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Analysis and Optimization of Varying Door and Windows Opening on Energy Consumption and Thermal Comfort in Air-Conditioner Office

Chunming Shen[1,*], Zhicheng Wang[2], Kailu Yao[3], Wenying Yuan[1] and Fangtian Sun[2]

[1]*Institute of Urban Systems Engineering, Beijing Academy of Science and Technology, Beijing 100089, China*
[2]*Beijing Building Energy Efficiency and Comprehensive Utilization Engineering Technology Research Center, Beijing University of Civil Engineering and Architecture, Beijing 100044, China*
[3]*Department of Urban Construction, Beijing City University, Beijing 101399, China*

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Abstract

The energy consumption of air conditioners (ACs) in buildings is particularly high during summer, thus placing high demands on indoor thermal comfort. However, previous studies have only focused on a single factor either AC energy consumption or indoor thermal comfort, and only a few comprehensive analyses have attempted to optimize the AC energy consumption and indoor thermal comfort in buildings during summer. In this study, the comprehensive evaluation model was introduced to quantitatively evaluate the performance of different ventilation and cooling systems. A total of 48 orthogonal tests were conducted to evaluate cooling efficiency under different working conditions. The degree of door and window opening/closing and the AC setpoint temperature were considered in the test, and the degree–power index was proposed as an evaluation metric. The effects of multiple working conditions on the energy consumption and thermal comfort of a single AC office were estimated using the Gray-Technique for Order Preference by Similarity to an Ideal Solution (GRA-TOPSIS) model. Results show that, AC energy consumption is positively correlated with the degree of door and window opening/closing, especially at an AC setpoint temperature of 28 ℃. The increase in energy consumption is especially significant, thereby highlighting the importance of window and door management in controlling the energy consumption of buildings at high summer temperatures. Meanwhile, reducing the AC setpoint temperature improved the comfort of the indoor environment. Opening one window at an AC setpoint temperature of 26 ℃ provides the best balance between energy saving and thermal comfort. The experiments demonstrate that optimizing the degree of door and window opening/closing and setting rational AC temperatures not only ensure thermal comfort but also effectively reduce energy consumption in buildings.

Keywords: Door and Window Status, Energy Saving, Thermal Comfort, GRA-TOPSIS, Multi-Index Evaluation

1. Introduction

Currently, energy consumption and protection of the environment have become global challenges. The problem of energy consumption in the building sector is particularly prominent, restricting the process of sustainable development of buildings and their energy equipment. With the accelerated pace of global urbanization, the energy consumption in the operation of buildings has become a major component of energy consumption, with buildings accounting for 34% of global energy demand and approximately 21% of global greenhouse gas emissions in 2022 [1]. In particular, the extensive use of air-conditioning and refrigeration systems in hot summer weather not only consumes large amounts of energy [2], but also has a potentially adverse impact on the environment. In China, the problem of building energy consumption has become increasingly prominent along with the rapid economic growth. In 2022, the average annual growth rate of energy consumption in China's building operations was more than 5%, and the related carbon emissions accounted for 21.3% of the building's whole life-cycle carbon emissions, or about 1.06 billion tons of standard coal, of which heating and cooling contributes to about 80% [3], exacerbating the pressure on the energy supply.

To address this challenge, the Chinese government has proposed the Carbon Peaking and Carbon Neutrality Goals, striving to achieve carbon peaking by 2030 and carbon neutrality by 2060 [4,5]. Energy efficiency in buildings is regarded as one of the key ways to achieve double goals and is highly valued. In particular, building cooling energy consumption in summer is closely related to air-conditioner usage behavior and the state of building body openings [6]. Therefore, it is of great practical significance for building energy efficiency optimization to study and analyze the changes in cooling energy consumption under different window and door openings and their impact on the indoor thermal environment.

Sociological, psychological, and environmental–physical factors that influence the usage time, setpoint temperature, operating mode, and other related behaviors of air-conditioner (AC) have been investigated in previous studies on the energy consumption of ACs and indoor thermocomfort [7]. Several studies have established a relationship between AC usage behavior and the users' lifestyles, awareness of energy costs, and indoor and outdoor environmental parameters through numerical simulations, real measurements, or questionnaire surveys. Valuable insights have also been provided for optimizing the control strategies for AC systems and enhancing their operational

*E-mail address: Chunming_Shen@126.com
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efficiency. However, a systematic quantitative analysis and evaluation of the effects of door and window opening/closing states is lacking. Doors and windows are the main channels for indoor and outdoor heat exchange in buildings. Therefore, their opening and closing inevitably affect the indoor thermal and humidity environment and lead the AC cooling load to affect energy consumption and thermal comfort [8]. The mechanism of influence and its quantitative relationship have also been ignored in the literature. Previous studies have mainly concentrated on a single factor, such as AC energy consumption or thermal comfort, and rarely investigate comprehensive multi-objective optimization. Comprehensive optimization strategies that take into account energy conservation and thermal comfort enhancement also warrant further research. Once developed, these strategies are poised to yield the dual benefit of reduced AC energy consumption and enhanced comfort level in indoor environments.

This study quantitatively analyzed the energy savings and thermal comfort in a single AC office under different door and window opening/closing conditions. An orthogonal test was designed, and the test factors were set for different door and window opening/closing conditions and setpoint temperatures. The cooling energy consumption and indoor thermal environment response under different working conditions were systematically analyzed using a multi-indicator evaluation model and the measured data obtained from a test platform. This study has also quantified the effect of door and window opening/closing on the operation of the AC system. The findings are combined with a multi-objective optimization strategy to provide a scientific basis for planning and optimizing AC operations.

2. State of the art

Many scholars have explored the effects of human behavior on building confinement and the impact of AC usage behavior on heating, ventilation and air conditioning (HVAC) system energy consumption and building occupant comfort. For instance, Yang Z. et al. [9] identified the key factors affecting indoor AC performance by conducting questionnaire surveys and objective field tests and found that eliminating draughts and providing fresh air were essential requirements for cooling. They also found that indoor AC energy efficiency may be affected by indoor temperature distribution. Shen C. et al. [10] investigated how the opening and closing of building doors and windows affect the cooling performance of a single AC. They adopted a single-factor analysis approach to analyze the dynamic correlation between THI and AC power consumption, explored indoor environment and energy efficiency, and offered suggestions for analyzing AC performance. They found that the correlation between AC power and the degree of windows or door opening/closing affects indoor comfort. Specifically, closing doors and windows and increasing the AC cooling temperature can reduce the AC cooling runtime, especially when the cooling temperature exceeds 26 ℃. Lyu J. et al. [11] conducted a questionnaire survey to understand the indoor thermal comfort zones for males and females under the operation of a combined cooling and ventilation system (FACS). Results show that FACS reduces the energy consumption of the HVAC system by 16%, thus increasing the indoor thermal comfort zones for both genders. The effects of indoor thermal comfort and AC energy consumption under different operating conditions were also analyzed based on actual measurements. Nonetheless, these analyses mostly focused on a single factor, and a comprehensive multifactorial analysis is yet to be conducted.

