Prediction of human thermal sensation based on improved PMV model

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Abstract: In the traditional PMV model, the calculation of human skin temperature is only related to the level of human activity. In fact, human skin temperature is related to many factors such as evaporative heat dissipation, radiation and convective heat transfer of human skin. Therefore, it is necessary to introduce human thermal physiological model to modify the skin temperature in PMV model. In addition, considering the impact of human activities on human metabolic rate, the formula of calculating human metabolic rate obtained from Pandolf was introduced to improve the original PMV model. Finally, the model is validated and analyzed with published experimental data. The results show that the improved model can accurately predict the thermal sensation of human body under the test condition, and the predicted thermal sensation is closer to the experimental value than the original PMV model.

1. Introduction

At present, professor Fanger’s PMV-PPD (Average thermal sensation index-predicted dissatisfaction percentage) model based on human thermal balance equation and ASHRAE seven point scale is widely adopted internationally as an index to evaluate human thermal comfort. However, with the further study of thermal comfort, relevant studies showed that PMV model overestimated people's thermal sensation in warm climate [3-6], so many researchers began to improve PMV model: Fanger and Toftum proposed a modified PMV model, which increased people's psychological expectation factors for thermal environment[7]. Amir et al. improved the sweat heat loss in PMV models by considering that sweat heat loss is related to more factors[6]. This paper found that in the PMV model, in addition to the human activity level, the calculation of human skin temperature should take into account the skin evaporation heat dissipation, radiation and convective heat transfer and other permissible factors. Therefore, this paper considers to introduce human thermal physiology model to modify the original PMV model to make the calculation results more consistent with the actual situation.

In this paper, the Gagge two-node model is used to calculate the skin temperature, and then the calculated skin temperature was input into the PMV model to calculate the thermal sensation of the body. This study can provide a reference for the further development of the thermal comfort model, and provide theoretical basis for air conditioning system design and building energy conservation.

With the improvement of people's living standard and the rapid development of science and technology, people have greater requirements for the comfort of working and living environment. A comfortable environment is conducive to physical health, improves the efficiency of work and study, and enables the human body to maintain a good mental state. According to the research, the energy consumption of air-conditioning in buildings in developed countries accounts for about 20-40% of the total energy consumption [1,2]. Studying the thermal comfort of human body and using the least energy to
create the most comfortable living and working environment can provide important scientific basis for energy conservation, emission reduction, building design and other aspects.

2. Method

2.1. Original PMV model

Based on the human body heat balance equation and ASHRAE seven point scale, Fanger established a PMV model for evaluating human thermal comfort \(^{[8-9]}\). The corresponding relationship between PMV value and human thermal sensation is shown in Figure 1. The calculation formula is as follows:

\[
PMV = [0.303e^{-0.036M}] + 0.0275L \tag{1}
\]

Where \(M\) is the energy metabolism rate of human body, \(\text{w/m}^2\); \(L\) is the heat load of human body, which is defined as the difference between the heat produced by human metabolism and the heat loss of human body. \(L\) is given as:

\[
L = (M - W) - (C + R + C_{res} + E_{res} + E_{sk})
\]

\[
= (M - W) - 3.05[0.254T_d - 3.335 - P_d] - 0.42(M - W - 58.15) - 1.73 \times 10^{-2}M(5.867 - P_d)
\]

\[-0.0014M(34 - t_a) - 3.96 \times 10^{-4}f_c[(t_r + 273)^4 - f_c(t_a + 273)^4] - f_c h_a(t_a - t_r) \tag{2}
\]

Where \(W\) is the mechanical work done by the human body, \(\text{w/m}^2\); \(C\) is the convective heat dissipation between the human body and the environment, \(\text{w/m}^2\); \(R\) is the radiation heat dissipation between the human body and the environment, \(\text{w/m}^2\); \(C_{res}\) is the sensible heat loss caused by respiration, \(\text{w/m}^2\); \(E_{res}\) is the latent heat loss caused by respiration, \(\text{w/m}^2\); \(E_{sk}\) is the total heat lost by skin evaporation, \(\text{w/m}^2\); \(f_c\) is the clothing area coefficient; \(t_a\) is the clothing surface temperature, \(\circ\text{C}\); \(t_r\) is the average ambient radiation temperature, \(\circ\text{C}\); \(h_c\) is the convective heat transfer coefficient, \(\text{w/(m}^2\cdot K)\); \(t_a\) is the ambient air temperature, \(\circ\text{C}\); \(v\) is the wind speed, \text{m/s}; \(P_a\) is the partial pressure of water vapor around the human body, \(\text{Pa}\); \(T_d\) is the skin surface temperature, \(\circ\text{C}\).

