THERMAL COMFORT IN TYPICAL SEASONS OF SUMMER AND WINTER IN PERSONNEL INTENSIVE AREAS OF UNDERGROUND PUBLIC BUILDINGS OF XI'AN IN CHINA

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Understanding the thermal comfort of densely populated areas in underground buildings is more significance. This paper takes two typical densely populated areas of underground buildings in Xi′an as examples, conducts questionnaire surveys and field tests on their thermal comfort. The results showed that in winter and summer, the frequency of thermal sensation of underground commercial buildings is higher than that of underground subway platforms, while not much difference in wet sensation and wind speed sensation. The thermal neutral operating temperature for underground commercial buildings in summer and winter is 27.1 ℃ and 20.2 ℃. The thermal neutral operating temperature for underground subway platforms in summer and winter are 26.7 ℃ and 21.8 ℃. The expected indoor temperature for underground commercial buildings in summer and winter is 26.6 ℃ and 19.2 ℃. The expected indoor temperatures for underground subway platforms in summer and winter are 25.2 ℃ and 20.6 ℃. It provides reference value for the creation of thermal environment in densely populated areas of underground buildings.

Keywords: *Underground buildings, densely populated areas, thermal comfort, temperature, evaluation*

1. Introduction

With the rapid development of cities, land resources are becoming increasingly scarce [1]. Therefore, cities both domestically and internationally are constantly exploring underground spaces during the construction process, which has become an inevitable choice for urban development [2-3]. The development and utilization of underground space can not only save surface land and effectively utilize urban land resources, but also reduce the complexity of surface transportation, especially noise interference [4]. Therefore, more and more underground spaces have experienced vigorous development. However, due to the special nature of its environment, underground space has a significantly different air environment from above ground space environment [5], so it is particularly necessary to understand the environmental conditions of underground space buildings.

At the same time, underground buildings have also shown a diversified development model, with underground buildings such as subways, underground shopping malls, underground supermarkets, and underground restaurants constantly emerging [6]. Whether the thermal and wet environment of underground spaces can meet people's needs is increasingly being a focus of attention. This is because compared to the above ground environment, the underground environment may have relatively insufficient air circulation due to factors such as ventilation [7]. In addition, as the depth of the underground increases, it is more affected by temperature factors such as underground rock mass, infiltration water [8], which can lead to different stress reactions or physical discomfort for personnel in relatively effective underground spaces. At present, a large number of experiments or tests have been conducted on indoor environment research [9], mainly focusing on the study of human thermal comfort in urban living environments, public buildings, and rural residences. The research revolves around five parameters of human thermal sensation [10]. Some scholars have also conducted research on clothing thermal resistance, activity level, and human metabolic rate [11], all of which have a certain impact on human thermal comfort. Although relevant research has achieved certain results, which are mainly focused on above ground or above ground buildings, and existing evaluation standards and indicators are also targeted at above ground buildings, lacking research on thermal comfort of underground spaces. This is because the thermal environment characteristics of underground spaces are significantly different from those of above ground buildings [12]. The air temperature, airflow velocity, relative humidity, surrounding surface temperature, and thermal radiation of underground spaces are completely different from those of above ground spaces, and the relevant conclusions drawn from their thermal comfort research are not applicable to underground spaces [13]. Therefore, there is a slight lack of research on the thermal environment of underground spaces.

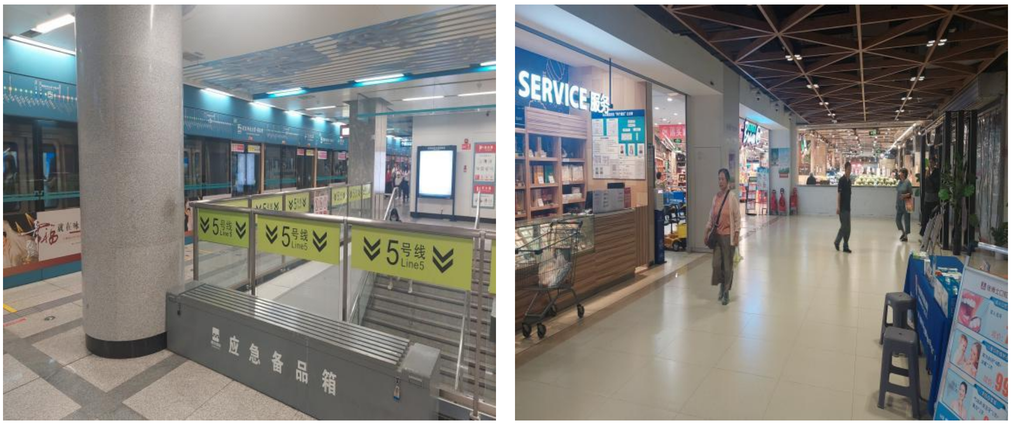
In addition, due to subjective factors of personnel [14], people will spend more time on consumption or enjoying life, which will lead to a large number of people gathering in some underground transportation venues and comprehensive shopping malls in a short period of time, resulting in a phenomenon of personnel gathering, especially during holidays, Spring Festival travel rush, student winter and summer vacations [15]. Among them, the subway, as a means of transportation within the city, is widely used due to its advantages such as large carrying capacity, short time consumption, and low traffic congestion [16]. However, currently, subways are all built underground, and existing research mainly focuses on the internal environment, pollutant distribution, and energy consumption of the ground [17]. Research on thermal comfort in densely populated areas is still relatively insufficient. The underground comprehensive shopping mall in the upper part of the subway is slightly different from the above ground. It is generally located on the first underground floor and is a shopping mall, mainly including supermarkets, restaurants, and department stores [18]. Although there are relevant studies, there is also a significant lack of research on densely populated areas during festivals, large-scale events, and promotions [19]. There is currently a serious lack of research on the thermal comfort of densely populated areas in underground public buildings during typical summer and winter seasons. Some studies tend to focus on one type, either through questionnaire surveys or field tests, lacking typical seasonal research specific to a particular region [20]. Therefore, it is of great significance and guidance value for underground public buildings that are gradually being widely promoted and constructed

