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A study on the summer thermal comfort and behaviour patterns in the residential buildings of Kashgar old City, China

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Abstract. Kashgar, located in China's far west, has a typical hot-arid climate. There are a large number of low-rise high-density Islamic housing in Kashgar old City. The thermal comfort in these buildings has not yet been adequately researched. In order to obtain a comprehensive understanding about the real indoor thermal environment and the residents' summer thermal comfort in Kashgar old City, a field investigation of 138 residential buildings was conducted in the summer time, including onsite environmental parameter measurements and simultaneous surveys using subjective thermal comfort questionnaires. Based on a statistical regression analysis of 182 valid questionnaires, a summer thermal comfort model was established. The results show that the measured summer neutral temperature of the local people is 23.4 °C, and the upper limit of acceptable summer temperature for 80% of the residents is 26.9 °C. The summer thermal tolerance of the residents in the Kashgar old City is lower than expected and also lower than that of the residents in rural Turpan with the same climate features. The survey also shows that the residents in the Kashgar old City have a habit of transferring living spaces over time, and the frequency of passive behaviours is higher than those of active behaviours. The above results are believed to be potentially valuable for the revision of energy conservation policies and the design practice of residential buildings in the hot-arid climate region of China, and also for areas under similar climate conditions in the world.

1. Introduction

Along with the rapid development of the world economy, people's need of quality living environment has been constantly raised. The economic development has led to large amounts of energy and resource consumption. Statistics show the building sector contributes to about 40% of global energy consumption, and China's building sector has accounted for more than 1/4 of the country's total energy consumption [1], among which energy consumption for heating, air conditioning and ventilation accounts for more



than 70% of the building sector [2]. As the basis for setting indoor air temperature range, Thermal Comfort Standards play an important role in determining building energy consumption. With global warming and the resulted air temperature rise in summer, the proportion of family using air conditioners and electric fans have increased significantly, as a result more and more attention is paid to the Thermal Comfort Standards. Scholars around the world have conducted a large number of field investigations on thermal comfort [3-4], concluding that there are obvious differences between the actual thermal sensation of people and the predicted results from employing ISO 7730[5] or ASHRAE 55[6] for different regions. These can be attributed to people's behavioral responsibility, living habits and psychological expectations [7].

China is a vast country with varied climates. Residents from different regions have different thermal comfort requirements due to cultural diversity, different living habits and behavioral patterns. In recent years, a lot of thermal comfort investigations have been carried out in different building types in different regions of China, such as Hot and Humid Region, Hot in Summer and Cold in Winter Region, Cold Region, Hot in Summer and Warm in Winter Region [8-11]. However, there are relatively few investigations in the hot-arid climate, which mainly focus on rural dwellings, so there is a lack of research on urban dwellings. For example, Scholars from Xi'an University of Architecture and Technology have been investigating residents' thermal comfort in the rural dwellings of Turpan, and have obtained the thermal neutral temperature and the thermal comfort range of the local residents in summer and winter respectively [12]. However, is the residents' thermal comfort range in Kashgar old City the same as that in Turpan? What are the residents' adaptive behavior patterns in Kashgar? In order to obtain a comprehensive understanding of the questions above, a field investigation was carried out in the residential buildings of Kashgar old City, hoping to get the neutral temperature and the thermal comfort range of the local residents, and to explore the specific characteristics of their adaptive behavior patterns. The aim of the study is to provide a basis for the revision of the Thermal Comfort Standards and the thermal environment design of the residential buildings in hot-arid climate of China, and also for areas under similar climate conditions in the world.

2. Methodology

2.1. Geography and climate

Kashgar lies at N 39° 25' -39° 35' and E 75° 56' -76° 04' , and is 1260 to 1300m above sea level. The Kashgar old City, located in the Centre of Kashgar, has an area of about 2.5 km² and a population of about 221,000(2010), nearly half of the population of Kashgar [13]. It is a multi-ethnic community with Uygur as the main body. Kashgar has a typical hot-arid climate, and is zoned as a part of the Cold Region according to the Standard for Climatic Region-alization for Building and Civil Engineering of China. Its climatic features include long sunshine duration, large annual air temperature range and daily air temperature range, little precipitation and huge evaporation.

2.2. The building features

The residential buildings in Kashgar old City are low-rise and high-density (Figure 1). The streets are narrow and winding, and the buildings grow like cells, forming maze-like blocks with strong Islamic Characteristics (Figure 2). The average building area of each dwelling is about 158 m², while the number of residents is often as many as 7-9. The buildings adopting a courtyard-centered layout, are open to the courtyards but closed to the streets. A large number of semi-open spaces such as eaves and high canopies are developed in the courtyard, and have become important activity venues in summer for the local residents (Figure 3). Most interior spaces have excellent thermal stability, as they are surrounded by 500-700 mm thick walls made by soil or brick-soil (Figure 4).



