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The Thermal Comfort of Urban Pedestrian Street in the Severe Cold Area of Northeast China

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Abstract

In this study, thermal environment parameters and questionnaire survey data were analyzed statistically to obtain the influence weight of thermal environment parameters and individual factors on thermal comfort in different seasons in Harbin as the representative of the cold areas. The aim is to find the main influencing factors of thermal comfort in the cold regions of Northeast China and to propose optimization strategies. The average temperature in cool season has the greatest influence on thermal comfort, followed by wind speed. In middle season, clothing thermal resistance has the greatest influence on thermal comfort, followed by average radiation temperature. In hot season, the average radiation temperature has the greatest influence on thermal comfort, followed by wind speed and air temperature. Finally, the thermal comfort optimization strategy is put forward according to research results.

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Keywords: Thermal comfort; Thermal environment; Severe Cold Area; Pedestrian Street

1. Introduction

In current cities, there are many different forms of outdoor space for residents to use, such as parks, squares, pedestrian streets and sports grounds. Service efficiency of the outdoor space is significantly affected by thermal comfort. When people's feeling for thermal environment is within the acceptable range of comfort, people tend to stay

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longer in the outdoors, while they will stay shorter when they feel uncomfortable [2]. Thus the level of thermal comfort is vitally important for outdoor space.

In 1962, Macpherson discovered that outdoor thermal comfort was determined by thermal environment parameters such as air temperature, relative humidity, air flow rate, average radiation temperature and personal characteristics such as metabolism and clothing thermal resistance [3]. In order to have a more comprehensive understanding of outdoor thermal comfort, Bosselmann et al. introduced subjective parameters for the first time [4]. Noguchi and Givoni showed that thermal environmental parameters have a significant influence on thermal sensation, and the differences in air temperature can cause significant differences in the thermal sensation of human body [5]. In the study conducted by Nikolopoulou, the researchers conducted interviews with residents on their subjective assessment of thermal sensations. They also took into account of the influences of the environmental characteristics (air temperature, solar radiation, wind speed, relative humidity, etc.) and personal characteristics (age, gender, clothing, etc.) on the thermal sensation [6]. Katzschner used PET (physiological equivalent temperature) to evaluate thermal comfort in the study, and application of PET made the evaluation results more informative and assessable for planners and decision makers [7]. Lin’s studies show that residents living under different climatic conditions have different thermal preferences. Thus, contrary to those who live in environment with mild climate, people living in subtropical zone prefer cold temperatures and solar radiation in hot seasons [8].

Many studies have shown that solar radiation has a critical influence on thermal comfort. Lin observed people in a park in Taiwan and found that solar radiation and thermal environment affected the total number of people in the park [9]. The results of Letizia Martinelli suggest a significant relationship between shadow situation and the number of the attendees. Shadow affects the distribution of the people over time and their decision on which part of the square to move. This suggests that solar radiation has a great influence on people's thermal comfort [10].

Nowadays, researches on thermal comfort in outdoor crows are concentrated in hot and mild areas, with few studies in cold regions. And most studies have only studied one influencing factor of thermal comfort, or have studied multiple influencing factors but have no comparative analysis of the impact of each impact factor on thermal comfort. Therefore, this study Harbin has been selected as the representative city of the cold area, and the outdoor thermal comfort has been investigated. Purpose to determine the influence weight of each influencing factor (individual factors and environmental factors) on thermal comfort in Severe Cold Area of northeast China in different seasons, and put forward thermal comfort optimization strategy according to research results.

2. Methodology

2.1. Study site

The study site is located at Harbin, the provincial capital of Heilongjiang Province in northeast China (east longitude: 125° 42' ~ 130° 10 '; northern latitude: 44° 04' ~ 46° 40', altitude: 180 to 200m) [17]. Fig. 1 shows the average monthly air temperature (Ta) and wind speed (WS) in Harbin from 1981 to 2010. The average monthly air temperature reached its peak in July, at 23.2 ℃, and reached its bottom in January, at -17.5 ℃. The average monthly wind speed fluctuates between 2.4m/s and 3.7 m/s [18].

