Power Saving Management Based on Simulation of Domestic Air Conditioning Operation

Fang Liu*, Hui Zhou
School of Beijing Jiao Tong University, Beijing, China

*Corresponding author e-mail: 17121465@bjtu.edu.cn

Abstract. With the continuous increase of building area and the improvement of people's economic level, the penetration rate of air conditioners in China has continued to rise. Scientific residents' air-conditioning behavior not only helps users save power, but also has important significance for rational planning on the power demand side, smooth operation of the power grid, and alleviating the contradiction between power supply and demand. This paper combines the thermal comfort theory of the human body with the thermal balance theory of the room, and establishes the thermal balance equation and thermodynamic model of the air-conditioned room. Different air-conditioning behavior models are designed for simulation. Through simulation, according to the simulation results, this paper puts forward air conditioning behavior recommendations for residents with different living habits in different cities in the north and south.

1. Introduction

With the continuous improvement of people's economic capabilities, the penetration rate of air conditioners in China is getting higher and higher [1]. The energy consumption of air conditioning systems accounts for about half of the total energy consumption of buildings [2]. A large number of air-conditioning equipment running at the same time will increase the peak-to-valley difference in power and power supply pressure.

Many countries have studied the behavior of air conditioners. In 2001, Raya found that residents' window opening behavior was closely related to people's indoor heat and cold. Yan Bin found that the set temperature of the air conditioner in a certain house was reduced by 1°C, and the energy consumption of air conditioning operation was reduced by about 7%. The team of Zhaojian Li [3] found that the ventilation conditions will affect the power consumption of the air conditioner.

Currently, the rapid increase in air-conditioning load increases the burden on the natural environment. Therefore, effective management of air-conditioning operation is conducive to rational planning on the power demand side and smooth operation of the power grid.

2. Air-conditioned room heat balance model

This chapter studies the various factors that affect people's thermal comfort when the air conditioner is turned on, combining air conditioning design standards and indicators that reflect human thermal comfort.

At present, most domestic air conditioners in China are split air conditioners. Based on the theory of room heat balance, this chapter considers the influence of the set temperature and ventilation of the
air conditioner on the heat balance process of the room, the power consumption of the air conditioner, and the behavior of the user's air conditioner. Finally, a room heat balance model is established.

2.1. Human Thermal Comfort
Numerous environmental factors can affect a person's thermal comfort. The indoor thermal environment has three parameters: temperature, humidity, and airflow. Among them, temperature has the largest weight on comfort [4], followed by humidity and airflow. Under cooling conditions, the Class I thermal comfort level corresponds to an air-conditioning indoor design temperature of 24 to 26°C [5].

According to the PMV (Predicted Mean Vote) index, when the air conditioner is set at 25 °C to 27 °C, the PMV value varies from -0.5 to 0.5, and human comfort is high. At the same time, 26 °C is the temperature value with the PMV value closest to 0 among these three values, and it is the best choice for indoor set temperature.

2.2. Thermal balance model of air-conditioned room
Two important factors that affect residents' air-conditioning behavior are temperature and indoor ventilation. Now consider these two factors influencing the power consumption of air conditioners in the process of room heat balance to build a room heat balance model. Residential air conditioners use split air conditioners.

Now consider the air-conditioning system including the room and air treatment equipment as a thermal system. In summer, the thermal balance of the entire system is:

$$ Q_0 = Q_1 + Q_w + Q_2 $$

Where, Where $Q_0$ is the cooling load of the air conditioner. $Q_1$ is the cooling load of the air-conditioned room. When the cooling load is constant and the outdoor meteorological parameters do not change, its value changes with the thermal characteristics of the envelope structure and the indoor air parameters. $Q_w$ is the fresh air cooling load. The specific enthalpy of indoor air decreases and increases (when the specific enthalpy of outdoor air is constant). $Q_2$ including the increase in the temperature of the fan, the reheat of the fan, and the loss of the cooling (heat) amount of the duct system, the increase in the cooling load.

On this basis, the load frequency table method is used to calculate the energy consumption of the air conditioner for the whole year (or season), in which the total heat $q_e$ and the sensible heat $q_s [kJ / (kg \cdot a)]$. The formula is as follows

$$ q_e = \sum_x [(h_{w,x} - h_N) f_x N] $$

$$ q_s = \sum_x [(t_{w,x} - t_N) f_x N] $$

In the formula, $h_{w,x}$ is the specific enthalpy of outdoor air at a time (kJ/kg); $h_N$ is the specific enthalpy of the indoor design state [6] (kJ/kg); $t_{w,x}$ is the dry-bulb temperature (°C) of outdoor air at a certain time; $t_N$ is Indoor design dry bulb temperature (°C); $f_x$ is the annual (or seasonal) hourly frequency value in percentage of an outdoor air enthalpy (or dry bulb temperature, moisture content value); $N$ is the whole year (or season) Running time (h).

