Practical thermal sensing measurement and neural-thermal comfort index

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ABSTRACT
The primary purpose of heating, ventilating and air-conditioning (HVAC) system is to make occupants comfortable. Without real-time practical measurement and method to determine human thermal comfort, it may not be feasible that the HVAC system can provide human comfortable all the time. This paper presents a practical measurement and model to determine human thermal comfort index for feedback control. The proposed model is developed based on the original thermal comfort index called predicted mean vote (PMV) index by applying feed-forward neural network model. The model was proposed as an explicit function of the interaction of the air temperature, wet-bulb temperature, global temperature, air velocity, clothing insulation and human activity. An experiment was done to demonstrate the effectiveness of the proposed PMV index by comparing to the original PMV index. The results show good agreement between the PMV values calculated from the proposed PMV model and the original one.

INDEX TERMS: Neural network; Predicted mean vote; Thermal comfort index

INTRODUCTION

One of the primary purposes of heating, ventilating and air-conditioning (HVAC) system is to make occupants comfortable in terms of thermal comfort. The index to indicate human thermal comfort is called thermal comfort index. One of the most widely used thermal comfort index is the Predicted Mean Vote (PMV), which was developed by Fanger (1972). The PMV model is a function of six variables: clothing insulation worn by the occupants, human activity, air temperature, air relative humidity, air velocity and mean radiant temperature. PMV model predicts mean thermal sensation vote on a standard scale for a large group of persons in a given indoor climate. PMV value has a range from –3 to +3 which corresponds to occupant's feeling from cold to hot where zero value means neutral.

Though the PMV model predicts thermal sensation well, it is governed by a non-linear equation, which involves iterative computation of its root and which may take long computation time. Therefore, Fanger (1972) and ISO (1987) suggest the use of tables to determine PMV values of various combinations between six variables. Int-Hout (1990) proposed a computer model according to Fanger's PMV model. However, the iterative step was still included in the computer model. Some researches were studied to avoid the iterative step by proposed simplified models of PMV (Sherman, 1985; Federspiel and Asada, 1994). However, the simplification of Fanger's PMV model results in significant error when the assumptions are not respected.

This study presents a new PMV model to predict PMV values that cover a wide range of each thermal environmental variable with certain accuracy and one that is practical to use in real-time applications. A field measurement was done to demonstrate the effectiveness of the proposed PMV model by comparing with Fanger's PMV model.

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THEORETICAL BACKGROUND

Predicted Mean Vote

The most common and widely used parameter for thermal comfort index is PMV (Fanger, 1972) which is a function of six variables: human activity and clothing insulation and four classical thermal environmental parameters: air temperature, air humidity, air velocity and mean radiant temperature. The value of PMV index has a range from –3 to +3 or corresponds to human sensation from cold to hot, respectively. The value of PMV can be determined by:

$$\begin{aligned}\mathrm{PMV} = {} & (0.325\mathrm{e}^{-0.042M} + 0.032)[M - 0.35(43 - 0.061M - P_\mathrm{v}) \\ & - 0.42(M-50) - 0.0023M(44 - P_\mathrm{v}) - 0.0014M(34 - T_\mathrm{i}) \\ & - 3.4\times10^{-8} f_\mathrm{cl}\left((T_\mathrm{cl}+273)^4 - (T_\mathrm{mrt}+273)^4\right) - f_\mathrm{cl}h_\mathrm{c}(T_\mathrm{cl} - T_\mathrm{i})]\end{aligned} \tag{1}$$

with

$$\begin{aligned}T_\mathrm{cl} = {} & 35.7 - 0.032M - 0.18I_\mathrm{cl}[3.4\times10^{-8} f_\mathrm{cl}\left((T_\mathrm{cl}+273)^4 - (T_\mathrm{mrt}+273)^4\right) \\ & - f_\mathrm{cl}h_\mathrm{c}(T_\mathrm{cl} + T_{st})]\end{aligned} \tag{2}$$

