An improved thermal model of the human body

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The goal of this study is to develop a more realistic human thermal model. Previous models have been based on simple cylindrical geometries. The current study uses shaped and refined body segments to simulate heat and mass transfer in the human body during a transient process. The body segments and blood vessels (or respiratory tract) were discretized into 3-D and 1-D elements, respectively. Criteria were developed to simulate the circulatory system, respiratory system, and human thermal responses. The finite element method was employed to solve the mass and energy equations which were written for each element.

The body model was compared against actual data available in literatures: cold, neutral, and warm conditions, with ambient temperatures of 15°C (59°F), 25°C (77°F), and 35°C (95°F). For steady state simulation, the results showed that the skin temperatures of head, trunk, and limbs matched the experimental data very well for all three conditions, while the neck and limb extremities (hand and foot) showed some difference, especially for the cold condition. In transient process, our simulation gives good predictions for warm and neutral conditions, but 1–2°C difference in skin for cold condition. The comparison of cylindrical-based model, our current model, and experimental data shows that our model is able to give more accurate prediction of human body temperatures than previous models.

Introduction

The human body is a complicated machine that is able to control the thermal responses. When exposed to a new environment, the human body can regulate heat production and blood flow rate to maintain a moderate temperature. Under extreme conditions, that is, very hot or very cold environments, thermoregulatory responses of the body will be activated. Vasodilation response and sudomotor response release heat from the body and keep the core temperature from rising further. The vasoconstriction response and metabolic response (shivering) function in an opposite way, preventing heat dissipation to the environment and generating extra heat due to muscle movement (shivering) of the body. Clothing plays an important role in simulation because of the moisture absorbing and desorbing on its surface, so the clothing effects should also be taken into consideration in the model. It is important and useful to predict thermal responses of the clothed human under different ambient temperatures, thermal stresses, and activity levels. The details of clothing model will be discussed in the next section.

There are both experimental and computational studies for human thermal response. Hardy and Stolwijk (1966) conducted an experiment on humans who were exposed to cold and hot environments. Hall and Klemm (1969) reported an experiment on thermal comfort of the human body in disparate conditions.
During the past 50 years, with development of powerful computers, computer simulation of human thermoregulation has advanced rapidly. Gagge et al. (1971) presented a two-node mathematical model to predict transient process of the human body in a uniform environment. It is a lumped-parameter model for two nodes: core and skin. The circulatory system was not simulated in Gagge’s model. The respiratory system was simulated as a mass transfer model, which calculated total heat loss due to respiration. Stolwijk (1970) developed a new model, which divided the human body into six segments. Each segment had four concentric layers representing core, muscle, fat, and skin. A central blood compartment linked the six segments together via appropriate blood flows to each of the segments, thus formulating the 25-node compartments. Wissler’s model (1985), based on the finite element method, was one of the most complete human thermal models. It divided the human body into 15 parts, and included a vascular system consisting of arteries, veins, and capillaries. Smith (1991) improved upon Wissler’s model in three major ways: (1) used cylindrical based parts, which means fingers and toes are not separately simulated in our model. But with the improvement of human body shape, more accurate bulk temperatures for hand and foot are expected from our model. A detailed explanation of these models is given in the next section.

Model

An integrated human thermal model consists of a geometry representation, passive system, and controlling system. A geometry representation of real body shape is presented in terms of base elements. Characteristics of these elements, such as element shape, surface area, and element volume, will be discussed. A passive system is determined by the heat and mass transfer among tissue elements, blood vessels, respiratory tracts, and the ambient environment. A controlling system refers to those body mechanisms, such as vasomotor, sudomotor, and shivering responses, which attempt to regulate heat and mass transfer of the passive system. Governing equations for the passive system and controlling system are also given. A computational model was then built to simulate the thermal activities and responses of human body.

The clothing model, used in our simulation, was developed by Fu (1995).Fu’s model has the following advantages: (1) simulates both heat and mass transfer, and provides history of temperature and humidity gradient on clothing surface; (2) takes many phenomena into consideration, such as non-flat cloth, mass transfer in fabric interstices,
fiber adsorption, and so forth; and (3) is able to handle multiple clothing ensembles, that is, hat, scarf, or vest. This transient model also allows users to create new clothing ensembles by combining different fabrics. In order to simulate clothing used in Zhang’s experiment (Zhang 2003), we created a new “leotard ensemble” by combining dimensions and thermal properties of leotard fabric. The insulation values for each body part were from Zhang’s report.