Some scholars have explored the relationship among human behavior, HVAC system energy consumption, and indoor thermal comfort by using real measurements and questionnaire surveys and even extended their investigations by performing simulations. Uno Tomoko et al. [12] analyzed the indoor thermal environment and assessed the energy consumption of ACs based on measured and simulated data. They found that air tightness and well-controlled ventilation are essential for achieving energy efficiency in buildings. They also proposed night-time ventilation as a strategic measure to reduce the energy consumption for residential cooling in climates with high heat and humidity. Reducing high indoor humidity through ventilation is particularly effective in enhancing indoor thermal comfort. Winkler et al. [13] evaluated the sensitivity of indoor humidity to changes in cooling setpoints, AC capacity, and fan control parameters by simulating typical homes in 10 US cities. Schünemann C. et al. [14] conducted surveys and simulations to determine the effects of different window ventilation behaviors on thermal comfort in dwellings. They found that the duration, timing, and type of window openings significantly affect the level of overheating. Keeping the windows and doors fully open can reduce the overheating of the building mass even if this ventilation is limited to the early morning and late evening periods. Daytime ventilation during the summer increases AC energy consumption and reduces indoor thermal comfort.

In their EnergyPlus simulation, Sekartaji D. et al. [15] found that increasing natural ventilation by opening doors and windows significantly affects indoor thermal comfort in classrooms. Continuous natural ventilation increased the indoor cooling load by 1.06 to 1.75 times, while natural ventilation at hourly intervals increased the cooling load by 1.05 to 1.46 times. Increasing the AC temperature can also effectively reduce cold load under natural ventilation conditions. P. V. Sasidhar et al. [16] proposed that the natural ventilation of classrooms in hot and humid environments can effectively reduce the consumption of energy-intensive environmental control systems and argued that the use of natural ventilation and thermal-adaptation-based strategies can significantly reduce discomfort. Moghadam et al. [17] summarized the challenges faced by HVAC systems with ventilation between 2020 and 2023 as follows: (1) the increased energy consumption after introducing ventilation, (2) the absence of effective control strategies, and (3) the lack of relevant studies on different types of buildings. They called for future studies to formulate optimization strategies for minimizing energy consumption while maintaining optimal indoor air quality. They also analyzed the relationship between AC energy consumption and indoor thermal comfort across different conditions by adopting an orthogonal experimental design, which effectively reduced the potential distortion of analog simulation during the testing process.

Ventilation significantly impacts AC power consumption and the indoor thermal environment, especially when doors and windows are open. Unlike previous studies, the current study takes into account multiple factors in the analysis. Lu G. et al. [18] developed an optimal control interval using a fuzzy control algorithm to achieve longer thermal comfort days with lower energy consumption levels. Pan L. et al. [19] optimized building performance using NSGA-II, an effective optimization tool that considers thermal comfort and energy consumption, and designed a comprehensive evaluation and analysis scheme based on discrete operating condition tests to determine the best operating conditions. Xin S. et al. [20] simulated the effects of floor ACs with different airflow organizations on indoor environment and energy efficiency via CFD, with air supply temperature and air supply velocity as input parameters, and then applied data envelopment analysis to assess the efficiency of the simulated scenarios in achieving the optimal layout and settings. The introduction of integrated analysis provides a solution to the Multi-indexes evaluation

Opening and closing doors and windows in buildings significantly influence AC system operations and indoor thermal comfort. Previous studies have analyzed the effects of buildings, AC, and the environment by using various methods, such as simulations and experiments with few test conditions. However, only a few studies have quantitatively analyzed the impact of the degree of door and window opening/closing under real experimental conditions and comprehensively optimized those energy-saving methods that take AC energy consumption and indoor thermal comfort into account.

To address these gaps, this study has investigated the impact of different ventilation methods on AC energy consumption and indoor thermal comfort based on an orthogonal experimental design. This design has quantitatively analyzed the energy savings and thermal comfort in a single AC cooling office under various door and window configurations. A multi-indicator evaluation method has been also applied to compare different working conditions and to offer scientific foundation for the planning and optimization of AC operations.

The rest of this study is organized as follows. The experimental design and comprehensive analysis methods are described in Section 3. The experimental single-factor results are analyzed in Section 4. The correlation analysis, corrections, and comprehensive evaluation of different working conditions are presented in Section 5. The research summary and conclusions are presented in Section 6.

3. Methodology

3.1 Similarity ratio and test materials

3.1.1 Test scenario

The test site was located in Xizhimen, Xicheng District, Beijing, and the test room was an ordinary office located on the 2nd floor of a 4-story office building. The test room has a floor area of 27.5 m^2 (5.50 m×5.00 m), located in the back of a shaded area, and has north-facing windows. The exterior enclosure on the north side includes two windows, and the interior wall on the south side includes a door. The remaining walls, except for the exterior wall on the back side, are all interior walls and do not adjoin the AC room. The door opens in a flush mode, and the windows open in a sliding mode. The specific structural dimensions of this room are listed in Table. 1.

The room is equipped with a KFR-50GW 50556Ba-3 wall-mounted AC. The temperature control is the start-stop control of the compressor with a dead zone (with a width of 0.5 ℃) and without a frequency conversion device. The AC has a cooling capacity of 5000 W, power supply of 220 V/50 Hz, a cooling power of 1587 W, and a circulating air volume of 850 m3. Based on the rated output power and room area, the capacity of the AC was computed as about 180 W/m^2.

Table 1 Test room enclosure dimensions

Envelope	Length/m	Height/m	Thickness/m
North exterior wall	5.50	3.50	0.45
East/West inner wall	5.00	3.50	0.30
South inner wall	5.50	3.50	0.30
Window	1.40	1.70	—
Door	0.90	2.10	—

The weather during the test period was sunny to cloudy with an average maximum outdoor temperature of about 34 ℃. The test was conducted from 11:30 to 17:30 each day, and two computers worked indoors during the test.

3.1.2 Monitoring system

The test was conducted in a single room within a brick-constructed office building. The monitoring system design schematic is shown in Fig. 1, including the basic information of the building room, fixed-frequency AC, and indoor air parameters detection system.