Based on the prominent issues mentioned above, this paper selects two typical densely populated areas of underground buildings in Xi'an as examples, and analyzes the indoor thermal environment and thermal comfort of underground spaces from both subjective (questionnaire survey) and objective (on-site testing) perspectives. It provide data reference value for the widespread development, application, and construction of ventilation systems in densely populated areas of underground spaces in the future.

2. Methods

2.1. Survey object and testing content

This paper takes the underground subway platform and underground commercial buildings in Xi'an as an example, as shown in Figure 1. Conduct on-site tests on the indoor thermal environment of the underground space, and the sampling points are arranged according to the testing requirements of ASHRAE55-2020 standard [21]. Sampling of breathing zone height (1.2-1.5 m). The testing time for each group is 5 minutes, and 3 points are selected on the diagonal of each position. The average value of the 3 points is selected for data processing and analysis. Based on the statistical analysis of the subjective questionnaire survey results, the voting rates of underground space subjects' feelings of heat, wet, wind speed sensation, and thermal comfort are obtained. The testing and research period is from March to December 2024, with daily testing time set from 9:00 to 17:00.



(a)underground subway platform (b)underground commercial buildings

Fig. 1 Underground construction personnel intensive area

2.2. Testing instrument

Temperature, humidity, and CO_2 were tested using the IAQ-Calc7525 indoor air quality detector. Temperature range was 0~60 ℃, with error of ± 0.6 ℃. Relative humidity range was 5~95% RH, with accuracy of ± 3.0% RH. CO_2 range was 0~5000 ppm, with accuracy of ± 3.0% of reading or ± 50 ppm. The Detu testo 480 multifunctional climate tester conducts on-site testing of wind speed and black sphere temperature. The wind speed testing range was

0 to +5 m/s, and the accuracy was ± (0.03 m/s + 4% of the measurement average). Black sphere temperature range was 0 ~ + 120 ℃, with accuracy of C1 level.

2.3. Evaluation criteria

The limit values of standard are shown in Table 1 [22].

Table 1 Standard parameter limits

Standard Name	Index	Require	Notes
Standards for indoor air quality (GB/T 18883-2022)	Temperature (℃)	22~28	Summer
	Temperature (℃)	16~24	Winter
	Relative humidity (%)	40~80	Summer
	Relative humidity (%)	30~60	Winter
	Wind speed (m/s)	≤0.3	Summer
	Wind speed (m/s)	≤0.2	Winter

Referring to relevant literature, a subjective questionnaire survey was conducted using the voting scale method [23], and Table 2 shows the voting scale.

Table 2 Subjective thermal reaction voting scale

Scale	Thermal sensation	Wet sensation	Wind speed sensation
-3	Cold	/	/
-2	Relatively cold	Relatively wet	Relatively small
-1	Little cold	Little wet	Little small
0	Comfortable	Comfortable	Comfortable
1	Little hot	Little dry	Little big
2	Relatively hot	Relatively dry	Relatively big
3	Hot	/	/

The relationship between the thermal resistance of a single piece of clothing and the total thermal resistance of the set can be calculated using Equations (1) and (2) [24].

Men, $$I_{cl} = 0.013 + 0.727 \sum I_{comp} \tag{1}$$

Female, $$I_{cl} = 0.05 + 0.77 \sum I_{comp} \tag{2}$$

Where I_{cl} is the total thermal resistance of clothing (clo); I_{comp} is the estimated value of thermal resistance for a single piece of clothing (clo).

The thermal neutral temperature is evaluated using the operating temperature $t_{op,}$ the operating temperature refers to the synthetic temperature obtained by comprehensively considering the effects of air temperature and average radiation temperature on human thermal sensation. Mean Thermal Sensation (MTS) refers to the average thermal sensation of the human body within a certain temperature range. Performing linear regression on both can be calculated using Equation (3) [25].

$$MTS = \text{a} + bt_{op} \tag{3}$$

Where MTS=0, the thermal neutral temperature can be calculate.

The expected temperature is calculated using the probability method [26], which used the Predicted Percent Dissatisfied (PPD). The PPD is used to represent the percentage of indoor personnel who are dissatisfied with the thermal environment.

3. Results and discussion

3.1. Indoor and outdoor parameters of densely populated areas

The range of indoor and outdoor environmental parameters in densely populated areas of underground subway platforms and underground commercial buildings in Xi'an during winter and summer seasons is shown in Table 3.

