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A thermophysiological model of the human hand

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SUMMARY
Human extremities have a significant role in dissipating body heat and are sensitive to thermal environment. Therefore, human hands have become interesting subjects when considering indicators of body thermal status under various environmental exposures. Specifically, several research showed that hand and finger skin temperature might be useful to predict perceived thermal comfort and sensation. This paper presents how the two node model based on Gagge’s approach was applied to predict human hand temperature in different environment. The hand is represented by two concentric cylinders. The outer cylinder represents the skin layer and the inner cylinder represents the core of the hand (skeleton, muscles and internal organs). The model is based on the energy balance equations for skin and core compartments. The model was validated by comparisons with the published experimental data for different exposures (cold, neutral and hot environment). The computed results agree well with the compared data. In addition, the simplicity of the two node model could be the advantage when considering application in the built environment.

PRACTICAL IMPLICATIONS
Thermophysiological models are valuable for predicting thermal comfort. With predicting occupant thermal state and local skin temperatures, these models can provide useful insight into indoor thermal comfort.

KEYWORDS
hand skin temperature, thermophysiological model, two-node hand model

1 INTRODUCTION
Mathematical modelling of the human physiological thermal responses is helpful tool to comprehend how human body reacts under different environmental exposure. The thermophysiological models are used in thermal comfort research for improving thermal comfort prediction in the built environment (Schellen et al., 2013). The high energy demand in built environment resulted in the need to develop more energy efficient conditioning systems (Salloum et al., 2007). For these systems, thermal comfort and sensation is a significant performance indicator (Zhou et al., 2013). The overall thermal comfort in non-uniform and transient environment is influenced by the thermal sensation of local body parts (Zhang et al., 2010). Considering the human local body parts, it has been shown that human extremities are important for thermal regulation (Wang et al., 2007). The prediction of human thermal responses can benefit from accurate thermophysiological models (Salloum et al., 2007), and models like Tanabe (Tanabe et al., 2002), Fiala (Fiala et al. 2001; Fiala et al. 1999), the Berkeley Comfort Model (Huizenga and Hui, 2001) and ThermoSEM (Kingma, 2012; Kingma et al. 2012) were developed that can evaluate skin temperatures of different body regions. To assess the thermal responses of human extremities and other body parts in different environment, development of thermophysiological models for the isolated body segments became valuable in different areas, as medicine and built environment. A variety of thermophysiological models
for isolated body parts were developed by Wong (Wong et al., 2012), Deshpande (Deshpande, 2007), Ferreira (Ferreira and Yanagihara, 2012) and Shitzer (Shitzer et al., 1997). In this study, the transient two-node hand model was developed in order to estimate physiological parameters for the given thermal environment. This model doesn’t suppose that the metabolic heat production and blood flow rates are independent of temperature, but it assumes that they are influenced by the temperature change following Arrhenius law. This work aims to contribute to accurate predictions of hand skin temperature over a range of environmental condition. This paper shows our work on hand skin temperature prediction over a range of environmental conditions.

2 TWO-NODE HAND MODEL

The hand is modeled as two concentric cylinders based on a well-known Gagge’s model developed in 1971 (Gagge and Stolwijk, 1971). The inner cylinder represents the body core tissue and the outer cylinder represents the skin. Skin and core temperatures are simulated by using energy balance equations for each node. The heat production is the core metabolic rate and additional external work done by the muscles, however in the cases presented here external work is assumed to be zero. The model includes the effects of heat conduction and heat transfer by blood. The generated heat in the hand segment is lost via evaporation, radiation and convection. The energy balance equations for the hand segment can be written separately for each node as:

\[
\frac{C_{cr}}{A_h} \frac{dT_{cr}}{dt} = \frac{M - W - H_{cr-sk} + H_{bl,cr}}{A_h} \tag{1}
\]

\[
\frac{C_{sk}}{A_h} \frac{dT_{sk}}{dt} = \frac{H_{cr-sk} + H_{bl,sk} - Q_{c+r} - E_{sk}}{A_h} \tag{2}
\]

where \(C_{sk}\) and \(C_{cr}\) are core and skin thermal capacitance (J/°C), \(t\) is time (s), \(M\) is metabolism (W/m²), \(W\) is external work done by muscles (W/m²), \(H_{cr-sk}\) is conduction transfer between the two nodes, \(H_{bl,cr}\) and \(H_{bl,sk}\) is a heat transfer by the skin and core blood flow, \(T_{sk}\) and \(T_{cr}\) are skin and core temperatures (°C), \(Q_{c+r}\) is convection and radiation (W/m²), \(E_{sk}\) is the evaporative heat loss from skin (W/m²) and \(A_h\) is the hand surface area (m²).

