Optimal Indoor Air Temperature Considering Energy Savings and Thermal Comfort in the Shanghai Area

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Abstract: Indoor air temperature is the most important control parameter in air conditioning systems. It not only impacts the thermal comfort of occupants, but also also greatly affects the energy consumption in air conditioning systems. The lower the indoor air temperature is in summer or the higher the indoor temperature is in winter, the more energy the air conditioning system will consume. For the sake of energy conservation, the indoor air should be set as high as possible in summer and as low as possible in winter. Meanwhile, indoor thermal comfort should be considered. This paper will establish the optimal indoor air temperature for an air-conditioning system aiming at both energy savings and thermal comfort in the Shanghai area, based on the PMV equation and extensive field investigation.

Keywords: Air-conditioning system, Indoor air temperature, PMV, Energy conservation, Thermal comfort

1. INTRODUCTION

With the economic development of China, energy crisis begins to occur in China. Energy saving has become one of the most important things of the government. Air-conditioning systems, which have been indispensable for many advanced buildings in big cities, are consuming more and more energy. Especially for Shanghai area, the electric consumption by air-conditioning systems sometimes accounts for more than 30% of total in the summer season [1]. Therefore, the Shanghai government has stipulated that the indoor air temperature in all air-conditioned buildings should be set above 28 degrees in summer. Some specialists have announced that about 300,000 kW electric power may be conserved in Shanghai area if the indoor air temperatures of all buildings in the city were adjusted from 26 degrees to 28 degrees in the hottest day [2]. Thus it can be seen that the indoor air temperature is the critical parameter for energy-saving of air-conditioning systems. In this paper, the optimal indoor air temperature in Shanghai area is studied. The model, which is the function of non-liner regression, has been established through extensive field investigation in Shanghai area. Both energy conservation and occupants' thermal comfort have been taken into consideration in this model. The model will be of great value for the energy saving control in the air-conditioning systems in Shanghai area.

2. THEORETIC MODEL OF OPTIMAL INDOOR AIR TEMPERATURE

PMV index represents most people's feeling of cold or hot to the same environment. It was firstly developed by Prof. Fanger [3] in 1970s and widely been used to evaluate the human's thermal comfort [4、5]. The PMV model can been expressed as follows:

$$PMV = (0.303e^{-0.036M} + 0.028)\cdot \left\{ \begin{aligned} &(M-W) - 3.05\times 10^{-3}\times\left[5733 - 6.99(M-W) - p_a\right] \\ &-0.42\left[(M-W)-58.15\right] - 1.7\times 10^{-5} M(5867 - p_a) \\ &-0.0014M\times\left[34 - t_{air}\right] + \varepsilon\sigma f_{eff} f_{clr} F_{clr}(T_r^4 - T_{skin}^4) + \\ &f_{clo} h_c (T_{air} - T_{skin}) \end{aligned} \right\} \quad (1)$$

where,

$$f_{clr} = 1 + 0.155 I_{clo} \quad (1a)$$

$$F_{clr} = 1/[1 + 0.155\times 5.2 I_{clo}] \quad (1b)$$

$$f_{clo} = 1/[1 + 0.155\times 2.9 I_{clo}] \quad (1c)$$

$$t_{skin} = 35.7 - 0.028\frac{M}{A_D} \quad (1d)$$

$$h_c = 8.3V_{air}^{0.6} \quad (1e)$$

$$p_a = \phi_{air} \cdot p_{a,b}(t_{air}) \quad (1f)$$

When sitting, standing, or walking on the flat, the output mechanical power of human is taken as zero, namely $W = 0$.

The average radiation temperature of air-condition room, t_r ,can be calculated by:Beltin empirical equation [6]:

$$t_r = t_g + 2.4V_{air}^{0.5}(t_g - t_{air}) \quad (2)$$

The black globe temperature, t_g ,which takes account of the environmental calorific radiation, is measured by the thermometer whose probe is surrounded by a black hollow ball with the diameter of 150mm . It can be written as:.

$$t_g = K \cdot t_{air} + C \quad (3)$$

where, K and C are the experimental coefficients.. .

Known from Eq.(1), the value of PMV can be theoreticlly calculated with the following variables: M、I_{clo}、$T_{air}(t_{air})$、ϕ_{air}、V_{air} . And different values of PMV denote different thermal sensation of human, which is shown in Table 1.

