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An Investigation into the Dynamics of the Thermal Environment of Split Air-conditioned Buildings in Summer

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Abstract: *The indoor thermal environment is crucial for human thermal comfort. This study focuses on the dynamic changes of the thermal environment of split air conditioners in summer, analyzes their main influencing factors, and compares them with domestic and international thermal comfort standards. The results show that: during the air conditioning on phase, the indoor temperature decreases rapidly and then slowly, the wind speed fluctuates within a certain range, and the relative humidity decreases, forming a coupled environment of wind speed and temperature slope; during the off phase, the temperature rises rapidly and then slowly, and the wind speed exhibits a drifting characteristic. Existing thermal comfort standards mostly focus on air temperature changes, ignoring the coupling effect of multiple factors such as wind speed. This study provides an important theoretical basis and practical reference for optimizing the thermal comfort standard, guiding the actual air conditioning usage pattern and improving the quality of indoor thermal environment.*

Keywords: *split air conditioner; dynamic environment; thermal environment*

1. Introduction

Indoors is the main place where people live and spend most of their time, so the indoor thermal environment is crucial for people[1]. As occupants' requirements for a comfortable and healthy indoor thermal environment increase, air-conditioning energy consumption increases dramatically, which is not conducive to the conservation of social resources[2]. Chinese air conditioners are divided into centralized systems and split air conditioners, both of which are convection cooling forms in summer[3]. Central air conditioning is constantly on, the operation mode is fixed; split air conditioning can be freely controlled time, place and mode, with personalized control and intermittent characteristics, and in China's civil buildings are commonly installed, more energy-saving potential.

Split air conditioning operation cycle “start-stop alternation”, the formation of a dynamic thermal environment, there are three core features: non-uniformity of the temperature field (vertical temperature difference of up to 3 - 5 ℃), thermal parameters of the time-varying (start-stop cycle temperature fluctuations of up to 2 - 4 ℃ / h)[4] and airflow organization randomness (the angle of the air supply and the speed of the changes in the use of behavior). However, intermittent operation may trigger human physiological stress response, which requires the establishment of a dynamic thermal comfort evaluation system to seek a balance between the temperature fluctuation threshold and energy efficiency.

In view of the above, how to explore the energy-saving potential of intermittent convection cooling buildings, and explore its impact on human physiological parameters according to its dynamic change characteristics, so as to ensure the real indoor thermal environment, so that people can achieve the purpose of energy saving and carbon reduction while being comfortable and healthy.

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2. Manuscript Preparation

2.1 Experimental Design

The experiment was conducted in laboratory A (6.01 m × 4.24 m) of a university in Jiaozuo City, China, as shown in Fig. 1. The building structure of the experimental laboratory is a common brick-concrete structure in Jiaozuo locality, and the building is selected to better fit the real-life scenario. The room is facing north, and there are tall trees on the outer wall, which have a shading effect on the sunlight, and all the shading curtains are used to shade the room during the experimental period to reduce the influence of outdoor radiation. Split-type air conditioners are selected from common domestic wall-mounted air conditioners, wall-mounted air conditioners belong to the common types of air conditioners in our country, and their model number is specification model: KFR - 35GW / R1X1, relevant parameters such as rated cooling (W): 3500. according to the relevant provisions of the ASHREA55-2020[5], the indoor thermal environment of the four measurement points in the vertical direction of the arrangement of three (0.1 m, 0.6 m, 1.1 m), use the indoor thermal environment of the four measurement points in a vertical direction, and the indoor thermal environment is arranged in the vertical direction of the measurement point (0.1 m, 0.6 m). 1.1 m), the indoor temperature and humidity as well as the wind speed were collected using a temperature and humidity self-logger TR-72U and a portable universal wind speed and wind temperature logger WFWZY-1. The range and accuracy of the instruments used are in accordance with the ISO 7726[6] standard. The experimental conditions are taken for the split air conditioner related settings, in GB/T 50736 - 2012 [7] in the I building and II building long-term stay in the region of indoor air temperature 22 °C - 28 °C interval, and ASHREA55 - 2020 in the wind speed selected in the 0.3 m / s for the high and low wind speed boundaries. In this paper, based on energy saving considerations in the health and comfort objectives, the final selection of three different temperature slopes and wind speed combined with the selection of wind speed that is, Case 1: 30 °C - 28 °C - 0.2 m/s Case 2: 30 °C - 26 °C - 0.2 m/s, Case: 30 °C - 28 °C - 0.2 m/s.