![Figure 1. Thermal sensation index of 7 grades](image)

2.2. Improved PMV model

The energy metabolism rate of human body \((M)\) is not easy to measure in practice, which greatly limits the practical application of PMV model. Some studies have shown that it is relatively reliable to predict the energy metabolism rate by using the empirical formula with high accuracy. Therefore, this paper considers to improve the PMV model by applying the metabolic rate formula of human body under the condition of weight-bearing and exercise obtained by pandolf \(^{[10]}\). The specific formula is as follows:

\[
M = 1.5 \cdot m + 2.0 \cdot (m + L) \cdot \left(\frac{L_c}{m}\right)^2 + \eta \cdot (m + L) \cdot (1.5V^2 + 0.35V \cdot G) \tag{3}
\]

Where \(m\) is the weight of the human body, \(\text{kg}\); \(L_c\) is the quality of human body load, \(\text{kg}\); \(V\) is the walking speed of the human body, \(\text{m/s}\); \(G\) is the slope, \%; \(\eta\) is the terrain influence factor, which is usually taken as 1.
In the original PMV model, the skin temperature of human body \( T_{sk} \) is calculated as follows:

\[
T_{sk} = 35.7 - 0.0275(M - W)
\]  

From the above formula, it can be seen that the skin temperature in the original PMV model is only related to the heat production under a certain activity level of human body, but in actual situation, the skin temperature will be affected by the skin evaporation and the heat transfer between skin and the environment through convection and radiation. These factors are considered in the skin temperature calculation by human thermal physiological model. Therefore, it is necessary to calculate skin temperature through human thermal physiological model, then the skin temperature is brought into PMV model. In this paper, the commonly used Gagge two node model is used to calculate skin temperature. The specific operation is as follows:

In the Gagge two node model, the human body is regarded as composed of two concentric cylinders, and each cylinder represents the human skin layer and core layer respectively. The energy balance equations of the core layer and skin layer of the human body are as follows \[11\]:

\[
\frac{(1-\alpha)mC_b}{A} \frac{dT_{cr}}{dt} = M - W - Q_{res} - Q_{cr-sk}
\]

\[
\frac{\alpha mC_b}{A} \frac{dT_{sk}}{dt} = Q_{cr-sk} - E_{sk} - Q_{c-r}
\]

Where \( C_b \) is the specific heat of the body, \( \approx 3490 \text{ J/kg °C} \); \( t \) is the time, s; \( T_{cr} \) and \( T_{sk} \) are the core temperature and the skin temperature (°C); \( A \) and \( \alpha \) are the body surface area (m²) and skin mass ratio (n.d.); \( Q_{res} \) is the heat lost by gas exchange between the core layer and the outside world, W/m²; \( Q_{cr-sk} \) is the heat transferred from the core layer to the skin layer, W/m²; \( Q_{c-r} \) is the heat exchange between skin layer and environment through convection and radiation, W/m².

In the Gagge two-node model, skin temperature of human body can be calculated by inputting environmental parameters and simple basic human body parameters. Then skin temperature and energy metabolism rate of human body are brought into PMV model, and the prediction of human thermal comfort can be realized.

3. Model test and analysis

In this paper, the original PMV model was improved by combining the Gagge two-node model and considering the influence of skin temperature on evaporation and dispersion of human skin layer, convective heat transfer between hot skin and the environment, radiant heat loss and other factors. The skin temperature value of the human body is calculated through the two-node model, and then the skin temperature value is input into the PMV model, which will make the thermal sensation of the human body more accurate. In addition, a more accurate formula for calculating human metabolic rate proposed by Pandolf is introduced into the PMV model, so that the PMV model can be better applied in practice. To test the accuracy of the model, the model prediction results were compared with the previously published experimental data. Finally, complete content and organizational editing before formatting. Please take note of the following items when proofreading spelling and grammar:

The experimental data of Cao et al.\[12\] are used as a case to verify the applicability of the improved model. Cao et al. conducted an experimental investigation on the thermal comfort of 82 healthy college students in Beijing area in summer. The environmental and clothing parameters monitored during the experiment were as follows: relative humidity (RH) was 51.8%, wind speed (V) was 0.17m/s, clothing thermal resistance (Icl) was 0.56 clo, and energy metabolic rate (M) was 1.1 met (equivalent to office typing).
As can be seen from Figure 2, compared with the original PMV, the improved PMV model under this condition is closer to the experimental data when the ambient temperature is less than 24°C, and the maximum error between the model and the experimental value is less than 0.5. When the ambient temperature is greater than 28°C, the original predicted PMV value is significantly higher, and overestimation of thermal sensation in warm climate has been recognized as one of the main shortcomings of PMV models. This may be because in the original PMV model, human skin temperature was only related to the metabolic heat production of human body under a certain activity state, the evaporation heat dissipation of human skin and the convection and radiation between the human body and the external environment was ignored.

In the second case, the applicability of the improved model was verified by the data from Tongling et al. ’s experiments on the comfort of office workers in Guangzhou in summer[13]. According to Tongling et al., the relative humidity in most time of summer in Guangzhou is more than 70%, and the thermal resistance of human clothing is 0.35 clo. In Figure 3, the thermal sensation votes predicted by this model are compared with the original PMV model and experimental data from Tongling et al.

According to Figure 3, it is also noted that the original PMV model predicts a higher thermal sensation of the human body in a hotter environment. The improved model is more consistent with the experimental values. By using the root mean square deviation (RMSD) analysis method to calculate the difference between the simulation results and experimental data of the PMV model and the original PMV model, the RMSD of the improved PMV model and the original PMV model to predict the thermal sensation was 0.27 and 0.57 scale respectively, thus it can be seen that the improved PMV model has a high accuracy in predicting the thermal sensation of human body.
4. Conclusion

Based on Gagge two-node model, PMV model is improved in this paper. The improved model can more accurately predict the thermal sensation of human body in different environmental conditions, which is of great significance for building energy conservation and HVAC design in China. The improved PMV model is compared with the published experimental data, and the analysis shows that the predicted thermal sensation is closer to the actual thermal sensation than the original PMV model. In the future research on human thermal comfort, the PMV model can also be improved by considering individual differences, human adaptability and other factors, so as to make the prediction results of human thermal comfort more scientific and accurate.

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