The study site is located at Harbin Centre Avenue, close the Songhua River (Fig2). The Centre Avenue is the most famous outdoor leisure space in Harbin, and is relatively representative. The pedestrian street contains leisure area, grassland and other recreational areas. The Centre Avenue is not only the top choice for the locals' entertainment and shopping, but also a must for tourists. People often take a walk, rest, go shopping and sightseeing in the Street [19].

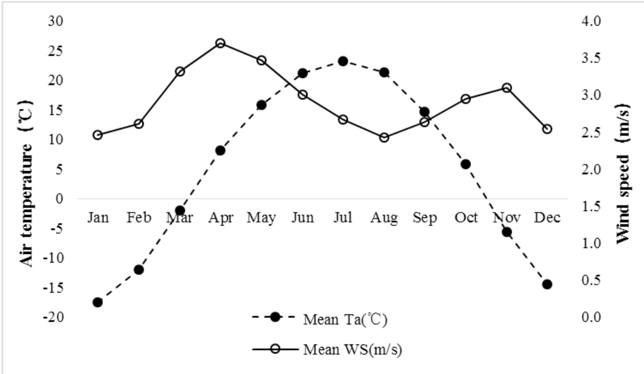

Fig. 1. Change of average monthly air temperature and wind speed in Harbin from 1988 to 2010.Source: China Meteorological Data Network.

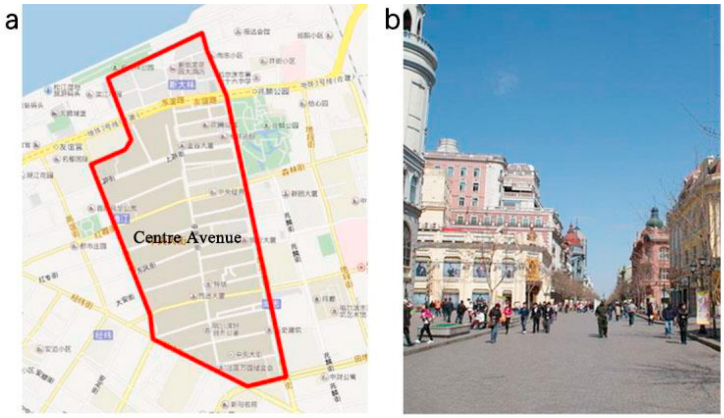

Fig. 2. Centre Avenue (a) Centre Avenue plan graph; (b) Centre Avenue street view. Source: Baidu Map.

2.2. Thermal environment parameters measurements & thermal comfort investigation

Thermal environment parameters were measured respectively on January 9, 2016, April 21, 2016 and July 7, 2016. According to CIBSE Guide A, the period from July to August is summertime and the period from November to February of next year is wintertime [20]. As the spring and autumn are both the transition of winter and summer, so spring and autumn are collectively referred to as the transition season. Therefore, the three dates are in these three ranges respectively and represent "cool season", "middle season" and "hot season". Table1 is the data table of the air temperature during those three days. The table shows that the temperatures of the three days are within the fluctuation range of the air temperature of season the date represents. According to the field survey records, the sunrise happened at 7:14, 4:37 and 3:52 in January 9, 2016, April 21, 2016 and July 7, 2016, and the sunset time is 16:07, 18:28 and 19:25 respectively. Therefore, the period that is daytime in all seasons is 7: 00~16: 00. On the day of the test, the thermal environmental data of the pedestrian street from field measured data was recorded every minute in the period (7:00~16: 00).

Table 1. The air temperature data.