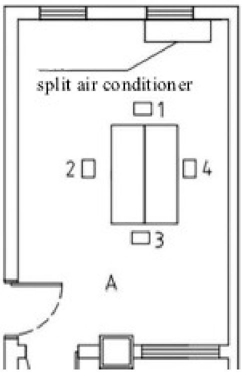

Figure 1 Laboratory floor plan

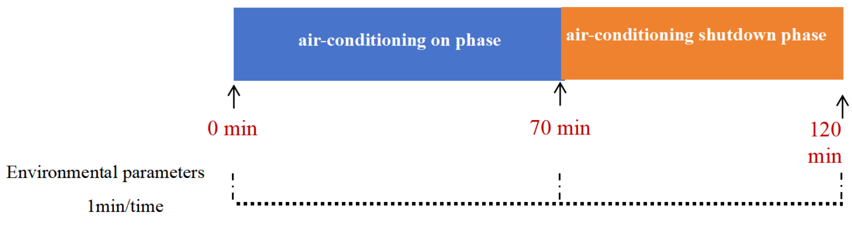

Figure 2 Laboratory floor plan

2.2 Data Analysis Methods

First of all, the K-S test is performed on the data to see whether the data meets the normal distribution and variance is equal, then the independent samples T-test or paired samples T-test as well as to analyze the difference between the two groups of data, if the data does not meet the normal distribution, then use the Wilcoxon sign test in the non-parametric test. The Joeere-Terpstra test was used to test for monotonic changes in indoor air temperature.

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3. Content of Research

3.1 Indoor Air Temperature

Figure 3 demonstrates the change of indoor air temperature after the split air conditioner was turned on in summer. By the Joeere-Terpstra test, the air temperature change for each condition was monotonic (P1 < 0.01, P2 < 0.01; P3 < 0.01), indicating a temperature-sloped environment after turn-on. To clearly demonstrate the changes, the turn-on phase was divided into a rapid (0 - 10 min) and a slow (10 - 70 min) cooling phase. Based on the rate of temperature change, the rate of cooling was fast in the first 10 min and slowed down thereafter. Case 1 (30 °C - 26 °C - 0.3 m/s) and Case 2 (30°C - 26 °C - 0.2 m/s) had similar cooling rates, with the lowest temperature reaching 26°C; Case 3 (30°C - 28 °C - 0.2 m/s) had a slow cooling rate, with the lowest temperature about 28°C. Paired-sample t-tests showed that there was no significant difference between conditions 1 and 2, and there was a significant difference between condition 3 and 1 and 2 (P1 = 0.493; P2 < 0.05; P3 < 0.05). The rate of temperature change for the three working conditions first increased and then stabilized, reaching a maximum value of 0.26 °C / min, 0.26 °C / min, and 0.16 °C/min in 0 - 5 min, and then gradually decreased. Analysis shows that the temperature decline rate of each condition peaked at 5 minutes, due to the air outlet braking mechanism, the air outlet temperature is the lowest at 5 minutes and then remain stable, resulting in the rate of temperature change first fast and then steady.

Due to the high outdoor temperature, after turning off the air conditioner, the indoor temperature is gradually increased by the outdoor influence, which belongs to the temperature drift stage. The indoor temperature under different working conditions first rises rapidly, and then approaches the outdoor temperature with time, and the rate of change slows down. The temperatures of each working condition at 70 min were 26.20 °C, 26.17 °C, 28.42 °C, and finally rebounded to 29.56 °C, 29.56 °C, 29.26 °C, 3.36 °C, 3.39 °C, and 0.84°C, respectively. The lower the temperature at the final moment of the opening phase, the faster the rate of rebound in the closing phase, and the final rate of temperature rise in each condition tends to be the same. In this study, the shutdown phase was divided into a fast warming phase (70 - 80 min) and a slow warming phase (80 - 120 min). The temperature recovery was fast in the first 10 min and slowed down after that. The rate of temperature recovery was similar for Case 1 and Case 2, and slower for Case 3, with a final temperature of about 29.76 °C. Paired-sample t-tests showed that there was no significant difference between Case 1 and Case 2 (P1 = 0.853), and Case 3 was significantly different from Cases 1 and 2 (P2 and P3 both < 0.05).