Table 3 Indoor and outdoor environmental parameters of underground buildings

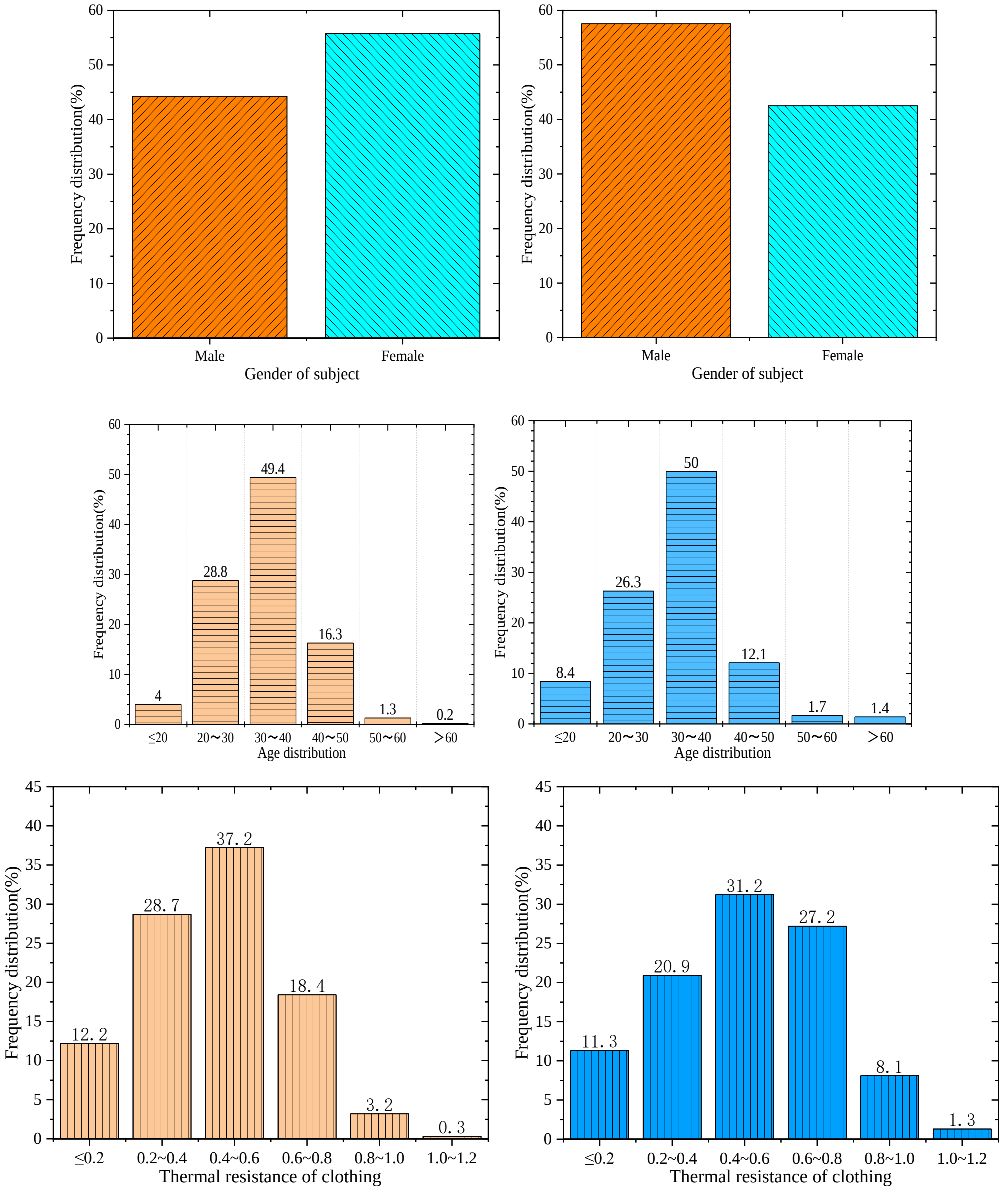
Type	Time	Result	Indoor air temperature	Indoor relative humidity	Indoor globe temperature	Indoor wind speed	Outdoor dry bulb temperature	Outdoor relative humidity
underground commercial buildings	Summer	Average	25.4	50.8	27.5	0.19	28.6	43.7
		Minimum	21.8	42.3	23.2	0.12	23.7	38.4
		Maximum	28.9	61.6	30.7	0.22	37.8	56.2
	Winter	Average	19.6	25.1	23.1	0.16	8.9	24.8
		Minimum	16.5	21.9	18.3	0.07	3.7	20.3
		Maximum	27.6	35.3	25.9	0.19	18.1	34.1
underground subway platform	Summer	Average	23.8	50.6	26.3	0.18	29.6	44.7
		Minimum	21.2	42.5	23.4	0.11	26.8	39.1
		Maximum	26.7	61.3	28.9	0.23	37.9	58.3
	Winter	Average	18.4	24.9	20.4	0.16	9.7	25.1
		Minimum	16.3	21.7	16.7	0.08	4.1	18.3
		Maximum	20.7	32.6	23.4	0.19	17.9	31.2

From Table 3, it can be seen that due to the use of air conditioning, the temperature and indoor relative humidity of underground subway platforms are lower than those of underground commercial buildings. This is because the air conditioning system control for the indoor hot and humid environment of underground subway platforms and underground commercial buildings in summer [24] is less affected by the outdoor environment, and has little impact on thermal comfort. However, there are relatively more changes in underground commercial buildings, mainly due to the presence of different functional zones inside, which have a significant impact on temperature due to different functional differences. On the other hand, except during specific times such as peak commuting hours, the flow of people in the subway is relatively small, resulting in relatively small changes in indoor temperature, which is lower than that of underground commercial buildings [27]. The indoor wind speed of underground commercial buildings meets the standard limit of 0.3 m/s [22], while the indoor wind speed of underground subway platforms meets the standard limit of 0.5 m/s [28]. Overall, the temperature of the black sphere tends to be higher than that of the air dry sphere.