Geometry representation

It is difficult to represent the human body because of its irregular shape and complicated structure of tissues and organs. As discussed in the introduction, the models of Gagge et al. (1971), Stolwijk (1970), and Wissler (1985) models are lumped parameter models, using bulk properties, that is, bulk temperature, for individual parts or segments, making these models unable to calculate temperature distribution throughout the body. Smith (1991) used the finite element method to model body parts. As shown in Figure 1, Smith used 15 cylinders to represent 15 major body parts, just as Wissler did, and then divided each part into several elements in axial, angular, and concentric directions. Smith’s model gave a close estimation of temperature distribution of the human body when the simulation results were compared with Hardy and Stolwijk (1966), Hall and Klemm (1969), and Saltin and Hermansen’s (1966) experimental results. However, Smith’s model is also limited to cylindrical body segments and not all parts of the body can be represented by strict cylindrical shapes.

Our model is a finite element model, which is based on finite element method (FEM). The reasons for choosing FEM are because (1) FEM is an accurate method to solve partial differential equations, (2) FEM is better in handling complicated domain geometries of heat conduction and low-speed fluid problems in the human body, and (3) FEM can deal with domain changes (with moving boundaries), which will be one of our future issues for the simulation of moving human body. Like the Smith model, the human body was divided into 15 parts, but the parts were no longer limited to cylindrical shapes. Figure 2 shows our shaped body parts compared to previous cylindrical body parts in Figure 1. Figures 3 and 4 show a layout of the upper arm and two types of elements in this part, respectively. The cylinder was angularly divided into four slices, and the angle for each slice was 90°. Generally, the shape of a segment was described by a series of radius (i.e., \( r_1 - r_4 \) in Figure 3b), and all of these radius data were stored in a pre-set shape-description file. Therefore, it was possible to change the shape of body segments for individuals, who had different body shapes, just by changing the radius data in this pre-set file. For each simulation, this shape-description file was read as input, and all parameters and dataset arrays concerning body shape were recalculated or updated for this case.

Since our model was based on the finite element method, surface area and volume of each element needed to be evaluated, as shown in Figure 4a and 4b. It was assumed that (1) curve AB was an ellipse with \( r_1 \) and \( r_2 \), (2) curve CD was an ellipse with \( r_5 \) and \( r_6 \), (3) on any cross-section of the element, the curve
Figure 2. Shaped human body in our model.

was ellipse (Figure 4a), and (4) the curved surface A-B-C-D was continuous and smooth. There are two types of 3-D element. The triangular 3-D element (element I) in Figure 4a is located in the center of the segment, representing core substance, that is, bone or brain. The rectangular 3-D element (element II) in Figure 4b denotes other elements outside the core elements, for example, muscle, fat, and skin. The skin elements include top, bottom, and lateral surfaces of the elements. By noting that angle A-O₁-B is 90°, the top or bottom surface area can be determined by

\[ A_s = \frac{1}{4} \pi r_1 r_2 \]  
for element I, \hspace{1cm} (1)

\[ A_s = \frac{1}{4} \pi (r_7 r_8 - r_1 r_2) \]  
for element II. \hspace{1cm} (2)

Figure 3. (a) Layout of upper arm. (b) Cross-section of upper arm.

The lateral surface area needs to be calculated for outside element (element II) in Figure 4b. By assumptions (1)–(4), the lateral surface area (3-D) can be approximated as a 2-D surface as shown in Figure 5. \( P_1 \) and \( P_2 \) are perimeters of quarter ellipses \( EO_1 F \) and \( GO_2 K \). A good approximation to ellipse perimeter was given by Ramanujan (1913) as follows:

\[ P_1 = \frac{1}{4} \pi \left[ 3(r_7 + r_8) - \sqrt{(r_7 + 3r_8)(3r_7 + r_8)} \right]. \]

\[ P_2 = \frac{1}{4} \pi \left[ 3(r_9 + r_{10}) - \sqrt{(r_9 + 3r_{10})(3r_9 + r_{10})} \right]. \]  
(3)
The lateral surface area in Figure 5 can be given by

$$A_s = \frac{1}{2} S (P_1 + P_2),$$

(5)

where $S$ is vertical height of trapezoid EFKG in Figure 5.

