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SPECIAL TOPIC — 80th Anniversary of Northwestern Polytechnical University (NPU)

Three-dimensional human thermoregulation model based on pulsatile blood flow and heating mechanism*

Si-Na Dang(党思娜), Hong-Jun Xue(薛红军)†, Xiao-Yan Zhang(张晓燕), Jue Qu(瞿珏), Cheng-Wen Zhong(钟诚文), and Si-Yu Chen(陈思宇)

Department of Fluid Mechanics, School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, *China*

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A three-dimensional thermoregulation mathematical model of temperature fluctuations for the human body is developed based on predecessors' thermal models. The following improvements are necessary in real situations: ellipsoids and elliptical cylinders are used to adequately approximate body geometry, divided into 18 segments and five layers; the core layer consists of the organs; the pulsation of the heart cycle, the pulsatile laminar flow, the peripheral resistance, and the thermal effect of food are considered. The model is calculated by adopting computational fluid dynamics (CFD) technology, and the results of the model match with the experimental data. This paper can give a reasonable explanation for the temperature fluctuations.

Keywords: thermoregulation, pulsating laminar flow, heat transfer, computational fluid dynamics (CFD)

PACS: 44.90.+c, 44.05.+e, 44.10.+i, 05.70.Ce **DOI:** 10.1088/1674-1056/27/11/114402

1. Introduction

The thermal regulation system of the human body can be considered as the unsteady thermal conduction system with the internal heat source and local regulation ability.[1] The system involves two processes: i) the heat transfer between the human body and the thermal environment is called the passive system,[2] including radiation, convection, conduction, evaporation, and respiration;[3] ii) the self-regulation function of the body which responds to the varied thermal environment, such as vasoconstriction, vasodilation, shivering, and sweating, is known as the active system.[4] In order to study the human body temperature distribution, Pennes first used the differential equation in heat transfer to establish the differential equation of heat conduction in the human body.[5] The passive system includes the heat source and boundary conditions, while the active system adjusts the coefficients of heat source and boundary conditions.[6]

Over the past fifty years, with the in-depth study, the human body thermal regulation system has been refined.[7–10] The simplified Gagge's 2-node model of thermoregulation is one of the most popular models in the field of thermal comfort study.[11] Moreover, various complex thermoregulation models have been further developed by improving the model of body segments, the layers and geometry.[12–15] When establishing the human body model, the predecessors simply considered the heat transfer model from the core layer to the skin layer, but failed to take the specific effect of viscera and the thermal effect of the food into consideration.[16] The brain, lungs, and heart were not taken into account in the geometric model, until Ferreria built the transient three-dimensional heat transfer model.[17] However, in this model, the size and the location of the brain, heart, lungs and other organs, and the influence of thermal effects on food were not considered. In the study on physiology, the quantity of heat production mainly depends on the liver in the quiet condition,[18] and the heat is different in the viscera. The liver has a higher heat production rate than the brain and the heart. The stomach, the small intestine, and the large intestine produce more heat than the lungs.[18] Previous studies have assigned a fixed value of the basal metabolic rate for the core layer, which is quite different from the metabolic rate of different viscera.[18] The basic metabolic rate is defined as the metabolic rate measured after 12 hours of fasting,[18] but it is impossible to do the experiment after 12 hours of fasting for people. This is the reason why the previous models are more than 1.5 degrees and different from the real experimental data.[19] Based on the problems mentioned above, in this paper, a 3D geometric model that involves the viscera and the heat effect of food is established. The human body is divided into 18 segments and 5 layers. The head is simplified into an ellipsoid, while the body is simplified into ellipsoid cylinders. The viscera is divided into brain, lungs, heart, liver, stomach, small intestine, and large intestine.

In previous models, a central blood pool was used instead of the heart.[20] The central temperature of the core is given to the arteries,[21] and the blood vessels exchange heat with the tissue at the temperature, without considering the temperature change in the arteries.[22] In the extremities, the coun-

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†Corresponding author. E-mail: xuehj@nwpu.edu.cn

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tercurrent heat transfer between arterial and venous blood is considered.[23] Through the study of hemodynamics, the author found that the temperature of the blood vessels keeps changing, as the blood flows.[24] The heart will give a temperature value to the entrance of the blood vessel, and the blood pressure and velocity will change periodically in every heart period.[25] The emergence of peripheral resistance results from the viscosity of the blood and will affect the temperature distribution in the blood vessels. In this paper, the author combines the Windkessel model[26] and the peripheral resistance heat generation[27] with the blood temperature model established by others, and takes the pulsation and fluidity of blood into account. Finally, a new method for calculating blood temperature is proposed.

The present paper is composed of two parts. In the first part (Section 2), the author built a three-dimensional physical model to describe the heat transfer of the human body. The model includes four points: first, the geometric model of Chinese is established; second, heat production in the thermal conduction differential equation is described detailedly; third, the boundary condition is compatible for the equation; fourth, the control equation is appropriate for the differential equation. In the second part (Section 3), the author built a three-dimensional human body model, and calculated the overall temperature distribution of the human body by adopting the CFD method. When compared with the experimental data and other models, it proves that the present model is correct and accurate. Finally, through error analysis, we can prove the effectiveness of the present model.

2. Methods

2.1. Modeling concerning the geometry size of the human body

2.1.1. Calculation of Chinese people's body parameters

By comparing the anthropometric dimensions of the Chinese with Europeans, we find that the existing methods cannot effectively simulate the geometry size of Chinese people. In this paper, the anthropometry data of the Chinese are employed to build a mathematical model.

The average density of the human body is described by[28]

$$\rho = \frac{0.8h^{0.242}}{(1000m)^{0.1}} + 0.162, \tag{1}$$

where h and m are the height and the weight of the human body.

The body fat mass equation is

$$m_{\mathrm{bf}} = \omega_{\mathrm{bf}} m, \tag{2}$$

where ω_{bf} is the fat mass coefficient of the whole body. The equation of ω_{bf} is

$$\omega_{\mathrm{bf}} = \frac{5.548}{\rho} - 5.044. \tag{3}$$

The other parts' body mass is described by

$$m_{\mathrm{bl}} = m - m_{\mathrm{bf}}. \tag{4}$$

All of the mass of segment and layer can be calculated by

$$m_{\mathrm{f},i} = \omega_{\mathrm{f},i} m_{\mathrm{bf}}, \tag{5}$$

$$m_{\mathrm{k},i} = \omega_{\mathrm{k},i} m_{\mathrm{bl}}, \tag{6}$$

where $\omega_{\mathrm{f},i}$ and $\omega_{\mathrm{k},i}$ are the fat layer and other layer mass coefficients for every segments.

The surface area of the human body can be calculated by[29]

$$A = 0.00607h + 0.0127m - 0.0698. \tag{7}$$

The volume of each layer for one segment is

$$V_{\mathrm{k},i} = \frac{m_{\mathrm{k},i}}{\rho_{\mathrm{k},i}}. \tag{8}$$

The volume of each segment is

$$V_i = \sum_{k=1}^{5} V_{\mathrm{k},i}. \tag{9}$$

The length of each segment is

$$L_i = \alpha_i h, \tag{10}$$

where $m_{\mathrm{k},i}$ and $\rho_{\mathrm{k},i}$ are the mass and the density of each layer for one segment, respectively, while α_i is the coefficient of length.

