Comparison Study of Human Thermoregulation Models

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Abstract

Human thermoregulation model is a kind of models simulating human thermal response in complex thermal environments. Since then, several human thermoregulation models have been developed and widely applied. However, the selection of models is still a problem for researchers. This paper introduced a comparison study involving popular thermoregulation models. Boundary condition formulation, models’ accuracy and extensibility were compared. The comparison considers both parameter selection and performance of prediction on real experiments. The results showed that the overall performance of the UTCI-Fiala model is relatively better. The Tanabe model, JOS-3 model is also acceptable. However, prediction accuracy of local segments is still a challenge for existing models.

Highlights

- The two-node model, the Stolwijk 25-node model, the Tanabe 65-node model, the JOS-3 model and the UTCI-Fiala model were selected in this comparison.
- A simulation study was conducted against real experiment data to compare the performance of human thermoregulation models.
- The UTCI-Fiala model has relatively better performance, while the performance of JOS-3 model and the Tanabe model is also acceptable.
- Prediction accuracy of local segments should be improved in future model development.

Introduction

Indoor thermal comfort is an important factor that affects both building energy consumption and the well-being of occupants(Ortiz et al. 2017). Several methods have been proposed to predict the thermal comfort of indoor environments(Schweiker et al. 2018). One such method is the thermal comfort model. The most well-known model is the PMV-PPD model, which was proposed by Fanger(Fanger 1970). This model combines the state of occupants (clothing level, activity level) with environmental parameters (air temperature, radiation temperature, air speed, and humidity) through a physiological-physiological heat balance equation to predict occupants’ thermal comfort and thermal satisfaction in a given environment. This approach is a classical research paradigm and is widely used in many research and standard settings (EN ISO 7730. Moderate thermal environments – Determination of the PMV and PPD indices and specification of the conditions for thermal comfort 2005; ASHRAE 2017). However, extensive field surveys on thermal comfort conducted in recent years have shown that the PMV model can deviate from predicting human thermal sensation in the actual environment(Han et al. 2009; Cao et al. 2011; Luo et al. 2015; Cao et al. 2016; Luo et al. 2016; Zhang et al. 2016; Takasu et al. 2017). One possible reason for this deviation is that the model is designed for static conditions. Therefore, some researchers have focused on an alternative approach, namely the human thermoregulation model. Thermoregulation is a critical physiological process that maintains the stability of the human body temperature, despite changes in the external environment. It is a complex system that involves multiple physical and physiological mechanisms. As such, this type of model can simulate human thermal response in transient or non-uniform conditions.

The formulation of heat exchange and temperature distribution within the human body commenced almost a century ago. Machle and Hatch(Machle and Hatch 1947) developed a human heat transfer model comprising of a core and skin node, which laid the foundation for the concept of skin temperature and core temperature. In 1948, Pennes(Pennes 1948) formulated heat transfer in a human arm, which became the fundamental equation for heat transfer in the human body. Since then, several human thermoregulation models have been developed and widely applied. However, the application of the human thermoregulation model in thermal comfort research is relatively decentralized and not systematic. The selection of models is still a problem for researchers who managed to apply a human thermoregulation model in their study. Thus, we conducted this study, to compare the popular models, and to provide researchers with a point of reference for selecting existing models and creating new ones.

Methods

To determine the models involved in this comparison, we used the following search query in the Web of Science database: “TS=(comfort) AND TS=(thermoregulation OR thermal regulation) AND TS=(model or modeling or modelling)”, where TS represents the topic. As shown in Figure 1, the Fiala model(Fiala 1998; Fiala et al. 2012), the Tanabe model(Tanabe et al. 2001), the two-node model(Gagge et al. 1985), the Berkeley Comfort Model(Huizenga et al. 2001), the Stolwijk...
model (Stolwijk 1971), and the JOS model (Kobayashi and Tanabe 2013; Takahashi et al. 2020) are most used models in the past decade. It is noteworthy that most of the recent studies of human thermoregulatory models [Geng, 2023 #415] [Ou, 2023 #416] [Zhang, 2022 #297] have also been parameter adaptations of these classical models rather than structural changes. Therefore, five typical models have been selected for comparison: the two-node model (Gagge et al. 1985), the Stolwijk 25-node model (Stolwijk 1971), the Tanabe 65-node model (Tanabe et al. 2001), the JOS-3 model (Takahashi et al. 2020) and the UTCI-Fiala model (Fiala et al. 2012).