To approximate $S$, we assumed circle shape for top and bottom surfaces, that was, $r_7 = r_8$ and $r_9 = r_{10}$. So vertical height $S$ was expressed in terms of side length $L$ as

$$S = \sqrt{L^2 - \left(\frac{P_1 - P_2}{2}\right)^2},$$

(6)

where $L$ can be obtained from geometrical calculation as

$$L = \sqrt{H^2 + (r_7 - r_9)^2}.$$  

(7)

When applying to general cases (arbitrary $r_7 - r_{10}$), it is a good approximation to replace $r_7$ and $r_9$ in Equation (7) with average radius $\frac{r_7 + r_9}{2}$ and $\frac{r_9 + r_{10}}{2}$, respectively, yielding

$$L = \sqrt{H^2 + \left(\frac{r_7 + r_8}{2} - \frac{r_9 + r_{10}}{2}\right)^2}.$$  

(8)

By substituting Equations (3), (4), (6), and (8) into Equation (5), lateral surface area can be calculated for every surface element.

The element volume was calculated for two types of element respectively. Note that $r_7 - r_{10}$ were also radius from the center point to the edge. Yet by assumptions (1)–(4), the element volume can be obtained by the following integral

$$V = \int_{h=0}^{H} A dh,$$

(9)

where $A$ is the cross-section area of the element, $H$ is height of the element.

Equation (9) is the general formula to calculate element volume. It is also assumed in our model that the cross-section has a linear change from top surface to the bottom one, so the radius on any cross-section can be calculated by applying linear interpolation of two radii on top and bottom surfaces, as shown in Equations (10) and (11)

$$r' = r_1 + (r_5 - r_1) \frac{h}{H}.$$  

(10)
\[ r'' = r_2 + (r_6 - r_2) \frac{h}{H}, \]  
\[ (11) \]

where \( r', r'' \) are radius of arbitrary cross-section shown in Figure 4a, and the elliptic cross-section area can be calculated as
\[ A = \frac{1}{4} \pi r' r''. \]  
\[ (12) \]

By substituting Equations (10)–(12) into Equation (9) and integrating, the element volume for triangular and rectangular elements can be obtained as shown in Equations (13) and (14)
\[ V = \frac{1}{12} \pi H \left( r_1 r_2 + r_5 r_6 + \frac{1}{2} r_2 r_5 + \frac{1}{2} r_1 r_6 \right) \times \text{for element I}, \]  
\[ (13) \]
\[ V = \frac{1}{12} \pi H \left( r_7 r_8 + r_9 r_{10} + \frac{1}{2} r_8 r_9 ight. \\
\left. + \frac{1}{2} r_7 r_{10} - r_3 r_2 - r_5 r_6 - \frac{1}{2} r_2 r_5 - \frac{1}{2} r_1 r_6 \right) \times \text{for element II}. \]  
\[ (14) \]

It should be noted that Equations (5), (13), and (14) are based on mathematical approximation, and are capable of obtaining relatively accurate results as long as the body parts are not “extremely irregular,” which means the shape of top and bottom surfaces is roughly similar and the lateral curved surface is not twisted. In reality, most body parts of a human are continuous and smooth, except the hand and foot, so Equations (5), (13), and (14) are applicable to those parts. The irregular parts, hand and foot, are still treated as “cylinders” for the sake of simplicity.

**Passive system**

The passive system included all elements throughout the human body. With the element area, \( A_s \), and the element volume, \( V \), an energy balance equation can be written for any tissue element in Figures 4a and 4b:
\[ \rho c_p \frac{\partial T}{\partial t} = k \nabla^2 T + \frac{q'}{V}, \]  
\[ (15) \]

where the term on the left-hand side of Equation (15) is heat storage in element, the first term on the right-hand side is heat conduction throughout this element, and the second term is heat generation rate (\( J/m^3 \)) in tissue. The solution method for Equation (15) will be discussed in the next section.

The circulatory system was modeled as a network of blood vessels—veins and arteries, as was also done by Smith (1991). Figures 6a and 6b illustrate blood vessel distribution in the upper arm. A pair of blood vessels (one artery and one vein) was assigned between two adjacent nodes of the element, except for the nodes of the skin elements, since there were only superficial veins on the skin. In this work, blood vessel elements were considered 1-D elements for simplicity. Blood originated from the left ventricle, flowing everywhere through arteries, exchanging mass and nutrition with tissue, then returning to the right atrium through veins. An energy balance can be built for any blood vessel element as
\[ \rho c_p \frac{\partial T}{\partial t} = k \frac{d^2 T}{dz^2} - \rho c_p v_{bl} \frac{dT}{dz}. \]  
\[ (16) \]

In Equation (16), \( v_{bl} \) is mean blood velocity, which depends on cardiac output, blood pressure, and blood radii. \( \rho, c_p, \) and \( k \) are density, specific heat, and thermal conductivity of blood, respectively.
The respiratory system was modeled as an inhale-exhale tract as shown in Figure 7. Similar to the blood vessel element, respiratory tract elements were also 1-D elements. For any given tract element, the energy equation was written as

\[ \rho c_p \frac{\partial T}{\partial t} = k \frac{d^2 T}{dz^2} - \rho c_p v_{resp} \frac{dT}{dz}. \]  