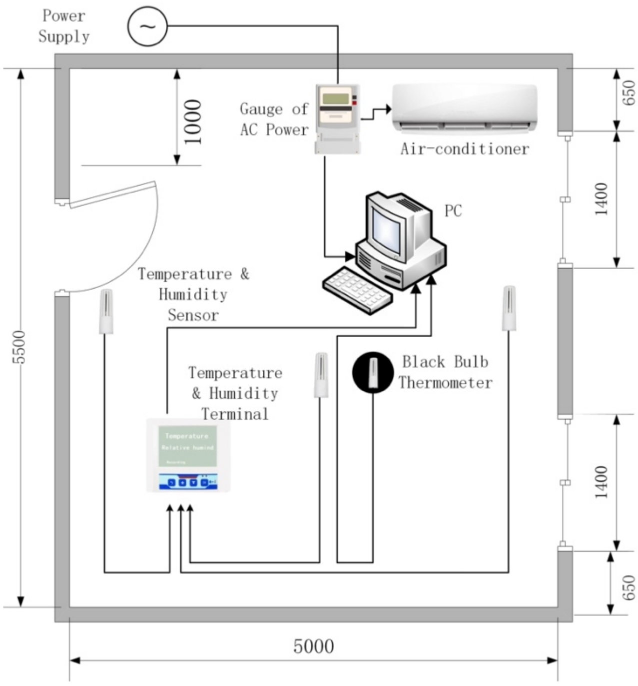

Fig. 1. Experimental monitoring system diagram

A parameter monitoring system was used to monitor the electric power and indoor environment parameters. The electric power parameters were monitored using a non-invasive single-phase electric power monitoring terminal (Beijing Zhixiang Science and Technology Co. Ltd.), while the indoor environment parameters were monitored using a USB-type temperature and humidity recorder (JD Renco Company) and a AZ8758 black ball thermometer (Taiwan Hengxin Company). The monitoring parameters of the sensors and the frequency of the signal acquisition are shown in Table 2.

Table 2. Monitoring equipment and signal collection frequency

Sensors	Parameters	Frequency/s
Single-phase power monitoring terminal	Voltage, Amps, Active power	10
USB-type temperature and humidity recorder	Air temperature, Relative humidity	10
AZ8758 black ball thermometer	Blackball temperature	10

3.1.3 Test conditions
Prior the test, the door and windows were opened to ventilate the room and to set the starting temperature for the environment. Afterward, the door and window openings were adjusted, and the AC setpoint temperature was set at 24 ℃, 26 ℃, and 28 ℃. Each condition was tested for 30 min, and the changes in the power consumption and indoor environmental parameters of the AC under different degrees of door and window opening/closing were measured across the three setpoint temperatures. Based on historical documentation, AC users usually prefer setting the wind speed to Auto [21]. Therefore, the wind speed of air was set to Auto. Given the large area of the test room, three temperature sensors were arranged, and their captured values were averaged to determine the average room temperature for achieving indoor thermal comfort. The temperature-specific test conditions were set to 28 ℃. In Table. 3, the test number of the former represents the AC set temperature group, while the test number of the latter represents the test conditions number of each group.

Table 3. Experimental conditions with a set temperature of 24℃

Test No.	Set Point/℃	Door opening	Windows opening
1-1	24	0%	0%
1-2	24	0%	50%
1-3	24	0%	100%
1-4	24	0%	200%
1-5	24	33%	0%
1-6	24	66%	0%
1-7	24	100%	0%
1-8	24	33%	50%
1-9	24	33%	100%
1-10	24	33%	200%
1-11	24	66%	50%
1-12	24	66%	100%
1-13	24	66%	200%
1-14	24	100%	50%
1-15	24	100%	100%
1-16	24	100%	200%

3.2 Test procedure and analysis
The overall test and analysis flow is shown in Fig. 2. Prior the experiment, the experimental room was ventilated by opening the door and windows, and the indoor temperature was restored to 29 ℃. After reaching the desired test condition, the ventilation behavior was simulated for 30 min. During the test, the horizontal height was recorded as 1 m, the air temperature and relative humidity were set at 3 points, the black sphere temperature was set at 1 point, and the AC power was running in real time. At the end of the experiment, the door and windows were opened and left to stand, and the above steps were repeated. The original data and calculations of the thermal comfort were processed and checked for anomalies. If any anomalies were observed, then these data were discarded, and the experiment was repeated. All experimental working condition data were collated, the weights under different focus ratios were determined, comprehensive evaluation and analysis were conducted, and the different types of working conditions under all weights were ranked.

3.3 Methods for analysis of AC and indoor thermal comfort

3.3.1 Degree-power index
Summer AC cooling power is closely related to the indoor temperature and outdoor meteorological environment, which directly affects cooling energy consumption. Therefore, the interference of the initial temperature environment should be minimized in the energy consumption test. The degree–power index takes into account the variations in energy consumption and air temperature, thus offering a more comprehensive performance assessment. To eliminate the influence of the initial temperature on the changes in room and air temperature, the degree–power index was used to measure the current working conditions as follows:

$$\varepsilon = \frac{E}{\Delta T} \tag{1}$$

$$\Delta T = \max(T_i) - \min(T_i) \tag{2}$$

where ΔT is the difference between the maximum and minimum indoor air temperatures in the experimental room during the test period, ℃, and E is the cumulative power consumption during the test, kWh. The degree–power index provides a better measure of the relationship between power consumption and AC cooling effect. A lower index indicates a lower power consumption required by the AC to produce an indoor cooling temperature difference of 1 ℃ (i.e., the AC is more efficient). This index helps eliminate the effect of deviations in power consumption due to different set temperatures.

3.3.2 PMV thermal comfort model
The predicted mean vote (PMV) is used to evaluate human thermal comfort in indoor thermal environments and reflects the variation in indoor thermal comfort under dissimilar working conditions. Fange and Toftum [22] used the PMV obtained in artificial experiments involving an AC system to capture the indoor parameters. Therefore, the PMV test regression equation is only applicable to thermal environments where the indoor parameters are stable and uniformly distributed around the human body [23]. PMV was used as a reference indicator of thermal comfort in the experiment and was computed as follows:

$$PMV = (0.303\mathrm{e}^{-0.036M} + 0.028)L \tag{3}$$

where L is the solution to the heat balance equation, which represents the heat exchange between the body and the environment and is computed as:

$$L = \begin{cases} (Met - W) - 3.05\times10^{-3}[5573 - 6.99\times(Met - W) \\ -Pa] - 0.42[(Met - W) - 58.15] - 1.7\times10^{-5} \\ Met(5867 - Pa) - 0.0014 Met\times(34 - t_a) \\ -3.96\times10^{-8} f_{cl}[(t_{cl}+273)^4 - (\overline{t_r}+273)^4] \\ -f_{cl}h_C(t_{cl} - t_a) \end{cases} \tag{4}$$