Metabolic heat and shivering

Metabolic heat is usually obtained by summing up active metabolic heat and shivering heat. However, the shivering heat production in the hand is assumed to be zero. The metabolic rate changes with a constant ratio for a given temperature change according to the Arrhenius law or the \(Q_{10}\) effect (Kingma, 2012). \(Q_{10}\) factor is an indicator of the magnitude of temperature-induced changes in biological, chemical and physiological rates. \(Q_{10}\)-effect accounts for the regulation of the metabolic rate and skin blood flow (Kingma, 2012). If the tissue temperature differs from the temperature of thermal neutrality the metabolic heat generation and blood perfusion changes. The \(Q_{10}\)-effect is included in the model when calculating metabolism of the hand as follows:

\[
M = M_{act} \cdot Q_{10}^{(\Delta T_{cr})/10} \tag{3}
\]

where \(M\) is overall metabolic heat production of the hand, \(M_{act}\) is the metabolic heat of the hand, \(Q_{10}\) is the factor by which the rate changes and for the human tissue it is between 2 and 2.5
(Bennett, 1985), in the model 2 is used for $Q_{10}$, and $\Delta T_{cr} = T_{cr} - T_{n-cr}$ is the temperature change between actual core temperature and neutral core temperature ($T_{n-cr}$).

**Heat transfer from the core to the skin**

Following the approach of the Foda model (Foda and Sirén, 2011), the heat transfer from the core to the skin is divided into two components:

1. Heat transfer through the tissue:

   $$H_{cr-sk} = K(T_{cr} - T_{sk})$$

   where $K$ is the heat conductance of the hand tissue. Kohri and Mochida (2002) presents comparison of the tissue conductance for the upper arm for the different operative temperature, calculated with the detailed model. The values were adopted from Kohri and Mochida (2002) and the values for the hand conductance were considered equal to that of the upper arm. Table 1 shows the values of the conductance of the hand tissue used in this model.

   **Table 1. Heat conductance of the tissue for the hand (Kohri and Mochida, 2002)**

<table>
<thead>
<tr>
<th>Operative temperature (°C)</th>
<th>10</th>
<th>15</th>
<th>24</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat conductance of the hand tissue (W/m²K)</td>
<td>6</td>
<td>7.2</td>
<td>9.2</td>
<td>10.56</td>
</tr>
</tbody>
</table>

2. Heat transfer by the skin and core blood flow:

   $$H_{bl-sk} = \rho_{bl} \cdot c_b \cdot m_{bl-sk} \cdot (T_{bl} - T_{sk})$$

   $$H_{bl-cr} = \rho_{bl} \cdot c_b \cdot m_{bl-cr} \cdot (T_{bl} - T_{cr})$$

   where $c_b$ is the blood specific heat of the blood (3850 J/kgK), $\rho_{bl}$ is density of the blood (kg/m³), $m_{bl-sk}$ is the hand skin blood flow (m³/s), $m_{bl-cr}$ is the hand core blood flow (m³/s) and $T_{bl}$ is the blood temperature in the hand. $Q_{10}$ effect on skin blood flow is given by:

   $$m_{bl-sk} = m_{bl-sk,b} \cdot Q_{10}^{\frac{\Delta T_{sk}}{10}}$$

   $$m_{bl-cr} = m_{bl-cr,b} \cdot Q_{10}^{\frac{\Delta T_{cr}}{10}}$$

   Where $m_{bl-sk,b}$ and $m_{bl-sk,b}$ are skin blood flow rates for the hand and $\Delta T_{sk} = T_{sk} - T_{n-sk}$ is the temperature change between actual skin temperature and neutral skin temperature ($T_{n-sk}$). Blood flows for the hand were taken from Takemori at al. (Takemori et al. 1995; Ferreira and Yanagihara, 2012), and the data set is presented in Table 2. To obtain blood flows for different environmental exposures, linear interpolation of the data set is assumed (Figure 1).