(17)

Equation (17) has the same form as Equation (16), except that air velocity \( v_{resp} \) was substituted for blood velocity \( v_{bl} \). \( \rho \), \( c_p \), and \( k \) are the same properties of the air. To solve Equations (16) and (17), blood velocity \( v_{bl} \) and air velocity \( v_{resp} \) needed to be evaluated. The method to obtain \( v_{bl} \) and \( v_{resp} \) will be discussed in Section 2.3.

**Controlling system**

As discussed in the last section, there were three types of elements in our model: tissue, blood vessel, and respiratory tract. Tissue elements were 3-D. All body tissue and organs, such as bone, muscle, fat, skin, brain, lung, and so forth, were modeled as tissue elements. Blood vessel and respiratory elements were 1-D. Equation (15) was written for 3-D tissue elements, and the properties were obtained for different tissue types. The heat generation, \( \dot{q}^V \), was a summation of three effects: metabolic rate, physical activity level, and shivering, and can be expressed as

\[ \frac{\dot{q}^V}{V} = M_{basal} + M_{activity} + M_{shivering}. \]  

(18)

The basal metabolic generation \( M_{basal} \) were obtained from the work of Charney et al. (1987), Ganong (1983), and Gordon (1974), shown in Table 1. The metabolic generation due to physical activity, \( M_{activity} \), is shown in Table 2, from the work of Benzinger (1970). The metabolic generation due to shivering, \( M_{shivering} \), was also calculated from Benzinger’s work. In Equation (16), mean blood velocity \( v_{bl} \) needs to be determined for every blood vessel element. The blood flow in circular vessels can be considered as a pressure-driven flow problem, which was described in the Hagan-Poiseuille problem. The mean blood velocity can be expressed in terms of pressure gradient, \(-\frac{dP}{dz}\), in Equation (19). By assuming (1) blood flow is continuous and steady, and (2) cross-section of blood vessel remains constant along any 1-D blood vessel element, Hagan-Poiseuille problem reduces to Equation (20). With the proper boundary conditions, \(-\frac{dP}{dz}\) can be solved from Equation (20), and then substitute back into

<table>
<thead>
<tr>
<th>Tissue type</th>
<th>Basal metabolic heat generation rate, J/100 g min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>76.15</td>
</tr>
<tr>
<td>Abdomen</td>
<td>23.00</td>
</tr>
<tr>
<td>Lung</td>
<td>4.03</td>
</tr>
<tr>
<td>Bone</td>
<td>0</td>
</tr>
<tr>
<td>Muscle</td>
<td>4.03</td>
</tr>
<tr>
<td>Fat</td>
<td>0.024</td>
</tr>
<tr>
<td>Skin</td>
<td>6.03</td>
</tr>
</tbody>
</table>

**Table 1. Basal metabolic heat generation rate of different tissues.**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Metabolic generation, W/m² (BTU/(hr ft²))</th>
<th>Met*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleep</td>
<td>40 (12.7)</td>
<td>0.7</td>
</tr>
<tr>
<td>Seated</td>
<td>60 (19.0)</td>
<td>1.0</td>
</tr>
<tr>
<td>Walking (0.9 m/s)</td>
<td>115 (36.5)</td>
<td>2.0</td>
</tr>
<tr>
<td>Calisthenics</td>
<td>175 (55.5)</td>
<td>3.0</td>
</tr>
<tr>
<td>Heavy machine work</td>
<td>185 (58.7)</td>
<td>4.0</td>
</tr>
<tr>
<td>Basketball</td>
<td>290 (91.6)</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Equation (19) to obtain $v_{bl}$.

$$v_{bl} = -\frac{r_0^2}{8\mu} \frac{dP}{dz}. \tag{19}$$

$$-\frac{r_0^2}{8\mu} \frac{d^2 P}{dz^2} = 0. \tag{20}$$

Equation (17) is an energy balance equation for the respiratory tract element. In addition, the mass balance equation needed to be established in terms of the humidity ratio, $w_{air}$, which is defined as the quantity of water vapor in a mixture relative to the amount of dry air present. For any respiratory tract element, the mass balance equation is written as

$$D \frac{d^2 W}{dz^2} - v_{resp} \frac{dW}{dz} = 0, \tag{21}$$

where $D$ is the constant diffusivity of air. The air velocity, $v_{resp}$, can be calculated from the oxygen consumption rate as shown in Equation (22).

$$v_{resp} = \frac{\dot{V}_O_2}{\pi r_0^2}. \tag{22}$$

ASHREA Handbook (ASHREA 2005) gives a correlation of $\dot{V}_O_2$ in terms of metabolic generation as

$$\dot{V}_O_2 = \frac{M}{21.12(0.23RQ + 0.77)} \tag{23}$$

$RQ$ is called respiration quotient, varying between 0.7 for light work and 1.0 for heavy work.