The total energy consumption of the air-conditioning system throughout the year (or season) $Q(kJ / a)$ is shown in equation (4), Where $G$ (kg) is the amount of air being treated.

$$ Q = Q_e + Q_s = Gq_e + Gq_s $$

Now, the room under study is regarded as a whole thermodynamic system, and two subsystems are set up, namely, the indoor air subsystem and the indoor enclosure subsystem. The three subsystems are
combined to establish a general control mode of the room thermodynamic system as equation (5) shows.

\[ \int_{t}^{t+\Delta t} (Q_a + Q_b + Q_c) \, dt = \rho_a V_a C_a (T^{t+\Delta t} - T^t) \]  \hspace{1cm} (5)

Where \( T \) is the indoor air temperature variable, \(^\circ\)C; \( \tau \) is the time variable; \( Q_a \) is the convective heat transferred to the air from each inner surface of the room, W; \( Q_b \) is the heat transferred from the indoor heat source to the air, W; \( Q_c \) is the ventilation exchanged to Heat of air, W.

\[ Q_c = C_a R_a (t_a - T) L \]  \hspace{1cm} (6)

Where \( L \) is the ventilation rate, m\(^3\)/S; \( R_a \) is the density of indoor air, kg/m\(^3\); \( C_a \) is the specific heat of indoor air, J/kg \( \cdot \)\(^\circ\)C; \( t_a \) is the dry bulb temperature of outdoor air, \(^\circ\)C

It can be seen from formula (6) that when the other conditions are the same, the larger the amount of ventilation, the greater the energy consumption of the air conditioner.

3. The influence of air conditioning behavior on power consumption

According to a survey of air conditioner usage and personnel behavior in summer and winter, it is found that there is a north-south difference in power consumption of air conditioners in summer, with the south being higher and the north being lower. In addition, considering the impact of occupation on air-conditioning behavior, residents of different occupations also have different behaviors in using air-conditioning. In addition, ventilation conditions also affect residents' air conditioning behavior.

3.1. Air conditioning behavior patterns in the north and south

This paper selects two typical cities, Beijing and Hangzhou, and establishes four models of Beijing office workers (B1 is replaced in the following tables), Beijing office workers (B2), Hangzhou office workers (H1) and Hangzhou office workers (H2). The air conditioning operation days in Beijing and Hangzhou are 60 days and 90 days respectively. By changing some of the behavior elements individually, we can get different air conditioning behaviors, which are summarized in the following table. The following table shows the air conditioning on time and temperature. Among them, A represents the intermittent operation of the air conditioner (closed when leaving and opened again when returning); B represents the continuous operation of the air conditioner (not closed when leaving); C represents the non-intermittent operation of the air conditioner (not closed when leaving, raising the temperature to 27\(^\circ\)C, reducing the temperature to the original temperature when returning). Among them, air conditioning residents set the temperature at 25\(^\circ\)C, 26\(^\circ\)C and 27\(^\circ\)C. In the simulation process, the three temperatures are selected for simulation according to the scheme in Table 1.

| Mode               | A                     | B                     | C                      |
|--------------------|-----------------------|-----------------------|------------------------|
|                    | 12:00 ~ 16:00        | 12:00 ~ 24:00         | 12:00 ~ 16:00          |
|                    | 20:00 ~ 24:00        | Residence set temperature | Resident set temperature |
| Non-office worker  |                       |                       |                       |
|                    |                       | 16:00 ~ 20:00         | 27\(^\circ\)C           |
|                    |                       | 20:00 ~ 24:00         | Resident set temperature |
| Office worker      | 19:00 ~ 21:00        | 19:00 ~ 1:00          | 19:00 ~ 21:00          |
|                    | 23:00 ~ 1:00         | Residence set temperature | Resident set temperature |
|                    |                       | 21:00 ~ 23:00         | 27\(^\circ\)C           |
|                    |                       | 23:00 ~ 1:00          | Resident set temperature |

Table 1. Behavior of residents in different modes of air conditioning.
3.2. Simulation and Analysis

The typical residential buildings in Beijing and Hangzhou were selected to build a model, and the building room size was: 5m * 5m * 3m. Install the most commonly used split air conditioning system in home air conditioners in the model.

3.2.1. Simulation under different set temperatures. In four modes, when considering the situation that residents leave the room midway, the data of power consumption per unit area of air conditioning is shown in Table 2. Among them, A represents the intermittent operation of the air conditioner (turn off when leaving and turn on when returning); B represents the continuous operation of the air conditioner (turn off when leaving); C represents the non- intermittent operation of the air conditioner (turn off when leaving and adjust the setting and temperature to 27℃, and turn the setting temperature down to the original temperature when returning).

