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Study on the Relationship between Thermal Comfort and Air-Conditioning Energy Consumption in Different Cities

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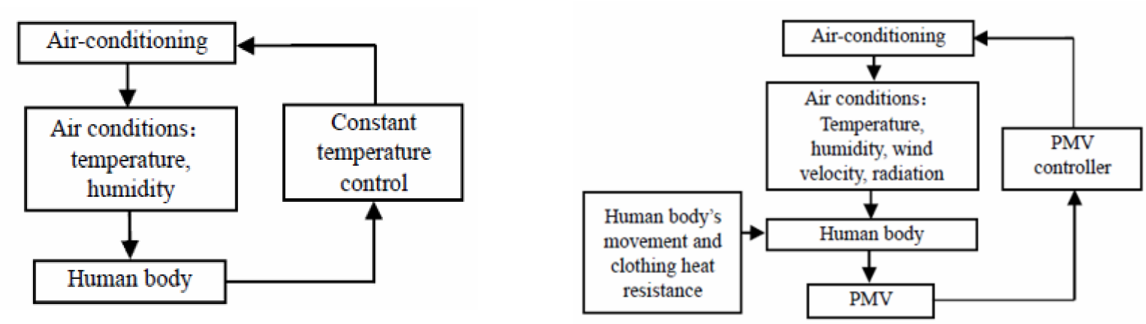
Abstract. Thermal comfort and air-conditioning energy consumption are two important issues in office buildings. This paper mainly analyze the relationship between air-conditioning energy consumption and thermal comfort in different cities. Firstly, we introduce the definition of indoor cooling load, and calculate the typical office's indoor cooling load in thirteen cities; Secondly, based on a simple equation for Predicted Mean Vote (PMV), a personalized power optimization method for air-conditioning control systems has been proposed in the paper; At last, we simulate the air-conditioning energy consumption under different thermal comfort range. The results show that air-conditioning energy saving efficiency is closely related with the acceptable comfort range and city's geographic location. Another contribution of this study is an optimal range of thermal comfort has been presented, and this research indicates the reasonable range of PMV is about 0.5~0.7 for most of cities in China.

Keywords: air-conditioning control, energy optimization, PMV, thermal comfort

1 Introduction

With the rapid development of the world's economy, the problem of insufficient power supply has taken place in many countries in recent years, especially during the peak period [1]. As the related research shows, building energy consumption accounted for 40% of the total energy consumption in the world [2]. Meanwhile, air-conditioning systems in buildings consume about 60% to 70% of total electricity consumption in some countries [3]. Therefore, a power optimization method for air-conditioning control systems is worth studying.

At present, most of the air-conditionings are controlled by a constant temperature in buildings. However, this control method has two serious problems: low comfort for users and extreme waste of energy. As we all know, human body has different feelings to the same indoor temperature under different conditions (humidity, wind speed, illumination and so on). For example, people will feel more comfortable in low humidity environment when the indoor temperature is same. In order to solve this problem, a feedback control method for indoor thermal environment has been presented in [4]. This new control method considers the predicted mean vote (PMV) as the thermal comfort index, by updating indoor set-temperature value in real time to ensure the indoor thermal environment is suitable for people to learn or work. A more detail analysis about the PMV compute method has been investigated [5-6]. The diagrams of traditional method and thermal comfort control method are shown in Fig. 1.



(a) Traditional temperature control method (b) Thermal comfort control method

Fig. 1. Traditional temperature control method and thermal comfort control method

To optimize the energy consumption, a lot of research focus on the design and control method of air-conditioning systems [7-12]. However, most of the researches have a common problem, they focus on the energy saving efficiency but neglect people's thermal comfort [11-12]. Based on these foundation, an energy optimization method for air-conditioning control systems based on PMV index has been proposed in this paper. On the other hand, although the PMV calculation method presented in [6] is detailed and accurate, the calculation process is complex. Therefore, we propose a simple PMV calculation formula depend on the actual conditions for our air-conditioning control method. Simulation results show that the proposed method can improve human comfort and save energy consumption. Another study of this article is an optimal thermal comfort range has been given for China's thirteen most important cities.