The human body is simplified into a structure that combines an ellipsoid and multiple elliptical columns; the head is an ellipsoid structure, and the trunk, arms, and legs are simplified into elliptical columns. The calculation formula of their major axis and minor axis is as follows.

The ratio of width to thickness of each segment is given by

$$A_i = \beta_i B_i. \tag{11}$$

Since the head is simplified as an ellipsoid, the formula for calculating the width and thickness is as follows:

$$B_1 = \sqrt{\frac{6V_1}{\pi\beta_1 L_1}}. \tag{12}$$

The rest of the body is simplified into ellipsoidal columns,

$$B_i = \sqrt{\frac{4V_i}{\pi L_i \beta_i}}. \tag{13}$$

The human parameters calculated in the model are extracted to obtain the parameters needed for the subsequent thermal regulation model. In respect of this model, various body parameters can be calculated only by inputting the height and weight, and the numerical values of α_i and β_i refer to the measured physical data of Chinese people.

2.1.2. Body segments and layers simplification

The human body segments are divided into the front 1/2 and rear 1/2 of the head, the neck, the front 2/5, the middle 1/5, and the rear 2/5 of the trunk, the arms, the forearms, the hands, the thighs, the legs, and feet, with a total of 18 segments. The layers of the model are divided into the skin layer, the fat layer, the muscle layer, the skeletal layer, and the visceral layer, which is divided into specific organs (brain, lungs, heart, liver, stomach, large intestine, small intestine, etc.). Specific trunk division and layering are shown in Fig. 1. Segments and layers of the head and limbs refer to M. S. Ferreira's model.[17]

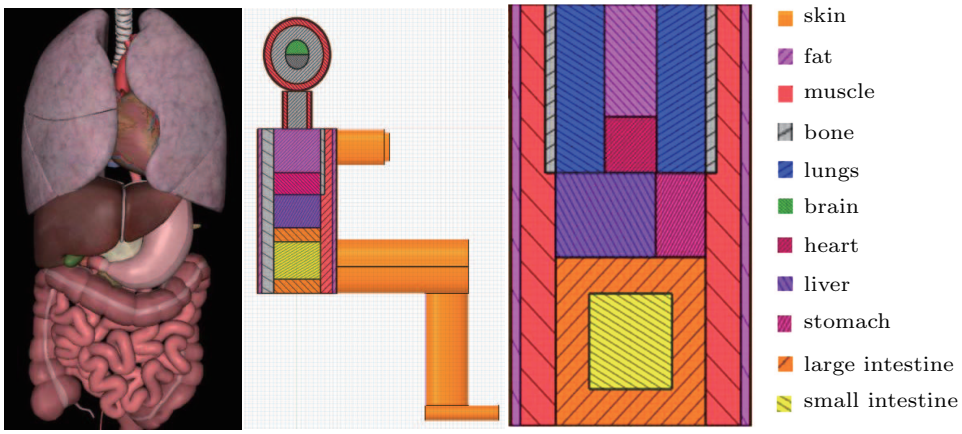


Fig. 1. (color online) (a) Simplification of internal organs and (b) stratification of the trunk.

2.2. The differential equation of heat conduction

The heat conduction of the human body is of the constant physical property and the unsteady state, and contains the heat conduction system of the internal heat source. The differential equation concerning heat conduction of the human body adopts the form under the Cartesian coordinate system[30]

$$\rho_k c_k \frac{\partial t}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial t}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial t}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial t}{\partial z}\right) + \dot{\emptyset}. \tag{14}$$

Simplification of original items. The original item of the differential equation concerning heat conduction of the human body is the internal heat source item, and the internal heat source includes the body's own metabolic heat production and the heat transferred from the blood circulation to the tissue. These two kinds of heat constitute the heat production item of the differential equation concerning heat conduction[31]

$$\dot{\emptyset} = q_{\mathrm{m}} + \rho_{\mathrm{bl}} \omega_{\mathrm{bl}} c_{\mathrm{bl}} (T_{\mathrm{peri}} - T). \tag{15}$$

2.2.1. Heat production of the tissue

The first item is the heat production of the tissue, including metabolic heat production, heat production of skeletal muscle shiver, and heat production of human sports

$$q_{\mathrm{m}} = q_{\mathrm{m,bas}} + \Delta qm. \tag{16}$$

Metabolic heat production includes heat production of basic metabolism $q_{\mathrm{m.bas.0}}$, heat production of food's special effect $\Delta q_{\mathrm{m.bas.SPA}}$[32,33] and heat production by changing temperature $\Delta q_{\mathrm{m.bas.\Delta T}}$,

$$q_{\mathrm{m,bas}} = q_{\mathrm{m.bas.0}} + \Delta q_{\mathrm{m.bas.SPA}} + \Delta q_{\mathrm{m.bas.\Delta T}}, \tag{17}$$

$$\Delta q_{\mathrm{m,bas.\Delta T}} = q_{\mathrm{m,bas,0}}[2^{\frac{T-T_0}{10}} - 1], \tag{18}$$

$$\Delta q_{\mathrm{m.bas.SPA}} = \begin{cases} 0.1 q_{\mathrm{m.bas.0}} t, & t_{\mathrm{SPA}} < 1\ \mathrm{h}, \\ -0.0167 q_{\mathrm{m.bas.0}} t + 0.1167 q_{\mathrm{m.bas.0}}, & t_{\mathrm{SPA}} > 1\ \mathrm{h}, \end{cases} \tag{19}$$

where T_0 and T are the setpoint temperature and local tissue temperature, while t is the time after the dinner.

Heat production of skeletal muscle shiver is $\Delta q_{\mathrm{m,sh}}$ and heat production of human sports is $\Delta q_{\mathrm{m,w}}$[34]

$$\Delta q_{\mathrm{m}} = \Delta q\mathrm{m,sh} + \Delta q_{\mathrm{m,w}}, \tag{20}$$

$$\Delta q_{\mathrm{m,sh}} = a_{\mathrm{sh}} \frac{sh}{v_{\mathrm{m}}}, \tag{21}$$

$$\Delta q_{\mathrm{m,w}} = \frac{\partial (a_{\mathrm{m,w}} H)}{\partial V_{\mathrm{mus}}}. \tag{22}$$

The terms of Eqs. (21) and (22) are calculated from the following equations:

$$H = \mathrm{act} \frac{M_{\mathrm{bas,0}}}{\mathrm{act_{bas}}} (1 - \eta) - M_{\mathrm{bas,0}}, \tag{23}$$

$$\eta = 0.2 \tanh(b_1 \mathrm{act} + b_0), \tag{24}$$

where b_1 and b_0 are constants.

The second item is the heat transferred from the blood to the tissue, and the temperature of the tissue is the one after the countercurrent, and peripheral resistance produces heat. The specific calculation process is described in Section 2.2.2.

