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Heat Index Estimation of Ventilating Air-Conditioning Heating Area Considering Thermal Comfort

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ABSTRACT

The heat metering of heating is a main link in energy conservation of ventilating air-conditioning (VAC) heating. It is of great practical significance to study the heat metering of heating. However, not many scholars have estimated the heat index based on building heating area, in the light of thermal comfort. Therefore, this paper estimates the heat index of VAC heating area considering thermal comfort. Firstly, we analyzed the various factors affecting human thermal comfort. Then, four environmental factors were selected, namely, indoor air temperature, relative air humidity, mean radiation temperature of envelope surface on human body, and indoor vertical air error. In addition, we selected suitable thermal comfort indices to predict and assess the thermal environment under indoor VAC heating. After that, we analyzed the indoor heat flow under VAC heating, examined the components of energy consumption of indoor VAC heating, and estimated the heat index of VAC heating area. Next, a mathematical model was constructed for heat metering, according to the heat consumption of the building VAC, and the composition of the heat consumption of occupants. Experimental results verify the effectiveness of the proposed thermal metering model.

1. INTRODUCTION

With the growth of economy and the improvement of our living standard, there is a growing demand for buildings, as well as the functions of the ventilating air-conditioning (VAC) system. The VAC applications are increasingly diversified [1-9]. More and more attention has been paid to the thermal comfort and energy conservation of the indoor environment, in the presence of air-conditioning. The VAC system consumes nearly half of the energy utilized by a building [10-14]. It is the core difficulty of the VAC industry to find an innovative VAC model or VAC technology, which is comfortable, convenient, economical, energy-saving, and environmentally friendly [15-20]. The heat metering of heating is a main link in energy conservation of VAC heating. It is of great practical significance to study the heat metering of heating.

Yusuke et al. [21] developed an approach to assess the thermal sensation of the human body using different thermal control devices. The approach evaluates the thermal balance of the human body, by calculating the amount of heat exchange between the human body and the external environment. By virtue of the thermal balance of the human body, the standard ambient temperature was derived, that is, the local standard new effective temperature for each part of the human body (local setting). Local thermal sensation was defined by a model equation that takes into account transient changes in thermal balance, and the effects of whole-body thermal storage. Therefore, the thermal comfort of the occupants in the vehicle was evaluated under transient and non-uniform conditions.

Wu et al. [22] conducted a long-term field study on an office building in Guangzhou, which is located in China's hot summer and warm winter climate zone. Three seasons were covered in the study: summer, autumn and winter. Alashaab and Alamery [23] attempted to investigate and improve the thermal comfort of worshippers in an Iraqi mosque, which has a hot and arid climate in summer. The mosque was meshed into 4 million grids, and simulated by Ansys-Fluent v.18. Then, the thermal comfort was assessed by finding the predicted mean vote (PMV). The percentage of dissatisfaction was predicted according to ASHRAE Standard-55. In addition, the thermal comfort was optimized by the adaptive device redistribution strategy.

To explore the thermal comfort of the human body under the radiant cooling air-conditioning system, Gao et al. [24] explored the heat transfer mechanism of the system, derived the relationship between thermal comfort index and the sensible heat loss of the human body, and obtained the ratio of radiative heat loss to convective heat loss. Both the experimental and numerical results show that, under the radiant cooling air-conditioning system, the thermal comfort index (PMV) of the human body has an approximately linear relationship with the sensible heat loss of the human body.

Through measurements and questionnaires, Takuya et al. [25] demonstrated the effectiveness and comfort of the variable air rate (VAV) air-conditioning system, which generates horizontal and vertical airflows through a special air outlet. Besides, the system can adjust the air volume. With this system, it is possible to choose the preferred airflow in different air-conditioned zones. The airflow can be configured using the five-stage mode of the occupant interface installed in the room. Measured results prove that the thermal sensations have a difference in air speed, and the air volume adjustment function is effective.