Figure 1. Low-rise and high-density buildings



Figure 2. The narrow and winding streets



Figure 3. The semi-open spaces



Figure 4. The thick soil wall

2.3. Data collection

The field investigation was carried out from 26th to 29th July 2018, which is normally the hottest period of the year in Kashgar. The sites in Kashgar old City were selected for the survey. The Random Sampling method was used in the field investigation, ensuring the same number of households were selected from each block site. In total 186 residents from 138 dwellings were surveyed, and 182 valid samples were obtained excluding unhealthy individuals and individuals younger than 10 years. Subjective and objective research methods were combined and employed in the survey.

2.3.1. Sample size and the subjects. A summary of the residents' background characteristics is provided in Table 1. For gender composition, there are 52 males (29%) and 130 females (71%). The subjects' ages range from 10 to 85, with an average of 45.5 years. Their average height is 160 cm and their average weight is 64.7 kg. 63.9% of the subjects have been living there for more than 20 years. All the valid samples were in good health. The clothes of individual subjects were recorded in detail. The insulation property of each garment was estimated according to ASHRAE Standard 55-2010 [6], and the clothing insulation values of individual residents were then estimated, varying between 0.3 and 0.6clo, with an average of 0.5clo, which is close to the summer clothe insulation provided by ASHRAE. In order to ensure the objective authenticity of the thermal sensation data from the questionnaire, the subjects were required to stabilize for 20 minutes before filling out the questionnaire, and their metabolic rates are taken as a unified value of 1.1 met, which is the metabolic level in the sedentary state.

Table 1. A summary of the background characteristics of the subjects.

Sample size	Age(years)	Height(cm)	Weight(kg)	Length of residence (years)	Clothing (clo)
Mean	45.50	160	64.70	28.89	0.50
Maximum	85	194	100	83	0.63
Minimum	10	95	20	1	0.37
Standard deviation	18.77	11.59	15.04	20.72	0.10

2.3.2. Subjective investigation. The subjective investigation adopts the method of questionnaire, which mainly covers the following aspects: 1) background information of the residents, including gender, education level, age, height, weight, occupation, length of residence, etc.; 2) residents' subjective sense of the thermal environment, such as thermal sensation, humidity sensation, thermal satisfaction and humidity satisfaction; 3) adaptive behaviour patterns, including clothing habit, living habit and frequency of thermal behaviour. According to ASHRAE thermal sensation scale, the subjective sensation is divided into seven grades (Table 2).

Table 2. The rating scale for the thermal responses of the subjects.

	-3	-2	-1	0	1	2	3
Thermal sensation	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Humidity sensation	Very dry	Dry	Slightly dry	Neutral	Slightly humid	Humid	Very humid
Thermal satisfaction		Very dissatisfied	Slightly dissatisfied		Slightly satisfied	Very satisfied	
Humidity satisfaction		Very dissatisfied	Slightly dissatisfied		Slightly satisfied	Very satisfied	

2.3.3. Objective investigation. The objective investigation employs two methods, such as measurements of indoor thermal environment synchronized with questionnaire and continuous on-site monitoring of outdoor thermal environment of typical dwellings. Details of the instruments are shown in Table 3. The indoor air temperatures and humidities in the semi-open spaces and interior spaces were measured by hand-held digital recorders (AS817) at the time of the questionnaire survey, and the instruments should be let stand for at least 5 minutes after being taken to the centre of the spaces, to provide reliable readings. The automatic digital recorders (TR72U) were placed in the courtyards which are normally shady and ventilated, and at 2m above the ground. The data loggers were set to record data every 10 minutes over 5 days to obtain outdoor air temperatures and humidities. Through measurements of air speed in most semi-open and interior spaces, it is found that they are all below 0.03m/s during the investigation period, namely the spaces are approximately in a quiet state, therefore impact of air movement can be ignored in the survey.

Table 3. Details of the instruments.

Description	Trade name	Measurement parameter	Range	Accuracy
Hand-held digital recorder	AS 817	Indoor air temperature, Humidity	-10 to 50°C, 5-98% RH	±1.5°C, ±4%
Automatic digital recorder	TR 72U	Outdoor air temperature, Humidity	-20 to 70°C, 0-100% RH	±0.5°C, ±3%
Hot wire Anemometer	Testo425	Air velocity	0-20 m/s	±0.03m/s, ±5%

2.3.4. Thermal comfort evaluation index. The measured air temperatures (t_a) are used in a thermal comfort analysis. With consideration to the randomness of a single sample, a frequency method is used to group the air temperatures into several temperature ranges at a 0.5°C interval. Then a linear regression analysis was performed using the mean air temperature of each temperature range and the Actual Mean Vote (AMV) of the subjects as independent and dependent variables, respectively.