2.2.2. Blood circulation and tissue heat transfer

2.2.2.1. Simplification of the Flow Mode Concerning Blood in the Human Body

In this paper, the Windkessel model is adopted, and it is similar to the flow of water in the single plunger reciprocating pump and its transmission pipelines,[35] as shown in Fig. 2. Besides, the blood flow is compared with the abstract model of water flow.[34] Stephen Hales first proposed that due to the elastic expansion of the aorta, the periodic ejection of the heart becomes a smooth flow of blood in blood vessels. Thus, he compares the aorta with the air-filled cavity and introduces the concept of peripheral resistance of blood flow.

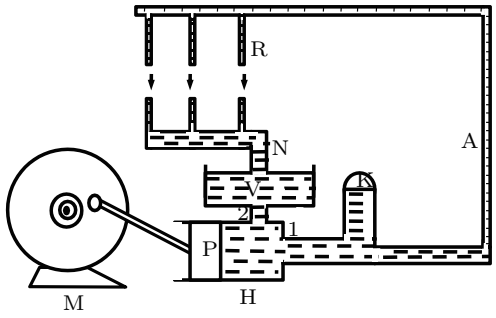


Fig. 2. Flow of water in the single plunger reciprocating pump.

The blood circulation system of human body is compared with the reciprocating pump water supply system of water, as shown in Table 1.

Table 1. Blood circulation system is compared with reciprocating pump water supply system.

Blood circulation system	Water supply system
heart	M, H, P, V, 1, 2
Aorta	K
artery	A
blood capillary	R
vein	N

In this paper, the Stokes number and the Reynolds number are adopted to determine the flow of blood, and it is defined that if α is approximate to 1, it is pulsating flow, and if it is far less than 1, it is steady flow; if R_e is greater than 2300, it is turbulent flow, and if it is less than 2300, it is laminar flow.

$$\alpha = \sqrt{S_t} = \frac{D}{2}\sqrt{\frac{\omega}{\nu}}, \tag{25}$$

$$R_e = \frac{\rho_{bl} U D}{\eta}, \tag{26}$$

where D is the diameter of the arterial canal, $\omega = \frac{2\pi}{t_h}$, and here t_h is the cardiac cycle, $\nu = \eta/\rho_{bl}$; η is the viscosity coefficient of blood, and the average flow velocity of blood is U.

According to the calculation, the time of turbulent flow accounts for 9.125% of the cardiac cycle, while the time of laminar flow is 90.875% of the cardiac cycle. The aorta, large artery, and general artery are pulsating flow, while the small artery, arteriole, and capillaries can be seen as a steady flow. Through calculation, the hypothesis is made by the author, and blood flow is regarded as an incompressible Newtonian fluid, when the aorta and large artery are regarded as laminar flow and pulsating flow, which is unsteady flow, and small vessels and capillaries are regarded as a steady laminar flow.

Human blood vessels are divided into artery blood vessels and venous blood vessels. To be specific, artery blood vessels are distributed in the deep part of the human body, while venous blood vessels include deep veins and superficial veins. The deep part of the human body, venous blood vessels, and artery blood vessels go hand in hand, while venous blood vessels are thicker than artery blood vessels, but their flow velocity is not as fast as that of artery blood vessels, and the change of pressure difference is smaller than that of artery blood vessels as well. The distribution and size of the human body's artery blood vessels are shown in Fig. 3.

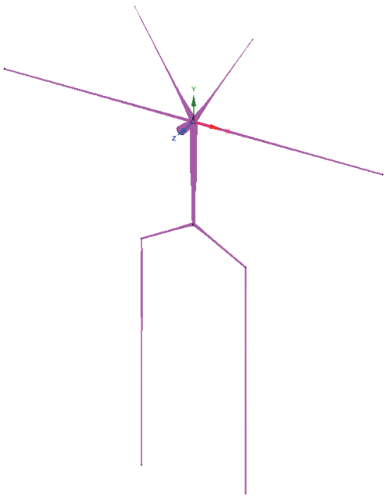


Fig. 3. (color online) A simplification of artery blood vessels.

2.2.2.2. Temperature distribution during blood flow

The blood flowing out of the heart is of pulsatility, and both its velocity and pressure will change with time. The velocity and pressure change periodically with time, which makes the peripheral resistance of blood vessels produce heat, and blood circulation produces heat, which is characterized by periodic fluctuations. After blood flows out of the heart, pulsatile laminar flow first occurs in the large artery, aorta and arteries; after reaching the arterioles, it becomes laminar flow and flows back to the heart through capillaries and then veins.

We assume that the blood pressure and flow velocity flowing out of the heart fluctuate periodically,[37] as shown in Figs. 4 and 5.

The input equation of blood pressure is

$$P_{\text{inlet}}(t) = \begin{cases} 71 + 32.967\,\mathrm{e}^{2.8308t}\sin(11.2143t), & 0 + t_{\text{h}} \ll t < 0.247\ \text{s} + t_{\text{h}}, \\ -43.4t + 105.72, & 0.247\ \text{s} + t_{\text{h}} \ll t < 0.8\ \text{s} + t_{\text{h}}. \end{cases} \tag{27}$$

The input equation of flow velocity is

$$V_{\text{inlet}}(t) = \begin{cases} 240\,\mathrm{e}^{-7.557t}\sin 13.09t, & 0 + t_{\text{h}} \le t \le 0.24\ \text{s} + t_{\text{h}}, \\ -34.3\,\mathrm{e}^{-7.557t(t-0.24)}\sin 13.09(t-0.24), & 0.24\ \text{s} + t_{\text{h}} < t \le 0.2743\ \text{s} + t_{\text{h}}, \\ 0, & 0.2743\ \text{s} + t_{\text{h}} < t \le 0.8\ \text{s} + t_{\text{h}}. \end{cases} \tag{28}$$

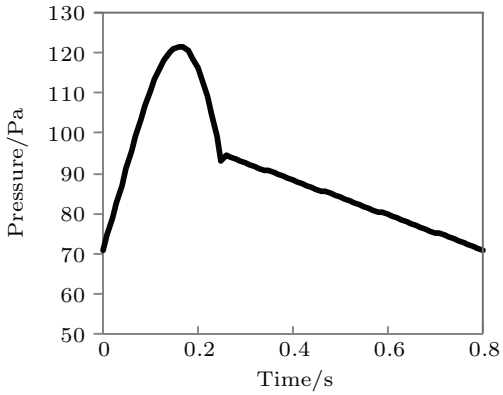


Fig. 4. Pressure change in a cardiac cycle.

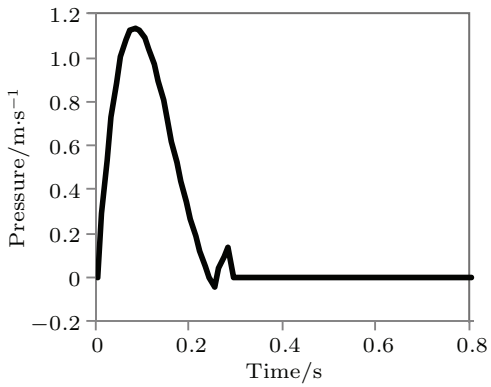


Fig. 5. Velocity at entrance in a cardiac cycle.