Where Met is the metabolic rate, and a metabolic equivalent met = 1.20 (office sitting) was selected (i.e., 70 W/m^2). W denotes the mechanical power, W/m^2, Pa is the water vapor pressure, Pa, t_a is the air temperature, °C, f_{cl} is the ratio of the surface area of the dressed human body to the surface area of the exposed human body, t_{cl} is the surface temperature of the garment, °C, $\overline{t_r}$ is the average radiant temperature, °C , and h_c is the convective heat transfer coefficient, W/m^2·K. These t_{cl}, h_c and f_{cl} are computed as:

$$t_{cl} = 35.7 - 0.028 - I_{cl}\{3.96\times10^{-8} f_{cl} \times[(t_{cl}+273)^4 - (\overline{t_r}+273)^4] + f_{cl}h_c(t_{cl}-t_a)\} \quad (5)$$

$$h_c = \max\{2.38(t_{cl}-t_a)^{0.25}, 12.1\sqrt{\mathrm{v_{ar}}}\} \quad (6)$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 I_{cl}, I_{cl} \leqslant 0.078 m^2 \cdot ℃ / W \\ 1.05 + 0.645 Icl, I_{cl} > 0.078 m^2 \cdot ℃ / W \end{cases} \quad (7)$$

where I_{cl} is the clothing thermal resistance, the I_{cl} is to 0.085 °C/W. where v_{ar} is the airflow velocity, m/s, and $\overline{t_r}$ is the average radiation temperature, which is computed as:

$$\overline{t_r} = t_g + 2.73\sqrt{\mathrm{v_{ar}}}(t_g - t_a) \quad (8)$$

where t_g is the black ball temperature, °C.

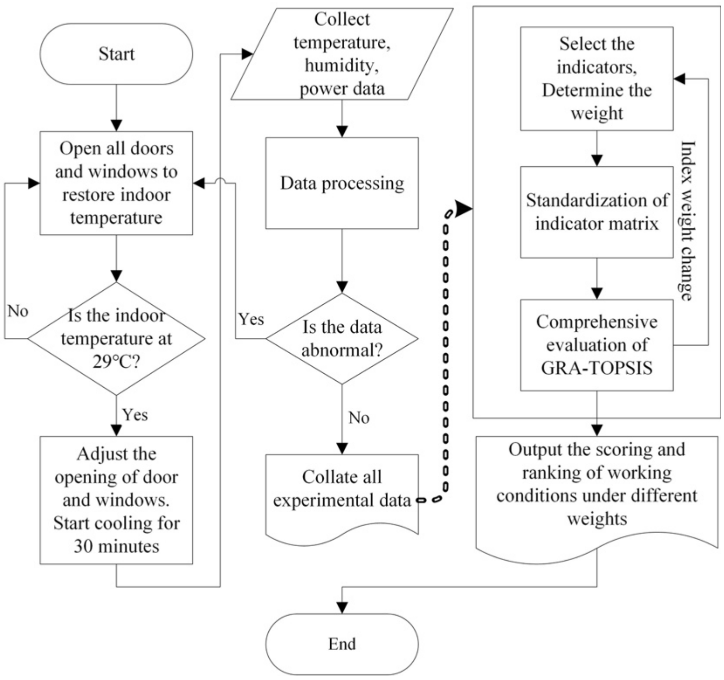

Fig. 2. Experiment and data processing flow chart

According to GB/T 18049-2017, the ergonomics of thermal environments should comply with the requirement that the human body is in a thermally comfortable environment (Table. 4).

Table 4. Indoor environment thermal comfort requirement

PMV	PPD/%	ΔT/°C
-1.0 < PMV < +1.0	<15	3

3.3.3 GRA-TOPSIS model

Gray correlation analysis (GRA) reflects the degree of geometric similarity between the evaluation sequences and the optimal sequence. The lack of non-linear or non-monotonic relationships in the data can distort the evaluation results, and analyzing some strong correlation indicators may lead to an unreasonable allocation of weights and the ineffectiveness of most indicators [24]. To overcome these challenges, this study applies GRA-Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) analysis, where grey relative proximity was used to replace the Euclidean geometric distance, the proximities of the evaluation sequences to the optimal and worst sequences were calculated, and the schemes were ranked by the combined grey proximity.

Step 1) Construct and standardize a matrix of raw indicators.

$$\boldsymbol{X}_{m\times n} = \begin{bmatrix} x_{11} & \cdots & x_{1j} \\ \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} \end{bmatrix} = \left(x_{ij}\right)_{m\times n} \quad (9)$$

where $\boldsymbol{X}_{m\times n}$ is the constructed $m\times n$ evaluation matrix, and x_{ij} is the element of rows i and j.

Step 2) Normalize the original evaluation matrix to obtain the standard matrix $\boldsymbol{Y}_{m\times n}$.

$$y_{ij} = \begin{cases} \dfrac{x_{ij}}{\max x_{ij}}, j = 1,2,3,...,n \\ \text{When the sequence j is a positive indicator.} \\ \dfrac{\min x_{ij}}{x_{ij}}, j = 1,2,3,...,n \\ \text{When the sequence j is a negative indicator.} \end{cases} \quad (10)$$

$$\boldsymbol{Y}_{m\times n} = \begin{bmatrix} y_{11} & \cdots & y_{1j} \\ \vdots & \ddots & \vdots \\ y_{i1} & \cdots & y_{ij} \end{bmatrix} = \left(y_{ij}\right)_{m\times n} \quad (11)$$

where $\boldsymbol{Y}_{m\times n}$ is the normalized m × n criterion matrix, and y_{ij} is the element of rows i and j in the evaluation matrix.

Step 3) Determine the optimal and worst sequences.

$$\begin{cases} \boldsymbol{Z}_j^+ = [z_1^+, z_2^+, ..., z_j^+], z_i^+ = \max\limits_{i=1}^{m} \{y_{ij}\} \\ \boldsymbol{Z}_j^- = [z_1^-, z_2^-, ..., z_j^-], z_i^- = \min\limits_{i=1}^{m} \{y_{ij}\} \end{cases} \quad (12)$$

where $\boldsymbol{Z}_j^+$and $\boldsymbol{Z}_j^-$are the optimal and worst sequences, respectively, and z_i^+ and z_i^+ are the maximum and minimum values in the no. j indicator.