3. Results and analysis

3.1. Thermal environment conditions

More than 80% of the indoor measurement points were located in the semi-open spaces, and the rest were located in the interior spaces. A statistic of indoor and outdoor environmental parameters is shown in Table 4. It can be seen that during the investigation period, the average outdoor air temperature was 29.4°C, the maximum outdoor air temperature was 36.1°C, the average indoor air temperature was

28.4°C, the maximum indoor air temperature was 35.8°C. Since the average and the maximum indoor air temperatures are lower than the relevant outdoor air temperatures respectively, it proves the cooling effect from the semi-open spaces.

Table 4. Environmental parameters during the investigation.

	Indoor air temperature (°C)	Outdoor air temperature(°C)	Indoor relative humidity (%)	Outdoor relative humidity (%)
Mean	28.4	29.4	40.7	42.2
Maximum	35.8	36.1	61.6	74
Minimum	23.8	24.7	16.6	19.6
Standard deviation	2.6	2.13	8.53	2.5

3.2. Thermal comfort responses

It is required that the corresponding vote of a comfort temperature range should be between -1 and 1 according to ASHARE. Figure 5 shows the distribution of the residents' thermal sensation votes. It can be seen that the proportion of thermal sensation in the comfort range is about 68%, and the majority of the votes are slightly warm (1), neutral (0) and warm (2), which are 33%, 29% and 22% respectively. It indicates that the residents feel slightly warm in summer in terms of thermal sensation. Figure 6 presents the distribution of the residents' humidity sensation votes. It can be seen that the proportion of humidity sensation in the comfort range is about 94%, and the majority of the votes are neutral (0) and slightly dry (-1), which are 47% and 32%, respectively. This indicates the residents' humidity sensation is moderate in summer. Figure 7 and Figure 8 present the subjects' thermal satisfaction and humidity satisfaction votes. It illustrates that the slightly satisfied vote (1) is the majority for both the thermal satisfaction votes (69%) and the humidity satisfaction votes (53%).

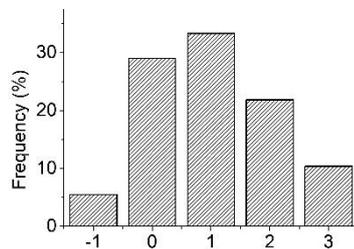


Figure 5. Thermal sensation vote

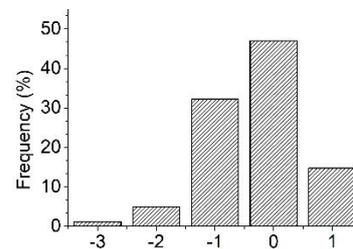


Figure 6. Humidity sensation vote

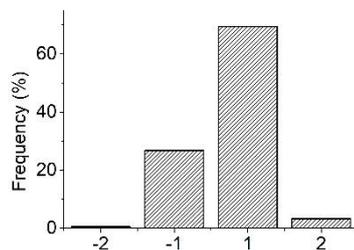


Figure 7. Thermal satisfied vote

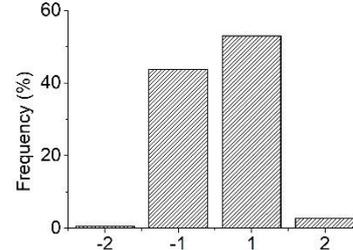


Figure 8. Humidity satisfied vote

3.3. Thermal neutral temperature

The Predicted Mean Vote and the Predicted Percentage of Dissatisfied (PMV-PPD) model were compiled using MATLAB. The measured air temperature, relative humidity, metabolic rate and clothing thermal resistance were brought into the program to calculate the Predicted Mean Vote (PMV) [14]. Actual Mean Vote (AMV) of each temperature range was obtained using the temperature frequency method. AMV and PMV were then linearly regressed with measured air temperature (t_a), as shown in Figure 9. When AMV and PMV values approach 0, the actual and the predicted thermal neutral

temperatures fall to 23.4°C and 25.1°C respectively. It can be seen that the distribution of AMV is more discrete than that of PMV, implying bigger variations of actual thermal sensation among individuals compared with prediction, mainly impacted by physiological and psychological adaptation. The PMV line is steeper compared with that of the AMV, indicating that the actual thermal sensitivity of the residents is lower than what is predicted. The actual thermal neutral temperature is 1.6 °C higher than what's predicted, indicating that the residents' real thermal tolerance is lower than that from prediction.