The original literature in which the corresponding models were published was reviewed. The parameters of the models were extracted from the corresponding literature. In this paper, boundary condition formulation, models’ accuracy and extensibility were compared.

**Figure 1 Number of publications of different human thermoregulation models in the past decade.**

### Studied models

The Stolwijk model (Stolwijk 1971) was published in 1971, designed to simulate the human thermoregulation system and protect astronauts from the hostile space environment. The human body was modelled as 7 segments: head, trunk, arms, hands, legs, and feet. The thermoregulation system was also modelled. This model can be considered a basic form of the latter human thermoregulation models.

The two-node model (Gagge et al. 1971) was developed in 1971 based on the thermoregulation simulation research of Stolwijk and Hardy (Stolwijk and Hardy 1966). This model used lumped parameters of the human body, so there is only one segment with two nodes in the model. It was not the most sophisticated model available at the time of its publication. However, it included important parameters of thermal comfort: skin temperature, core temperature and skin wettedness (Gagge et al. 1971). It is also the origin of the new effective temperature (ET*) and standard effective temperature (SET*) (Gagge et al. 1985).

The Tanabe model (Tanabe et al. 2001) was an improved version of the Stolwijk model. This model is more similar to the Stolwijk model but the segmenting was more detailed.

The JOS model (Kobayashi and Tanabe 2013) was published in 2013, which is based on the Stolwijk model (Stolwijk 1971) and the AVA model (Tanabe et al. 2001). The latest version, JOS-3 (Kobayashi and Tanabe 2013), was published in 2013, which is based on the Stolwijk model (Stolwijk 1971) and the AVA model (Tanabe et al. 2001). And the latest version, JOS-3 (Yokoyama et al. 2007), was released in 2020. The JOS-3 model is more detailed compared with the Tanabe model. The general active system of this model is inherited from the Tanabe model, while non-shivering thermogenesis and arteriovenous Anastomosis blood flow are added to this model. The input to this model takes more human characteristics into account. Age, sex and body fat are taken into account to determine the constants in the model. In addition, the code of this model is open source, which makes it more convenient for academic and industrial users to use this model.

The UTCI-Fiala model (Fiala et al. 2012) is an improved version of the Fiala model published in 1999 (Fiala 1998). In the UTCI-Fiala model, the human body was modelled as 12 cylindrical or spherical segments. A segment was divided into 4 or 5 layers, depending on the anatomy of each segment and the thermal characteristics of different tissues. Each layer was divided into one or more nodes. In this model, a segment can be divided into several sectors, e.g. anterior, posterior, etc. This division allowed the model to handle asymmetric conditions of a segment, such as a chest sector and a back sector of the thorax segment. In the active system of this model, the equation of regulation response was modified.

### Accuracy comparison

The predictive performance of the models in the real situation needs to be compared with real experimental results. Thus, we selected a published experimental thermal comfort study by our team to compare the accuracy of the models. In the study, 20 male participants aged around 25 took part in the experiment. They were asked to sit quietly for 60 minutes in a climate chamber with an air temperature of 26°C and 45% humidity. They were then asked to move to a chamber with an air temperature of 36°C and 45% humidity and continue to sit. Their skin temperature was continuously recorded. The details of the experiment were presented in the research paper (Yu et al. 2012).

Considering the similarity between the Stolwijk model and the Tanabe model, we selected four models to in this comparison: the Tanabe model, the JOS-3 model, the UTCI-Fiala model and the two-node model. The Tanabe model, the UTCI-Fiala model in this comparison were developed according to the description from the literature (Tanabe et al. 2001; Fiala et al. 2012). The JOS-3 model was from the open source Python code (Takahashi et al. 2020). Two-node model was developed based on code in ASHRAE Standard 55-2017 (ASHRAE 2017). Environmental conditions, including air temperature, relative humidity, clothing insulation and active level and duration of each phase, were the same as the experiment in the literature.
Radiative temperatures were assumed to be equal to air temperatures. Air velocity was set at 0.10 m/s to represent still air. Root mean square error (RMSE) was used to quantify the accuracy of the models. It can be calculated as follow:

\[
RMSE = \sqrt{\frac{1}{m} \sum_{i=1}^{m} (T_i - \hat{T}_i)^2}
\]