	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00
Cold season	-17.08℃	-18.40℃	-14.82℃	-14.09℃	-12.28℃	-11.51℃	-11.39℃	-12.11℃	-12.66℃	-12.80℃
Middle season	12.20℃	14.22℃	18.67℃	20.8℃	21.85℃	22.42℃	22.98℃	22.37℃	19.91℃	18.21℃
Hot season	17.13℃	28.61℃	29.78℃	31.48℃	32.48℃	33.61℃	33.27℃	34.47℃	34.50℃	33.66℃

In this study, four thermal environmental parameters including air temperature, relative humidity, wind speed and globe temperature were measured and studied. Air temperature, relative humidity and globe temperature were monitored with BES-01 (02) temperature and humidity logging recorder (temperature measurement range: -30 ℃ ~50 ℃, measurement accuracy: ≤ 0.5 ℃; humidity measurement range: 0~99 % RH, measurement accuracy: ≤ 3% RH). The black globe used for measurement is standard matte black paint globe. The BES-01 (02) temperature and humidity monitoring recorder for monitoring temperature and humidity was covered by a highly reflective aluminum film box to block solar radiation. The box can be naturally ventilated. Wind speed was measured with kestrel 5500 handheld weather station (measuring range 0.4~40m/s; accuracy ± 3%; resolution 0.1 m/s). All instruments are in accordance with the ISO 7726 standards [14] and are set on a 1.1 m tripod.

During the thermal environment test, questionnaire investigation was conducted on pedestrians near the measuring equipment. The design of the questionnaire refers to the existing research, and is divided into basic information and thermal comfort investigation. The basic information section includes gender, age, time of residence and dressing. The question of thermal comfort investigations involves the local thermal comfort of the respondents at that time. Respondents were asked to describe their thermal comfort through a 5-level scale, ranging from very comfortable (2) to very uncomfortable (-2). The middle is comfortable (0). Fig. 3 is the picture about the thermal environment parameters measurements and questionnaire survey.

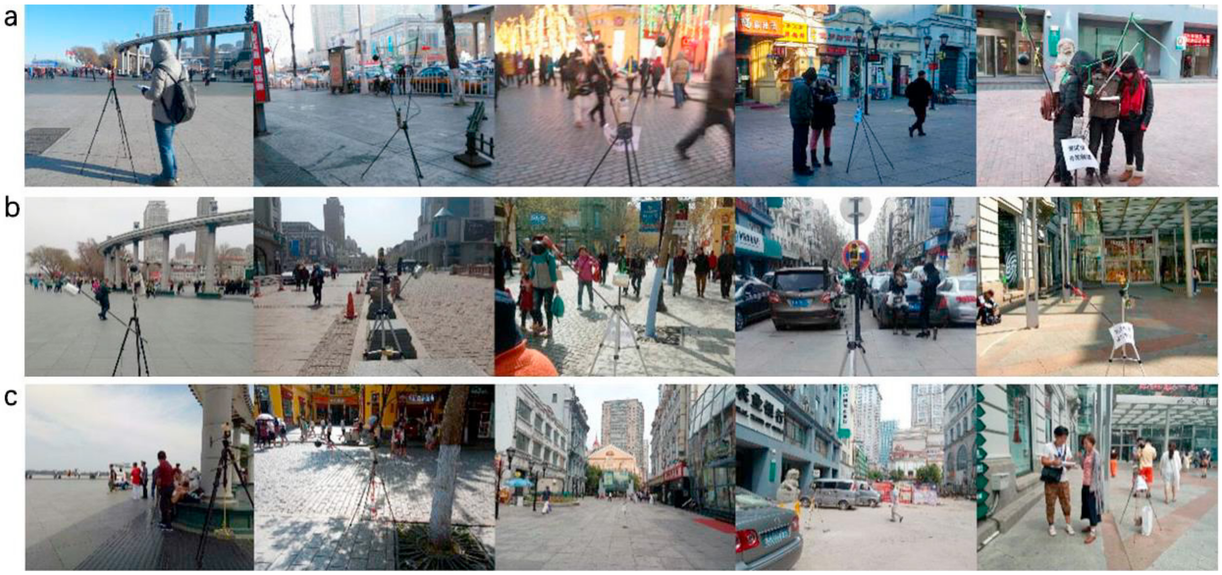

Fig. 3. Picture of the scene of thermal environment parameters measurements & questionnaire investigation (a) cool season; (b) middle season; (c) hot season.

