The outdoor thermal comfort of urban square: A field study in a cold season in Chongqing

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Abstract. With the development of urban development and various outdoor activities, the outdoor activities time of residents continue to grow, and the good outdoor environment have an important impact on the physical and mental health of residents. For the winter outdoor thermal comfort problem with less attention, taking the Chongqing Three Gorges Square in the hot summer and cold winter area as an example, a winter thermal environment measurement and thermal comfort questionnaire were conducted. The Rayman software is used to calculate the PET (physiological equivalent temperature) value as thermal comfort evaluation parameters, establish a functional relationship between TCV (thermal comfort voting value), TSV (thermal sensation voting value) and PET. The winter thermal comfort range of different outdoor environmental spaces were obtained, and propose a suitable winter thermal comfort evaluation model for hot summer and cold winter area. The research results can provide basic data reference for the improvement of outdoor thermal comfort research in hot summer and cold winter areas.

1. Introduction

In the Sustainable Development Goals Report 2018 released by the United Nations, “make cities and human settlements inclusive, safe, resilient and sustainable” is proposed. Outdoor space is the main place for residents to travel and conduct outdoor activities, which are beneficial to people's physical and mental health [1, 2]. A favorable outdoor environment can effectively improve the quality of urban life, urban livability and vitality also is an important part of sustainable urban construction.

The physical (including heat, light, acoustic environment, etc.) and social characteristics of the outdoor environment affect the quality of space environment [3]. The results of studies on the impact of microclimate environments in related urban outdoor activities [4, 5] indicate that the comfortable microclimate environment attracts people to stay and stimulate outdoor activities; while the uncomfortable microclimate environment reaches a certain threshold, it will inhibit outdoor activities. The main indicator for measuring the comfort of microclimate environment is “outdoor human thermal comfort evaluation index”, which is affected by meteorological parameters (air temperature, relative humidity, wind speed and heat radiation).Thermal comfort evaluation indicators have been applied more in the evaluation and improvement of urban thermal environment, which has played a positive role in promoting urban planning and design [6].
With the urbanization and global climate change, urban centers are more susceptible to extreme weather conditions than suburbs, resulting in greater changes in the outdoor environment. As the main outdoor place of urban resident activity and the core of urban planning, City Square is one of the important space for outdoor thermal comfort research. In the hot summer and cold winter areas, there are more extreme weathers, and the outdoor thermal comfort is the poorest. Most of the studies focus on the effects of summer thermal environment [7], but insufficient research on winter thermal comfort. Taking Chongqing City in the hot summer and cold winter area as an example, this paper investigates the thermal environment characteristics of urban squares in wet and cold winter, and analyzes outdoor thermal comfort based on physiological equivalent temperature (PET) the human thermal indicator [8]. Through the calculation of PET, the outdoor thermal comfort range in winter is studied, which provides a reference for establishing a suitable outdoor thermal comfort index in Chongqing.

2. Research methods

2.1. Field measurement
Residents in Chongqing prefer outdoor activities in spite of the poor climate conditions and there are plenty of outdoor square in the city. Located in the central area of Shapingba, Chongqing, the Three Gorges Square has a total area of about 8hm² and a green space rate of 37%. It is a compound square with pedestrian transportation, commercial entertainment and landscape leisure functions for residents and tourists. According to different environmental characteristics, there are three main forms of square space: 1) the space under the tree in the green area; 2) the open space of the active area; 3) the waterfront space of the shallow water landscape area. Taking the influence of different characteristics of the square space on the outdoor thermal comfort in winter as the research goal, an experimental observation point is set for each forms of square space, as shown in Figure 1: Location A is covered by the canopy; location B is in the open space without cover around; location C is in the waterfront space of the Three Gorges Landscape Park.