In this paper, it is considered that the blood flow in blood vessels is a fully developed laminar flow, and Chang makes the following assumptions about blood vessels:[38]

(i) The blood vessels can be seen as cylindrical tubes; the blood flow is axisymmetric laminar flow, and blood vessel walls are rigid.

(ii) Blood vessels are incompressible Newton fluids, and various physical parameters do not change with temperature and are constants.

(iii) The period of pulsation in blood vessels is constant, and the distribution of velocity and pressure of pulsation in blood vessels is uniform.

This paper only considers the change of blood along the x axis rather than the change along the r direction. The simplification of blood flow is shown in Fig. 6, and a one-dimensional N–S equation is established here.

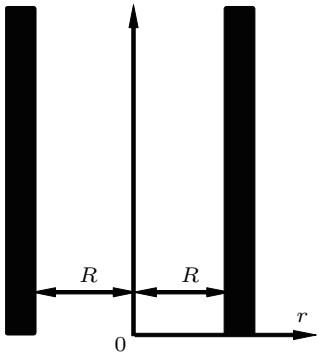


Fig. 6. Flow of blood.

Continuous equation:

$$\frac{\partial u}{\partial x} = 0.$$

Momentum equation:

$$\frac{\partial u}{\partial \tau} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + v\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r}\right). \tag{29}$$

Energy equation:

$$\frac{\partial T_{\text{bl}}}{\partial \tau} + u\frac{\partial T_{\text{bl}}}{\partial x} = \frac{k}{\rho c_{\text{bl}}}\left(\frac{\partial^2 T_{\text{bl}}}{\partial r^2} + \frac{1}{r}\frac{\partial T_{\text{bl}}}{\partial r}\right).$$

The pressure, velocity, and temperature distribution of each grid node in the blood flow model can be obtained by solving the N–S equation.

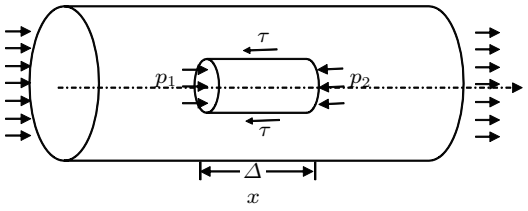


Fig. 7. Poiscuilie flow in the blood vessel.

When blood is doing laminar flow, it is believed that the flow of blood in blood vessels is a fully developed laminar flow,[39] as shown in Fig. 7, and the calculation of heat production concerning peripheral resistance is as follows:

$$Q = \int_0^R u 2\pi r \mathrm{d}r, \tag{30}$$

$$R = \frac{8\eta l}{\pi r^4}, \tag{31}$$

$$q = \frac{Q^2 Rt}{\pi r^2 l}, \tag{32}$$

$$T_{\mathrm{R}} = \frac{Q}{\rho_{\mathrm{bl}} c_{\mathrm{bl}}}, \tag{33}$$

where R is the peripheral resistance, η is the viscosity coefficient, and Q is the heat production of peripheral resistance. r and l are the radius and leight of blood vessel, ρ_{bl} and c_{bl} are density and capacitance of blood. T_{R} is the temperature change caused by heat generation in peripheral resistance.

In terms of temperature of blood perfusion tissue, counter-current heat transfer is considered in limbs when it is not considered in the rest of the body. The author defines that the equation of perfusion temperature in the body except the limbs is

$$T_{\mathrm{peri}} = T_{\mathrm{bl}} + T_{\mathrm{R}}. \tag{34}$$

The heat transfer of the limbs is more complex than the rest of the body, and the heat transfer method between the blood of limbs and that of tissue is shown in Fig. 8, and the calculation method for perfusion temperature of blood flow is shown in Fig. 9.

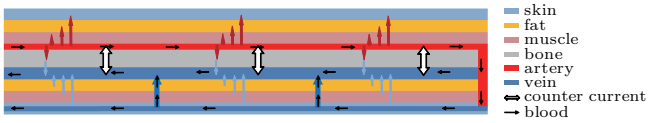


Fig. 8. (color online) Heat transfer of the limbs.

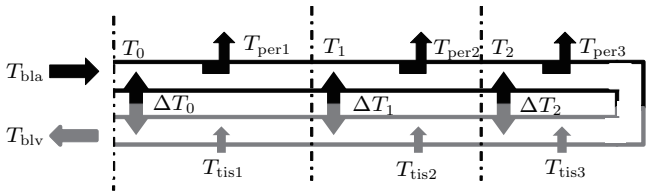


Fig. 9. Perfusion temperature of blood flow.

$$\begin{aligned}
T_{\mathrm{blp1}} &= T_0,\\
T_{\mathrm{blp2}} &= T_{\mathrm{per1}} - (T_0 - T_1),\\
T_{\mathrm{blp3}} &= T_{\mathrm{per2}} - (T_1 - T_2),\\
T_{\mathrm{bla1}} &= T_{\mathrm{blp1}} - \Delta T_0,\\
T_{\mathrm{bla2}} &= T_{\mathrm{blp2}} - \Delta T_1,\\
T_{\mathrm{bla3}} &= T_{\mathrm{blp3}} - \Delta T_2,\\
T_{\mathrm{per1}} &= T_{\mathrm{bla1}} + T_{\mathrm{R1}},\\
T_{\mathrm{per2}} &= T_{\mathrm{bla2}} + T_{\mathrm{R2}},\\
T_{\mathrm{per3}} &= T_{\mathrm{bla3}} + T_{\mathrm{R3}}.
\end{aligned} \tag{35}$$

This formula takes blood counter current into consideration in the heat transfer from blood to tissue, and unlike previous models which set the central blood temperature as the arterial blood flow temperature, it takes the heat loss into account during the counter current. The heat dissipated by arteries through counter current is equal to the heat obtained by the veins. The heat actually dissipated from the arteries is the heat energy lost in the back flow, and it is dissipated through tissue exchanges. The above formula reveals the heat conservation through counter current from the arteries to the veins by assuming that there is no heat loss in this process,[34]

$$Q_X = h_X (T_{\mathrm{blai}} - T_{\mathrm{blvi}}). \tag{36}$$

When using the right end of this formula to replace the right end of the above formula, T_{blvx} is eliminated. Since T_{blp} is a known quantity, to calculate T_{bla}, it is only necessary to calculate T_{blv}.