The rest of the paper is as follows. In Section 2 we describe the basic work, the definition of PMV and indoor cooling load have been presented. In Sections 3 we propose a new air-conditioning control method based on thermal comfort. Detailed simulations and results analysis have been presented in section 4. We summarize the full paper and discuss the next research work in Section 5. Then the Acknowledgement is shown. The last part of this paper is the references.

2 Basic Work

2.1 PMV in Thermal Comfort Model

The thermal comfort PMV model was advanced by Professor Fanger primarily [13]. Fanger's human thermal comfort model is based on a large number of experiments, it represents the feelings for most people in a same environment. The influence elements of PMV include thermal environment and human body, where the former contains air temperature, average radiation temperature, wind speed and air humidity; the latter is concerned with human body's metabolism rate and clothing insulation. The calculation formula of PMV value can be expressed as [10]

$$PMV = \left(0.028 + 0.3033e^{-0.036M}\right)H \quad \textbf{(1)}$$

Where M stands for the metabolism rate (W/m^2), and H is the human body's clothing insulation, it can be computed by

$$\begin{aligned} H = {} & M - W - 3.05\times10^{-3}\left[5733 - 6.99\left(M-W\right) - P_a\right] - 0.42\left(M - W - 58.15\right) - 1.7\times10^{-5}M\left(5867 - P_a\right) \\ & -0.0014M\left(34 - t_a\right) - f_{cl}h_c\left(t_{cl} - t_a\right) - 3.96\times10^{-8}f_{cl}\left[\left(t_{cl}+273\right)^4 - \left(\bar{t}_r + 273\right)^4\right] \end{aligned} \quad \textbf{(2)}$$

The convection heat transfer coefficient h_c is evaluated by

$$h_c = \begin{cases} 2.38\left(t_{cl} - t_a\right)^{0.25}, & 2.38\left(t_{cl} - t_a\right) > 12.1\sqrt{V} \\ 12.1\sqrt{V}, & 2.38\left(t_{cl} - t_a\right) < 12.1\sqrt{V} \end{cases} \quad \textbf{(3)}$$

and the surface temperature of clothing t_{cl} can be expressed as

$$t_{cl} = 35.7 - 0.028(M - W) - 0.155 I_{cl} \left\{ 3.96 \times 10^{-8} \times f_{cl} \left[\left(t_{cl} + 273 \right)^4 - \left(\overline{t_r} + 273 \right)^4 \right] + f_{cl} \times h_c \left(t_{cl} - t_a \right) \right\} \quad \textbf{(4)}$$

Where W represents the external work, which is equal to zero in most cases; P_a is the partial water vapor pressure (kPa); t_a stands for the indoor air temperature (℃); f_{cl} is the clothing area parameter; $\overline{t_r}$ is the average radiation temperature (℃); V is the air flow velocity (m/s); I_{cl} is the thermal resistance of clothing ($(m^2 \cdot ℃)/W$). Among them P_a is calculated by

$$P_a = \phi \times \exp\left[16.6536 - 4030.183 / \left(t_a + 235\right)\right] \quad \textbf{(5)}$$

and ϕ stands for the air humidity.

PMV value is contacted with thermal sensation level, which defined by ASHRAE. The detailed relationship between PMV index and thermal sensation is shown in Fi. 2. ISO7730 recommended value for the appropriate range of thermal comfort is -0.5~0.5, while Chinese standard recommended value is -1~1 [14].