Tab.1 The corresponding relationship between PMV and the thermal sensation

PMV	-3	-2	-1	0	1	2	3
thermal sensation	cold	cool	a little cool	favorable	a little warm	warm	hot

ISO7730 [6] agrees that PMV ranging from -0.5 to +0.5 stands for the acceptable thermal envionment by people. For the consideration of energy conservation, PMV of thermal enviroment should be +0.5 in summer and -0.5 in winter, based on which the optimal indoor air temperature is determined in this paper.

Fig.1 shows the influence of indoor air velocity (<0.3m/s) on the optimal indoor air temperature in summer. Seen from Fig.1 (left), the optimal indoor air temperature will increases by 0.5℃ when the indoor air velocity changes from 0.1m/s to 0.3m/s, which indicates that the influence of indoor air velocity on the optimal indoor air temperature is not very great when the air velocity is under 0.3m/s. According to the curves in Fig.1(right), when M=70W/m^2, the relation between the optimal indoor air temperature and indoor air velocity can be expressed by Eq.(4):

$$t_{air,optimal} = f_1(\phi_{air}, I_{clo}, C) \cdot V_{air}^2 + f_2(\phi_{air}, I_{clo}, C) \cdot V_{air} + f_3(\phi_{air}, I_{clo}, C) \qquad V_{air} \le 0.3 \quad (4)$$

In Eq.(4):

$f_1(\phi_{air}, I_{clo}, C)$、$f_2(\phi_{air}, I_{clo}, C)$、$f_3(\phi_{air}, I_{clo}, C)$ are functions of ϕ_{air}、I_{clo}、C .

Fig. 2 shows the influence of indoor air humidity(30%—80%) on the optimal indoor air temperature in summer. Known from Fig.2 (left), indoor air humidity will make very small influence on the optimal indoor air temperature. Every 10% of variation of indoor air humidity only brings about 0.1 ℃ of change of the optimal indoor air temperature. With respect to the curves in Fig.2 (right), the optima indoor air temperature can be expressed by one linear model:

$$t_{air,optimal} = f_4(V_{air}, I_{clo}, C) \cdot \phi_{air} + f_5(V_{air}, I_{clo}, C)$$

$$0.3 \le \phi_{air} \le 0.8 \quad (5)$$

In Eq.(5), $f_4(V_{air}, I_{clo}, C)$ 、 $f_5(V_{air}, I_{clo}, C)$ are functions of V_{air}、I_{clo}、C .According to the results of simulation, the values of $f_4(V_{air}, I_{clo}, C)$ range about from –1.70 to –1.90 under the calculation conditions in Fig.2 (right). The thermal resistance of clothes will produce great influence on the optimal indoor air temperature. As is shown in Fig. 3, when the thermal resistance of clothes increases by 0.1 clo, the optimal indoor air temperature will decrease by about 0.4℃ in summer. With respect to the curves in Fig.3 (right), the optimal indoor air temperature can also be expressed by one linear equation:

$$t_{air,optimal} = f_6(V_{air},\phi_{clo},C)\cdot I_{clo} + f_7(V_{air},\phi_{clo},C) \quad (6)$$

In Eq.(6)， $f_6(V_{air},\phi_{clo},C)$、$f_7(V_{air},\phi_{clo},C)$ are functions of V_{air}、ϕ_{clo}、C. According to the results of simulation, the values of $f_6(V_{air},\phi_{clo},C)$ range about from –4.0 to –4.2 under the caluculation conditions in Fig.3 (right).

From above analysis, the following conclusions can be got as follows:

(1) When the indoor air velocity is below 0.3m/s and the indoor air humidity is within 30%～80%, the themal resistance of clothes will produce much greater influence on the optimal indoor air temperature than other influential factors.

(2) The optimal indoor air temperature is nonlinear with the air velocity, and be linear with the air humidity and the clothes thermo-resistance.