Domestic and foreign scholars often calculate the load of indoor VAC through numerical simulation, technical and economic energy-saving analysis, etc. Many results have been achieved by comparing the indoor human thermal comfort under different indoor VAC heating schemes, and cold and heat source schemes. However, not many scholars have estimated the heat index based on building heating area, in the light of thermal comfort.

This paper estimates the heat index of VAC heating area considering thermal comfort. Section 2 analyzes the various factors affecting human thermal comfort, selects four environmental factors, namely, indoor air temperature, relative air humidity, mean radiation temperature of envelope surface on human body, and indoor vertical air error, and identifies suitable thermal comfort indices to predict and assess the thermal environment under indoor VAC heating. Section 3 analyzes the indoor heat flow under VAC heating, examines the components of energy consumption of indoor VAC heating, and estimates the heat index of VAC heating area. Section 4 constructs a mathematical model for heat metering, according to the heat consumption of the building VAC, and the composition of the heat consumption of occupants. Experimental results verify the effectiveness of the proposed thermal metering model.

2. THERMAL COMFORT EVALUATION

This paper firstly analyzes the various factors affecting human thermal comfort, selects four environmental factors, namely, indoor air temperature, relative air humidity, mean radiation temperature of envelope surface on human body, and indoor vertical air error, and identifies suitable thermal comfort indices to predict and assess the thermal environment under indoor VAC heating.

Let Φ_s be the radiation temperature; Φ_h be the black globe temperature; Φ_x be the air temperature; u be the airflow rate. Then, the mean radiation temperature can be calculated by:

$$\Phi_s = \Phi_h + 2.4u^{0.5}\left(\Phi_h - \Phi_x\right) \tag{1}$$

The magnitude of the vertical air temperature difference is characterized by the mean temperature difference between the head and the feet in the standing and sitting postures of the human body during the study period. Let M_i be the number of temperatures recorded during the study period; $\Phi_{H,i}$ and $\Phi_{F,j}$ be the measured temperature of the head and the feet at time i, respectively. Then, we have:

$$\Delta\Phi_{a,v} = \frac{\sum_{i=1}^{M_i}\left(\Phi_{H,i} - \Phi_{F,i}\right)}{M_i} \tag{2}$$

Let MY_j be the thermal comfort dissatisfaction rate caused by the vertical air temperature difference between the head and feet of the human body on the i-th vertical line; $\Delta\Phi_{x,b}$ be the mean air temperature difference between the head and feet of the human body during the study period in the direction of the same vertical line. Then, we have:

$$MY_j = \frac{100}{1 + exp\left(5.76 - 0.86 \times \Delta\Phi_{x,b}\right)} \tag{3}$$

As for the prediction and evaluation of the thermal environment under indoor VAC heating, this paper constructs a heat balance equation that can comprehensively quantifies the relationship between the human body and various physical quantities. By solving the equation, it is possible to plot the thermal comfort curve, which visually displays the relationship between the human body and various thermal comfort factors in the indoor environment. Let w_n be the heat production of the human body; w_d be the evaporative heat dissipation of the human body; w_s be the radiative heat exchange of the human body; w_Q be the heat consumption of doing work of the human body. Then, the heat gain or loss Δw of the human body can be calculated by:

$$\Delta w = w_n - w_d \pm w_s \pm w_Q \tag{4}$$

3. HEAT INDEX ESTIMATION

Before estimating the heat index of the building heating area, it is first necessary to analyze the flow of indoor heat and the composition of the indoor energy consumption in the presence of VAC heating. To ensure the thermal comfort of occupants in different locations of the building, the VAC system must provide them with different amounts of heat. For occupants in different locations, the ambient temperature is higher or lower than the mean indoor temperature in the building. Let Φ_{mi} be the mean indoor temperature of each occupant; $\bar{\Phi}_m$ be the mean temperature of building foundation; $\Delta\Phi_i$ be the change of the mean indoor temperature of each occupant. Then, we have:

$$\Phi_{mi} = \bar{\Phi}_m \pm \Delta\Phi_i \tag{5}$$

The heat consumption of occupants consists of two parts: mean heat consumption, and variable heat consumption. Let W_i be the heat consumption of occupants; W_{fi} be the mean heat consumption of each occupant; ΔW_i be the variable heat consumption of each occupant. Then, we have:

$$W_i = W_{fi} + \Delta W_i \tag{6}$$

To meet the thermal comfort requirements of occupants at different locations, the entire VAC heating system arranges the heat flow in the building, and distributes and transmits heat, according to the heat consumption of different occupants. Figure 1 shows the indoor heat flow under VAC heating. Let W_C be the total heat provided by the heat source; W_R be the heat loss by ventilation. If W_R is so small as to be negligible, then $W_C=\Sigma W_F$. From the law of conservation of heat, the following formula can be derived:

$$W_C = W_R + \sum W_F \tag{7}$$

Formula (7) shows that the total heat supply of VAC equals the sum of heat consumptions of different rooms in the building. Similarly, the VAC heat gain of the entire building can be obtained from the law of conservation of heat, which equals the sum of the heat consumption of occupants at different locations:

$$W_F = \sum W_i \tag{8}$$

Furthermore, the relationship between total heat supply of VAC and the heat consumption of each occupant can be obtained:

$$W_C = \sum \sum W_i \tag{9}$$

Let w_F be the heat consumption index of the building; X_i be the building area per occupant. Then, the mean heat consumption of occupants can be defined as the product between w_F and X_i:

$$W_{fi} = w_F X_i \tag{10}$$

By evenly distributing W_C, the heat transfer between adjacent rooms in the building can be effectively mitigated.

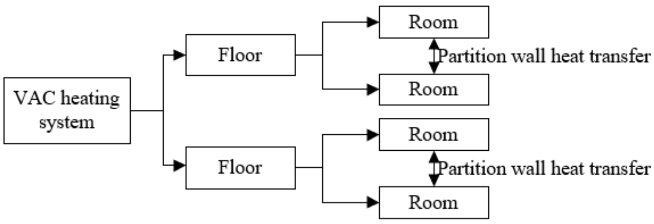

Figure 1. Indoor heat flow under VAC heating

To determine the mean temperature of building foundation, and the mean heat consumption and variable heat consumption of occupants, this paper uses the effective heat transfer coefficient to analyze the total heat consumption of the building. Let w_F be the public heat consumption index of the building; $w_{F\cdot P}$ be the heat loss in heat transfer via the envelope per unit building area; w_{AMG} be the heat loss in air infiltration per unit building area; $w_{U\cdot F}$ be the indoor heat gain per unit building area. Then, the total heat consumption index of the building can be calculated by:

$$w_F = w_{F\cdot P} + w_{AMG} - w_{U\cdot F} \tag{11}$$

Let Φ_m be the indoor temperature of the room; Φ_q be the mean outdoor temperature during the heating period; Ψ_i be the correction coefficient of the heat transfer coefficient of the envelope; L be the heat transfer coefficient of the envelope; G be the area of the envelope; X be the building area. Then, the heat loss $w_{F\cdot P}$ in heat transfer via the envelope per unit building area can be calculated by:

$$w_{F\cdot P} = \left(\Phi_m - \Phi_q\right)\left(\sum_{i=1}^{n} \sigma_i \bullet L_i \bullet G_i\right) / X \tag{12}$$

Let SH_φ be the specific heat capacity of the air; φ be the air density; M be the ventilation times; U be the ventilation volume. Then, the heat loss w_{AMG} in air infiltration per unit building area can be calculated by:

$$w_{AMG} = \left(\Phi_m - \Phi_q\right)\left(D_\phi \cdot \phi \cdot U \cdot M\right) / X \tag{13}$$

Then, the heat consumption index of the building can be calculated by:

$$w_F = \begin{Bmatrix} \left(\Phi_m - \Phi_q\right)\left(\sum_{i=1}^{n} \sigma_i \bullet L_i \bullet G_i\right) \\ + \left(\Phi_m - \Phi_q\right)\left(D_\phi \cdot \phi \cdot U \cdot M\right) \end{Bmatrix} / X - w_{U\cdot F} \tag{14}$$