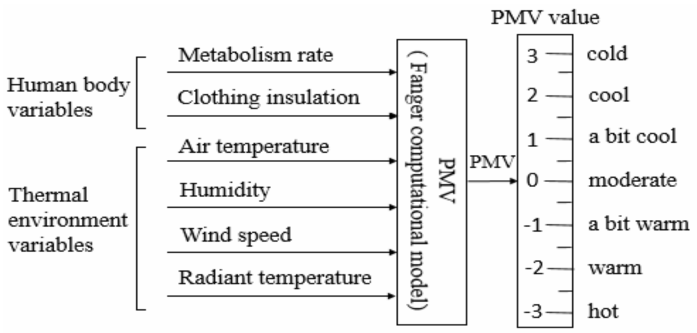


Fig. 2. Relationship between PMV value and thermal sensation

2.2 Calculation of Indoor Cooling Load

In summer, in order to keep the indoor temperature constant, heat must be removed from the room, and this heat is called cooling load. The cooling load of air-conditioning room is mainly caused by two aspects: instantaneous heat transfer by building enclosure structure ($Q_c(\tau)$) and heat emerged by indoor heat source [14]. The former includes instantaneous heat transfer through external wall and roof ($Q_{c1}(\tau)$), transient heat transfer of window ($Q_{c2}(\tau)$) and insolation through glass window ($Q_{c3}(\tau)$); the latter is comprised by equipment heat loss and human body heat loss. Due to the indoor heat source is difficult to control and compute, we mainly consider the change of indoor heat which caused by building enclosure structure [14].

Cooling load factor method is a typical idea to calculate the cooling load for the air-conditioning room. Specific calculation formulas are as follows [14]

$$Q_c(\tau) = Q_{c1}(\tau) + Q_{c2}(\tau) + Q_{c3}(\tau) \quad \textbf{(6)}$$

$$Q_{c1}(\tau) = AK\left[\left(t_c(\tau) + t_{d1}\right)k_\alpha k_\rho - t_R\right] \quad \textbf{(7)}$$

$$Q_{c2}(\tau) = C_w K_w A_w \left(t_c(\tau) + t_{d2} - t_R\right) \quad \textbf{(8)}$$

$$Q_{c3}(\tau) = C_\alpha A_w C_s C_i D_{j\max} C_{LO} \quad \textbf{(9)}$$

The symbols involved in above formulas are defined as Table 1. All of these parameters is concerned with air-conditioning room's geographic location, structure and size, concrete numerical values are derived from [14].

Table 1. Notations definition

Symbol	Definition	Symbol	Definition
A	roof area	K	heat conduction coefficient of roofing
t_{d1}	location correction of the wall	k_ρ	correction value of absorption coefficient
k_a	exterior heat absorption value	$t_c(\tau)$	hourly cooling load calculation temperature
t_R	indoor calculation temperature	C_w	heat transfer coefficient of window glass
A_w	window area	K_w	heat transfer coefficient of external window
C_s	window's sunshade index	C_a	effective area coefficient of glass window
D_{jmax}	insolation heat gain index	C_i	sunshade index of window shade
t_{d2}	location correction of window	C_{LO}	window glass cooling load factor

3 A New Air-conditioning Control Method Based on Thermal Comfort

In this section, we proposed a personalized power optimization method for air-conditioning control systems. Firstly, due to PMV calculation formula is complex to handle in computer, a simple equation for PMV has been put forward; In addition, the problem about how to calculate the PMV value in real time has been solved.

3.1 Simplified Calculation of PMV Equation

To Simplify the PMV calculation equation, in this paper, we made the following assumptions according to the actual situation [15-16]:

a. People usually wear a short sleeve shirt and a thin trousers in summer, so the thermal resistance of clothing I_{cl} is suggested to be 0.082, the clothing area parameter f_{cl} is taken as 1.15.

b. The metabolism rate may be taken as 65 W/m^2 when people in meditation or minor labor.

c. Average radiation temperature $\overline{t_r}$ is generally equal to the indoor air temperature t_a.

d. Indoor air flow velocity V is taken as 0.2 *m/s*, the value of air humidity we choose 50%.

According to the setting of these parameters, the simplification process of PMV formula is as follows:

Step 1. Substitute relation parameter values, the surface temperature of clothing t_{cl} can be calculated by

$$t_{cl} = 33.7781 - 0.3734\times10^{-8}\times\left[\left(t_{cl}+273\right)^4-\left(t_a+273\right)^4\right]-0.5092\times\left(t_{cl}-t_a\right) \quad \textbf{(10)}$$

Formula (10) is still hard to calculated, a simpler formula can be expressed as (11), and Fig. 3 gives the comparison between Equation (10) and Equation (11).

$$t_{cl} = 0.47t_a + 17.89 \quad \textbf{(11)}$$

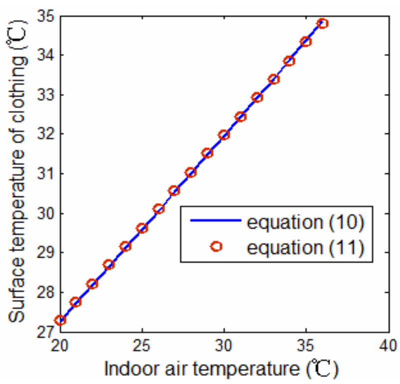


Fig. 3. Relationship between indoor air temperature and the surface temperature of clothing