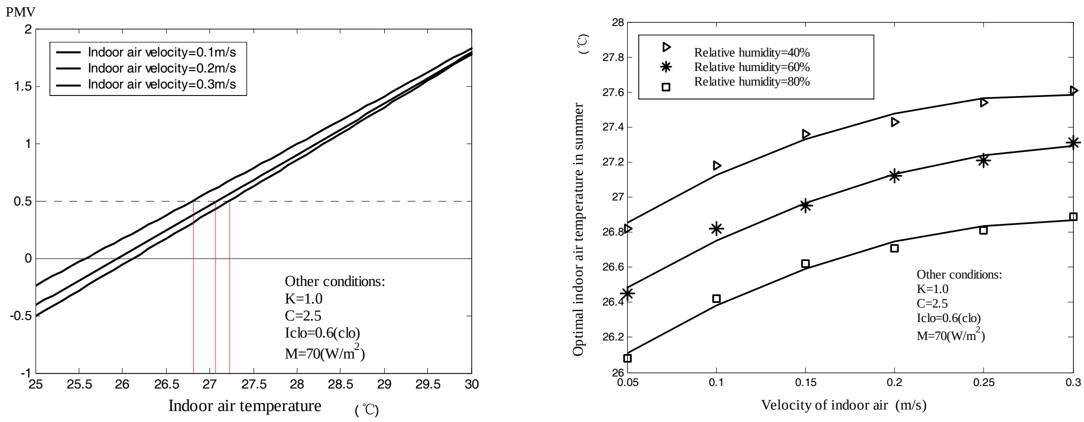

Fig.1. Influence of air velocity (<0.3m/s) on the optimal indoor air temperature

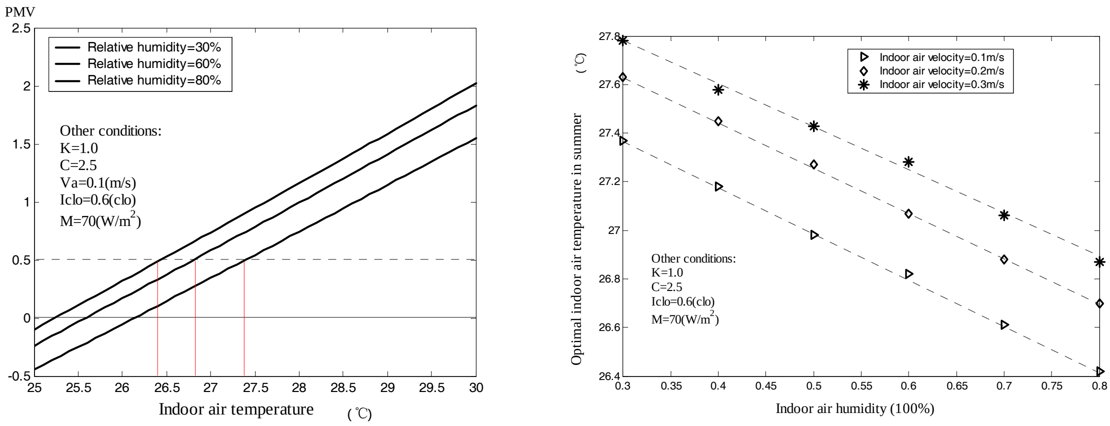

Fig. 2. Influence of indoor air humidity (30%～80%) on the optimal indoor air temperature

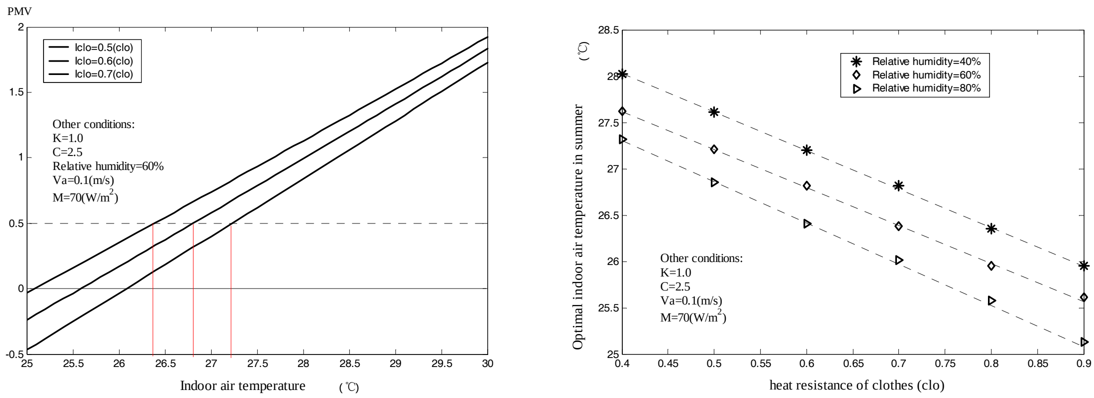

Fig. 3 Influence of clothes thermo-resistance on the optimal indoor air temperature