   **Table 2. Blood flow rates for the hand segment (Takemori et al., 1995)**

<table>
<thead>
<tr>
<th>Segment</th>
<th>Minimum skin blood flow (cm³/h)</th>
<th>Basal skin blood flow (cm³/h)</th>
<th>Maximum skin blood flow (cm³/h)</th>
<th>Core blood flow (cm³/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand</td>
<td>0</td>
<td>4699</td>
<td>5723</td>
<td>264</td>
</tr>
</tbody>
</table>
The input parameters used in this model, including the metabolic heat of the hand and initial neutral conditions of skin and core temperatures ($T_{n-sk}$ and $T_{n-cr}$) are presented in Table 3.

Table 3. Input parameters for the hand model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand surface area $A_h (m^2)$</td>
<td>0.05</td>
</tr>
<tr>
<td>Hand metabolism $M_{act} (W/m^2)$</td>
<td>4.8</td>
</tr>
<tr>
<td>Blood temperature $T_{bl} (^\circ C)$</td>
<td>35</td>
</tr>
<tr>
<td>Neutral skin temperature $T_{n-sk} (^\circ C)$</td>
<td>34.05</td>
</tr>
<tr>
<td>Neutral tissue temperature $T_{n-cr} (^\circ C)$</td>
<td>35</td>
</tr>
<tr>
<td>Convective heat transfer coefficient $h_c (W/m^2K)$</td>
<td>4.5</td>
</tr>
<tr>
<td>Radiative heat transfer coefficient $h_r (W/m^2K)$</td>
<td>3.9</td>
</tr>
<tr>
<td>Core thermal capacitance $C_{cr} (J/^\circ C)$</td>
<td>791.4</td>
</tr>
<tr>
<td>Skin thermal capacitance $C_{sk} (J/^\circ C)$</td>
<td>723.5</td>
</tr>
</tbody>
</table>

**Latent heat loss and sweating**

Werner and Reents (1980) measured the heat loss by evaporation in the hand. In Figure 2 the evaporative heat losses used in the model are shown.

**Sensible heat loss from the skin**

Radiation and convection are usually combined to describe the total sensible heat exchange. The calculation of the sensible heat loss can be found in ASHRAE Fundamentals Handbook (ASHRAE, 2001). The convective and radiative heat losses of the hand segment at the skin surface are calculated by:

$$ Q_{c+r} = \frac{T_{sk} - T_o}{R_t} $$  \hspace{1cm} (9)
where $R_t$ is the total insulation, the total uniform thermal resistance between the body and the environment including clothing and boundary resistance, $T_{sk}$ and $T_o$ are skin and operative temperature. In the case of the hand model the hand segment is presented as nude part. For the nude segment $R_t$ is calculated as:

$$R_t = \frac{R_a}{f_{cl}} \quad \text{with} \quad R_a = \frac{1}{h_c + h_r}$$

where $R_a$ is thermal resistance at the skin boundary for the nude body, $f_{cl}$ is the clothing area factor (for the nude body $f_{cl}$ is equal to 1), $h_r$ (W/m²K) is radiative heat transfer coefficient and $h_c$ (W/m²K) is convective heat transfer coefficient.

The hand model can be shown using a typical segment node structure shown in Figure 3.

The simulations were performed for three different environmental conditions. The cases were chosen to represent the cold, neutral and hot conditions in an office environment. The specific input parameters used for specific simulation case are given in Table 4.

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_a$ (°C)</th>
<th>$T_t$ (°C)</th>
<th>RH (%)</th>
<th>$E_{evap}$ (W/m²)</th>
<th>$K$ (W/Km²)</th>
<th>$m_{bl,sk,b}$ (cm³/h)</th>
<th>$m_{bl,cr,b}$ (cm³/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>15.5</td>
<td>15</td>
<td>55</td>
<td>13.3</td>
<td>7.2</td>
<td>0</td>
<td>264</td>
</tr>
<tr>
<td>Neutral</td>
<td>24.6</td>
<td>24.9</td>
<td>48</td>
<td>28.8</td>
<td>9.2</td>
<td>2282.4</td>
<td>264</td>
</tr>
<tr>
<td>Hot</td>
<td>30.1</td>
<td>30</td>
<td>43</td>
<td>43</td>
<td>10.56</td>
<td>4699</td>
<td>264</td>
</tr>
</tbody>
</table>