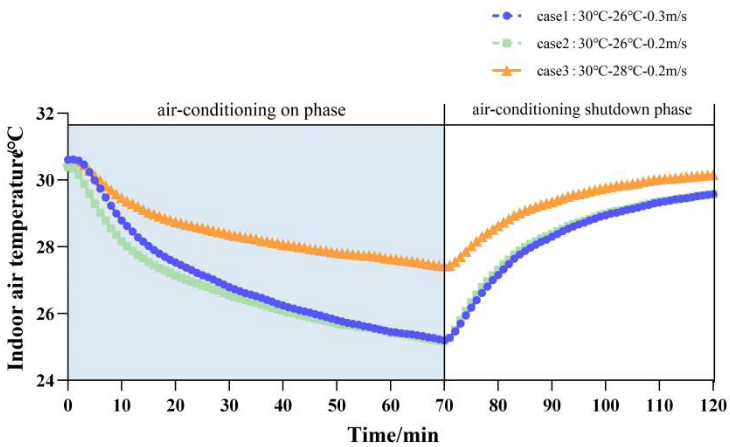

Figure 3 Indoor air temperature change over time

3.2 Air Velocity

The variation of indoor air velocity in the experiment is shown in Fig. 4. After turning on the split air conditioner, the wind speed of each working condition increased and fluctuated rapidly due to convection cooling. Working condition 1 (30°C - 26 °C - 0.3 m/s) has a maximum air velocity of 0.36 m/s, a minimum of 0.24 m/s, and a mean value of 0.31 m/s; working condition 2 (30 °C - 26 °C - 0.2 m/s) has a maximum of 0.24 m/s, a minimum of 0.09 m/s, and a mean value of 0.21 m/s; and working condition 3 (30 °C - 28 °C - 0.2 m/s) has a maximum of 0.22 m/s and a Minimum 0.09 m/s, mean value

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0.21 m/s. Taking the arithmetic mean value of wind speed for each condition, the average wind speed of condition 1 is 0.3 m/s, the highest; and that of both condition 2 and 3 is about 0.2 m/s. After paired-sample t-test, there was a significant difference between Case 1 and Cases 2 and 3 (P1 and P2 were <0.001), while there was no significant difference between Case 2 and Case 3 (P3 = 0.719).

After turning off the air conditioner, the indoor air velocity decreased rapidly and stabilized. The air velocity for all three conditions decreased within 1 minute and stabilized in the range of 0.06 - 0.1 m/s after about 5 minutes, which is a stationary air condition. The wind speeds of Case 2 and Case 3 decreased faster than Case 1, and Case 3 had the lowest initial wind speed. Although there were slight fluctuations in wind speeds at 110, 120, 130, 140, and 150 min due to staff movement, the overall condition remained stationary. There was no significant difference in wind speed between the conditions (P1 = 0.532, P2 = 0.875, P3 = 0.357).

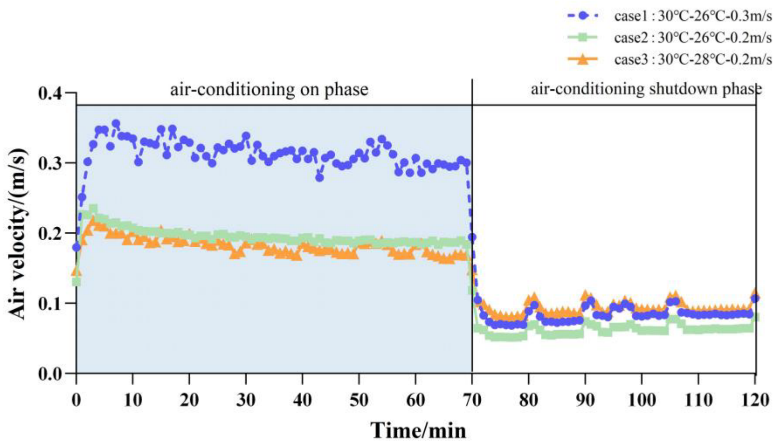

Figure 4 Air velocity over time

3.3 Indoor Relative Humidity

The variation of average indoor relative humidity with time under different working conditions during the experiment is shown in Fig. 5. When the air conditioner was turned on, the indoor RH decreased rapidly due to cooling and dehumidification. The relative humidity decreased to 45.78%, 48.34%, and 51.37% under the three working conditions, and the rate and degree of decrease varied depending on the working conditions. Despite the numerical differences in relative humidity between conditions, the test results showed no difference in statistical significance. The study shows that when the indoor relative humidity is below 70%, its effect on thermal comfort is negligible. In this experiment, the relative humidity under different working conditions was lower than 70%, so the difference had a negligible and insignificant effect on thermal comfort. In summary, the main influencing factors of indoor thermal environment are still air temperature and wind speed.