$$h_\mathrm{c} = \begin{cases} 2.05(T_\mathrm{cl} - T_\mathrm{i})^{0.25} & \text{for } 2.38(T_\mathrm{cl} - T_\mathrm{i})^{0.25} > 10.4\sqrt{v} \\ 10.4\sqrt{v} & \text{for } 2.38(T_\mathrm{cl} - T_\mathrm{i})^{0.25} < 10.4\sqrt{v} \end{cases} \tag{3}$$

$$P_\mathrm{v} = P_\mathrm{s}\mathrm{RH}/100 \tag{4}$$

where T_i is the indoor air temperature ($^\mathrm{o}$C), T_mrt is the mean radiant temperature ($^\mathrm{o}$C), M is human activity (kcal/h/m^2), v is the air velocity (m/s), P_v is vapour pressure in the air (mmHg), I_cl is thermal resistance of the clothing (clo: 1 clo = 0.18°C m^2 h/cal), h_c is the convective heat transfer coefficient (kcal/m^2/h/°C), f_cl is the ratio of the surface area of the clothed body to the surface area of the nude body, T_cl is the outer surface temperature of clothing (°C), RH is the relative humidity in percent, P_s is the saturated vapour pressure at a specific temperature.

Mean radiant temperature, T_mrt, relating to a person in a given point in an enclosure consisting of N surfaced room, can be determined accurately from measuring temperature of the surrounding walls and surfaces and their positions with respect to the person as the following equation (Fanger,1972):

$$T_\mathrm{mrt}^4 = T_1^4 F_{P-1} + T_2^4 F_{P-2} + \cdots + T_N^4 F_{P-N} \tag{5}$$

where $T_1, T_2, T_3, \ldots, T_N$ are temperatures of N surfaces and $F_{P-1}, F_{P-2}, \ldots, F_{P-N}$ are angle factors between the person and the surrounding N surfaces. Summation of all angle factors should be equal to 1.

PROBLEM STATEMENT

Although PMV is widely used, it is noticed that the T_cl must be determined by iteratively computing the root of the non-linear function. This step may take long computation time and is not practical in real-time applications. Moreover, in real-time control, although the method to determine mean radiant temperature by measuring all the surrounding surface temperature and calculating according to Eqn (5) is accurate, it still requires a considerable amount of calculation work. In measuring relative humidity, the sensors are mostly complex and costly. Therefore, feed-forward Neural Network Model (FNN) (Leephakpreeda, 2001) is used to determine the value of PMV instead of applying Eqns (1)–(5). Conceptually, FNN is a mathematical model that is capable of approximating any continuous complex functions with certain accuracy. This new PMV will be called neural-PMV. The global temperature, T_g, is used instead of using the mean radiant temperature. Wet-bulb temperature, T_{wb}, is used instead of using air relative humidity. The neural-PMV model now relates to six variables: air temperature, air wet-bulb temperature, globe temperature, air velocity, clothing insulation and human activity as summarized in Eqn (6).

$$\text{neural-PMV} = f_{\text{NNM}}(T_{\text{i}}, T_{\text{wb}}, T_{\text{g}}, v, I_{\text{cl}}, M) \qquad (6)$$

To develop neural-PMV model, a set of output PMV and input variables for training neural is calculated according to Eqns (1)–(5). The ranges of each input variable for training neural-PMV are [16, 34] for air temperature, [8, 31] for wet-bulb temperature, [14, 36] for global temperature, [0.1, 1] for air velocity, [50, 80] for activity level and [0.5, 1] for clothing insulation and [–8, 5] for the range of PMV values. The training data points covering the above range are 23 040 and sum of square error between the values of PMV calculated from Eqns (1)–(4) and the values obtained from neural-PMV is 0.10 with an appropriate $6 \times 8 \times 4 \times 1$ NNM structure.