Step 2. Take Formula (11) into Equation (3), the convection heat transfer coefficient h_c can be simplified by

$$h_c = \begin{cases} 2.38\times(17.94-0.53t_a)^{0.25} & t_a < 16.57 \\ 5.41 & t_a > 16.57 \end{cases} \quad \textbf{(12)}$$

The average indoor air temperature in summer is generally greater than 17℃,so h_c is equal to 5.41.

Step 3. Take relation simplified Formula into Equation (1), the simplified PMV formula can be expressed as

$$PMV = 1.19\times10^{-4}\times\exp\left[16.65-4030.18/(t_a+235)\right]+0.19t_a-4.35-2.605\times10^{-9}\times\left[(0.47t_a+291.07)^4-(t_a+273)^4\right] \quad (13)$$

Based on the simplified PMV calculation formula, we get the relationship between the indoor air temperature t_a and the PMV value. Table 2 shows the detailed relation.

Table 2. Relationship between t_a and PMV

PMV	-1.5	-1	-0.5	0	0.5	1	1.5
t_a	23.1	24.6	26.1	27.6	29.1	30.5	31.9

3.2 Calculation of the Real-time PMV Value

After opening air-conditioning, the heat lost from room per minute by air-conditioning is $Q_{air\text{-}conditioning}$; the heat obtained from outdoor per minute is Q_{out} and can be calculated with Equation (6). Therefore, the change of indoor heat per minute can be calculated as

$$\Delta Q_t = Q_{air-conditioning} - Q_{out} \quad \textbf{(14)}$$

Air-conditioning control systems will control air-conditioning's operation state automatically according to the earlier setup, and ensure the value of indoor PMV is in [PMV_{min} PMV_{max}]. If PMV value exceeds PMV_{max}, α_t=1, means the air-conditioning start to work at the moment; While PMV value less than PMV_{min}, α_t=0, means it's a right time to close the air-conditioning. The indoor temperature change rate per minute when the air-conditioning is on (off) can be represented with ΔT_on (ΔT_off). Therefore, the indoor temperature (per minute) can be computed by

$$T_t = T_{t-1} - [(1-\alpha_t)\Delta T\_off + \alpha_t \Delta T\_on] \quad \textbf{(15)}$$

4 Simulation

In this part, we do a series of simulations and analysis the results. We select thirteen representative cities in China to analyze the relationship between acceptable thermal comfort range and air-conditioning power consumption. Furthermore, a detailed energy saving efficiency comparison between Beijing and Nanjing has been presented.

Firstly, we choose a typical office room as the simulation object, detailed simulation parameters are as follows:

(1) The office room is 6-meterlong, 4 meter-wide and 3.6 meter-high;

(2) There is only one window in the office, which is 2.5-meter long and 2-meter wide; the window adopts 3-mm thick double-deck common glass;

(3) Rated power of air-conditioning is 900W.

Secondly, considering human feelings and the air-conditioning energy saving demand (the background of the study is during the summer), we consider the value of PMV_{min} is equal to zero. When PMV_{max} changes from +0.1~+1.5, we calculate the total energy consumption of air-conditioning between 10:00 and 14:00.

At last, in order to study the relationship between the thermal comfort range and the power consumption of air-conditioning, this paper takes thirteen provincial capital cities in China as an example. Table 2 gives the detailed geographic information for the thirteen cities.