By formula (14), the mean heat consumption of occupants can be obtained. Then, the total heat consumption of the building can be calculated by:

$$\begin{aligned} W_F = w_F \times X = \left(\Phi_m - \Phi_q\right)\left(\sum_{i=1}^{n} \sigma_i \bullet L_i \bullet G_i\right) \\ + \left(\Phi_m - \Phi_q\right)\left(D_\phi \cdot \phi \cdot U \cdot M\right) - w_{U\cdot F} \times X \end{aligned} \tag{15}$$

Then, $(\Sigma^n{}_{i=1}\sigma_i \cdot G_k) + (D_\varphi \cdot_\varphi \cdot U \cdot M)$ is defined as the composite energy-saving parameter Y of the envelope. Then, the above two formulas can be converted into:

$$w_F = Y \frac{\left(\Phi_m - \Phi_q\right)}{X} - w_{U,F} \tag{16}$$

$$W_F = Y\left(\Phi_m - \Phi_q\right) - w_{U,F} \times X \tag{17}$$

When the total heat in the building is fixed, the influence on w_F can be seen as the relationship of the ambient temperature of an occupant and the outdoor temperature with the area of the room where the occupant is located. The mean temperature of building foundation can be calculated by:

$$\overline{\Phi_m} = \frac{W_F + w_{U,F} \times X}{Y} + \Phi_q \tag{18}$$

Let Δw_i be the variable heat consumption index of occupant i. Then, the variable heat consumption can be defined as the product between Δw_i and the building area of the occupant:

$$\Delta W_i = \Delta w_i X_i \tag{19}$$

To reflect the fairness of heat metering for air-conditioning heating, Δw_i can be calculated from w_F, based on the difference between the temperature at the location of the occupant and the mean temperature of the foundation. Let β be the conversion coefficient of the variable heat consumption index of occupants; $\Delta w_j^{'}$ be the value converted from Δw_i. Then, we have:

$$\Delta w_i^{'} = \beta w_F \tag{20}$$

Let $\Delta W'_i$ be the variable heat consumption of occupant i. Then, the variable heat consumption of the occupant can be calculated by:

$$\Delta W_i^{'} = \Delta w_i^{'} \bullet X_i = \beta w_F \bullet X_i \quad (21)$$

4. HEAT METERING MODEL

To meet the basic conditions of the heat metering method described in the previous section, this section constructs the mathematical model of the heat metering method, according to the heat consumption under VAC heating, and the composition of the heat consumption of occupants.

The heat consumption index w_i of occupant i is the ratio of the heat consumption of each occupant to the area of the room of that occupant:

$$w_i = \frac{W_i}{X_i} \quad (22)$$

The heat consumption index w_F of the building is the ratio of the total heat consumption W_F under VAC heating to the total indoor area PV of the building:

$$w_F = \frac{W_F}{\sum_{i=1}^{n} X_i} \quad (23)$$

The variable heat consumption index Δw_i of occupant i is the ratio of the variable heat consumption ΔW_i of occupant i to the area PV_i of the room of that occupant:

$$\Delta w_i = \frac{\Delta W_i}{PV_i} \quad (24)$$

The heat consumption index of occupant i can be calculated by:

$$w_i = w_F \pm \Delta w_i \quad (25)$$

In the building, the VAC heating supplies different amounts of heat for occupants in different rooms to reach the same temperature. To ensure the fairness of heat metering, the total heat consumption of the building needs to be converted from the heat consumption indices:

$$w_i^{'} = w_F + \beta w_F \quad (26)$$

Let $w_i^{'}$ be the converted heat consumption index of the heat consumption obtained by an occupant; Φ_m be the mean temperature of building foundation; Φ_{mi} be the mean temperature of the room of the occupant. To facilitate the heat measurement, $w_i^{'}$ can be solved solely based on the mean temperature of the room and the area of the room of the occupant:

$$w_i^{'} = \frac{\Phi_{mi} - \Phi_q}{\Phi_m - \Phi_q} w_F = \left(1 + \frac{\Phi_{mi} - \Phi_m}{\overline{\Phi}_m - \Phi_q}\right) \times w_F \quad (27)$$