The testing site is not turning on air conditioning in winter, the temperature and indoor relative humidity of the underground subway platform are also lower than those of underground commercial buildings. However, the winter climate in Xi'an is dry, and underground spaces do not have air conditioning and ventilation in winter. The indoor relative humidity is slightly higher than the outdoor environment, but significantly lower than the seasonal indoor relative humidity. Similarly, underground commercial buildings and underground subway platforms exhibit a trend where indoor wind speeds meet standard limits and black bulb temperatures are higher than air dry bulb temperatures.

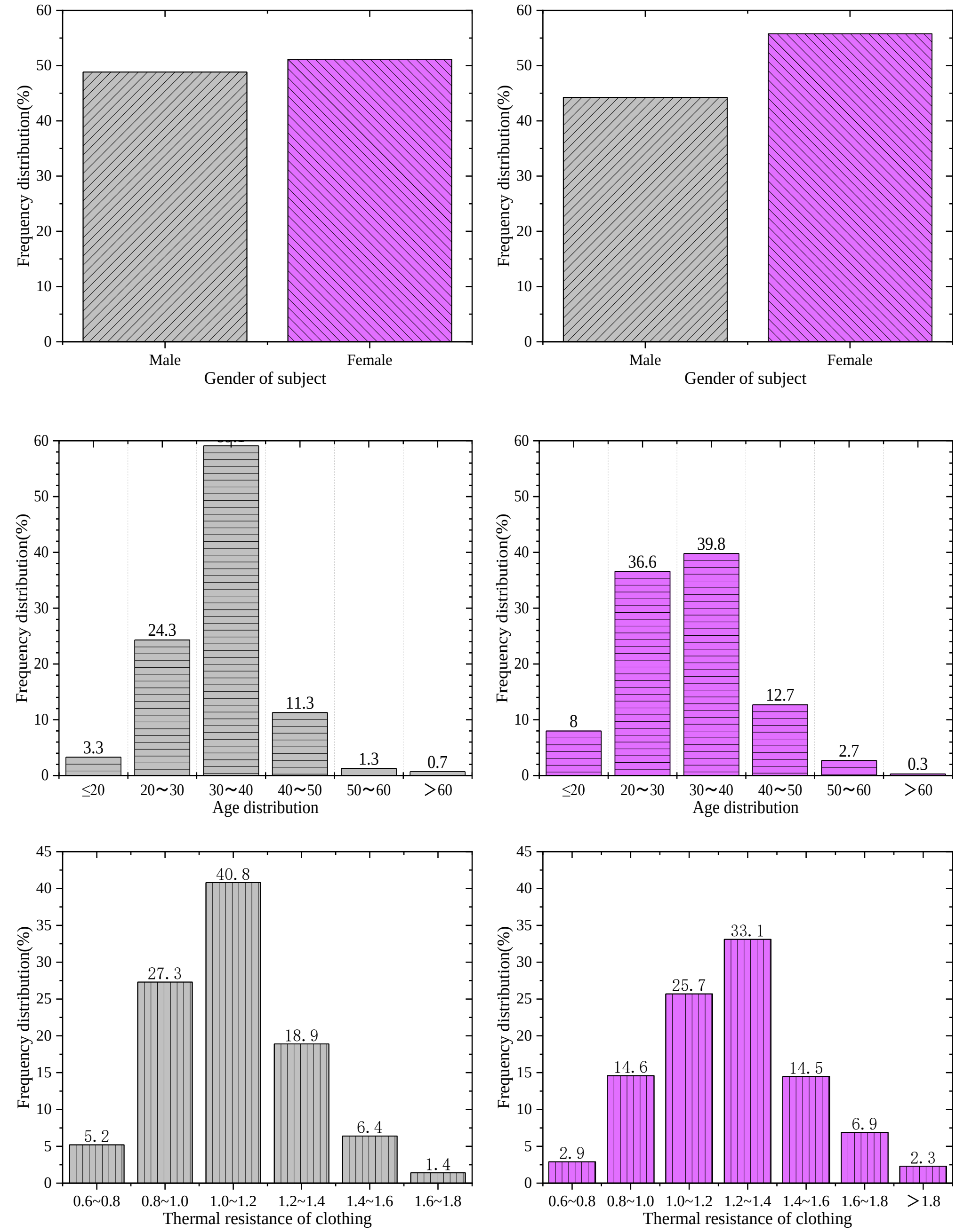
3.2. Basic information of the researcher

A total of 685 valid questionnaires were obtained from underground subway platforms and 773 valid questionnaires were obtained from underground commercial buildings in this survey. Among them, there are 346 underground subway platforms in summer and 339 in winter. Underground commercial buildings have 472 units in summer and 301 units in winter. The specific situation of the summer subjects is shown in Figure 2, and the specific situation of the winter subjects is shown in Figure 3.



