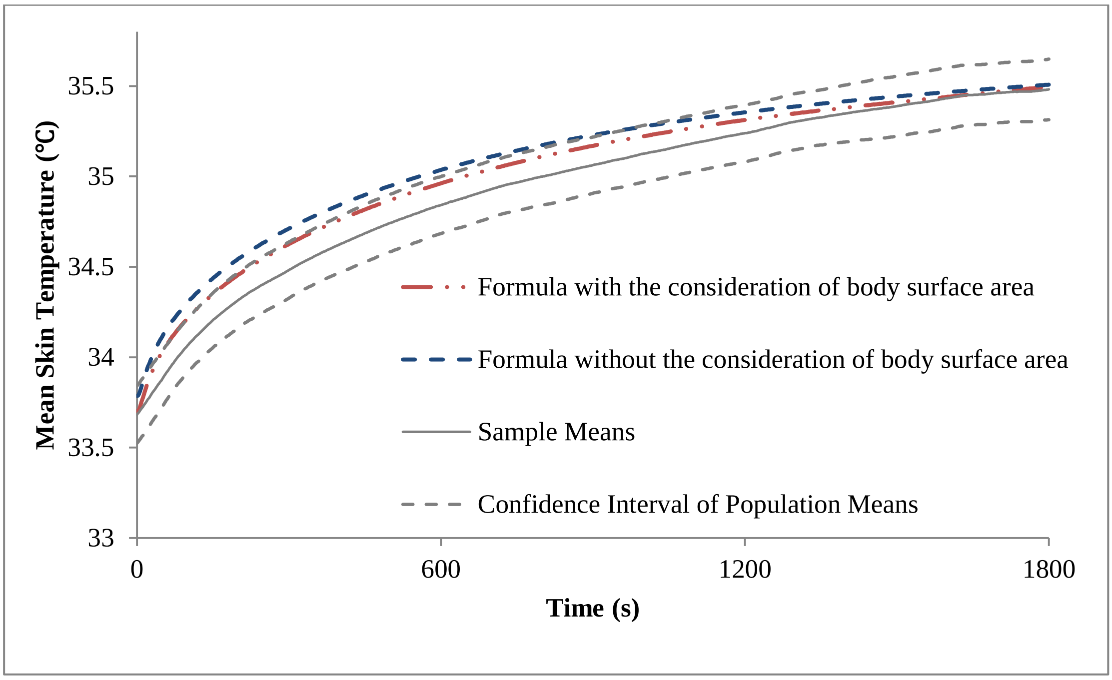


Figure 10. Example to illustrate the effect of body surface area on thermoregulatory calculations

4.3 Gender difference

In the new model, the difference in gender is introduced into calculations of basal metabolic rate, fat percentage, body surface and evaporation heat loss etc., all of which will affect in the final temperature distribution of the body. The experiment in Case 1 shows that under the same thermal conditions (e.g. Condition 5), the characteristics of temperature regulation are significantly different for male and female subjects. As shown in Figure 11, these experimental results can be well illustrated by the new model with the consideration of gender difference, which is an improvement on the existing models.

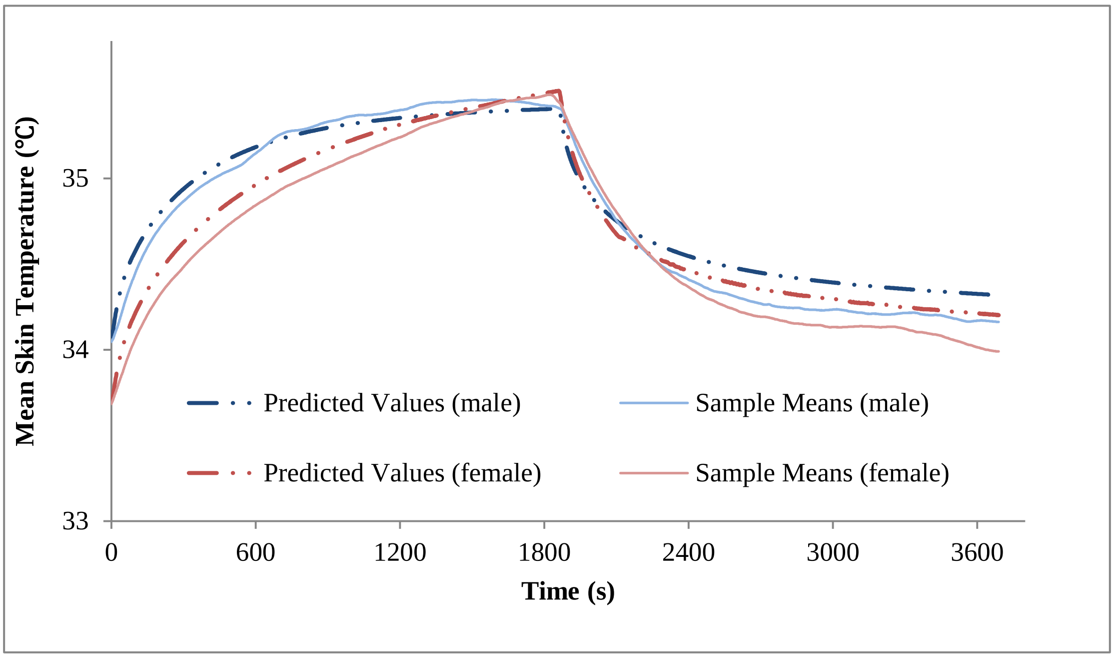


Figure 11. Example to illustrate the gender difference

The differences in the thermal responses of males and females have been noticed by many studies because of their different physiological characteristics. The discriminations have been made in this study such as the calculation of body surface area "A" and the mean basal metabolic rate. Besides, the gender factor has a direct influence on the physical model of the human body including the height, weight and body fat percentage which cannot be avoided. So this study tries to solve the prediction deviation caused by gender by deducing a separate formula for males and females, together with certain actual measured data for the two groups.

5. Conclusions

This paper presents a simplified thermoregulation model of the human body. The new model is statistically accurate in predicting mean skin temperature in warm environments and has been verified by three sets of experiments including 21 typical conditions with 400 subjects in total. This model consists of three parts: i) the physical model, which is an abstraction of the real body; ii) the controlled system, which is used to simulate the heat transfer of the body and environment; and iii) the controlling system, which describes the thermoregulatory control mechanisms of the human body.

This newly-developed model has been used to analyse the mean skin temperate based on the data from the group of subjects and reveals three key phenomena which are normally ignored in the existing models: a) the role played by the evaporation efficiency of regulatory sweating; b) the proportional relation of total skin blood flow and total heat loss by regulatory sweating against body surface area and c) there are discrepancies in the mean skin temperature between the genders. The newly-developed model has been subject to experimental validation which supports its optimizational modifications that lead to advantages in application accuracy compared to current mainstream models. Meanwhile, the introduction of a cylinder model and the development of control plates make it more convenient in application compared to other human thermal prediction models.

This model can be widely applied in the field of thermal comfort study, in particular for the prediction of transient skin temperature in different thermal processes. It is applicable for the iterative calculation of environmental and physiological parameters in the dynamic thermal environments in terms of different times and spaces.

ACKNOWLEDGEMENT

The authors would like to thank the Natural Science foundation (No. 51561135002) and 111 Project (No. B13041) for their financial support on the research. Yu Yang and

Yongqiang Li would like to thank the China Scholarship Council for the sponsorship for a one-year academic visiting study at the University of Reading.

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