The conversion coefficient of the variable converted heat consumption index of the occupant can be obtained by:

$$\gamma = \frac{\Phi_{mi} - \Phi_m}{\Phi_m - \Phi_q} \quad (28)$$

The above analysis shows that the index γ can be determined, when W_F, Φ_{mi}, Φ_q and Φ_m are known. The index γ multiplied with the room area of the occupant is the heat consumption of the occupant:

$$W_i^{'} = w_i^{'} \bullet X_i = (1+\gamma) w_F X_i \quad (29)$$

The ideal conditions for the balance between the occupants and the VAC heating system include the accurate calculation of the heat load, the reasonable design of the heating strategy, and the consistency of the ambient temperature of occupants. Based on the heat distribution principle, the converted heat distribution of occupants can be derived as:

$$w_i^{'} = w_F \pm \Delta w_i^{'} = w_F = \frac{W_F}{\sum_{i=1}^{n} X_i} \quad (30)$$

Since the occupants in different locations of the building have the same ambient temperature, Φ_m equals Φ_{mi}. That is, $w_j^{'}$ is in default equal to w_F.

In actual situation, occupants at different locations demand different actual heat supplies. After fully considering the $w_i^{'}$ and Φ_{mi} of occupants, we converted $w_j^{'}$ from w_F. Through the conversion, the occupants at different locations obtain the same starting point of heat metering. The heat consumption of the occupants at different locations can be calculated by:

$$W_i^{'} = w_i^{'} \bullet X_i = w_F \bullet X_i \times \frac{X_i}{\sum_{i=1}^{n} X_i} \bullet W_F \quad (31)$$

Considering the entire building, the heating target of the building is that: the heat consumed to maintain the indoor temperature of occupants in any room equals the heat supplied by the VAC heating system to that occupant. However, the equality cannot be maintained continuously, owing to practical reasons like the calculation error of heat load, the ventilation heat loss, and real-time indoor temperature control. In the real situation, the converted heat consumption obtained of each occupant can be solved as:

$$w_i^{'} = \frac{\Phi_{mi} - \Phi_q}{\Phi_m - \Phi_q} w_F = \left(1 + \frac{\Phi_{mi} - \overline{\Phi}_m}{\overline{\Phi}_m - \Phi_q}\right) w_F \quad (32)$$

In the real situation, the heat supply to each occupant can be solved as:

$$W_i^{'} = w_i^{'} \bullet X_i = \left(1 + \frac{\Phi_{mi} - \overline{\Phi}_m}{\overline{\Phi}_m - \Phi_q}\right) \times \frac{X_i}{\sum_{i=1}^{n} X_i} \bullet W_F \quad (33)$$

5. EXPERIMENTS AND RESULTS ANALYSIS

In winter, the outdoor temperature is low, and the indoor temperature rises with the heating of the VAC heating system. There are certain differences in the thermal comfort evaluation of occupants on different floors, even under the same heating strategy. Table 1 shows the percentage of thermal comfort distribution of occupants on different floors. It can be seen that the percentage of thermal comfort distribution of occupants in winter under VAC heating mainly concentrated in slightly cold and moderate classes, and rarely fell in strongly cold and strongly hot. This means the occupants adapt well to the ambient temperature of VAC heating.

Table 1. Percentage of thermal comfort distribution of occupants on different floors

Thermal comfort distribution	Tall floor	Middle floor	Low floor
Strongly cold-4	3	9	5
Cold-3	1	5	2
Slightly cold-2	41	3	7
Moderate 1	58	48	48
Slightly hot+3	16	41	36
Hot+1	14	13	12
Strongly hot+4	6	4	7