Step 4) Calculate the gray superiority correlation based on equation (12).

$$\zeta_{ij}^+ = \frac{\min\limits_i \min\limits_j |z_i^+ - y_{ij}| + \xi \max\limits_i \max\limits_j |z_i^+ - y_{ij}|}{|z_i^+ - y_{ij}| + \xi \max\limits_i \max\limits_j |z_i^+ - y_{ij}|} \quad (13)$$

$$\zeta_{ij}^- = \frac{\min\limits_i \min\limits_j |z_i^- - y_{ij}| + \xi \max\limits_i \max\limits_j |z_i^- - y_{ij}|}{|z_i^- - y_{ij}| + \xi \max\limits_i \max\limits_j |z_i^- - y_{ij}|}$$

where ζ_{ij}^+ and ζ_{ij}^- are the grey superior and inferior closeness of condition i to the optimal and inferior sequences, respectively. The resolution factor ξ is generally taken as an empirical value of 0.5.

Step 5) Calculate the GRA-proximity of each evaluation object based on the grey correlation coefficient.

$$D_i = \sum_{j=1}^{n} \omega_j \frac{\zeta_{ij}^+}{\zeta_{ij}^+ + \zeta_{ij}^-} \quad (14)$$

where ω_i represents the weights of different indicators.

4. Result analysis and discussion

The operating condition indicator data used in the test trials are shown in the **Auxiliary Information**. $\overline{\text{PMV}}$ denotes the average PMV at all times during the test period. Power consumption was calculated as the sum of the quasi-dynamic power consumption, standby power consumption, start-up power consumption, running power consumption, and compressor shutdown power consumption. The degree–power index was calculated as shown above. The 48 tests were divided into 3 groups of operating conditions, and the tests in each group were assigned sequential numbers.

4.1 Analysis of AC power consumption

The 16 conditions were divided into 5 groups. Group 1 consisted of working condition sequences 1 to 4 to observe the effect of changes in the degree of window opening/closing on the power consumption and degree–power index when the door was closed. Group 2 consisted of working condition sequences 1, 5, 6, and 7 to observe the effect of changes in the degree of door opening/closing when the windows were closed. Groups 3 (including sequences 5, 8, 9, and 10), 4 (including sequences 6, 11, 12, and 13), and 5 (including sequences 7, 14, 15, and 16) observed the effect of changes in the degree of window opening/closing when the door was left 33%, 66%, and 100% open, respectively. Groups 2 to 7 were considered non-convective groups, while groups 8 to 16 were considered convective groups.

The AC setpoint temperature has a significant impact on power consumption As shown in Fig. 3, at a setpoint temperature of 24 °C, power consumption gradually increased as the degree of door and windows opening/closing increased. Opening the door or windows increased the power consumption by approximately 0.044 kWh and 0.016 kWh, respectively. In the other setpoint temperatures, even if the degree of door opening/closing was fixed, opening the window increased the power consumption. A comparison between the convection and non-convection groups showed that the average power consumption of the non-convection group is 0.695 kWh, which is slightly lower than that of the convection group (0.721 kWh, representing a 3.74% increase). A similar trend was observed at the AC setpoint temperature of 26 °C, but the electrical energy consumption increased by only about 0.001 kWh to 0.009 kWh. Opening the windows also increased the electrical energy consumption at higher setpoint temperatures even when the degree of door opening/closing was fixed. In addition, the average energy consumption of all convection groups was 0.731 kWh, which was higher than that of the non-convection group (0.709 kWh, representing a 3.10% increase). Although the convection group was more effective in terms of ventilation, a corresponding increase was observed in its consumption of electrical energy.

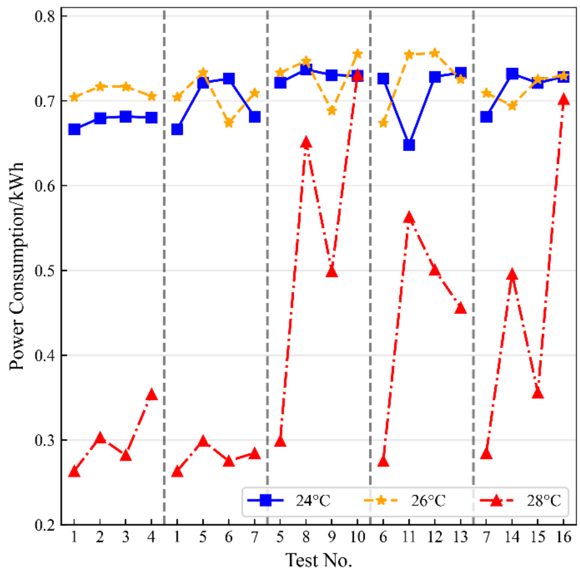

Fig. 3. Power consumption under all working conditions

At the setpoint temperature of 28 °C, increasing the degree of door and window opening significantly increased the power consumption. The average power consumption of the convection group was much higher than that of the non-convection group (0.551 kWh and 0.300 kWh, respectively, representing an 83.7% increase). As the degree of door and windows opening/closing increased, the downtime of the AC compressor decreased, thus increasing AC energy consumption. In the non-convective group, the hot outside air only had minimal impacts on the setpoint temperature of 28 °C but still led to an increase in energy consumption. An anomalous state of reduced power consumption was observed in some test scenarios, which may be attributed to the fact that the indoor thermal balance is very easily disturbed by external meteorological conditions due to the dead zone of the AC temperature control of the set temperature of T ± 0.5 °C.

4.2 Analysis of degree-power index

The degree–power indexes under different working conditions are shown in Fig. 4. Processing the degree–power index can eliminate the large differences in power consumption shown in Fig. 3, which may be due to the switching off of the AC at different setpoints. Groups A and B, C and D, and E, F correspond to the AC setpoint temperatures of 24 °C, 26 °C, and 28 °C, respectively. A1 represents the average change in the degree–power index of four groups when the degree of door opening is 0%.

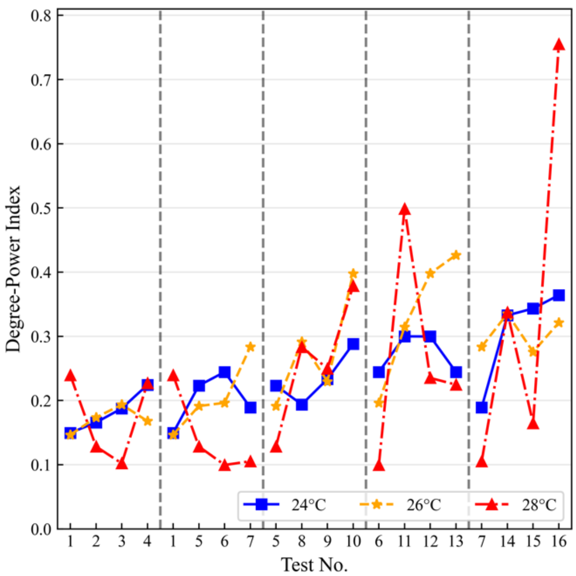

Fig. 4. Degree-Power Index under all working conditions

As shown in Table. 5, the overall average changes for groups A and B are 0.063 and 0.090, respectively, when the AC setpoint temperature was 24 °C. Window opening had a greater effect on the degree–power index than door opening. The most dramatic change was observed in A4, where the degree of window opening significantly affected the degree–power index when the door was fully open.