(1)

In this equation, \(m\) is the number of observations. \(T_i\) and \(\hat{T}_i\) are the i-th measured temperature value and its predicted value. A lower RMSE indicates better prediction accuracy. Root mean square error (RMSE) was used to quantify the accuracy of the models. It can be calculated as follow:

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Skin temperatures of forehead, chest, back, upper arm, lower arm, hand, upper leg, lower leg, foot and mean skin temperature were selected for validation. As the two-node model is a single-segment model, it was only included in the validation of mean skin temperature. Mean skin temperature was calculated according to the method presented in the original experiment (Yu et al. 2012):

\[
T_{sk,m} = 0.07T_{\text{forehead}} + 0.18T_{\text{chest}} + 0.18T_{\text{back}} + 0.07T_{\text{upperarm}} + 0.07T_{\text{lowerarm}} + 0.05T_{\text{hand}} + 0.19T_{\text{upperleg}} + 0.13T_{\text{lowerleg}} + 0.09T_{\text{foot}}
\]

(2)

Results and discussion

Boundary condition formulation

The boundary conditions describing the heat transfer between the human skin and the environment were formulated differently in the models. The main differences are in the heat transfer coefficients. A previous study has shown that the difference in heat transfer coefficients significantly affects the simulation result (Xu et al. 2021). Therefore, it is necessary to discuss the difference in coefficient selection between models. In this comparison, we selected 5 popular models: two-node model, Stolwijk 25-node model, Tanabe 65-node model, JOS-3 model and UTCI-Fiala model.

The convective heat transfer coefficient in the two-node model and the Stolwijk 25-node model is evaluated by the naphthalene sublimation method (Nishi and Gagge 1970a; Nishi and Gagge 1970b). Tanabe 65-node model and JOS-3 use coefficients measured from thermal manikin tests (Ichihara et al. 1997; Kurazumi et al. 2008). The convective heat transfer coefficient of the UTCI-Fiala model was derived from other thermal manikin tests (Wang 1990c; Wang 1990b; Wang 1990a). The convective heat transfer coefficients are shown in Figure 2. The coefficient of the Stolwijk model is lower than that of the other models. At low air velocities, the coefficients of the manikin-measured models are close, while the discrepancy appears when the air velocity is higher than 0.5 m/s. This implies that the convective coefficient of the later models is relatively reliable at low air velocities or in still air. The formula of the two-node mode seems to underestimate the coefficient.

The radiative heat transfer coefficient in Stolwijk 25-node model was estimated. In Tanabe 65-node model and JOS-3 model, the coefficient was measured from thermal manikin tests (Ichihara et al. 1997; Kurazumi et al. 2008). The coefficients of the above models are constants, while those of the two-node model and the UTCI-Fiala model are calculated from the radiative temperature and surface temperature of the models. The radiative heat transfer coefficients are shown in Figure 3. The coefficients of the models vary in a wide range. This may be a result of the different methodology used to estimate the coefficient. In general, the coefficients of the Fiala model are higher, especially in the standing position. In addition, the calculation shows that the radiative heat transfer coefficient varies significantly due to the change in the mean radiant temperature of the environment. Therefore, a constant radiative heat transfer coefficient can lead to errors in very hot or very cold conditions.
Figure 3 Radiative heat transfer coefficient of different models (surface temperature of models are set to be 34 °C)

Accuracy of the model

The simulation result and the measured value of each segment are shown in Figure 5. The comparison of mean skin temperature is shown in Figure 4. The relative RMSE is listed in Table 1. It can be seen that the accuracy of Fiala model is better than other models in simulating mean skin temperature, especially when it was 26 °C. The results of the two-node model are better when it was 36 °C. Meanwhile, the RMSE of the Fiala model is lower in most segments, indicating that the performance of the Fiala model is better than other models in this case. Simulation results from all models have similar tendency to the measured value, indicating that human thermoregulation models can simulate human thermal response in transient environment.

```
<table>
<thead>
<tr>
<th>Segment</th>
<th>Fiala model</th>
<th>JOS-3 model</th>
<th>Tanabe model</th>
<th>Two-node model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forehead</td>
<td>0.70</td>
<td>0.88</td>
<td>1.21</td>
<td></td>
</tr>
<tr>
<td>Chest</td>
<td>1.05</td>
<td>0.90</td>
<td>1.08</td>
<td></td>
</tr>
<tr>
<td>Back</td>
<td>0.87</td>
<td>0.89</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>Upper arm</td>
<td>0.99</td>
<td>1.19</td>
<td>1.07</td>
<td></td>
</tr>
<tr>
<td>Lower arm</td>
<td>2.43</td>
<td>1.06</td>
<td>1.02</td>
<td></td>
</tr>
<tr>
<td>Hand</td>
<td>1.82</td>
<td>1.22</td>
<td>1.29</td>
<td></td>
</tr>
<tr>
<td>Upper leg</td>
<td>0.87</td>
<td>1.14</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Lower leg</td>
<td>0.75</td>
<td>1.03</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td>Foot</td>
<td>1.57</td>
<td>1.88</td>
<td>1.43</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.58</td>
<td>0.73</td>
<td>0.62</td>
<td>0.66</td>
</tr>
</tbody>
</table>
```