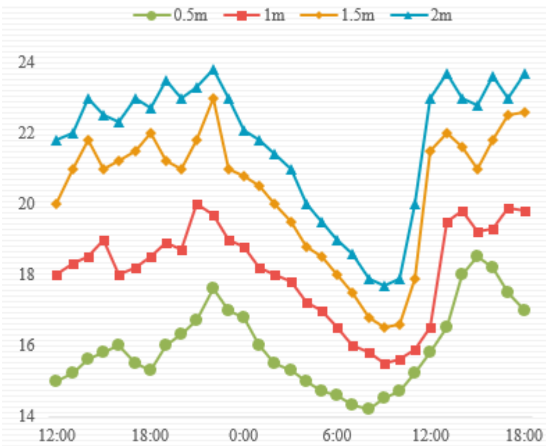

Figure 2. Indoor temperature curves in winter

In winter, the indoor temperatures of different rooms of the target building were measured for two days. Figure 2 shows the indoor temperature variation of rooms at different heights in winter.

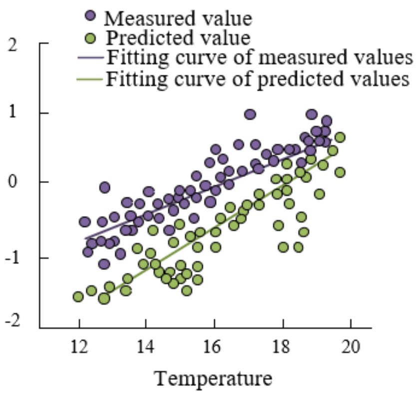

Figure 3. Linear regression results of heat flow in VAC heating system

This paper carries out linear regression between the target temperature of VAC heating system and the measured thermal comfort values of occupants in the target building, and between that temperature and the predicted thermal comfort values of occupants in the target building. The regression results are recorded in Figure 3. It can be seen that the thermal comfort evaluation of occupants had a certain linear relationship with the target temperature. The linear slope between predicted values and the target temperature was greater than that between measured values and the target temperature. Hence, the relationship between predicted values and the target temperature is more sensitive than that between measured values and the target temperature. The measured neutral temperature was not very different from the predicted neutral temperature. This means the occupants in different rooms of the building have a certain adaptability to temperature, but the thermal performance of the building envelope greatly affects the actual thermal comfort evaluation of occupants in rooms of different orientations in the building.

Furthermore, we estimated the heat index of VAC heating area, and further realized the heat metering of the indoor heating area. Table 2 shows the collected data on heat distribution in some rooms of the building. Table 3 gives the calculated heat distribution data. Comparing the two tables, a gap was found between the collected data and the calculated data, which verifies the validity of the proposed heat metering model.

Table 2. Collected data on heat distribution

Room number	Heating area (m^2)	Mean indoor temperature (℃)	Mean outdoor temperature (℃)
1	55.41	22.14	-7
2	66.24	18.47	-7
3	43.51	23.63	-7
4	45.87	20.47	-7
5	46.58	21.95	-7
6	50.87	23.61	-7
7	48.57	22.47	-7
8	65.74	19.68	-7
9	77.64	18.59	-7
10	66.24	19.47	-7

Table 3. Calculated data on heat distribution

Room number	Heating area (m^2)	Mean temperature of occupants (℃)	Building heat consumption index (kW/m^2)	Heat distribution (kW)
1	55.41	22.73	0.263	28.47
2	66.24	18.62	0.263	22.16
3	43.51	21.41	0.263	25.69
4	45.87	25.63	0.263	23.47
5	46.58	18.47	0.263	21.39
6	50.87	20.59	0.263	24.57
7	48.57	22.68	0.263	29.38
8	65.74	19.47	0.263	25.68
9	77.64	19.37	0.263	22.37
10	66.24	24.15	0.263	20.59

Calculations show that the heat gain of occupants obtained without area-based heat metering is the mean of the heat gain of occupants obtained through area-based heat metering. Figure 4 shows the relationship between heat distribution of VAC heating system and mean indoor temperature. The figure was plotted based on the mean indoor temperature of all rooms, and the obtained heat values. It can be seen that, when the indoor VAC heating area is fixed, the higher the VAC heating temperature, the more the heat gain of the occupants; when the VAC heating temperature is relatively low, the occupants gain relatively few heats. The above conditions all satisfy the basic principles of heat metering.