At the setpoint temperature of 26 °C, the average changes for groups C and D were 0.075 and 0.110, respectively. Opening windows had a greater effect on the degree–power index than opening doors. The most drastic change was reported in C4, where the degree of window opening significantly influenced the degree–power index when the door was fully open.

At the setpoint temperature of 28 °C, the average changes for groups C and D were 0.086 and 0.123, respectively. Opening the windows had a greater effect on the index than closing the door. The most dramatic change was reported in F4, where the degree of window opening significantly affected the degree–power index when the window was fully open.

At setpoint temperatures of 24 °C and 26 °C, the effect of opening the external windows on the indoor thermal environment was greater than that of opening the doors. Keeping the windows slightly open when ventilation and air exchange are needed (i.e., the window is half open, while the door is fully open) is a tried and tested ventilation and energy-saving strategy. The greatest increase in the degree–power index was reported at a setpoint temperature of 28 °C because as the degree of door and window opening/closing increased, the heat flow from outside also increased and broke the equilibrium in the room. While the maximum temperature difference in the room did not change much in the start–cool–shutdown cycle of the AC, the AC power consumption increased as a result. Therefore, the degree–power index significantly increased at the setpoint temperature of 28 °C.

Table 5. Average changes in electricity indicators

Group Name	Door	Windows	ΔDegree-Power Index
A1	0%	—	0.043
A2	33%	—	0.015
A3	66%	—	0.037
A4	100%	—	0.158
B1	—	0%	0.069
B2	—	50%	0.110
B3	—	100%	0.104
B4	—	200%	0.750
C1	0%	—	0.032
C2	33%	—	0.115
C3	66%	—	0.183
C4	100%	—	0.027
D1	—	0%	0.077
D2	—	50%	0.140
D3	—	100%	0.107
D4	—	200%	0.214
E1	0%	—	-0.128
E2	33%	—	0.245
E3	66%	—	0.114
E4	100%	—	0.226
F1	—	0%	-0.087
F2	—	50%	0.175
F3	—	100%	0.220
F4	—	200%	0.314

4.3 Analysis of correlation

The parameters affecting thermal comfort were determined by indoor air temperature and humidity. While indoor thermal comfort could change drastically due to the air flow after opening the windows and doors, the outdoor temperature and humidity can potentially affect indoor thermal comfort. Similarly, those parameters affecting AC power consumption are closely related to outdoor parameters. The $\overline{PMV}$ and AC power consumption were analyzed and corrected by considering the Pearson correlation coefficients of outdoor temperature and outdoor humidity on $\overline{PMV}$ and AC power consumption in conjunction with indoor heat balance equations.

4.3.1 Correlation analysis of outdoor temperature and power consumption

The scatter plot of the distribution of outdoor temperature and average indoor temperature is presented in Fig. 5, and the correlation coefficients and significant P-values for different setpoint temperatures are listed in Table 6. The correlation was weaker at the AC setpoint temperature of 24 °C and stronger at 26 °C, thereby allowing for a linear regression. The significance levels of these two setpoint temperatures were lower than 0.005, and the significance level of the 28 °C setpoint temperature was greater than the test value of 0. Therefore, the outdoor meteorological parameters during the test were assumed to slightly influence the AC power consumption at a setpoint temperature of 28 °C, and no significant correlation was observed.

Table. 6. Correlation analysis between outdoor humidity and power consumption

Setpoint	γ_p	P-value
24°C	0.658	0.0060
26°C	0.896	0.0002
28°C	0.067	0.8040

4.3.2 Correlation analysis of outdoor weather and average PMV

The scatter plot of the distribution of outdoor temperature versus mean indoor temperature is shown in Fig. 6, while the correlation coefficients and corresponding P-values for various setpoint temperatures are listed in Table. 7. The significant levels of the three setpoint temperatures were below 0.005, indicating a linear regression. The correlation coefficient was greater than 0.7, thereby suggesting that $\overline{PMV}$ is correlated with outdoor temperature.

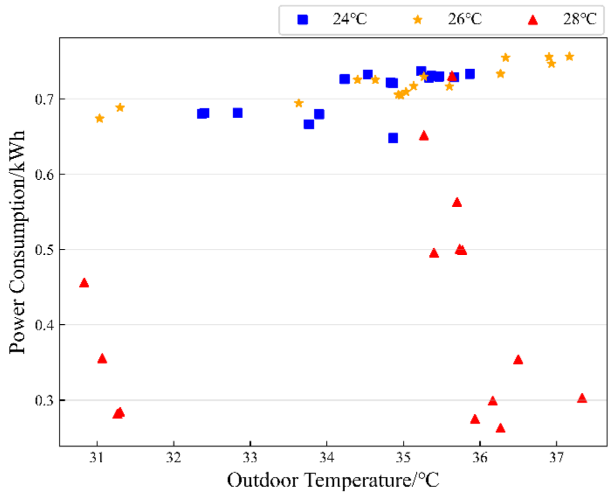

Fig. 5. Scatter plot of outdoor temperature and power consumption

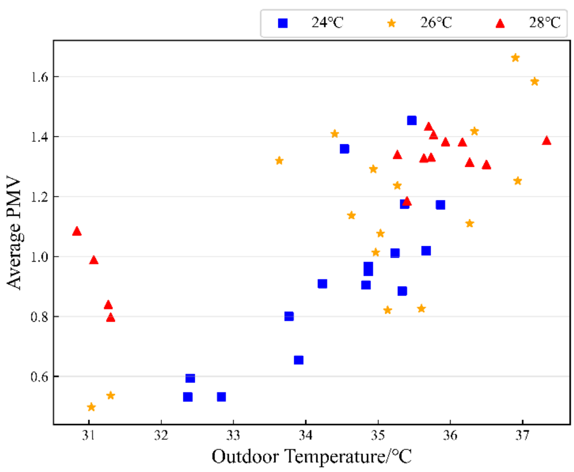

Fig. 6. Scatter plot of outdoor temperature and $\overline{PMV}$

Table 7. Correlation analysis between outdoor temperature and $\overline{PMV}$

Setpoint	γ_p	P-value
24°C	0.795	0.0002
26°C	0.752	0.0010
28°C	0.871	0.0001

The scatter plot of the distribution of outdoor temperature and indoor mean temperature is illustrated in Fig. 7, while the correlation coefficients and significant P-values of different setpoint temperatures are listed in Table. 8. The significant levels of 24 °C and 26 °C were greater than 0.005 and were thus not considered for linear regression.The correlation coefficients of less than 0.7 indicated a weak linear correlation between indoor mean PMV and outdoor humidity. The AC setpoint temperature of 28 °C had a high level of significance, which was below the test value of 0.005, and a strong correlation coefficient of 0.8340.