2.3. Selection of thermal comfort indicators

At present, there are many indicators based on human body heat balance used to measure thermal comfort levels, such as PMV (predicted mean vote), ET * (effective temperature), SET * (standard effective temperature), OUT_SET* (standard effective temperature used in outdoor situations) [13] and physiological equivalent temperature (PET). Both

PET and OUT_SET * take into account the influence of short-wave and long-wave radiation flux on thermal balance of human body in outdoor environment, and they are all suitable for measuring outdoor thermal comfort. In this study, PET was selected as the reference outdoor thermal comfort index. PET is defined as follows: when one (male, a height of 180cm, a body weight of 75kg, a clothing thermal resistance of 0.9clo, a metabolic rate of 80W) is in a certain environment, his core temperature and skin was the same as which in a typical room (the average radiation temperature is equal to the air temperature; the water vapour pressure is 1200Pa; the air velocity is 0.1m/s), then the air temperature of this typical room is equal to the physiologically equivalent temperature (PET) [1].

3. Results

3.1. Eliminate irrelevant variables

According to the definition of physiologic equivalent temperature (PET), the thermal comfort of human body in outdoor is mainly affected by individual differences (gender, age, height, weight, metabolic rate, clothing thermal resistance), and thermal environment parameters (air temperature, relative humidity, airflow velocity, average radiation temperature) [1]. In order to collect research data, we conducted a questionnaire survey in Harbin, northeast China, which can represent the climatic conditions in the cold regions of China. A total of 833 valid questionnaires were obtained from this questionnaire. The gender, age, occupation and the time of residence in Harbin of the samples are equally distributed, which can represent the whole state of all people in the cold area. The study was carried out in the pedestrian street, so generally, the respondents were all walking, shopping and carrying out other walking movement, with the same metabolic rate (115 W). Thus, the influence of metabolic rate on heat comfort is not taken into account. Height and weight are taken the average value of respondents.

Multivariate linear regression analysis was carried out on the data of the three seasons to determine the influence weight of each influence factor of thermal comfort. The VIF (variance inflation factor) values of the regression analysis results are less than 10, which can be used as the research basis. Prior to weight analysis, irrelevant variables, namely the factors having no connection to thermal comfort, were excluded. As shown in Table 2, only average radiation temperature and wind speed have an influence on thermal comfort in cool season. In middle season, only clothing thermal resistance and average radiation temperature affect thermal comfort. In hot season, average radiation temperature, wind speed and air temperature affect thermal comfort. Seen from the whole year, the average radiation temperature, wind speed, air temperature and clothing thermal resistance affect thermal comfort of outdoor people. And relative humidity, gender and age have no connection with thermal comfort.

Table 2. The irrelevant variables data. Factors that affect thermal comfort are marked in bold.

	Sex	age	clothing thermal resistance	air temperature	relative humidity	wind speed	average radiation temperature
Cold season	-0.086	-0.002	-0.097	-0.012	0.000	**-0.165**	**0.187**
Middle season	0.057	-0.09	**0.172**	0.051	0.054	-0.105	**0.155**
Hot season	-0.006	0.036	-0.011	**-0.140**	-0.074	**0.153**	**-0.241**

3.2. Influence weight of thermal comfort influence factors

After excluding variables that are independent of thermal comfort, weight analysis is performed on variables related to thermal comfort in each season. The normalized regression coefficients in the multivariate regression analysis can measure the influence of each factor on thermal comfort. The absolute value of the coefficient can represent the contribution rate of this factor to thermal comfort, that is, the weight. The coefficient is positive, indicating that the factor is positively correlated with the thermal comfort; the coefficient is negative, indicating that factor is negatively correlated with the thermal comfort.