2.2. Microclimate measurement
The experiment uses the US OREGON SCIENTIFIC WMR300 small mobile weather station and thermal radiation meter for the meteorological test. The instrument is assumed to be on a 1.5m high

Figure 1. Location of field measurement.
tripod, which is close to the height of the human head and neck. The meteorological data include radiation, wind speed, temperature and relative humidity, recorded every 15 minutes. The experiment was conducted from January 11 to 13, 2019, for a total of three test days, and the test time for each test day was 8:00 to 19:00.

2.3. Questionnaire survey
In the range of 5m from the fixed observation point, a questionnaire survey was conducted. The questionnaire consists of two parts, the first part is the basic information of the respondents, including age, gender, clothing, activity status, the second part is the respondent's subjective feelings on the real-time microclimate thermal environment, including Thermal Comfort Voting (TCV, using a five-point scale) and Thermal Sensation Voting value (TSV, using a seven-point scale). The survey also records real-time microclimate data, including air temperature, relative humidity, wind speed and radiation.

3. The outdoor thermal environment in winter
Air temperature, the relative humidity of the air, thermal radiation and wind speed are the main climatic factors affecting human thermal comfort. The characteristics of thermal environment and microclimate change in different square spaces are analyzed to provide basic data for the next research of thermal comfort.

3.1. Air temperature
Figure 2 shows that the air temperature changes of each measuring point are similar, the highest temperature appears in the afternoon from 15:00 to 16:00. And the difference between average temperatures of the three measuring points on the square is small, the temperature varies from 8.0 °C to 11.6 °C. However, from the trend of the chart, location A is affected by the canopy shadow, the range of temperature is relatively smaller, and the maximum temperature is generally lower than other measuring points. There is no shelter around location B with hard ground, which is greatly affected by temperature changes, the maximum temperature range reaches 3.2 °C. Location C is located on the side of the water landscape, and the temperature variation is moderate.

3.2. Relative humidity
The relative humidity changes of the measuring points during the measurement are shown in Figure 3. The humidity changes of the three measuring points are similar, but since location C is on the side of the water landscape, the humidity is always higher than other measuring points. On the contrary, location B is in an open space of hard ground with the lowest humidity. Although the three experimental test days are cloudy days, the relative humidity of the outdoor square spaces is still as high as 61.5%~85.3%, which is higher than the comfortable air relative humidity recommended value (40%-60%).

3.3. Thermal radiation
Obtaining heat through solar radiation is a major way to increase the ambient air temperature in winter. However, Chongqing belongs to the light climate zone V, the annual sunshine time is short, and the relative sunshine duration is only 25%~35%, with the significant seasonal difference. The measured results shown in Figure 4 indicates that location A is blocked by the canopy against solar radiation, and the thermal radiation during the test is still 0 W/m². The thermal radiation changes of the curve in location B and C are the same. The total thermal radiation of location B is 833.9W/m², the highest thermal radiation is 92.8W/m², while the total thermal radiation of location C is 1094.3W/m², which is the maximum value, and the highest thermal radiation is 97.8W/m², indicating that the reflection of water surface and the high heat storage of the water will affect the thermal radiation of the surrounding environment.
3.4. Wind affection
In the winter, against the wind chill and reducing the wind speed is one of the ways to improve outdoor thermal comfort. As shown in Figure 5, there is no obvious pattern for the change of wind speed at each measuring point, but the wind speed of open space (location B and C) is obviously higher than that of semi-open space (location A), because the canopy of location A acts as a wind shield. The wind speeds of location B and C are generally 1.5 m/s and above during the test, and the maximum wind speed of location B is 2.1 m/s.

![Figure 2. Temperature of each location.](image1)

![Figure 3. Humidity of each location.](image2)

![Figure 4. Thermal radiation pattern of each location.](image3)

![Figure 5. Average wind speed at each location.](image4)

4. Results
4.1. Statistical analysis of subjective thermal comfort
The respondents of this questionnaire were mainly residents (about 62.4%) who often performed outdoor activities in the Three Gorges Square, or residents of other areas in Chongqing (about 29.1%) and a small number of tourists (about 8.5%). 500 questionnaires were distributed and 484 valid questionnaires were returned, location A, B and C account for 29.55%, 34.30% and 36.16% respectively.