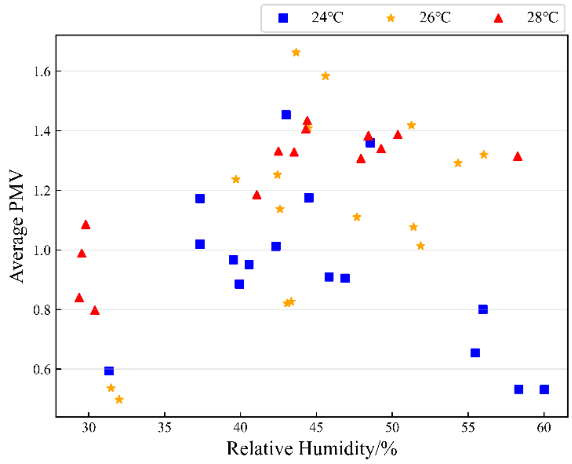

Fig. 7. Scatter plot of outdoor humidity and $\overline{PMV}$

Table. 8. Correlation analysis between outdoor humidity and $\overline{PMV}$

Setpoint	γ_p	P-value
24°C	-0.3977	0.1271
26°C	0.5654	0.0225
28°C	0.8340	0.0001

4.3.3 Modification based on correlation analysis

The correlation coefficients obtained in the previous section were not directly used in the comprehensive evaluation. A correction model for average indoor PMV was established to correct the differences due to outdoor meteorological parameters under all working conditions. According to the correlation analysis results, only the $\overline{PMV}$at the AC setpoint temperature of 28 °C showed a high correlation with outdoor humidity. However, outdoor relative humidity was not considered this time; instead, outside air temperature was used as a correction parameter. The corrected linear regression functions at different setpoints are listed in Table. 9. All outdoor temperatures were corrected to 35 °C based on the slope of the linear regression function. The full results of the correction are shown in the **Auxiliary Information**.

Table 9. Linear regression function at 2 setpoint temperatures

Setpoint	$\overline{PMV}$	Power consumption
24°C	$y = -5.69 + 0.19205x$	$y = 0.124 + 0.01693x$
26°C	$y = -3.75 + 0.13980x$	$y = 0.286 + 0.01245x$

4.4 Analysis of comprehensive evaluation

The 16 conditions within 2 temperature setpoints were comprehensively evaluated using GRA-TOPSIS. The weights of modified $\overline{PMV}$ ($\overline{PMV}_m$), modified power consumption (PC_m), and degree–power index were [1/3,1/3,1/3] (ω_1), [0.5,0.25,0.25] (ω_2), [0.25,0.5,0.25] (ω_3), and [0.25,0.25,0.5] (ω_4). These weights suggest that the three indexes above are equally important, that is, indoor thermal comfort, energy saving, and cooling efficiency are of equal significance. The results of the comprehensive evaluation and analysis are shown in Tables 10 and 11.

As can be seen in Table. 10, when 24 °C was selected as the AC setpoint temperature, the optimal experimental conditions were 1-2, 1-2, 1-1, and 1-1 under different weighting calculations. Meanwhile, as shown in Table. 11, when 26 °C was selected as the AC setpoint temperature, the optimal experimental conditions were 2-3, 2-3, 2-3, and 2-1 under different weighting calculations. The top eight conditions for each temperature at [1/3,1/3,1/3] were selected for the comprehensive evaluation and analysis.

Table. 10. Comprehensive evaluation analysis of set temperature 24°C

Test No.	$\overline{PMV}_m$	PC_m	DPI	GRA-Proximity							
				ω_1	Rank	ω_2	Rank	ω_3	Rank	ω_4	Rank
1-1	1.0369	0.6872	0.1497	0.7676	2	0.7497	2	0.7710	1	0.7808	1
1-2	0.8655	0.6983	0.1658	0.7695	1	0.7728	1	0.7700	2	0.7657	2
1-3	0.9486	0.7182	0.1878	0.7258	3	0.7268	4	0.7335	4	0.7167	3
1-4	1.0369	0.7247	0.2245	0.6854	10	0.6849	11	0.7031	11	0.6671	7
1-5	0.9365	0.7243	0.2234	0.7048	5	0.7131	6	0.7169	6	0.6831	6
1-6	1.0569	0.7391	0.2445	0.6680	13	0.6695	13	0.6873	13	0.6458	13
1-7	1.0928	0.7251	0.1892	0.7001	6	0.6902	9	0.7135	7	0.6961	5
1-8	0.9668	0.7330	0.1939	0.7133	4	0.7149	5	0.7213	5	0.7034	4
1-9	1.1044	0.7243	0.2334	0.6714	12	0.6670	14	0.6934	12	0.6526	10
1-10	1.3637	0.7216	0.2883	0.6239	15	0.6100	15	0.6606	15	0.5982	15
1-11	0.9929	0.6502	0.3000	0.6990	8	0.7006	8	0.7337	3	0.6579	9
1-12	0.8913	0.7172	0.2998	0.6908	9	0.7109	7	0.7081	9	0.6505	11
1-13	1.0063	0.7184	0.2444	0.6834	11	0.6872	10	0.7031	10	0.6583	8
1-14	1.4484	0.7399	0.3327	0.5966	16	0.5838	16	0.6365	16	0.5668	16
1-15	0.9760	0.7233	0.3433	0.6564	14	0.6713	12	0.6823	14	0.6132	14
1-16	0.8208	0.7228	0.3642	0.6999	7	0.7335	3	0.7129	8	0.6483	12