Table 2. Urban geographic information

City name	North latitude	East longitude	Altitude	t_{d1}	t_{d2}	D_{jmax}
Beijing	39°48′	116°28′	31.2	0.0	0	114
Tianjin	39°06′	117°10′	3.3	-0.2	0	114
Shenyang	41°46′	123°26′	41.6	-1.6	-1	114
Harbin	45°41′	126°37′	171.7	-3.4	-3	109
Shanghai	31°10′	121°26′	4.5	1.2	1	115
Nanjing	32°00′	118°48′	8.9	2.7	3	115
Wuhan	30°37′	114°08′	23.3	2.2	3	115
Guangzhou	23°03′	113°19′	6.6	1.7	1	134
Chongqing	29°35′	106°28′	259.1	2.8	3	115
Kunming	25°01′	102°41′	1891.4	-5.2	-6	134
Xi’an	34°18′	108°56′	396.9	1.8	2	122
Lanzhou	36°03′	103°53′	1517.2	-3.9	-3	122
Urumqi	43°47′	87°37′	917.9	-0.4	1	109

Supposing the air temperature in the room is even-distributed, we first calculate the real-time heat which come from the outside, then we can get the thermal comfort value in the room and control the operation state of air-conditioning. Therefore, the thermal comfort value can be limited between PMV_{min} and PMV_{max}. Fig. 4 shows the relationship between thermal comfort range and air-conditioning energy consumption for thirteen cities in China. From the picture we have the following findings:

(1) The larger thermal comfort range, the less energy consumption;

(2) The closer to the most comfortable area, the change of power consumption is significantly faster than other regions;

(3) When the value of PMV_{max} changes from +0.1 to +0.8, the power consumption of air-conditioning decreases more than 0.15 kWh universally; however, when PMV_{max} is greater than 0.8, its impact on the energy consumption of air-conditioning is gradually reduced;

(4) Under the same thermal comfort, there are huge differences in the power consumption of air-conditioning for different cities. Among them, the air-conditioning system energy consumption is significantly higher in Chongqing, Nanjing, Wuhan, Guangzhou and Xi’an, even two to three times of Kunming. These differences have a great relationship with the city’s geography and climate.

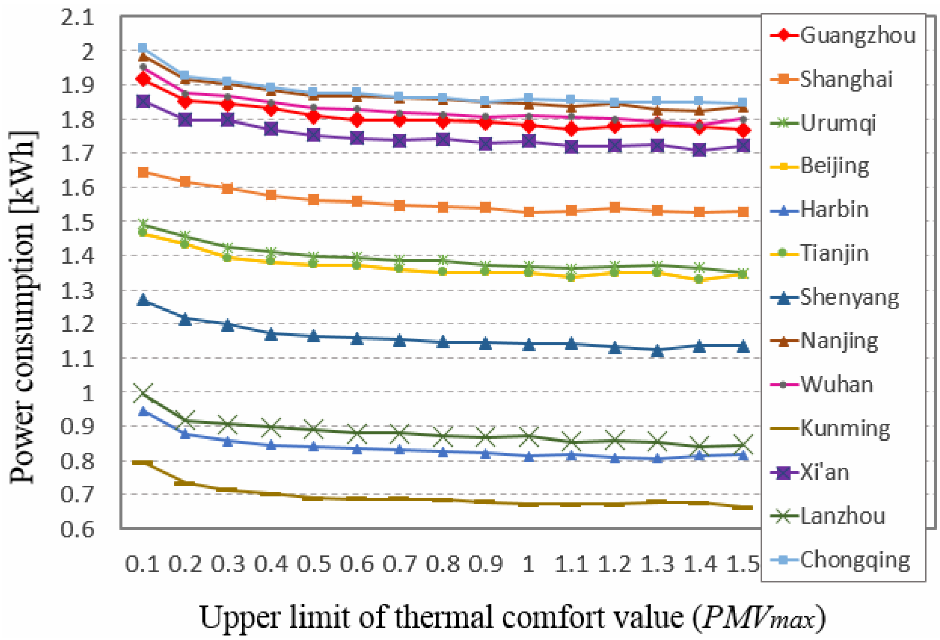


Fig. 4. Relationship between thermal comfort range and air-conditioning power consumption

Although the variation trend of the curves in Fig. 4 are similar, there are still some slight differences. For example, the variation trend of the air-conditioning power consumption in Chongqing is larger than Shanghai. In order to amplify these minor differences, we take Beijing and Nanjing as an example to do a further analysis for the obtained data. Specific analysis results is proposed in Fig. 5.