Solution method

Passive system equations were developed in last section. The finite element technique, which was described in Segerlind’s book (Segerlind 1984), was used to solve the differential equations for the passive system. To discretize governing equations which have first-order or higher derivatives, Galerkin’s method of weighted residual was applied to partial differential equations (PDEs) of pressure (Equation 20), humidity ratio (Equation 21), and temperature distribution (Equation 15).

For pressure distribution Equation (20), Galerkin’s method was applied and gave

$$-\frac{r_0^2}{8\mu} \int_V [N] \frac{d^2 P}{dz^2} dV = 0, \tag{24}$$

where $dV$ is the differential element volume and $[N]$ is a one-dimensional array of the shape functions, and where $z$ is the axial direction of 1-D blood vessel element, or

$[N] = \begin{bmatrix} N_1 \\ N_2 \end{bmatrix},$

$N_1 = \frac{\Delta z - z}{\Delta z}, \tag{25}$

$N_2 = \frac{z}{\Delta z}.$

Then the local pressure of any element, $P$, can be expressed in terms of the nodal pressure array $\{P\}$ and the shape function $[N]$

$$P = [N]^{T}\{P\}^e, \tag{26}$$

where

$$\{P\}^e = \begin{bmatrix} P_1 \\ P_2 \end{bmatrix}. \tag{27}$$

In order to lower the order of the derivative and evaluate the integral for Equation (24), Green’s first theorem was applied. The integral of $\frac{d^2 P}{dz^2}$ over element volume was broken into two parts, the integral of $\frac{dP}{dz}$ over element surface and integral of $\frac{dP}{dz}$ over element volume as follows

$$-\int_V [N] \frac{d^2 P}{dz^2} dV = -\int_{A_s} [N] \frac{dP}{dn} dA_s + \int_V \frac{d[N]}{dz} \frac{dP}{dz} dV. \tag{28}$$

Combining Equations (24) and (28) yielded the first-order integral form of a pressure distribution equation:

$$\frac{r_0^2}{8\mu} \int_V \frac{d[N]}{dz} \frac{dP}{dz} dV - \frac{r_0^2}{8\mu} \int_{A_s} [N] \frac{dP}{dn} dA_s = 0. \tag{29}$$

Boundary conditions shown in Equations (30) and (31), were evaluated at the left ventricle and right atrium, where the blood flow rate equals the cardiac output, $CO$, respectively. Cardiac output, $CO$, is basically a function of skin temperature and core temperature, according to the thermal state of
the human body (vasoconstriction or vasodilation).

$$- \frac{r_0^2}{8\mu} \int_{A_s} \frac{dP}{dn} dA_s = \begin{bmatrix} CO \\ 0 \end{bmatrix}. \quad (30)$$

$$- \frac{r_0^2}{8\mu} \int_{A_s} \frac{dP}{dn} dA_s = \begin{bmatrix} CO \\ 0 \end{bmatrix}. \quad (31)$$

Humidity ratio Equation (21) and temperature distribution Equations (15), (16), and (17) are transformed to integral forms by applying similar technique for pressure equation above. More details can be found in Fu’s thesis (Fu 1995).

Our computer program is capable of simulating thermal status of the human body in a stage-change environment, with different air temperatures and physical activity levels in different stages. Input variables are: shape information and initial temperature distribution of the human body (read-in files), controlling parameters for stage-change environment and activity levels, and local heat transfer coefficients for convection and radiation. Controlling parameters include timeline, air temperature, humidity ratio, mean radiant temperature, internal heat generation (in metabolic equivalent [MET]), and so forth, for each environment interval and activity level. The output of simulation include temperature distribution, blood pressure, humidity ratio for respiratory tract, latent and sensible heat losses, regional blood flow rate, and so forth.