After substituting it, we obtain[34]

$$T_{\mathrm{blai}} = \frac{\rho_{\mathrm{bl}} c_{\mathrm{bl}} \int w_{\mathrm{bl}} \mathrm{d}V T_{\mathrm{blpi}} + h_X T_{\mathrm{blvi}}}{\rho_{\mathrm{bl}} c_{\mathrm{bl}} \int w_{\mathrm{bl}} \mathrm{d}V + h_X}, \tag{37}$$

$$T_{\mathrm{blvi}} = \frac{\int w_{\mathrm{bl}} T_{\mathrm{tisi}} \mathrm{d}V}{\int w_{\mathrm{bl}} \mathrm{d}V}, \tag{38}$$

$$w_{\mathrm{blDC}} = \frac{w_{\mathrm{bl}} + a_{\mathrm{dl,i}} \mathrm{Dl}}{1 + a_{\mathrm{cs,i}} \mathrm{Cs} \times \mathrm{e}^{-\mathrm{Dl}/50}} 2^{\frac{T_{\mathrm{sk,i}} - T_{\mathrm{sk},0,i}}{10}}. \tag{39}$$

2.3. Boundary conditions

Heat exchange between the human body and the external environment takes the following forms.[34] The first form is the heat convection between the human body and the surrounding air, and it is expressed with q_{c}. The second is the heat radiation between the human body and the surface of the surrounding environment, and it is indicated with q_{R}. The third is the irradiation of high-temperature objects on the human body surface, represented by q_{sR}. The fourth is the evaporation of water vapor on skin q_{e}. The human body breathes and radiates heat q_{res}.

The equation of exchange between the human body and the external environment is[34]

$$q_{\mathrm{sk}} = q_{\mathrm{c}} + q_{\mathrm{R}} - q_{\mathrm{sR}} + q_{\mathrm{e}} + q_{\mathrm{res}}. \tag{40}$$

The equation of heat convection and heat radiation is

$$q_{\mathrm{c}} + q_{\mathrm{R}} = \frac{T_{\mathrm{cl}} - T_0}{R_{\mathrm{cl}} + \frac{1}{f_{\mathrm{cl}}(h_{\mathrm{c}} + h_{\mathrm{r}})}}. \tag{41}$$

Reference temperature T_0 is[40]

$$T_0 = \frac{h_{\mathrm{r}} T_{\mathrm{mrt}} + h_{\mathrm{c}} T_{\mathrm{a}}}{h_{\mathrm{r}} + h_{\mathrm{c}}}. \tag{42}$$

In Eqs. (41) and (42), the terms can be calculated from the following equations:

$$f_{\mathrm{cl}} = \begin{cases} 1.00 + 1.29 R_{\mathrm{cl}} R_{\mathrm{cl}} \le 0.078 m^2 c/w, \\ 1.05 + 0.645 R_{\mathrm{cl}} R_{\mathrm{cl}} \ge 0.078 m^2 c/w, \end{cases} \tag{43}$$

$$h_{\mathrm{c}} = \begin{cases} 2.38 (T_{\mathrm{cl}} - T_{\mathrm{a}})^{0.25}, & 0 < V_{\mathrm{ar}} < 0.1 \text{ m/s}, \\ 12.1 \sqrt{V_{\mathrm{ar}}}, & V_{\mathrm{ar}} > 0.1 \text{ m/s}, \end{cases} \tag{44}$$

$$h_{\mathrm{r}} = 5.67 \times 10^{-8} f_{\mathrm{eff}} \varepsilon \frac{(T_{\mathrm{cl}} + 273)^4 - (T_{\mathrm{mrt}} + 273)^4}{T_{\mathrm{cl}} - T_{\mathrm{mrt}}}. \tag{45}$$

Irradiation of high-temperature objects on the human body surface is[32]

$$q_{\mathrm{sR}} = \alpha_{\mathrm{s}} \varphi_{\mathrm{sf-sr}} s. \tag{46}$$

Evaporative heat loss from skin is[34]

$$q_{\mathrm{e}} = \frac{\omega(P_{\mathrm{sk}} - P_{\mathrm{a}})}{R_{\mathrm{ecl}} + \frac{1}{f_{\mathrm{cl}} h_{\mathrm{e}}}}. \tag{47}$$

The terms of Eq. (47) can be calculated from the following equations:

$$\omega = 0.06 + 0.94 w_{\mathrm{rsw}}, \tag{48}$$

$$w_{\mathrm{rsw}} = \frac{E_{\mathrm{rsw}}}{E_{\mathrm{max}}}, \tag{49}$$

$$E_{\mathrm{max}} = E_{\mathrm{rsw}} + E_{\mathrm{diff}}, \tag{50}$$

where E_{rsw} and E_{diff} are the evaporation of sweat secreted due to thermoregulatory control mechanisms, and the nature diffusion of water through skin.

Evaporation of water vapor on the skin surface is[41]

$$E_{\mathrm{diff}} = \sum_i \frac{\Delta p_{\mathrm{sk},i} \cdot A_{\mathrm{sk},i}}{R_{\mathrm{E,sk}}}. \tag{51}$$

Vapor of sweat secreted due to thermoregulatory control mechanisms

$$E_{\mathrm{sw}} = \sum_i a_{\mathrm{sw},i} \mathrm{SW2}^{\frac{T_{\mathrm{sk},i} - T_{\mathrm{sk},i,0}}{10}}. \tag{52}$$

The terms of (47) can be calculated from the follow equations.

$$P_{\mathrm{sk}} = 256 T_{\mathrm{msk}} - 3373, \tag{53}$$

$$R_{\mathrm{ecl}} = \frac{R_{\mathrm{cl}}}{I_{\mathrm{cl}} LR}, \tag{54}$$

$$h_{\mathrm{e}} = h_{\mathrm{c}} LR, \tag{55}$$

Heat (sensible and latent) loss from regulatory respiration is calculated from the following equation:[34]

$$q_{\mathrm{res}} = (E_{\mathrm{rsp}} + C_{\mathrm{rsp}}). \tag{56}$$

In Eq. (56), the terms can be calculated from[34]

$$E_{\mathrm{rsp}} = 4.373 \int q_{\mathrm{m}} \mathrm{d}V (0.028 - 6.5 \times 10^{-5} T_{\mathrm{a}} - 4.91 \times 10^{-6}\ \mathrm{Pa}), \tag{57}$$

$$C_{\mathrm{rsp}} = 1.948 \times 10^{-3} \int q_{\mathrm{m}} \mathrm{d}V \times (32.6 - 0.066 T_{\mathrm{a}} - 1.96 \times 10^{-4}\ \mathrm{Pa}). \tag{58}$$

2.4. The control mode of thermal regulation

Shivering and vasoconstriction in the cold environment are[34]

$$\mathrm{Sh} = 10 [\tanh(0.48 \Delta T_{\mathrm{skm}} + 3.62) - 1] \Delta T_{\mathrm{skm}} - 27.9 \Delta T_{\mathrm{hy}} + 1.7 \Delta T_{\mathrm{skm}} \times \frac{\mathrm{d}T^{-}_{\mathrm{skm}}}{\mathrm{d}\tau} - 28, \tag{59}$$

$$\mathrm{Cs} = 35 [\tanh(0.34 \Delta T_{\mathrm{skm}} + 1.07) - 1] \times \Delta T_{\mathrm{skm}} + 6.8 \Delta T_{\mathrm{skm}} \frac{\mathrm{d}T^{-}_{\mathrm{skm}}}{\mathrm{d}\tau}, \tag{60}$$

where Sh and Cs are the heat generated by shivering and decreasing the skin blood perfusion rate variation. ΔT_{skm} is the dispersion of skin and reference temperature; ΔT_{hy} is the dispersion of hypothalamus temperature and reference temperature. $\frac{\mathrm{d}T^{-}_{\mathrm{skm}}}{\mathrm{d}t}$ is the instantaneous decrease of temperature.