The results of the questionnaire for thermal comfort are shown in Figure 6. The ratio of "uncomfortable" and the following, the ratio of "comfortable" and above are both about one-third on each location. Among them, the ratios of "comfortable" and above of location A and C are 39.16% and 36% respectively, and location B is the lowest, only 24.70%. It is indicated that while the thermal comfort feeling of most people is not very well, but it is acceptable in outdoor winter.

The results of the questionnaires for thermal sensation are shown in Figure 7. The ratio of "neutral" and above for the three locations are less than one-third, the ratios of "neutral" and above for location A and B are respectively 27.27% and 26.51%, the third point is the lowest, only 10.28%. It means that when the human body feels deviated from "neutral" and feels "cool" or "cold" physically, people can also feel "neutral" or "comfortable" psychologically. In addition, the square space under the tree (location A) has the best overall performance of thermal comfort and thermal sensation.
4.2. Physiological equivalent temperature calculation and analysis

The physiological equivalent temperature (PET) of the three measuring locations was calculated by RayMan model software. PET considers individual parameters such as human activity heat production, metabolic rate, and clothing thermal resistance [9], and has obvious advantages in comprehensive evaluation of outdoor thermal environment quality. Therefore, PET is used as the thermal comfort evaluation index in this research. The results of the calculation are shown in Figure 8. In general, the minimum PET value is 4.2 °C, location C; the maximum value is 16.9 °C, which appears in location B. The minimum PET values of each location are similar, but the maximum difference is significant. The difference between location A and location B is 2.4 °C.

At the same time, the average value of location A and C is about 7.8 °C, and the average of location B is 8.1 °C. Consider that location B and C are unshaded and exposed to direct solar radiation for a long time, the PET fluctuates greatly. While location B is under the shade of trees, PET is relatively stable and mainly distributed in 5-10°C. It can be obvious that the PET is closely related to solar radiation.

5. Discussion

5.1. Correlation between microclimate and thermal comfort

In order to explore the relationship between TCV (thermal comfort vote), TSV (thermal sensation vote) and PET of the different location, the study takes PET as the independent variable, and the voting
values TSV and TCV of each location are dependent variables, respectively. A linear regression analysis was performed on the relationship between the voting results of the questionnaire and PET.

The fit curve for TCV and PET is shown in Figure 9. The regression equation is as follows:

\[
TCV_A = 0.409PET - 0.012PET^2 - 3.080 (R^2 = 0.660) \tag{1}
\]

\[
TCV_B = 0.476PET - 0.008PET^2 - 4.246 (R^2 = 0.885) \tag{2}
\]

\[
TCV_C = 0.433PET - 0.007PET^2 - 3.941 (R^2 = 0.850) \tag{3}
\]

Calculate the thermal comfort range corresponding to PET, it was found that when TCV=0, the PET values corresponding to each location are 11.04°C, 11.05°C and 11.07°C respectively, when TCV ≥ 1, the corresponding PET of thermal comfort range is 11.04 ± 6.71 °C, 11.05 ± 3.82 °C and 11.07 ± 3.96 °C. It shows that the thermal neutral temperature values of the three locations are very close, the thermal neutral temperature value of location A is slightly lower, but the thermal comfort zone is wider than that of location B and C.

The fitting curve for TSV and PET is shown in Figure 10, and the regression equation is as follows:

\[
TSV_A = 0.436PET - 4.416 (R^2 = 0.678) \tag{4}
\]

\[
TSV_B = 0.424PET - 4.748 (R^2 = 0.701) \tag{5}
\]

\[
TSV_C = 0.449PET - 5.434 (R^2 = 0.673) \tag{6}
\]

Similarly, when TSV=0, the PET corresponding to each location are 10.12°C, 11.19°C and 12.10°C respectively, when TSV=−0.5~0.5, the corresponding PET thermal neutral range is 10.12°C±1.15°C, 11.19°C±1.17°C and 12.10°C±1.12°C, respectively. It can be seen that the thermal neutral temperature of location A is the lowest, indicating that the thermal sensitivity of people is the least. Consider that there is a dense distribution of street trees where are seats set, led the wind speed lower, which reduces people’s attention to thermal sensation. Thus subjectively increases the body’s tolerance to cold, and accepts lower PET as neutral.