(a)Left: Underground commercial buildings (b)Right: Underground subway platform

Fig. 2 Specific situation of summer subjects



(a)Left: Underground commercial buildings (b)Right: Underground subway platform

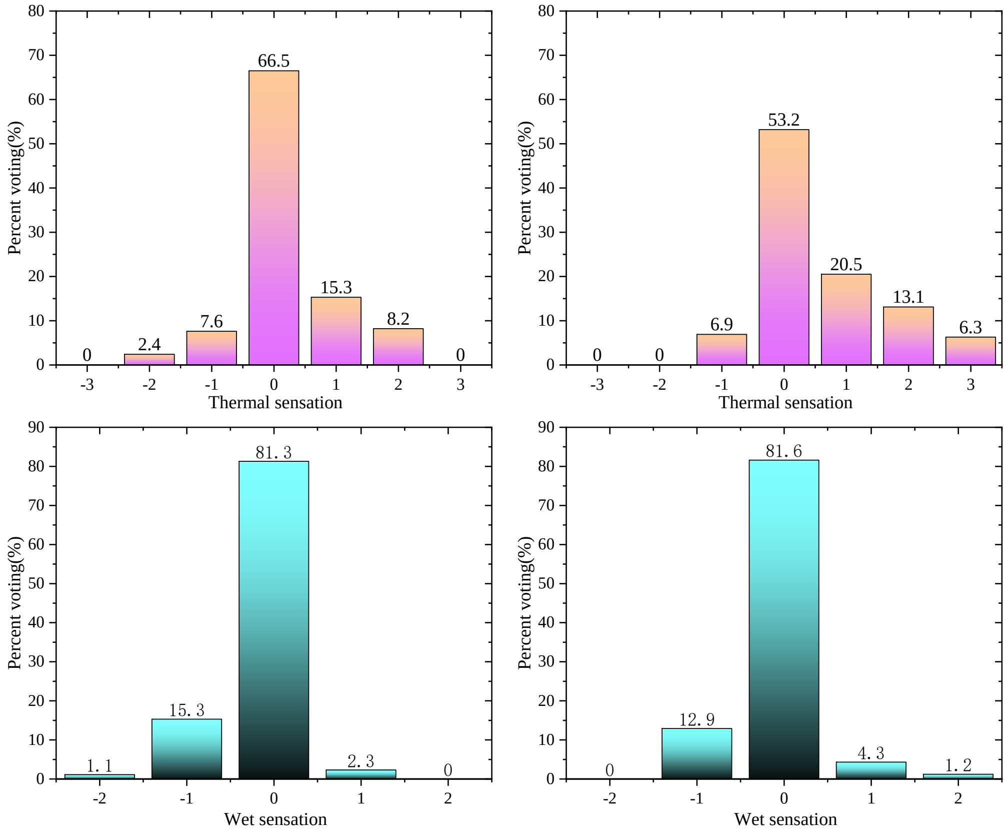
Fig. 3 Specific situation of winter subjects

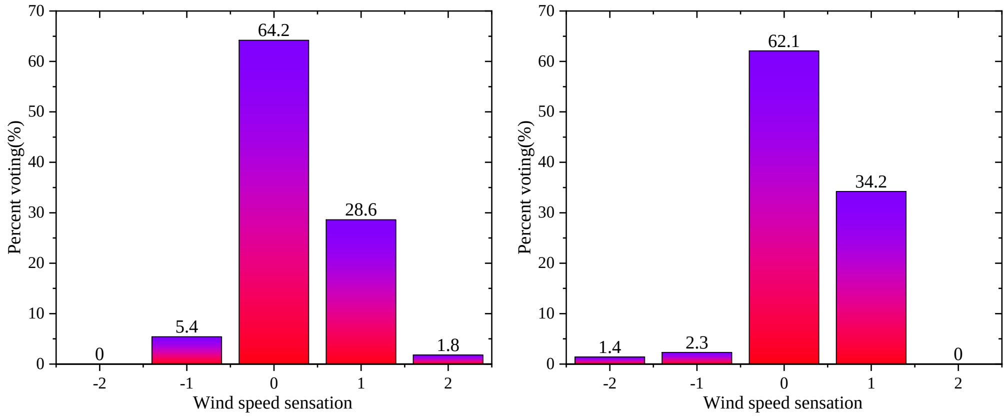
Figure 2 showed the ratio of males to females in summer statistics is nearly 1:1. For underground commercial buildings, males account for 44.3% and females account for 55.7%. The proportion of participants aged 30-40 is relatively large, accounting for 49.4%. Clothing thermal resistance ranges from 0.4 to 0.6, with the highest proportion of 37.2%; For underground subway platforms, males account for 47.5% and females account for 42.5%. The proportion of participants aged 30-40 is relatively large, accounting for 50.0%. The thermal resistance of clothing ranges from 0.4 to 0.6, with the highest proportion being 31.2%; Its activities indicate that there are relatively more women in the commercial buildings, while there are relatively more men in the subway, which is closely related to the lifestyle habits of men and women [29]. The age group indicates that the main activity is between 30-40 years old, and the thermal resistance of clothing is mainly considered based on the impact of climate change on the subjects. Therefore, the summer in Xi'an is relatively hot, and the proportion of clothing thermal resistance less than 0.4 clo is the highest.

While Figure 3 showed the gender ratio in winter statistics is nearly 1:1. For underground commercial buildings, males account for 48.8% and females account for 51.2%. The proportion of participants aged 30-40 is still relatively high, accounting for 59.1%. Clothing thermal resistance ranges from 1.0-1.2 clo, with the highest proportion at 40.8%. For underground subway platforms, males account for 44.2% and females account for 55.8%. The proportion of participants aged 30-40 is relatively large, accounting for 39.8%. Clothing thermal resistance ranges from 1.2-1.4%, with the highest proportion at 33.1%. It also indicates that more women were relatively in testing process, with the age group of 30-40 years old being the main active group. Due to the influence of the colder winter in Xi'an, the clothing thermal resistance was concentrated between 1.0-1.4 clo. Therefore, participants tend to adapt to the relatively cold winter environment by adding clothing.