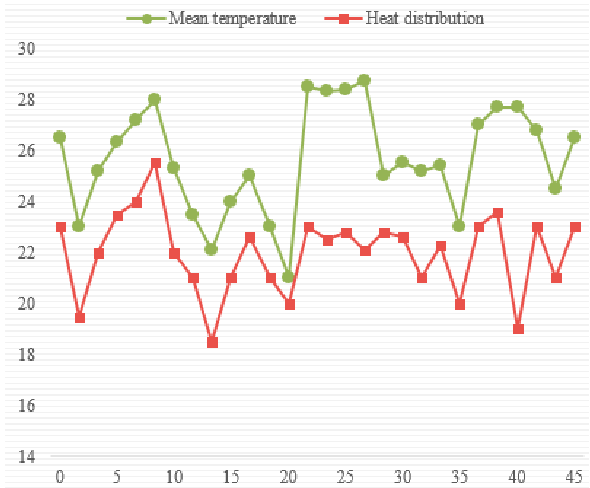

Figure 4. Relationship between heat distribution of VAC heating system and mean indoor temperature

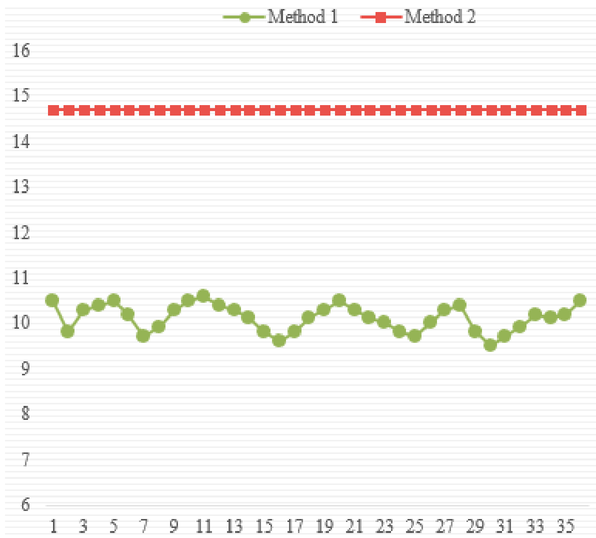

Figure 5. Heat metering charging vs. area charging

Figure 5 compares the experimental results on heat metering charging, and those on area charging. It can be seen that the charging by our heat metering principle reduced the expenditure of occupants, and increased the heat supply to them at the same heating area of the building, than the traditional charging based on heating area. Therefore, our heat metering model for VAC heating area can reasonably allocate the thermal energy of the building, and maximize the energy-saving awareness of occupants, under the premise of minimizing the energy consumption of VAC system.

6. CONCLUSIONS

Considering thermal comfort, this paper devises a method for estimating the heat index of VAC heating area. After analyzing the various factors affecting human thermal comfort, we selected such four environmental factors as indoor air temperature, relative air humidity, mean radiation temperature of envelope surface on human body, and indoor vertical air error, and identified suitable thermal comfort indices to predict and assess the thermal environment under indoor VAC heating. Moreover, we analyzed the indoor heat flow under VAC heating, examined the components of energy consumption of indoor VAC heating, and estimated the heat index of VAC heating area. After that, we established a mathematical model for heat metering, according to the heat consumption of the building VAC, and the composition of the heat consumption of occupants.

Through experiments, we determined the percentage of thermal comfort distribution of occupants on different floors. The results verify that the occupants adapt well to the ambient temperature of VAC heating. Moreover, plotted the indoor temperature curves in winter, and carried out linear regression between the target temperature of VAC heating system and the measured thermal comfort values of occupants in the target building, and between that temperature and the predicted thermal comfort values of occupants in the target building, and estimated the heat index of VAC heating area. Based on the estimation, we further analyzed the relationship between the heat distribution of VAC heating system and mean indoor temperature. Finally, we compared the heat metering charging with area charging. The comparison shows that our heat metering model for VAC heating area can reasonably allocate the thermal energy of the building, and maximize the energy-saving awareness of occupants, under the premise of minimizing the energy consumption of VAC system.

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