FIELD MEASUREMENT

A field measurement was done in a rectangular room of dimensions $3.6 \times 3.6 \times 7.7$ m^3 from 8.00 a.m. to 5.00 p.m. to demonstrate the effectiveness of the PMV values obtained from the neural-PMV model and for comparing with those obtained from the Fanger's model. In measurement, room air temperature, air humidity, air velocity and globe temperature were measured. Room air wet-bulb temperature was measured by thermocouple covered with wet cotton wick under airflow around 3–4 m/s. Surface temperature of each wall was measured by infrared sensor. All values of each environmental variable were recorded every 10 min.

RESULT AND DISCUSSION

The PMV values were calculated according to Fanger's model in Eqns (1)–(5) and compared with PMV calculated from the neural-PMV model in Eqn (6). The same input variables in neural-PMV model and Fanger's PMV model are air temperature, air velocity, clothing insulation which was 0.6 for cotton work shirt and human activity at 60 kcal/h/m^2 for office work. The different input variables are those related to air humidity and mean radiant temperature. The air relative humidity and mean radiant temperature were input variables for calculating Fanger's PMV while air wet-bulb temperature and global temperature were input variables for calculating neural-PMV. The mean radiant temperatures were calculated according to Eqn (5). The angle factor between person and each surface was determined according to Fanger (1972). The sum of angle factors is 0.9954. PMV obtained from neural-PMV model and from Fanger's PMV model were compared and are shown in Figure 1. Although the different type of sensors were used for measurements between mean radiant temperature and global temperature and between relative humidity and wet-bulb temperature, the PMV value from both models tend to fluctuate in the same direction. The results showed good agreement between both models. The mean error between both PMV values was 0.1 which was not significant to human thermal sensation. The results show the effectiveness of the proposed neural-PMV model with the practical sensor of global temperature and wet-bulb temperature that can accurately and directly determine the PMV value.

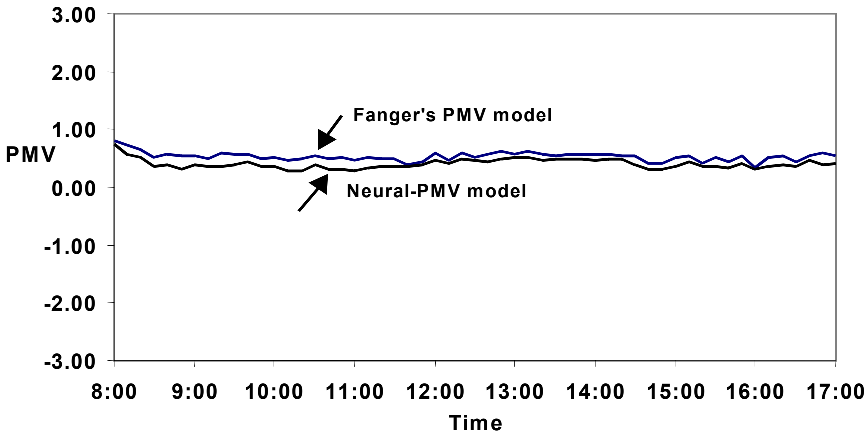

Figure 1 Comparison of PMV between neural-PMV and Fanger's PMV models.

CONCLUSIONS

In this paper, a neural-PMV model to calculate human's thermal sensation index from practical measurement is proposed. The model was proposed as an explicit function of the interaction of the air temperature, wet-bulb temperature, global temperature, air velocity, clothing insulation and human activity. The proposed model provided direct calculation of the thermal sensation index, which is practical for feedback control. Wet-bulb temperature and globe temperature were proposed to be used instead of relative humidity and mean radiant temperature, respectively. The neural-PMV model was proposed by applying the feed-forward neural network model. An experiment was done to demonstrate the effectiveness of the proposed model. The results show good agreement between the PMV values calculated from the neural-PMV model and Fanger's PMV model with different sensor types and input variables.

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