Sweating and vasodilation in the hot environment are[34]

$$\mathrm{Sw} = [0.8 \tanh(0.59 \Delta T_{\mathrm{skm}} - 0.19) + 1.2] \Delta T_{\mathrm{skm}} + [5.7 \tanh(1.98 \Delta T hy - 1.03) + 6.3] \Delta T_{\mathrm{hy}}, \tag{61}$$

$$\mathrm{Dl} = 21 [\tanh(0.79 \Delta T_{\mathrm{skm}} - 0.70) + 1] \Delta T_{\mathrm{skm}} + 32 [\tanh(3.29 \Delta T_{\mathrm{hy}} - 1.46) + 1] \Delta T_{\mathrm{hy}}, \tag{62}$$

where Sw and Dl are the heat lost by evaporation of sweat and increasing skin blood perfusion rate variation. ΔT_{skm} is the dispersion of skin and reference temperature; ΔT_{hy} is the dispersion of hypothalamus temperature and reference temperature.

Shivering is mainly to control the heat production of skeletal muscle, while vasoconstriction and vasodilation are mainly to control the blood perfusion rate, and sweating is only to control the evaporation and heat dissipation capacity of skin.

2.5. Simulation calculation by means of CFD technology

This paper carries out human modeling and mesh generation on the fluent platform, and the number of meshes of the whole body is 3.1 million. It builds a geometric model of the human body with a height of 170 cm and a weight of 66.6 kg, as shown in Figs. 10 and 11. Besides, C language is used to write programs on UDF. The flow chart of the human thermal regulation model is shown in Fig. 12.

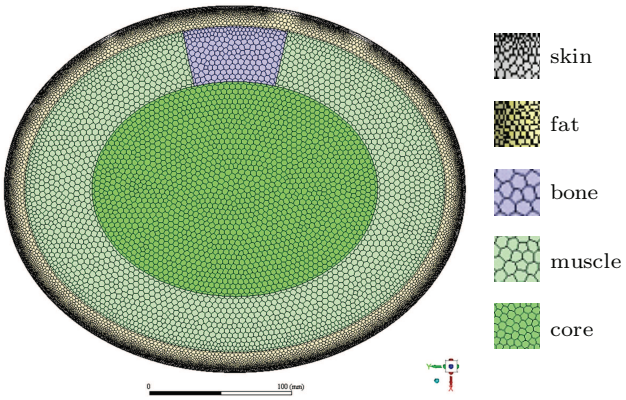


Fig. 10. (color online) Body grid division.

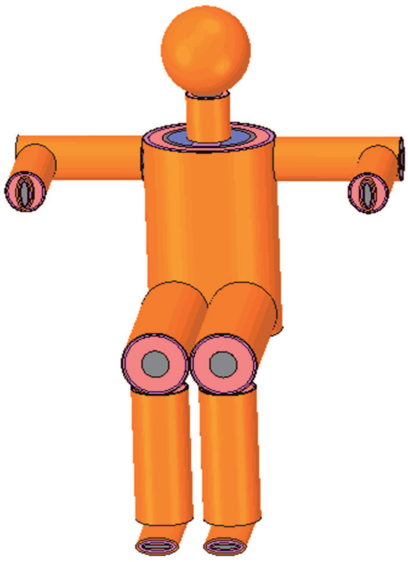


Fig. 11. (color online) Geometric model of body.

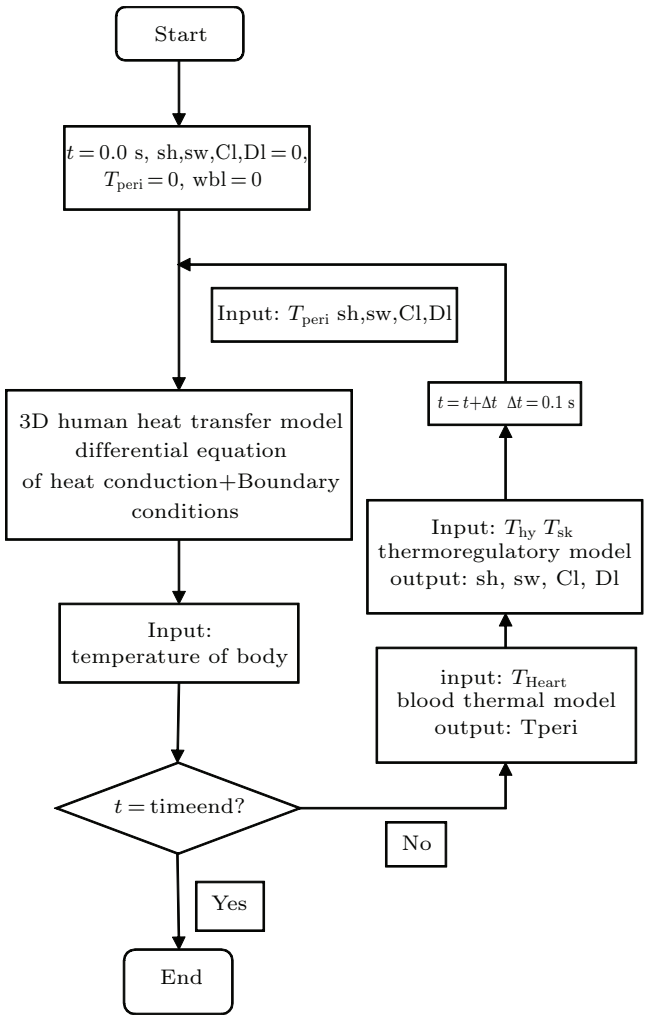


Fig. 12. Flow chart of the coupling thermal model.

3. Results and discussion

In this paper, the sitting posture model wearing shorts, T-shirt and sandals is used to simulate the human body temperature changes in hot and cold environments, respectively.

The personnel employed in the experiment were Chinese college students in the hot environment and Japanese college students in the cold environment. The reason for using these two sets of experimental data is that the two groups of people are more in line with Asian physical characteristics. The specific experimental conditions are shown in Table 2.[42,43]

Table 2. Condition of experiments.