Table 2. Percentage of increase/decrease of air conditioning power consumption compared to A (%).

| Mode | Operation mode | Resident set temperature:25℃ | Resident set temperature:26℃ | Resident set temperature:27℃ |
|------|----------------|-----------------------------|-----------------------------|-----------------------------|
| B1   | A              | 0                           | 0                           | 0                           |
|      | B              | +20.3                       | +18.3                       | 19.7                        |
|      | C              | +2                          | -1.9                        |                             |
| B2   | A              | 0                           | 0                           | 0                           |
|      | B              | +22.1                       | +21.7                       | 21.9                        |
|      | C              | +10.6                       | +11.9                       |                             |
| H1   | A              | 0                           | 0                           | 0                           |
|      | B              | +29                         | +19.6                       | 20.3                        |
|      | C              | +11.3                       | +2.2                        |                             |
| H2   | A              | 0                           | 0                           | 0                           |
|      | B              | +26.4                       | +24                         | 23.4                        |
|      | C              | +12.8                       | +9.89                       |                             |

For the users who choose the air conditioning set temperature of 25℃, the power consumption of mode C is increased by 10.6%, 11.3% and 12.8% respectively compared with mode A in Beijing, Hangzhou and Hangzhou. Therefore, mode A should be selected to save more power in these three modes. For residents of B1, although the power consumption of mode C is increased by 2% compared with mode A, the increase is small. If mode A is adopted, the residents’ comfort is poor. If C mode is adopted, better temperature experience can be obtained immediately when residents return to the room. Therefore, from the comfort point of view, it is recommended to use C mode when leaving the room.

For the users who choose the air conditioning set temperature of 26℃, the power consumption of mode C is 1.9% lower than that of mode A in B1 mode. In this mode, the air conditioner of residents shall be operated in mode C. For H1 residents, the power consumption of mode C is 2.2% higher than that of mode A, but the increase is relatively small. In summer, Hangzhou is hot, so residents should choose mode C to operate air conditioning in terms of comfort. For B2 and H2 people, the power consumption of mode C is increased by 10.9% and 9.7% respectively compared with mode A. Therefore, from the perspective of power saving, mode A should be selected to save more power in the two modes.

For the users who choose the air conditioning set temperature of 27℃, it can be seen from the table that in either mode the power consumption of mode B is greater than that of mode A. In order to save electricity, residents should turn off the air conditioning when they leave the room and turn it on when they come back.
3.2.2. *Simulation under different ventilation volumes.* When the other conditions are the same, under the condition that the air conditioner is set at 25°C and 26°C, the influence of different times of ventilation on the power consumption of the air conditioner is simulated. Only the case where the air conditioner is continuously running in each mode is considered here, that is, based on the case B. In case B, the ventilation rate is 1.0 times/h during air conditioning; D represents the window is closed during air conditioning; E represents 2.0 times/h during air conditioning. The other parameters of B, D, and E in the same mode are the same. The results are shown in Table 3 below.

As can be seen from the Table 3, Changing the amount of ventilation in the room can reduce air conditioning energy consumption.

For residents who choose an air conditioner with a set temperature of 25°C, in the B1, the power consumption of the D mode is 8.6% lower than the power consumption of the B mode, which is less than 10%. For residents of B2, H1 and H2, the energy consumption of the D-type air conditioner was reduced by 15.1%, 18.6%, and 22.1% of the latter, respectively. The reduction is significant. Therefore, for residents of B1, in order to save electricity, the number of ventilations can be reduced. For residents of B2, H1 and H2, It is best to close the windows to achieve better Power saving effect.

For residents who choose an air conditioner with a set temperature of 26°C, under the B1 and B2, the power consumption of the D mode is 7.7% and 8.9% lower than that of the B mode. For residents of H1 and H2, adopting the D method reduces the power consumption of the latter by 16.9% and 18.1%, respectively. The difference between the results may be related to the different meteorological parameters of Beijing and Hangzhou. Therefore, for B1 and B2, the number of times of ventilation should be reduced. For H1 and H2 residents, it is best to close the windows when air conditioning. In addition, under the H2 mode, reducing the ventilation volume has a significant impact on non-worker residents in Hangzhou. When using air-conditioning, residents in this mode can first consider this type of power saving.

When the air conditioner is set to 27°C, residents in the four modes should reduce the number of window openings to achieve power saving effects.