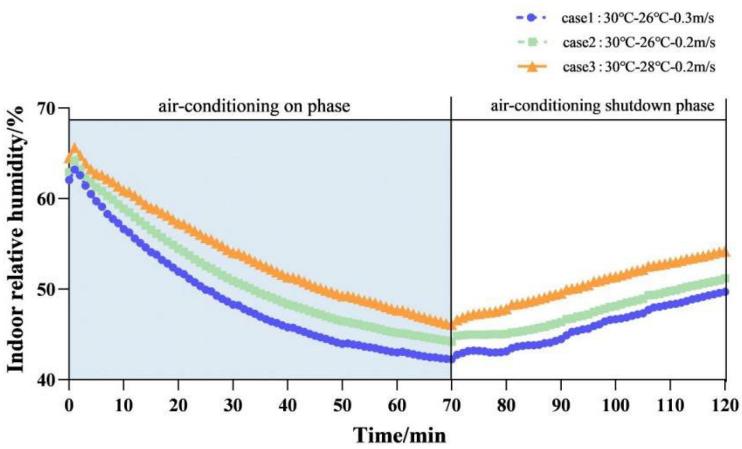

Figure 5 Laboratory floor plan

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When analyzing the three working conditions of relative humidity changes in the indoor thermal environment, in general, the indoor relative humidity showed an increasing trend. At 70 min after the air conditioner was turned off, the relative humidity of each working condition was 42.25%, 44.31%, and 46.22%, respectively, and then gradually increased to 49.58%, 50.99%, and 54.11%, which were 7.27%, 6.68%, and 7.89%, respectively. The relative humidity rose similarly under each working condition and were all below 70%, which is in the zone that does not affect human thermal comfort

3.4 Comparison of Environmental Changes in Intermittent Convection Cooling with Domestic and Tnternational Standards

Domestic and foreign standards for temperature gradient environment temperature slope and the maximum limit of indoor wind speed in this environment are organized and summarized, and compared with the indoor thermal environment under different working conditions in this study, as shown in Table 1. It can be seen that the standard has more accurate provisions for temperature slopes and temperature changes in temperature drift environments, and there are limits for temperature slopes in different time periods in the ASHERA 55 - 2020 standard. However, there is no specific consideration of wind speed conditions in temperature gradient environments, which lacks a cumulative effect on indoor cold stimulation and cold stimulation over time.

In reality, changes in the indoor thermal environment of split air conditioners are a result of the coupling of two cold stimuli: changes in ambient temperature and changes in wind speed, so the development of the relevant standards should take into account the effects of wind speed and the cumulative thermal experience over time.

Table 1 Changes in indoor thermal environment factors compared to each standard

standard	Temperature ramp and temperature drift rate	air velocity
ASHERA 2020[5]	0.07 ℃/ min	/
ISO - 2015[6]	0.03 ℃/ min	/
GBT 18049 - 2017	0.03 ℃/ min	/

4. Conclusions

This chapter investigates the dynamic changes of the intermittent convection heating and cooling environment, analyzes its main influencing factors, and discusses its comparison with domestic and international thermal comfort standards. The main conclusions are as follows:

(1) During the air conditioning turn-on phase, the indoor temperature drops rapidly, forming a temperature ramp environment. The first 10 min is the rapid cooling stage (0 - 0.36 °C/min), and 10 - 70 min is the slow cooling stage. The final temperatures of Case 1 and Case 2 were close to 26 °C, and Case 3 was kept at 28 °C. The wind speed increased rapidly and then fluctuated. The wind speed first rises rapidly and then fluctuates, with an average wind speed of 0.3 m/s for Case 1 and 0.2 m/s for Cases 2 and 3. The relative humidity is below 70% on average. Therefore, the air-conditioning on phase belongs to the thermal environment where the air temperature slopes down and the sustained wind speed is coupled.

(2) In the air-conditioning off phase, the indoor air temperature rises rapidly and then slowly. The first 10 min was a rapid warming phase, and 80 - 120 min was a slow warming phase, with the final temperature rising back to 29.26 - 29.56 ℃. The wind speed is maintained at 0.06 - 0.10 m/s, which is a stationary air state. Therefore, the air-conditioning off phase belongs to the thermal environment where the air temperature drifts and rises.

(3) Comparison with different standards reveals that the existing standards tend to focus on the effect of air temperature change, ignoring the coupling effect of multiple factors, especially the effect of wind velocity

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