Table. 11. Comprehensive evaluation analysis of set temperature 26°C

Test No.	$\overline{PMV}_m$	PC_m	DPI	GRA-Proximity							
				ω_1	Rank	ω_2	Rank	ω_3	Rank	ω_4	Rank
2-1	1.0205	0.7047	0.1467	0.7553	2	0.7275	3	0.7680	2	0.7680	1
2-2	0.7943	0.7152	0.1736	0.7493	3	0.7460	2	0.7613	3	0.7398	3
2-3	0.7076	0.7092	0.1937	0.7622	1	0.7730	1	0.7718	1	0.7401	2
2-4	1.3044	0.7064	0.1680	0.7038	5	0.6667	6	0.7318	5	0.7091	5
2-5	0.8591	0.7175	0.1914	0.7233	4	0.7167	4	0.7426	4	0.7092	4
2-6	1.2830	0.7232	0.1965	0.6730	7	0.6420	8	0.7062	7	0.6674	6
2-7	1.0705	0.7089	0.2837	0.6599	8	0.6458	7	0.7017	8	0.6273	9
2-8	0.8692	0.7228	0.2918	0.6778	6	0.6807	5	0.7093	6	0.6400	7
2-9	1.2686	0.7345	0.2295	0.6502	9	0.6243	9	0.6875	9	0.6351	8
2-10	1.2866	0.7318	0.3976	0.6021	15	0.5860	14	0.6544	15	0.5609	15
2-11	1.1539	0.7381	0.3145	0.6282	12	0.6145	11	0.6711	12	0.5948	12
2-12	1.1546	0.7293	0.3980	0.6141	13	0.6037	13	0.6634	14	0.5703	14
2-13	1.5279	0.7327	0.4266	0.5815	16	0.5584	16	0.6394	16	0.5412	16
2-14	1.5904	0.7113	0.3354	0.6085	14	0.5772	15	0.6653	13	0.5762	13
2-15	1.2097	0.7299	0.2758	0.6388	10	0.6190	10	0.6809	10	0.6120	10
2-16	1.1836	0.7262	0.3214	0.6296	11	0.6138	12	0.6755	11	0.5949	11

The optimal conditions for the comprehensive evaluation of working conditions are listed in Table 12. These conditions were 2-3, 2-3, 2-3, and 2-1 under different weighting calculations. When all indicators were given equal importance, the 24 °C and 26 °C setpoint temperatures had average rankings of 9 and 8, respectively. When indoor thermal comfort was given more importance, these two temperatures had average rankings of 8.375 and 8.625, respectively. When the reduction of electric power consumption was prioritized, the average rankings were 8.624 and 8.375. When cooling efficiency was prioritized, these rankings were 9 and 8. In sum, 26 °C is the best setpoint temperature for short-term ventilation and cooling. However, setting a lower AC temperature is acceptable in the short term to increase comfort. In the comprehensive judgement analysis, working condition 2-3 ranked first under the multi-scale judgement. Therefore, the best ventilation strategy is to close the inner door and open an outer window to enhance optimal indoor thermal comfort, energy savings, and cooling efficiency.

Table 12. Comprehensive optimal evaluation analysis

Test No.	$\overline{PMV}_m$	PC_m	DPI	GRA-Proximity							
				ω_1	Rank	ω_2	Rank	ω_3	Rank	ω_4	Rank
1-1	1.0369	0.6872	0.1497	0.7447	3	0.7178	5	0.7538	2	0.7602	2
1-2	0.8655	0.6983	0.1658	0.7387	5	0.7294	3	0.7470	4	0.7393	3
1-3	0.9486	0.7182	0.1878	0.6984	7	0.6880	7	0.7135	8	0.6931	8
1-5	0.9365	0.7243	0.2234	0.6755	11	0.6718	10	0.6958	12	0.6578	11
1-7	1.0928	0.7251	0.1892	0.6776	10	0.6581	13	0.6970	11	0.6763	10
1-8	0.9668	0.7330	0.1939	0.6862	9	0.6765	8	0.7015	10	0.6801	9
1-11	0.9929	0.6502	0.3000	0.6750	12	0.6656	12	0.7173	7	0.6365	13
1-16	0.8208	0.7228	0.3642	0.6545	15	0.6732	9	0.6803	15	0.6072	16
2-1	1.0205	0.7047	0.1467	0.7469	2	0.7210	4	0.7514	3	0.7658	1
2-2	0.7943	0.7152	0.1736	0.7397	4	0.7409	2	0.7439	5	0.7340	5
2-3	0.7076	0.7092	0.1937	0.7548	1	0.7714	1	0.7563	1	0.7349	4

2-4	1.3044	0.7064	0.1680	0.6882	8	0.6535	14	0.7088	9	0.7000	7
2-5	0.8591	0.7175	0.1914	0.7107	6	0.7087	6	0.7224	6	0.7004	6
2-6	1.2830	0.7232	0.1965	0.6558	14	0.6279	16	0.6820	14	0.6555	12
2-7	1.0705	0.7089	0.2837	0.6390	16	0.6301	15	0.6741	16	0.6099	15
2-8	0.8692	0.7228	0.2918	0.6615	13	0.6704	11	0.6859	13	0.6262	14

5. Conclusion

To achieve the best energy consumption and thermal comfort conditions for AC cooling with varying door and window configurations, this study analyzed the power consumption, degree–power index, and PMV variation under different test conditions. The evaluation indexes were corrected by performing correlation analysis, and the working conditions were evaluated using GRA-TOPSIS. The following conclusions could be drawn:

(1) The degree–power index was applied to analyze the energy efficiency of AC refrigeration. This index eliminates the influence of power consumption deviation caused by different refrigeration temperature setpoints. A correction model was also established to evaluate outdoor temperature and humidity, indoor average PMV, and AC power consumption. This model reduces the influence of the outdoor environment on the test results.

(2) AC cooling power consumption increased along with the degree of door and window opening. The impact was most significant when the cooling temperature was set to 28 ℃, during which the AC power consumption increased by 83.7% in the convection state. Similar changes in AC power consumption were observed under AC cooling temperatures of 24 ℃ and 26 ℃. The AC power consumption increased more when the windows were open than when the door was open. The degree–power index indicated that indoor comfort generally improved as the AC cooling setpoint temperature decreased. Opening the door and windows could also significantly reduce the impact of AC cooling setpoint on indoor cooling.

(3) Opening all external windows under an AC cooling temperature of 26 ℃ resulted in the optimal comprehensive evaluation performance of single-unit AC, thus providing support and reference for balancing building energy efficiency with thermal comfort.

The AC cooling energy consumption and indoor comfort in a building whose doors and windows were left either open or closed during summer was quantitatively analyzed in this study using various tests and the GRA-TOPSIS model. The proposed degree–power index effectively eliminates the influence of different setpoint temperatures on energy consumption, thus enhancing the accuracy of the analysis. Different working conditions were examined in the actual test environment by using an orthogonal experimental design. Correlation analysis was performed to reduce the impact of outdoor environmental changes on the test results and to improve the measurement accuracy of AC energy consumption and indoor thermal comfort.There are limitations to this study. First, the results might be influenced by external environmental changes due to the substantial number and duration of the experiments. Second, indoor ventilation volume was not thoroughly analyzed. Finally, the climatic characteristics of different regions and building structures were not considered. Future studies should incorporate smaller changes in the effects of outdoor environmental changes and ventilation calculations into their experimental designs. The application of experiments and models to different climatic characteristics and building scenarios should also be expanded to provide more accurate energy-saving recommendations for a wider range of climate and building types.

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