Fig.4 shows the comparison of the influence weight of the influence factors of thermal comfort factor. As shown in Fig.4 (a), in cool season, the average radiation temperature has the greatest influence on thermal comfort, followed by wind speed. The cool season air temperature is low and people usually feel cold. Thus, the greater the average radiation temperature is, the more comfortable people feel. Air flow can reduce shell temperature of people. In cool season, when the temperature is low, the larger the wind is, the more uncomfortable people feel.

As shown in Fig.4 (b), the clothing thermal resistance has the greatest influence on thermal comfort in middle season, followed by average radiation temperature. In the Severe Cold Areas of northeast China, the temperature difference between day and night in middle seasons is large, which is mainly related to solar radiation. Solar radiation directly affects the average radiation temperature, which in turn affects pedestrian comfort. At the midday when the solar radiation is strong, the average radiation temperature is greater and people feel more comfortable; in the evening after sunset, the average radiation temperature drops rapidly. On the day of the test, the average radiation temperature between16: 00 and 17: 00 is 23.9 ℃ lower than that between 12: 00 and 13: 00, which significantly affects the thermal comfort level of the outdoor people. The large temperature difference in the whole day has affected people's judgment about how much clothing to wear. In the middle season investigation, the range of clothing thermal resistance of outdoor people is relatively large (0.4 to 1.0clo), which also has great influence on people's thermal comfort.

As shown in Fig.4 (c), average radiation temperature has the greatest influence on thermal comfort in hot season, followed by wind speed and air temperature. Studies have shown that for the outdoor thermal comfort, the discomfort brought by strong solar radiation exposure is much greater than that brought by the increase of average air temperature in hot season. Some scholars have found that the changes in comfort caused by a 1 ℃ increase in temperature can be offset by radiation at about 70W/m^2 [11]. In other words, the average radiation temperature has a greater influence on thermal comfort than the smaller difference in air temperature. Thus, in hot season, the influence weight of average radiation temperature on thermal comfort is much greater than that of the air temperature. Air flow can reduce shell temperature. The greater the wind speed is, the more comfortable people feel.

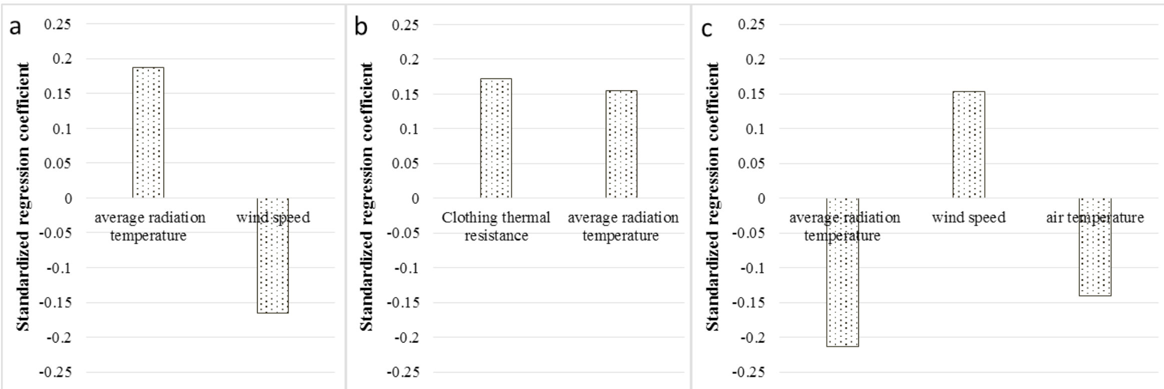

Fig. 4. Comparison of the standardized regression coefficient of the influence factors of thermal comfort (a) cool season; (b) middle season; (c) hot season.