**Results and discussion**

In this section, our simulation results were compared with Zhang’s experimental data (Zhang 2003) for transient and steady-state cases. For transient comparison, sets of initial condition for simulation were created according to Zhang’s experimental setup. By using these initial conditions, transient temperature history of head, trunk, hand, foot, and so forth, were calculated and compared to those experimental data reported by Zhang for neutral, cold, and warm environments. For steady-state comparison, the temperature distribution of all body parts obtained by our shaped model was compared with Smith’s cylindrical model and Zhang’s experimental data. Moreover, temperature contour for upper arm by our refined model (more elements generated) was compared to Smith’s cylindrical model (less elements), to show the advantages of our new model.

**Initial conditions for transient case**

Zhang presented two types of data in his work (Zhang 2003). First, he presented steady state values for the temperature distribution through the body after the subjects had been exposed to the specified conditions for 2 hours. Second, Zhang presented transient temperature distribution in segment of the body. To perform a detailed simulation that accurately models the experimental work of Zhang, many environmental and initial conditions must be set in the model. The next paragraph describes how these parameters and initial conditions were set.

The simulation was performed at the three different conditions: neutral, warm, and cold environments. The digital body was assumed to wear a leotard, and generate 23.1 J/cm²/hr (1.1 MET, or 20.4 Btu/ft²-hr). The leotard covers the whole body except face, hands, and feet (covered by socks). The clothing insulation values of leotard are from Zhang’s thesis (Zhang 2003), and coded into our clothing database to generate a new ensemble. The heat transfer coefficients for convection and radiation were 2.24 and 1.7 J/cm²·hr·°C (1.10 and 0.83 Btu/ft²·hr·K), respectively. The ambient temperatures were set at 26.9°C (80.4°F), 31.5°C (88.7°F), and 16.0°C (60.8°F) for neutral, warm, and cold environment, respectively. The metabolic rate is 1.1 MET for both Zhang’s test and our simulation.

Zhang used a bathtub (Zhang 2003) to precondition the human subjects before entering chamber, giving the subjects a more uniform thermal state before starting the study. One important consideration in the body model is the initial temperature of every element in the body. Obviously Zhang did not report such detailed information on the human subjects. To arrive at a realistic initial condition for the digital body, a preconditioning process was also simulated. Our simulation process is: (1) simulate “bathtub precondition process,” until a steady state temperature has been achieved and then output the temperature distribution; (2) simulate transient and steady-state human thermal process by using the body temperature distribution from the last step as the initial condition.

The pre-conditioning step was not negligible in our simulation because this process was used to precondition skin temperatures of subjects in Zhang’s experiment, and it was proved that the skin temperatures changed during this process, especially for cold environment test. The ambient temperatures were set the same as bathtub’s temperatures: 34.5°C (94.1°F), 35.6°C (96.1°F), and 31.6°C (88.9°F) for
Figure 8. Transient temperatures of preconditioning for neutral environment.

neutral, warm, and cold environments, respectively. All the thermal properties of air, such as conductivity, viscosity, density, and so forth, were replaced with those of water to simulate bathtub environment. It took several hours (simulation time) for skin temperatures to reach steady state. Figure 8 shows the transient average skin temperatures in the preconditioning simulation for neutral environment. Table 3 gives temperature comparison (steady state) of preconditioning between our simulation and Zhang’s experiment for three environments.

For the neutral environment, temperatures tend to reach steady state after about 2 hours (Figure 8). Our simulation shows a good prediction on head and foot, which are less than 0.2°C (0.3°F) to Zhang’s data; while our mean skin temperature is 1.1°C (2.0°F) lower than that found by Zhang. For cold environment, the temperatures of hand and foot are very close to experimental data, but at head and torso the temperatures differences exceed 1.5°C (2.7°F), and our core temperature is 1°C (1.8°F) lower than Zhang’s data. Our simulation gives a good prediction in warm environment, and all the temperature differences are less than 0.7°C (1.3°F): 0.5°C (0.9°F) for head, 0.7°C (1.3°F) for torso, 0.1°C (0.2°F) for hand and foot, and 0.4°C (0.7°F) for core temperature. It is observed from Table 3 that our preconditioning simulation provides a relatively good prediction of temperatures for three environments, so the temperature distributions of preconditioning can be used as initial condition for the main simulation.

Transient simulation discussion

The initial conditions of simulation are given in Table 4. The simulation time is 120 min, the same as the time used in Zhang’s experiment. The transient results for neutral, cold, and warm condition are shown in Figures 9, 10, and 11.

Table 3. Temperatures of body parts after preconditioning in three environments.