3. OPTIMAL INDOOR AIR TEMPERATURE

Known from the above analysis, when the indoor air velocity is below 0.3m/s and the indoor air humidity is within from 30% to 80%, the two parameters dosen't make obvious influence on the optimal indoor air temperature. Thus, the indoor air velocity and the indoor air humidity can be considered as constants. Therefore, the optimal indoor air temperature can be expressed as follows:

$$t_{air,optimal} = f_8\left(I_{clo}, K, C\right) \qquad (7)$$

3.1 Empirical model of I_{clo}

Since the dressing of people mainly depends on the outdoor air temperature, the clothes thermo-resistance, I_{clo} , can be expressed by the following equation::

$$I_{clo} = f_8(t_{out}) \qquad (8)$$

Fig. 4 plots the relation between clothes thermoresistance and the outdoor temperature in Shanghai area. The data in Fig.4 are derived from the great number of field investigations in Shanghai area throughout the year 2003 and 2004. Through the questionnaire investigation, the general people's dressing can be got. Then, the thermo-resistance of people's clothes, I_{clo} , can be calculated using the following equation [6]:

$$I_{clo} = (0.676\sum_{i=1}^{n} I_{clo,i}) + 0.117 \qquad (9)$$

Meanwhile, the intraday outdoor air temperatures will be recorded in detail. According to the thermo-resistance of people's clothes and the outdoor air temperatures, the following equation can be established in Shanghai area:

$$I_{clo} = 0.0007{t_{out}}^2 - 0.0638t_{out} + 1.6772 \qquad (10)$$

3.2 Determination of K and C

Fig.5 and Fig.6 plot the relation between the indoor air temperature and the indoor black globe temperature. All the data in Figs 5 and 6 are tested by two thermometers in one standard office room. One thermometer is placed in the air for testing the indoor air temperature, and another is for the indoor black globe temperature, which is. put into one black hollow brass ball with the diameter of 150mm. The tests last for two years (2003 and 2004). With respect to the testing data, the parameter K and C in Eq. (3) can be got, respectively, in summer and in winter. Eq.(3) can be empirically written as:

Summer: K=0.8866; C=3.7843

$$t_g = 0.8866t_{air} + 3.7843 \qquad (11)$$

Winter: K=0.9511; C=1.7362

$$t_g = 0.9511t_{air} + 1.7362 \qquad (12)$$

3.3 Optimal indoor air temperature

Assuming that the indoor air velocity is 0.1m/s, the indoor air humidity is 60%, and the metabolism rate of humanbody is 70W/m^2, the optimal indoor air temperature can be established, respectively, in summer and in winter using the PMV model together with Eqs.(11) and (12).

Summer

$$t_{air,optimal} = -4.269 I_{clo} + 27.118 \qquad (13)$$

Winter

$$t_{air,optimal} = -6.269 I_{clo} + 27.286 \qquad (14)$$

Combining Eq.(10) into Eq.(13) and Eq.(14), the optimal indoor air temperature dependent of the outdoor air temperature can be written as:

Summer

$$t_{air,optimal} = -0.00299 t_{out}^{\ 2} + 0.324 t_{out} + 19.96$$

Winter

$$t_{air,optimal} = -0.00439 t_{out}^{\ 2} + 0.475 t_{out} + 16.77$$

4. CONCLUSION

The models of optimal indoor air temperature are established for the air-conditioning systems in Shanghai area based on the theory of PMV and the field-testing data. The models take account of both energy conservation and the indoor thermal comfort, and are only dependent of the outdoor air temperature. Therefore, the models in this paper are adaptive and can be easily applied into the optimal control of all kinds of air-conditioning systems in Shanghai area.