4. Discussion

4.1. Thermal comfort factors in Severe Cold Area

According to the definition of physiological equivalent temperature (PET), this study selects the main factors affecting the thermal comfort of outdoor people, including thermal environment parameters (air temperature, relative humidity, airflow velocity, average radiation temperature) and human individual differences (gender, age, clothing thermal resistance) [1]. In this way, the influence weight of each influence factor (including thermal and environmental factors) on thermal comfort in different seasons is determined. By summing up 3.1, we can see that the average radiation temperature in cool season has the greatest influence on thermal comfort, followed by wind speed. In middle season, clothing thermal resistance has the greatest influence on thermal comfort, followed by average radiation temperature. In hot season, average radiation temperature has the greatest influence on thermal comfort, followed by wind speed and air temperature. From the perspective of the whole year, average radiation temperature, wind speed, air temperature and clothing thermal resistance affect the outdoor population thermal comfort, and relative humidity, gender and age have no connection with thermal comfort.

4.2. Strategies for improvement of thermal comfort in Severe Cold Area

As can be seen from the above results, the optimization of the thermal comfort of the streets in the Severe Cold Area of northeast China is mainly from the average radiation temperature, followed by wind speed. Seen from previous studies, the shield coverage is more relevant to the average radiation temperature than the paving material. Thus, the shield coverage has a greater influence on the thermal comfort of outdoor people. By summarizing the questionnaire for summer investigation, about 50% of the pedestrians chose to make themselves feel more comfortable through staying at shade place.

The shading facility commonly used in streets is green vegetation and structures. Green vegetation is the main means to improve the thermal environment of the street. The crown of the vegetation can block direct solar radiation in hot season, and provides a cool shelter for pedestrians. In the pedestrian street of the Severe Cold Area, it is best to use deciduous trees for street greening, thus ensuring shadow area in hot season and avoiding blocking direct solar radiation in cool season. In addition to vegetation, parasols or awnings also shall be commonly used in the pedestrian street to block the direct solar radiation. However, since there is short hot season in Severe Cold Area and more solar radiation is needed in the long cool season, the best choice is the flexible mobile shade facilities such as parasols.

In the design of the pedestrian street of the Severe Cold Area, different types of wind protection measures can be used to reduce the influence of wind on pedestrians in the streets. The planting density can be appropriately increased to block the cold air flow according to the prevailing wind direction of the pedestrian street, thus avoiding air temperature reduction caused by the invasion of cold wind. In addition to planting plants in the streets, flexible mobile outdoor items can also be arranged to block the wind in cool season and provide shades in hot season. Because in spring, the greatest factor that affects the thermal comfort is the thermal resistance of clothing, which can only be adjusted by the outdoor crowd themselves. The effect will be very limited by adjusting the thermal environment, so it is unnecessary to carry out optimization for thermal comfort in middle season.

5. Conclusions

In this study, the thermal environment of pedestrian street in the Severe Cold Area was measured and the pedestrians on the street were investigated about their thermal comfort. The aim of the study is to determine the influence weight of each influence factor on thermal comfort in different seasons.

The influence weight of each influence factor on thermal comfort in different seasons was calculated. The results show that three thermal environment parameters including average thermal temperature, wind speed and air temperature affect the thermal comfort, and the clothing thermal resistance is also one of the influence factors. However, the main influence factors in different seasons are very different. Average radiation temperature has the greatest influence on thermal comfort in cool season and hot season, and clothing thermal resistance has the largest influence in middle season.

Based on the results of the study on the influence factors of thermal comfort, the strategies of thermal environment optimization in Severe Cold Area are proposed. The optimization focus in different seasons is very different. Overall, the optimization in winter focuses on blocking the wind. The optimization in summer focuses on shading. it is unnecessary to carry out optimization of thermal comfort in middle season.

This study acquired the influence weight of each influencing factor in different seasons, and put forward thermal comfort optimization strategy. And the limitation of this paper is that it only involved the influence of each influence factor on thermal comfort, but there is no in-depth study of the influence range and principle of each influence factor on thermal comfort. Therefore, in the next work, we will continue to conduct in-depth study to find each impact factor's influencing scope on thermal comfort, for example, the average increase on radiation temperature will lead to significantly increased or decreased on thermal comfort of outdoor crowds. And based on physiology and psychology, we will explore the reasons for the effect of various factors on thermal comfort.

Acknowledgements

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