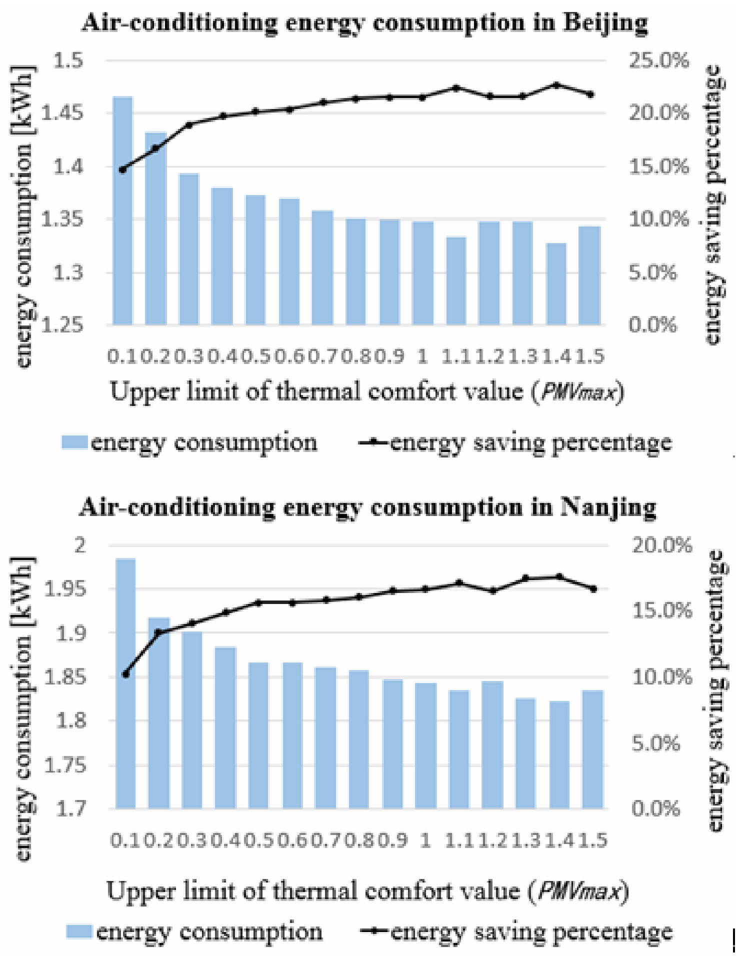


Fig. 5. Air-conditioning energy consumption and saving efficiency in Beijing and Nanjing

We can draw the following conclusions according to Fig. 5:

(1) When PMV_{max} changed from 0-0.2, the fall speed of air-conditioning energy consumption in Nanjing is faster than Beijing;

(2) When the value of PMV_{max} is no more than 1.1, with the increase of PMV_{max}, the power consumption of air-conditioning is reduced; however, when PMV_{max} is larger than 1.2, the change of air-conditioning power consumption is irregular with the increase of PMV_{max};

(3) For the Beijing city, setting the PMV_{max} value to +0.7~+0.8 will get a good effect, and the energy saving percentage is about 21%; As for Nanjing, the optimal range of thermal comfort is 0.5 to 0.6, and the energy saving efficiency is approximate 17%.

From the above analysis, users can expand the scope of thermal comfort value to achieve a relatively high economic benefits. Moreover, these simulation results can provide some guidance suggestions for future air-conditioning control scheme in different cities.

5 Conclusion and Future Work

Indoor thermal comfort control research has become a focus in construction industry, a reasonable adjustment to the indoor thermal environment can improve human body comfort and reduce the air-conditioning energy consumption. In this paper, a new air-conditioning control method based on thermal comfort has been proposed. The contributions of the article are as follows:

(1) A simple equation for PMV has been proposed;

(2) Simulation results verity when we expand the acceptable thermal comfort range appropriately, the air-conditioning power consumption will be obvious reduced;

(3) Proving the air-conditioning power consumption efficiency have a great relationship with city's geographic location and climatic conditions;

(4) For most of China's cities, setting the range of thermal comfort to 0.5~0.7 can make human body feel comfortable and save energy consumption.

On the other hand, in order to simplify the PMV calculation formula, a lot of environmental variables have been fixed in the paper. We just consider the variety of PMV value caused by indoor air temperature, this led to many limitations for the proposed scheme. Under such premise, we plan to establish a neural network model based on various environmental factors in the future, and a further detailed research about air-conditioning energy saving and human thermal comfort in different cities will be presented.

Acknowledgement

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