		Room-A	Room-B	Room-A	Room-B
Hot weather	Time/min	30	30	30	30
	Air temperature/°C	29	45	29	45
	Globe temperature/°C	29	45	29	45
	Relative humidity/%	40	40	40	40
	Air velocity (m/s)	0.06	0.06	0.06	0.06
Cold weather	Time/min	30	20	40	
	Air temperature/°C	29.4	19.5	29.3	
	Globe temperature/°C	29.5	20.4	29.4	
	Relative humidity/%	46.8	52.8	47.1	
	Air velocity (m/s)	0.09	0.21	0.09	

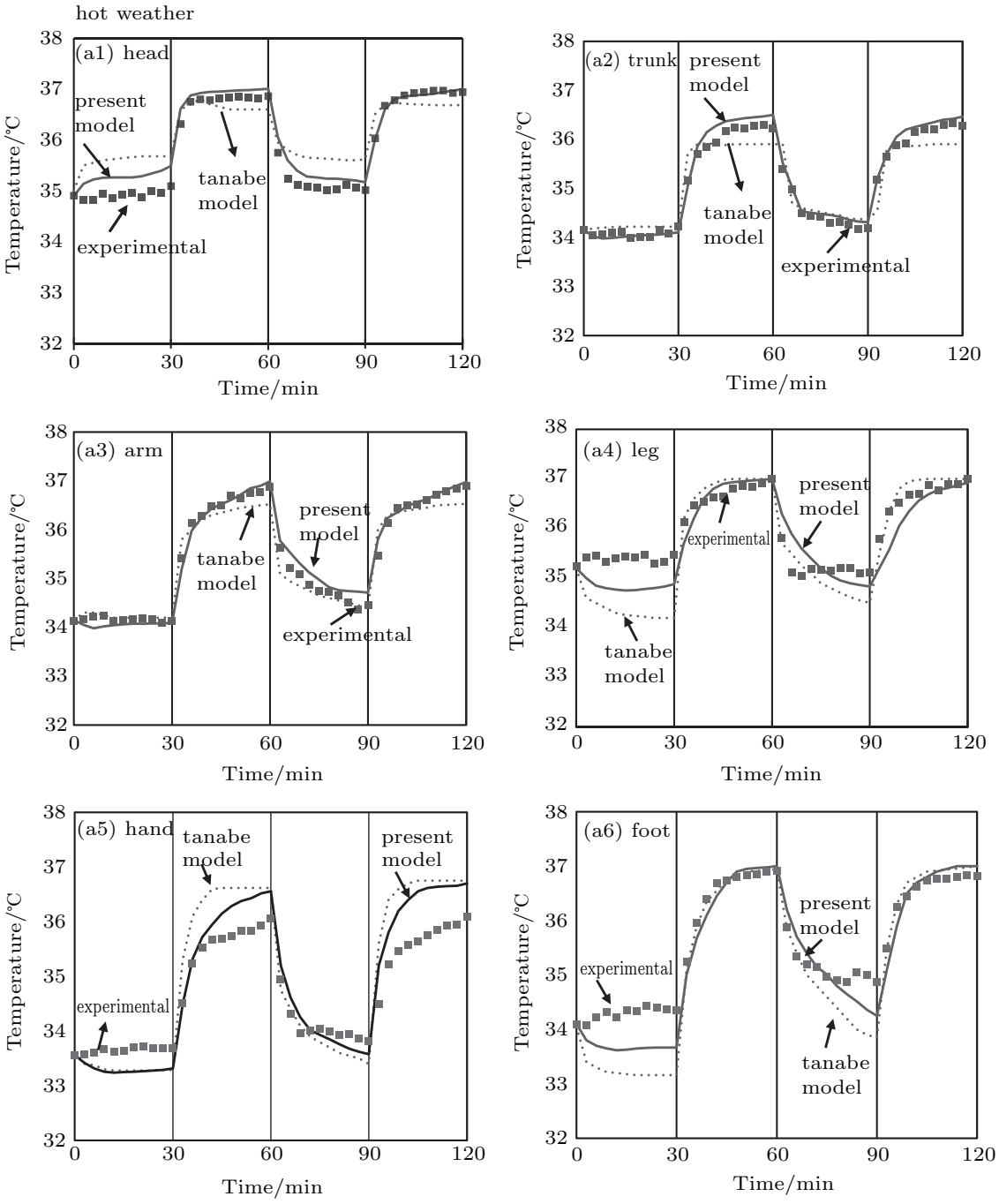
The hot environment: the human body wearing shorts at 29 °C and 40% humidity sits for half an hour, moves to 45 °C and 40% humidity, insists for half an hour, moves to 29 °C and 40% humidity for half an hour, and then enters 45 °C and 40% humidity for half an hour. The temperature data of skin nodes and rectal temperatures during these four time periods are recorded.

The cold environment: the human body wearing shorts at 29.4 °C and 46.6% humidity sits for 30 minutes, moves to 19.1 °C and 54.8% humidity, sits for 20 minutes, moves to 29.3 °C and 47% humidity and then insists for 40 minutes. The temperature data of skin nodes and rectal temperatures are recorded during these three time periods.

The distributions of human body temperatures in the cold and hot environments are output respectively and compared with the experimental results, as shown in Fig. 12. The temperature distribution of the human body in the cold environment and the hot environment was analyzed and compared with the experimental results, as shown in Fig. 13. In group a: (1), (2), (3), (4), (5), and (6), there are experimental measurements concerning temperature changes of the head, arms, trunks, legs, hands, and feet under hot conditions, and the models are built by the predecessors. We have built a model for comparison. Then, the experimental measurements of temperature changes in the head, arms, trunks, legs, hands, and feet under cold conditions in group b: (1), (2), (3), (4), (5), and (6) are shown, respectively, and the previous models and the model built in this paper are compared.

In the thermal environment, the error range of the simulation results and the real experimental results is ±0.1–0.4 °C, while the error between Tanabe's model and the experimental results is ±0.2–0.7 °C. In the cold environment, the error range between the simulation results and the true experimental results is ±0.4–0.8 °C, and the error between the Stolwijk model and the experimental results is ±0.3–1.8 °C. The

comparison shows that the model built in this paper can significantly simulate the experimental scene. In the simulated cold environment scene, it is obviously better than the previous model, and the thermal environment is not different from the previous one. Since the final temperature of the human body can only reach 37 °C in a hot environment, it cannot show the superiority of the model. However, in the cold environment, due to the addition of internal organs and the brain, these parts produce more heat than the core layer of the previous model, the blood peripheral resistance and the food product heat. Therefore, the cold environment is regulated, and it is closer to the real situation than the previous model. In the head and the trunk, the difference between the model and the experimental data is 0.5 °C and 0.7 °C, respectively, and the difference between the previous models is 1.8 and 1.3. These results further illustrate the correctness and advancement of the model built in this paper. As the pulsation of blood flow is added to the paper, it can simulate the fluctuation of temperature very well. In this case, it can give a reasonable explanation for the fluctuation of experimental data. The specific absolute error is compared, as shown in Fig. 13.