3.3. Researcher's thermal environment assessment

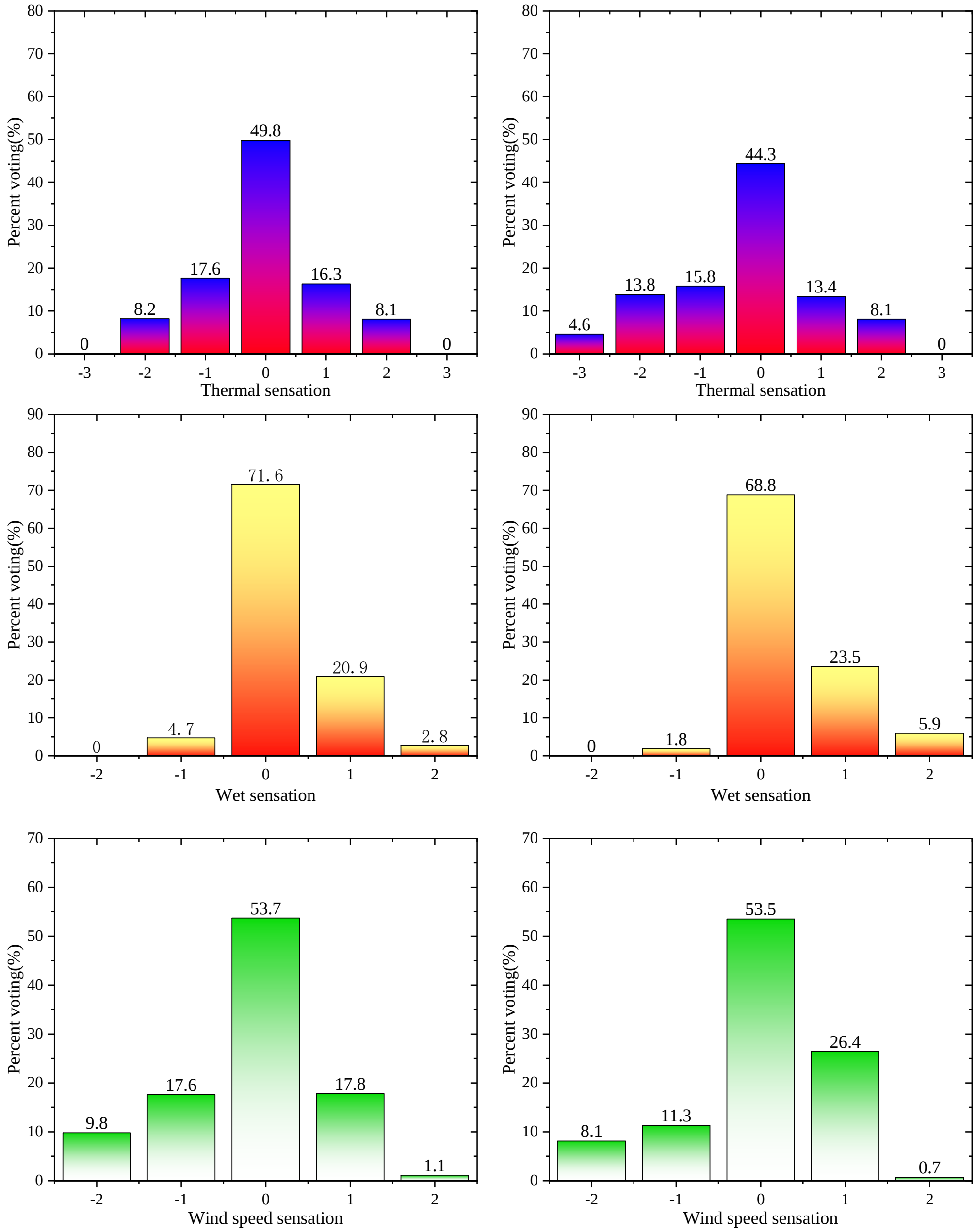
The results of the summer environmental evaluation and winter environmental evaluation for thermal sensation, wet sensation, and wind speed sensation are shown in Figure 4 and Figure 5.