Comparing the PET thermal neutral temperature range of the TCV and TSV calculated with the standard PET thermal comfort range (18°C ≤ PET ≤ 23°C), the minimum value is less than the standard value of about 7°C. It is indicated that in the hot summer and cold winter area like Chongqing, the people in outdoor can increase the thermal resistance of its own clothes and have certain activity to keep warm. Therefore, the outdoor thermal comfort feeling in winter can be appropriately lowered.

Figure 9. The correlations between the thermal comfort voting TCV and PET at each location.

Figure 10. The correlation between the thermal sensation voting TSV and PET at each location.
5.2. Outdoor thermal comfort model

In order to reveal the relationship between the comprehensive comfort of the outdoor environment and the outdoor microclimate factors, multiple linear regression methods were used to establish the winter outdoor thermal comfort prediction model in Chongqing, as follows:

\[ OCV = 0.384T_a + 0.01RH + 0.07R - 1.037W - 3.860 \]  

(7)

In this case, OCV is the comprehensive comfort voting value (the range is 1-7); \( T_a \) is the air temperature( °C); RH is the relative humidity(%); R is the solar radiation(W/m\(^2\)); \( W \) is the wind speed( m/s).

It can be seen from the equation that the outdoor temperature (\( T_a \)), relative humidity (RH) and solar radiation (R) are positively correlated with thermal comfort (OCV) in winter. The influence of the three factors on thermal comfort can be sorted by the coefficient: temperature > solar radiation > relative humidity. However, outdoor wind speed (W) is negatively correlated with thermal comfort (OCV) in winter, and the coefficient of wind speed is the largest among the four variables, indicating that the cold wind has the greatest impact on thermal comfort in winter. Therefore, the outdoor environment space in winter should focus on blocking the cold wind and increasing the heat of solar radiation.

6. Conclusions

In view of the thermal environment of outdoor space in winter, taking Chongqing in the hot summer and cold winter area as an example, based on the 3-day thermal environment field measurement and 484 questionnaire surveys of Chongqing Three Gorges Square, the microclimate characteristics and human thermal comfort evaluation of different square spaces are analyzed. A winter outdoor thermal comfort evaluation prediction model in hot summer and cold winter areas is established.

1) In winter, the outdoor space under the tree has the best combination of thermal comfort and thermal sensation. Because the canopy can effectively block the cold wind, reduce the temperature range, make people pay less attention to the thermal sensation, subjectively increase the human body's tolerance to cold, and accept a lower pet (10.12 ± 1.15 °C) as a moderate state. The water landscape can increase the humidity of the surrounding air, and decrease the temperature range by increasing the solar radiation, but it is not obvious to improve the human thermal comfort.

2) Due to the environmental adaptability of the long-term residents, as well as the increased thermal resistance of clothing and outdoor activities in winter, most of the respondents have low thermal comfort in the outdoor space in winter, but people can feel "comfortable" or "neutral" when the thermal sensation is "cool" or "cold".

3) Outdoor temperature, relative humidity and solar radiation are positively correlated with thermal comfort in winter, while wind speed is negatively correlated. The proportion of the effect on thermal comfort is: wind speed > temperature > solar radiation > relative humidity. Therefore, it should focus on the cold wind blocking effect, while increasing the solar radiation heat in winter to effectively improve the outdoor human thermal comfort.

In summary, the human body has good adaptability to thermal comfort at lower temperatures. Therefore, the outdoor thermal comfort feeling in winter can appropriately lower the standard. In addition, the green space is beneficial to the winter thermal environment and thermal comfort. The outdoor environment design should consider the landscape effect and human thermal comfort requirements.

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