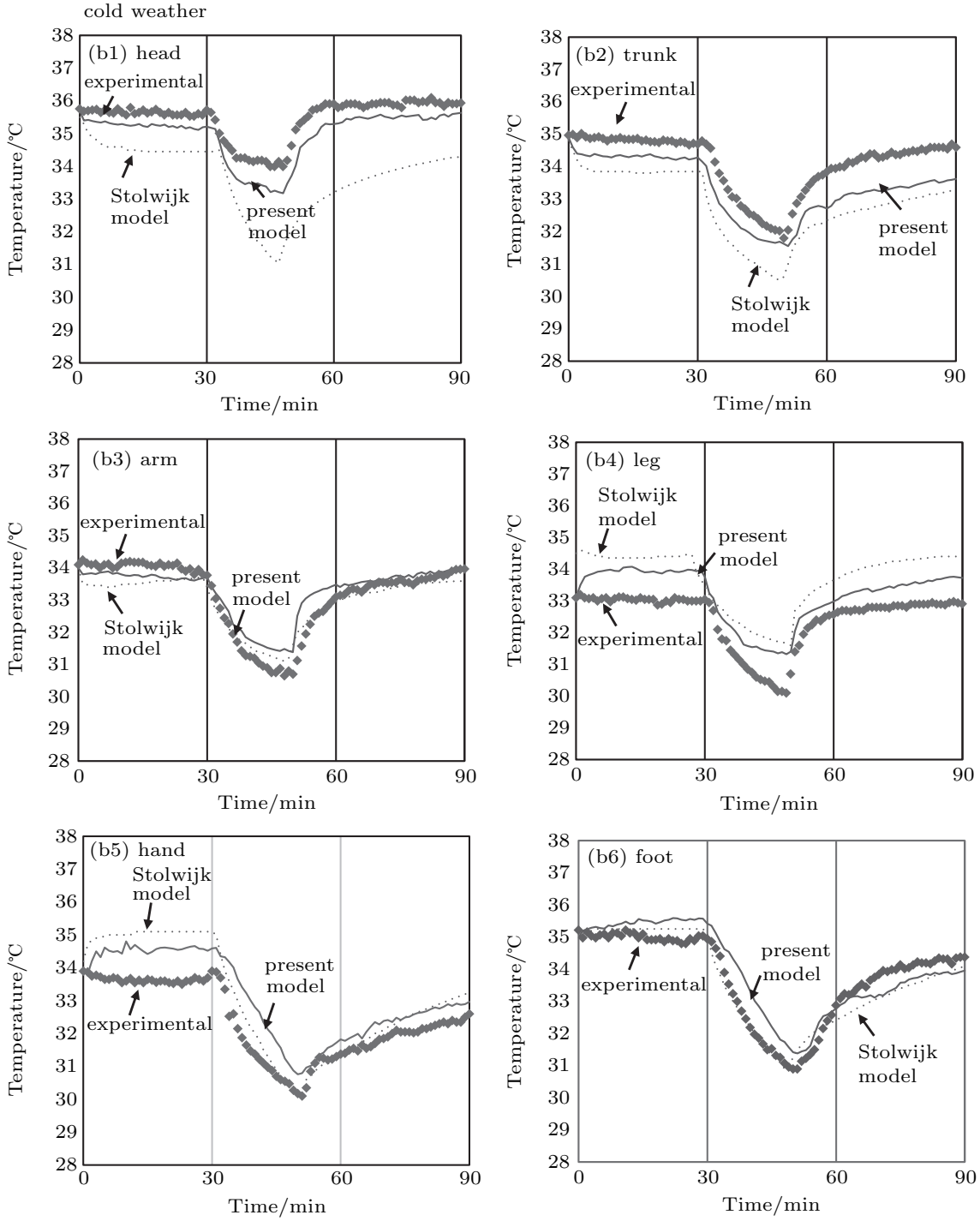


Fig. 13. Comparing the present model with Tanabe, Stolwijk, and experiment. (a) Hot weather; (b) cold weather.

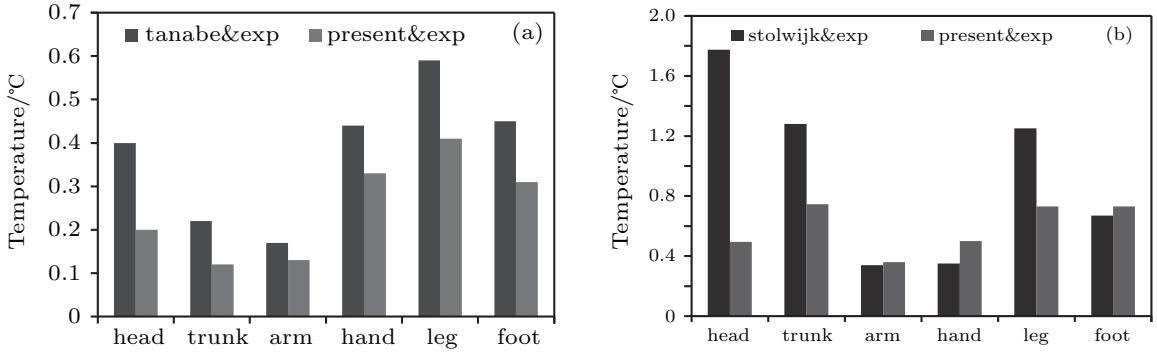


Fig. 14. Error analysis between present and predecessors' model.

4. Conclusions

In this paper, a three-dimensional mathematical model of human body heat transfer with temperature fluctuations is built, and the required parameters of the model include anthropometric data, data of human biological tissue characteristics and data of human physiological characteristics. In the process of modeling, in this paper, the related knowledge of heat transfer theory and fluid mechanics is used to calculate the overall temperature distribution of the human body by means of the CFD method.

In this paper, the human body is divided into 18 segments and 5 layers for research. The head of the human body is simplified into an ellipsoid, while the torso and limbs are simplified into elliptical columns, and the core layer is divided into the brain, lung, heart, liver, stomach, large intestine, and small intestine. The heart is regarded as the blood inlet, and the top of the head and the limbs are used as the blood outlets, when the temperature changes of the blood are simulated according to the given initial velocity, pressure, temperature values, as well as their changes. By coupling the blood temperature with the human tissue temperature, this paper finally obtains the passive heat transfer system of the human body. The system exchanges heat with the outside world through convection, evaporation, respiration, and radiation; temperature adjustment is carried out through the moderating equation of human body temperature, and finally, the human body moderating model is built. This model makes use of the finite volume method to discretize the heat conduction of the differential equation concerning the human body, calculates the distribution of blood flow velocity, pressure and temperature by means of a one-dimensional N–S equation, and finally solves numerical values with the CFD method and obtains the change curve of the human body's temperatures with time. Moreover, from the comparison between the results obtained in this paper and the experimental results of the existing model, it can be learned that the model built in this paper is more in line with the real situation and closer to the experimental results, and can give a reasonable explanation for the temperature fluctuations while the previous models fail to explain the temperature fluctuations in the experiments.

The geometric model of the human body and the blood vessel model built in this paper are relatively simple. In the subsequent work, it is necessary to consider the shoulder, face, fingers, and toes of the human body in the model, the microstructure and the tissue composition of blood vessels. With respect to experiments, further research should be carried out. For instance, after the human body takes food, the changes of eating time and human body temperatures should also be taken into account in the calculation, and it is suggested to shorten the measuring interval and measure the changes of human body temperatures under the same conditions.

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