(a)Left: Underground commercial buildings (b)Right: Underground subway platform

Fig. 4 Summer Environmental Assessment



(a)Left: Underground commercial buildings (b)Right: Underground subway platform

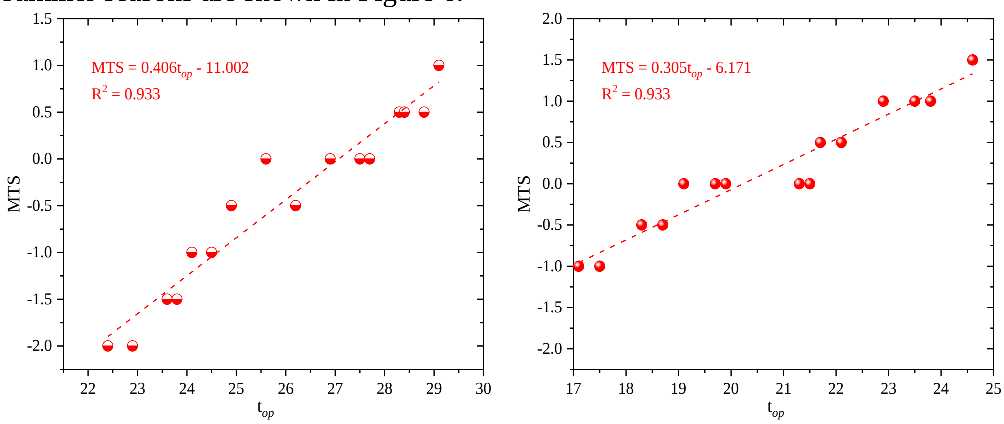
Fig. 5 Winter Environmental Assessment

From Figure 4, it can be seen that the proportion of thermal sensation is highest in summer, with 66.5% feeling comfortable in the underground commercial buildings. The proportion of comfortable feeling on underground subway platforms is 53.2%, and the thermal sensation of underground commercial buildings is 13.3% higher than that of underground subway platforms. The proportion of little cold feeling is relatively high. The main reason is that in summer, air conditioning is mainly relied on to regulate indoor temperature, so the overall thermal comfort feeling in summer is relatively good. The difference in wet sensation between underground commercial buildings and underground subway platforms is not significant, with comfort rates of 81.3% and 81.6%, followed by a relatively high proportion of little wet. This is mainly due to the seasonal characteristics of Xi'an, where there is more rainfall in summer. Similarly, there is not much difference in wind speed sensation between underground commercial buildings and underground subway platforms, with comfort rates of 64.2% and 62.1%, followed by a relatively high proportion of slightly higher wind speed sensation. This is mainly due to the fact that underground subway platforms are located in underground spaces and are less affected by outdoor wind speeds.

Similarly, through Figure 5, it was found that the thermal sensation accounts for the highest proportion in winter environments. The thermal sensation of underground commercial buildings is 5.5% higher than that of underground subway platforms, followed by a relatively high proportion of slightly hot environments, which is due to the fact that air conditioning is not turned on in winter. The wet sensation in underground commercial buildings is 2.8% higher than that in underground subway platforms, due to the relatively dry winter weather in Xi'an, followed by a little dry environment. There is almost no difference in wind speed sensation between underground commercial buildings and underground subway platforms, followed by a relatively high proportion of slightly lower wind speed sensation, which is related to the large passenger flow on underground subway platforms and the high thermal resistance of clothing in winter.

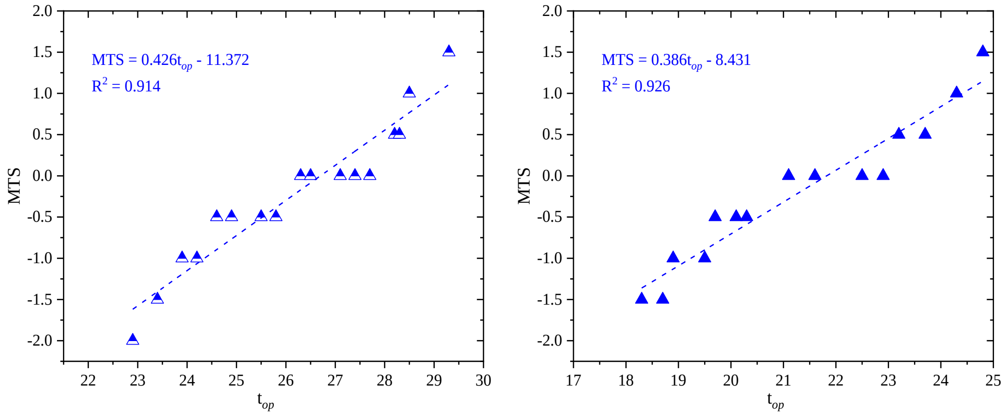
3.4. Thermal neutral operating temperature in densely populated areas

The thermal neutral operating temperature results in different locations during winter and summer seasons are shown in Figure 6.