<table>
<thead>
<tr>
<th></th>
<th>Neutral, °C (°F)</th>
<th>Cold, °C (°F)</th>
<th>Warm, °C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current</td>
<td>Zhang’s</td>
<td>Current</td>
</tr>
<tr>
<td>Head</td>
<td>35.8 (96.4)</td>
<td>35.6 (96.1)</td>
<td>33.1 (91.6)</td>
</tr>
<tr>
<td>Torso</td>
<td>34.8 (94.6)</td>
<td>35.7 (96.3)</td>
<td>33.1 (91.6)</td>
</tr>
<tr>
<td>Hand</td>
<td>34.4 (93.9)</td>
<td>n/a</td>
<td>27.0 (80.6)</td>
</tr>
<tr>
<td>Foot</td>
<td>34.5 (94.1)</td>
<td>34.5 (94.1)</td>
<td>27.2 (81.0)</td>
</tr>
<tr>
<td>Core</td>
<td>36.9 (98.4)</td>
<td>37.7 (99.9)</td>
<td>36.4 (97.5)</td>
</tr>
<tr>
<td>Skin</td>
<td>33.9 (93.0)</td>
<td>35.0 (35.0)</td>
<td>30.7 (87.3)</td>
</tr>
</tbody>
</table>
Table 4. Parameters used for simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation time</td>
<td>120</td>
<td>minute</td>
</tr>
<tr>
<td>Convective H. T.</td>
<td>2.24 (1.972)</td>
<td>J/cm²·hr·°C</td>
</tr>
<tr>
<td>coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiant H. T.</td>
<td>1.7 (1.5 BTU/hr·ft²·K)</td>
<td>J/cm²·hr·°C</td>
</tr>
<tr>
<td>coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative humidity</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>Metabolic generation</td>
<td>1.1</td>
<td>MET</td>
</tr>
</tbody>
</table>

It can be seen from Figure 9 that head and foot temperatures capture the experimental data very well; torso (chest) and core temperatures are about 1°C (1.8°F) lower than experiment, but the trend is the same as experiment: torso temperature goes up within 120 minutes, while core temperature keeps constant. In the cold environment shown in Figure 10, torso temperature is comparable to experimental data. Head and core temperatures are 2°C and 1°C (3.6°F and 1.8°F) lower than experiment, respectively. Hand temperature in our simulation shows a constant trend, while in experiment it drops dramatically after about 30 minutes. For warm condition shown in Figure 11, it is similar to neutral condition: head and hand temperatures agree with experiment data, while core and torso temperatures are slightly lower, but keep the consistent trend with experiment measurement. It is concluded that for neutral and warm environments, our simulation provide a good prediction (less than 1°C [1.8°F]) on both skin and core temperatures; while for cold environment, our simulation are 1–2°C (1.8–3.6°F) lower than experiment, especially for extremities such as hand and foot. There are two possible reasons for the temperature discrepancy in cold environment: (1) some body parts, such as hand and foot, are of complicated shapes, and the surface area of these parts is much larger than those used in simulation. When subject to cold environment (16°C or 61°F), the heat is easier to dissipate to ambient due to larger skin area, so the extremity’s temperatures from experiment are lower than those by our simulation. (2) vasoconstriction occurs when human stays in cold ambient for 10–15 minutes, and some superficial blood vessels are shut off to avoid more heat transfer on skin surface. Meanwhile, shivering also occurs to increase metabolic rate generation inside the human body, so that core temperature can keep on a safe level. Although these two phenomenons are simulated in our model, there is still room to improve them in order to get more accurate results.

Steady state simulations

Zhang presented temperature distribution for only a few body parts in transient process, but he presented temperature data for all body parts in steady state, so it was very significant to compare our simulation results and Zhang’s data in steady state.

Figures 12, 13, and 14 show the mean skin temperatures of different body parts in steady state. Zhang’s experiment data (Zhang 2003) and our...
simulation result with cylindrical body parts and shaped body parts were performed to make comparisons. Mean skin temperature (MST) was also calculated for each case by Hardy and Dubois’ (Hardy and Dubois 1938) seven-point formula. In neutral condition shown in Figure 12, the skin temperatures of neck, torso, thigh, and calf, predicted by refined shape model, showed much better agreement with Zhang’s experimental data than those predicted by cylindrical model. Temperatures at the head and forearm, predicted by both model, were very close to Zhang’s data, while temperatures at upper arm, hand, and foot from two numerical models show some differences with Zhang’s data. Overall, both refined-shape model and cylindrical model showed good predictions of mean skin temperature (MST), compared to Zhang’s data. In warm condition shown in Figure 13, the situation was similar: skin temperatures at neck, torso, and calf from refined shape model were closer to Zhang’s data than those from cylindrical model; both models gave good prediction at head and hand, as well as MST. But for other body parts such as arm, thigh, and foot, skin temperatures from these two models resulted in an error up to 0.5°C–1.5°C (0.9°F–2.7°F) compared to Zhang’s data. In cold condition shown in Figure 14, two numerical models showed very good prediction at the forearm and thigh; at head, neck, and torso, the refined-shape model gave better results than cylindrical model; at limb and on extremity such as upper arm, calf, hand, or foot, both numerical models brought a 1.0–2.5°C (1.8–4.5°F) error compared to Zhang’s data. The MST predicted by the refined-shaped model was 0.3°C (0.5°F) lower than Zhang’s data, while the MST by cylindrical model is about 1.0°C (1.8°F) lower.