### Table 3. Percentage increase/decrease in air conditioner power consumption compared to B (%).

| Mode | Operation mode | Air conditioning set temperature: 25°C | Air conditioning set temperature: 26°C | Air conditioning set temperature: 27°C |
|------|----------------|---------------------------------------|---------------------------------------|---------------------------------------|
| B    | B              | 0                                     | 0                                     | 0                                     |
| B1   | D              | -8.6                                  | -7.7%                                 | -6.9                                  |
|      | E              | +9.1                                  | +7.3%                                 | +7.1                                  |
| B    | B              | 0                                     | 0                                     | 0                                     |
| B2   | D              | -15.1                                 | -8.9%                                 | -13.1                                 |
|      | E              | +14.7                                 | +13.2%                                | +14.9                                 |
| H1   | D              | -18.6                                 | -16.9%                                | -9.8                                  |
|      | E              | +20.2                                 | +18.2%                                | +15.2                                 |
| H2   | D              | -22.1                                 | -18.1%                                | -17.7                                 |
|      | E              | +21.9                                 | +19%                                  | +18.9                                 |

3.2.3. *Summary of suggestions on air conditioning behavior of residents.* Based on the results in 3.2.1 and 3.2.2, recommendations for air conditioning behavior are shown in Table 4. Among them, 1 has a higher priority than 2, 3 is a power saving recommendation when considering intermittent operation of the air conditioner. In the table, a stands for “Increase the set temperature by 2°C”, b stands for “Increase the set temperature by 1°C”, c stands for “Leave the room halfway and set the air conditioner to operate at 27°C”, d stands for “Reduced ventilation”, e stands for “Close the window operation”.
when the air conditioner is on”, \( f \) stands for “Leave the room, turn off the air conditioner, return to the room, turn on again.”, \( g \) stands for “Keep the temperature of 26°C”.

### Table 4. Energy-saving recommendations for residents’ air-conditioning behavior in 4 modes.

| Mode | Setting temperature: 25°C | Setting temperature: 26°C | Setting temperature: 27°C |
|------|--------------------------|--------------------------|--------------------------|
| B1   | 1) \( a \)               | 1) \( b \)               |                          |
|      | 2) \( d \)               | 2) \( d \)               |                          |
|      | 3) \( c \)               | 3) \( c \)               |                          |
| B2   | 1) \( a \)               | 1) \( b \)               |                          |
|      | 2) \( e \)               | 2) \( d \)               |                          |
|      | 3) \( f \)               | 3) \( c \)               | \( d, f \)               |
| H1   | 1) \( a \)               | 1) \( b \)               |                          |
|      | 2) \( e \)               | 2) \( e \)               |                          |
|      | 3) \( f \)               | 3) \( f \)               |                          |
| H2   | 1) \( e \)               | 1) \( e \)               |                          |
|      | 2) \( a \)               | 2) \( g \)               |                          |
|      | 3) \( f \)               | 3) \( f \)               |                          |

### 4. Conclusion

In this paper, through the study of human thermal comfort, combined with PMV index analysis and room heat balance theory, a heat balance model for split-type air-conditioned rooms is established.

In addition, typical building and meteorological data in Beijing and Hangzhou were selected, and four residential air-conditioning behavior models were established and modeled. Through the analysis of the results, the residents of these four modes were put forward individualized and targeted power saving suggestions. Through research and simulation, it is found that scientific and reasonable residential air-conditioning behavior can not only help residents save electricity, but also have important significance for the rational planning of the electricity-using side and the safe and stable operation of the power grid, saving energy and reducing emissions.

This article only considers the behavior of single-room air conditioners, that is, only one air conditioner is installed per household. In fact, many homes have more than one air conditioner installed. In the future, it may be considered to operate the air conditioner separately in different rooms at the same time for further research.

### 5. Acknowledgments

I would like to thank Professor Hui Zhou for her guidance and help on this thesis.

### References

[1] Dongxu Yang. Research on Evaluation of Energy-saving Models of Public Buildings for Low-carbon Cities, D. Tianjin University, 2014.

[2] Liangguo Li. Reflection and Reconstruction of China's Shale Gas Development Strategy, J. Theory and reform, 2015, (02): 84-6.

[3] Zhaojian Li, Yi Jiang, Qingpeng Wei. Investigation and Analysis of the Impact of Environmental Parameters and Air Conditioning Behavior on Residential Air Conditioning Energy Consumption, J. HVAC, 2007, (08): 67-71+45.

[4] Mingzhi Luo. Study on the Influence of Indoor Air Velocity on Human Physiological Indexes and Thermal Comfort, D. Chongqing University, 2005.

[5] Chenglong He. Research on Integrated Management of Building Energy Efficiency Based on CIMS Environment, J. Building economy, 2006, (11): 84-7.

[6] Wentao Yao. Comparison of Cooling and Heating Sources for Air Conditioning in Water Supply Buildings, D. Xi'an University of Architecture and Technology, 2004.