However, the results show that the models still need improvement. Skin temperature tendency of the back segment cannot be predicted by any of the models. The simulated value of the Fiala model in the lower arm and hand is far from the actual value, while the results of JOS-3 are higher than the measured value in most of the segments. The performance of the JOS-3 model in the segments is slightly better than that of the Tanabe model. However, in the simulation of mean skin temperature, Tanabe model is better than JOS-3 model. The prediction of mean skin temperature by the two-node model is similar to that of the Tanabe model.

From the comparison with actual experimental observations, it can be seen that the overall prediction accuracy of the models for mean skin temperature is generally acceptable. As a result, the models mentioned are all available for the steady-state studies. However, when considering the simulation results in segments, the deviation between the models and the actual temperature is still significant. This result indicates that more attention should be paid to the accuracy of prediction of local skin temperature. In the study of local thermal exposure and personal thermal comfort systems, the local thermal state of the human body contributes more to the overall thermal sensation and thermal comfort. Therefore, it is important to predict the local thermal state more accurately.

Extensibility of the model

In recent years, thermal comfort research has gradually expanded to different populations and scenarios, and model extensibility has become an issue to be considered. Most thermoregulation models, such as the UTCI-Fiala model, have been developed to study specific scenarios according to their developers. Therefore, individual adaptation has not been taken into account. The parameters and matrices in the models cannot be individually adapted to the subject of other studies. Fortunately, the UTCI-Fiala model was developed on the basis of basic geometric parameters and thermal properties of tissues. Therefore, the methodology used to develop the UTCI-Fiala model can also be used to develop a new model in a specific study of this type.

As a result, to apply the UTCI-Fiala model in specific studies, researchers have to develop a new model using the same methodology of this model. The JOS-3 includes individualization methods, height, weight, age, sex were...
taken into account to model a specific subject. For different populations, such as the elderly and children, researchers can develop a new model based on the methodology of the Fiala model (Ma et al. 2017), or simply enter age as a parameter in the JOS-3 model, in which metabolic rate and heat transfer coefficients can be adjusted based on age. However, the method of adapting heat transfer coefficients in the JOS-3 model is proportional scaling. Whether scaling is reliable in a complex heat transfer system such as the human body is still questionable. Especially when the body size varies significantly, such as when modelling children. For different scenarios, such as sleeping environment and exercise condition, the key to modelling is a reasonable specification of the metabolic rate and heat transfer coefficients with the environment. Thus, all these models can be adapted to these scenarios with reasonable parameters. An advantage of the JOS-3 model is that it has been released as open-source code, so researchers can easily use and modify the model. The open-source community can contribute to both the application and improvement of this model.

Conclusion
Modelling human thermoregulation is important in the study of human thermal response. By comparing the popular models, it can be concluded that the Fiala model has better performance than other models. The boundary condition setting of the Fiala model is also relatively more rational. The overall prediction accuracy of mean skin temperature of the existing models is acceptable. Meanwhile, the prediction accuracy of local skin temperature should be improved, which should be given more attention in future thermoregulation model studies. In earlier model studies, individualization has not been a major consideration, while the methodology of model development can be applied to the development of new models. The open-source JOS-3 model provided inspiring ideas for improving the extensibility of the human thermoregulation model. Considerations of boundary condition formulation, accuracy and extensibility are important not only for model selection but also for model development.

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References


Figure 5 Simulated and measured skin temperature of each segment