3 RESULTS AND DISCUSSION

The two-node model for the isolated hand was used to simulate skin temperature. In order to validate the model, the results were compared with experimental data from Foda (Foda and Sirén, 2011). Figure 4.a) shows the hand skin temperatures of a two-hour simulation for all three cases. It can be seen that for the neutral and hot case the physiological steady state was achieved within one hour, however for the cold case the steady state was not attained. Simulation was then done for two hours of exposure. It can be observed that after two hours in the cold environment steady state was not attained. This phenomenon was observed in Foda’s experiments (Foda and Sirén, 2011). The five hours simulation was performed and it showed that physiological steady state of the hand temperature is attained after four hours in the cold environment (Figure 4.b).
The calculated hand temperatures are compared with the experimental results for cases with one hour of exposure, because the measurements done by Foda were under one hour exposure (Figure 5). It can be seen that the model has a good agreement with experimental data in neutral and hot environment. For the neutral case the absolute deviation is 0.9 °C and for hot case is 0.8 °C. The model predictability in the cold case is less accurate, and the simulated skin temperatures are lower than experimental results.

Comparison of the calculated hand temperatures and experimental steady state hand temperatures for cases with 2 hours of exposure are shown in Figure 6. Again the model has a good agreement with experimental data in neutral and hot environment with the absolute deviation of 0.9 °C and 0.9 °C, respectively. The model predictability in cold case is improved but still low with absolute deviation 4 °C.
To additionally investigate the predictability of the model, simulations were performed for ambient temperatures: 10 ºC, 20 ºC and 30 ºC. The results were verified with the experimental results of Werner and Reents (1980). In the experiment, subjects were wearing only shorts while resting in the hammock, and were exposed to constants environment for two hours (Werner and Reents, 1980). The input parameters for the model are shown in Table 5.

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_a$ (ºC)</th>
<th>$M_{act}$ (W/m²)</th>
<th>RH (%)</th>
<th>$E_{evap}$ (W/m²)</th>
<th>$K$ (W/Km²)</th>
<th>$m_{bl,sk,b}$ (cm³/h)</th>
<th>$m_{bl,cr,b}$ (cm³/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>10</td>
<td>2.7</td>
<td>40</td>
<td>10</td>
<td>6</td>
<td>0</td>
<td>264</td>
</tr>
<tr>
<td>Slightly cool</td>
<td>20</td>
<td>2.7</td>
<td>40</td>
<td>16</td>
<td>8.2</td>
<td>223.7</td>
<td>264</td>
</tr>
<tr>
<td>Hot</td>
<td>30</td>
<td>2.7</td>
<td>40</td>
<td>43</td>
<td>10.56</td>
<td>4699</td>
<td>264</td>
</tr>
</tbody>
</table>

Figure 7 shows the comparison of hand skin temperatures. The model has a good agreement with experimental data in hot environment with the absolute deviation of 0.18 ºC. The model predictability in cold (10 ºC) and slightly cool environment (20 ºC) is lower, with absolute deviation of 1.8 ºC for cold and 1.7 ºC for cool environment.

4 CONCLUSIONS
A two-node heat transfer model of the hand segment was developed. The result shows that the model predictability was good in neutral (24 ºC) and hot environment (30 ºC). However, for the cold and slightly cool environment (10 ºC, 15.5 ºC and 20 ºC) the predictability of the model is lower. The explanation may be found in the fact that the blood flow rates and blood temperature of the hand have a strong influence on the skin temperature. The model assumes constant blood temperature in the hand (35 ºC) and linear interpolation from the minimum skin blood flow data to the neutral skin blood flow. The two-node model offers a degree of simplicity and it is easy to implement. This can be seen as an advantage in application as the calculation time is short. In order to improve the accuracy of the model there is a need for more experimental data on blood flow rates in the hand, especially in cold and slightly cool environment. Modelling isolated body segment depends on accurate local inputs including the blood flow rates, evaporative heat loss, blood temperature and local metabolism. To achieve desirable predictability of the model, the accuracy of these inputs has to assured.

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