It can be seen that under neutral and warm conditions, the numerical results of the refined body shape
Figure 12. Comparison of simulation and experiment in neutral condition.

Figure 13. Comparison of simulation and experiment in warm condition.

Figure 14. Comparison of simulation and experiment in cold condition.
showed good agreement with Zhang’s experiment data (Zhang 2003) for most body parts. In contrast, results from the cylindrical body shape showed disagreement with Zhang’s data at several body parts, such as neck, torso, and calf. In Figure 14, this contrast became even more obvious. There might be two reasons for above observation: (1) the refined-shape model described a human body in a more accurate way than cylindrical model, especially for those body parts which had more complicated shapes other than cylinders, such as head, torso, calf, and so forth; and (2) in refined-shape model, the radius of the main artery at vasodilation process and blood flow rate through the neck were replaced by the new data according to the fact that the vasodilation phenomenon was stronger at the neck than at other body parts, so that the neck kept relative high temperatures at both warm and cold conditions. Under cold condition, the temperature prediction by the two numerical models at upper arm, calf, hand, and foot were much lower than Zhang’s data. This may be because the vasoconstriction effect of
limb and extremity were overestimated so that the heat generation, used for calculation, by vasoconstriction in a cold environment is higher than the body’s physical situation. It is possible to improve the prediction in these body parts, if more study is conducted on the mechanism of vasomotor responses. The predictions at neck and torso were still much lower than the experimental data, although the refined-shape model showed some improvement. It was indicated that neck and torso were capable of generating and restoring heat in cold condition and the vasoconstriction effect at neck and torso should be re-evaluated. Mean skin temperature predicted by the refined-shape model showed better agreement with Zhang’s experimental data than cylindrical model, especially in cold condition, which is a reflection of overall improvement of our new model.

Our refined-shaped model not only handled new data of body shape, but also provided more details of temperature in longitudinal direction of body parts. In general, the more slices were divided in longitudinal direction, the more details were shown, and the resolution of temperature map increased. Figures 15a and 15b show the skin temperature map of torso obtained by old and new models, and the longitudinal divisions of the old and new model were 6 and 12, respectively. It was observed that the new model in Figure 15b showed more details of variation of temperature in longitudinal direction than the old model in Figure 15a. If necessary, more longitudinal divisions could be made to raise the resolution of the temperature map in simulation. This new feature provided a more accurate way of observing temperature variation longitudinally.

**Conclusion**

This model was able to predict thermal behavior of the human body when exposed to a uniform environment. The transient temperature profiles predicted by our model showed good agreement with Zhang’s experiment data (Zhang 2003) in neutral and warm conditions. In cold condition, our hand temperature kept constant during the test, while the experiment showed a descending trend for hand. The maximal deviation for neutral and warm conditions was about 1°C (1.8°F) at core temperature, and for cold condition maximal deviation is 3.5°C (6.3°F) at hand. The steady-state temperatures by our refined-shape model showed better agreement with Zhang’s experiment data than the previous model, which used cylinders to simulate body parts. In the neutral and warm tests, skin temperatures of all body parts agreed with Zhang’s experiment data very well, and the maximal deviation was within 0.6°C (1.1°F). In the cold environment, the predicted temperatures still matched Zhang’s data, except for distal limbs such as hand and foot, where the deviation might reach 3°C (5.4°F). The blood flow rate through the neck was corrected in this model in order to simulate additional blood flow at the neck. This correction proved to be effective.

In conclusion, our refined-shape model described human body in more details, and provided a better prediction for both steady-state and transient temperatures than the previous cylindrical model. The agreement of mean skin temperature indicated that total heat transfer rate in simulation was on the same level of that in experiment. There is still room to improve the model on vascular system and mechanism of vasoconstriction and shivering, if we want to know more about the physiological mechanism of individual body parts.

**References**