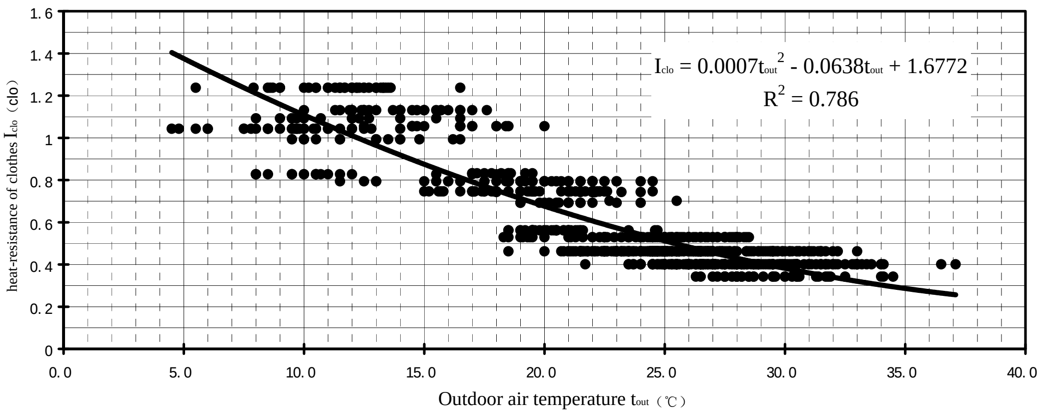

Fig. 4 The relation between clothes thermo resistance and outdoor temperature (Shanghai)

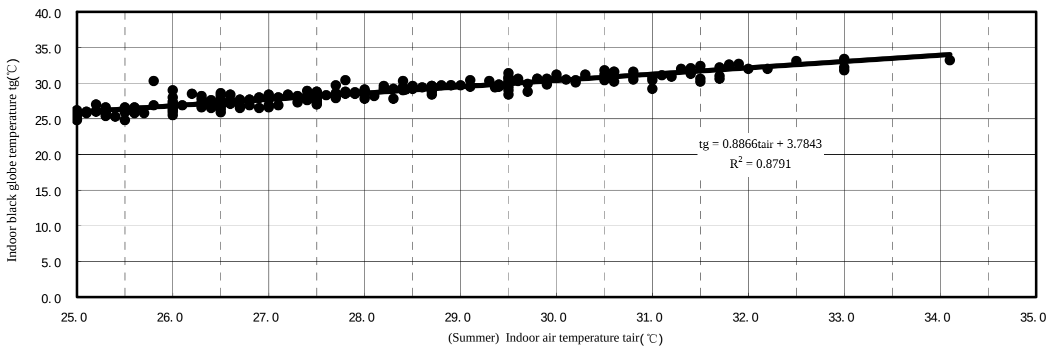

Fig.5 Relation between indoor air temperature and indoor black globe temperature in summer

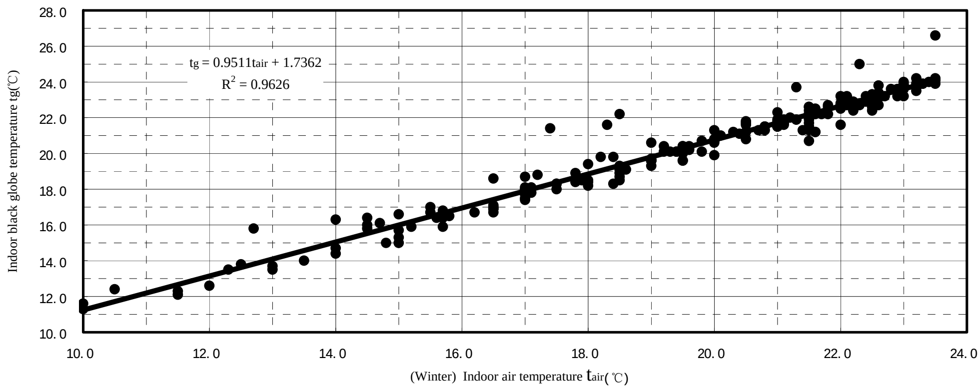

Fig.6 Relation between indoor air temperature and indoor black globe temperature in winter

NOMENCLATURE

A_D	Surface area of skin of human body， m^2	p_a	Partial pressure of water vapour in air，Pa
f_{eff}	Coefficient of Effective area of skin's radiation，Standing: 0.725，Sitting:0.696	t_{air} (T_{air})	Indoor air temperature, ℃（K）
f_{clr}	Correction coefficient of human body's surface area due to the dressing	t_{out}	Outdoor air temperature, ℃
f_{clo}	Correction coefficient of heat convection due to the dressing	t_g	Indoor black globe temperature, ℃
F_{clr}	Correction coefficient of heat radiation due to the dressing	T_r	Indoor mean radiant temperature, K
h_c	coefficient of heat convection, $W/(m^2 \cdot K)$	T_{skin}	Temperature of skin of human body, K
I_{clo}	Thermo-resistance of clothes, clo, 1clo=0.155 $m^2 \cdot K/W$	W	Output working power of human, W
M	Rate of metabolism of human，W	ε	Emission rate, 0.99 for skin, 0.7 for clothes

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