(a)Summer (b)Winter

(a)Underground commercial buildings



(a)Summer (b)Winter

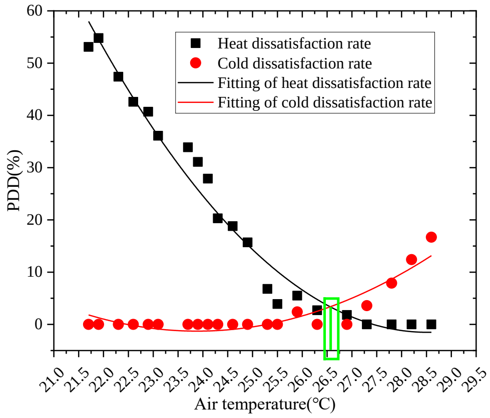
(b)Underground subway platform

Fig. 6 Thermal neutral operating temperature

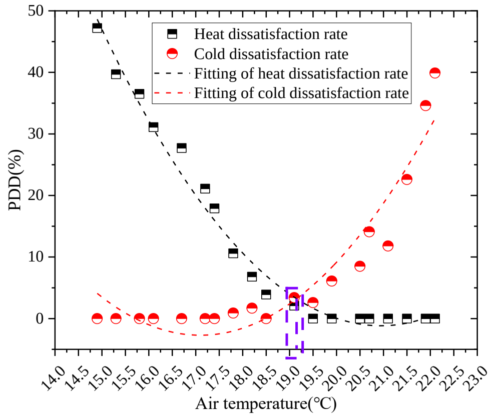
After calculation, it was found that the summer thermal neutral operating temperature in underground commercial buildings is 27.1 ℃, and the winter thermal neutral operating temperature is 20.2 ℃. The summer thermal neutral operating temperature for underground subway platforms is 26.7 ℃, and the winter thermal neutral operating temperature is 21.8 ℃. In summer, the thermal neutral operating temperature of underground commercial buildings is higher than that of underground subway platforms, with a difference of 0.4 ℃. However, in winter, with the thermal neutral operating temperature of underground commercial buildings being lower than that of underground subway platforms, with a difference of 1.6 ℃. This is because the indoor thermal environment of underground spaces in Xi'an during summer is controlled by air conditioning systems, with differences in people's living habits, their leisure and shopping time in underground commercial buildings is much longer than in underground subway stations. Therefore, the requirements for indoor temperature are higher than those for underground subway platforms. However, due to the lack of control over air conditioning and ventilation systems in winter in Xi'an, and the high thermal resistance of clothing in winter, the time spent in underground commercial buildings is longer, with the lower temperature requirements than those of underground subway stations. The results given in relevant literature are similar to those in this paper [30], which verifies the correctness of this paper.

3.5. Expected thermal temperature in densely populated areas

Figure 7 shows the expected temperature in different locations.

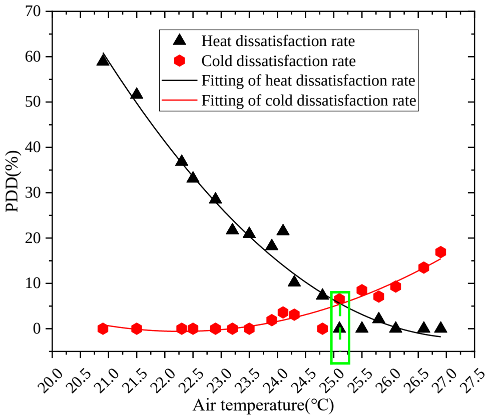


(a)Summer

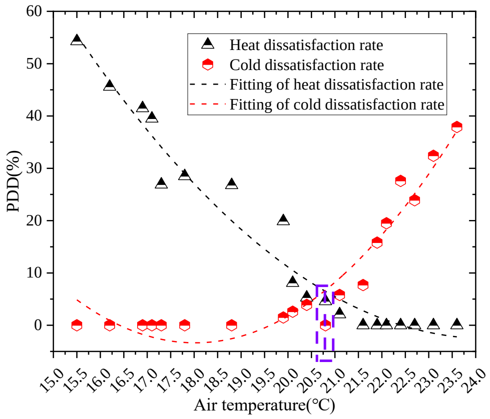


(b)Winter

(a)Underground commercial buildings



(a)Summer



(b)Winter

(b)Underground subway platform

Fig. 7 Expected thermal temperature

According to Figure 7, it can be observed that the expected summer heat temperature in underground commercial buildings is approximately 26.6 ℃, and the expected winter heat temperature is approximately 19.2 ℃. The expected summer temperature for underground subway platforms is about 25.2 ℃, and the expected winter temperature is about 20.6 ℃. In summer, the thermal expected temperature of underground commercial buildings is higher than that of underground subway platforms, with a difference of 1.4 ℃. However, in winter, the opposite trend is observed, with the thermal expected temperature of underground commercial buildings being lower than that of underground subway platforms, with a difference of 1.4 ℃. Among them, the acceptable temperature range for underground commercial buildings in winter is relatively high. The main reason may be that people are in public underground spaces in summer, and the thermal resistance of clothing is difficult to adjust. In winter, subjects stay on underground subway platforms for a shorter period of time and generally do not change the thermal resistance of clothing. Some subjects located in underground commercial buildings will adjust their own thermal comfort by changing the thermal resistance of clothing [31]. Therefore, the acceptable operating temperature range for underground commercial buildings in winter is relatively wide.

4. Conclusion

This paper conducted a questionnaire survey and field testing on the thermal comfort of densely populated areas in two types of buildings in Xi'an, the conclusions are as follows:

- The thermal comfort parameters of underground commercial buildings and underground subway platforms meet the range of standard limits in winter and summer.
- Proportion of clothing thermal resistance, less than 0.4 clo is the highest in summer, while between 1.0-1.4 clo in winter.
- Commercial buildings have higher thermal comfort than subway platforms.
- Neutral temperatures differ significantly between building types and seasons. Underground commercial buildings summer is 27.1 ℃, winter is 20.2 ℃. Underground subway platforms summer is 26.7 ℃, winter is 21.8 ℃.
- In winter, the differences in temperature preference between building types are greater.
- It provides value for creating a thermal environment in densely populated areas of underground buildings, which is conducive to the high-quality construction of living environments.
- With the increasing convenience of transportation, people can go to any corner of the world, so there will also be a phenomenon of short-term overcrowding. Through the research in this paper, reference can be provided for the thermal comfort of densely populated areas, which is helpful for differentiated regulation of different types of functional areas, thus meeting the physiological and psychological needs of personnel and further creating a good indoor environment. Overall, this paper has broad practical value and provides reference for architectural design.
- However, with the personalized differences in the needs of different personnel, personalized air supply areas can be added to densely populated areas in future research to meet the differentiated thermal comfort requirements of personnel. For example, further research on parameters such as air supply device, air supply outlet form, air supply temperature, humidity, etc. It provides recommendations for more specific and in-depth research on thermal comfort in densely populated areas.

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