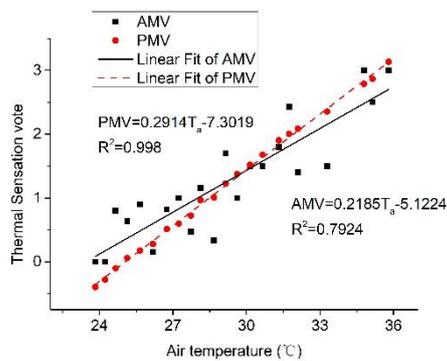


Figure 9. Relationship between PMV(AMV) and air temperature

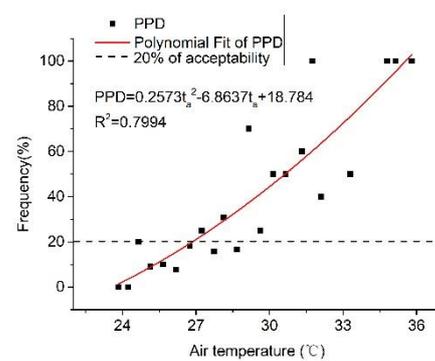


Figure 10. Relationship between PPD and air temperature

3.4. Thermal acceptable temperature

The Predicted Percentage of Dissatisfied (PPD) was obtained by calculating the percentage of the overall votes of -2, -3 and 2, 3 in each temperature range, which had been produced using the temperature frequency method. The Predicted Percentage of Dissatisfied (PPD) and the measured air temperatures (t_a) were then analyzed using polynomial regression, results from which are shown in Figure 10. According to Fanger [15], the thermal sensation vote for a comfort temperature range should be between -1 and 1, and this temperature range corresponds to the temperature range when the PPD is 20%. Therefore, the intersection point of the PPD curve and the line of the 20% thermal unsatisfactory rate is taken as the acceptable temperature range for 80% of the local residents, thus it can be concluded that the upper limit of the residents' acceptable comfort temperature range is 26.9°C in summer.

3.5. Comparison with other locations in the Cold Region of China

By comparing the findings above with residents' thermal comfort in other locations of the Cold Region of China (Table 5 [12,16-17]), it shows that the thermal neutral temperature and the upper limit of the residents' acceptable temperature in Kashgar old City are lower than those in Yinchuan and Weinan, and slightly higher than those in Hanzhong. The actual thermal neutral temperature and the upper limit of the residents' acceptable temperature in Kashgar old City are significantly lower in summer compared with those in Turpan, which has the same climate as that of Kashgar old City. Since the measured daily average air temperatures in Kashgar are lower than those in Turpan, and there are differences in residents' living habits and economic gaps between urban and rural dwellings, the residents in Kashgar old City are less tolerant to summer overheating than those rural residents in Turpan.

Table 5. A comparison of residents' summer comfort in different locations in the Cold Region of China.

Location	Regression equation	Neutral temperature(°C)	Acceptable temperature range(°C)	Mean value and range of indoor air temperature (°C)
Yinchuan ^a	$MTS = 0.357t_a - 9.239$	25.9	28.3/none	28.9 [24.0,35.4]
Weinan	$MTS = 0.178t_a - 4.589$	25.8	29.5/27.0	26.9 [24.0,29.6]
Hanzhong	$MTS = 0.221t_a - 5.091$	23.0	26.6/22.6	26.0 [22.0,20.0]
Turpan	$MTS = 0.225t_a - 7.129$	28.3	31.8/none	35.0 [28.0,41.2]
Kashgar	$MTS = 0.219t_a - 5.124$	23.4	26.9/none	28.4 [23.8,35.8]

^a From unpublished sources.

3.6. Thermal behaviour pattern

3.6.1. Clothing behaviour. A linear regression analysis of the relationship between clothing insulation and measured air temperature is presented in Figure 11. It shows that with the increase of air temperature, the total amount of clothing tends to decrease, implying that the residents adapt to the climate through increasing or decreasing clothing in summer. However, since very little clothing is needed in summer and there is a large randomness, no significant linear relationship is shown between resident' clothing insulation and measured air temperature in Kashgar old City.

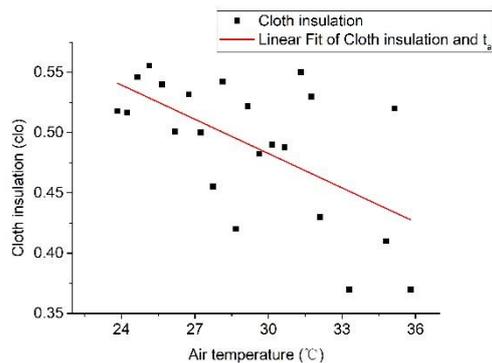


Figure 11. Relationship between clothing insulation and air temperature

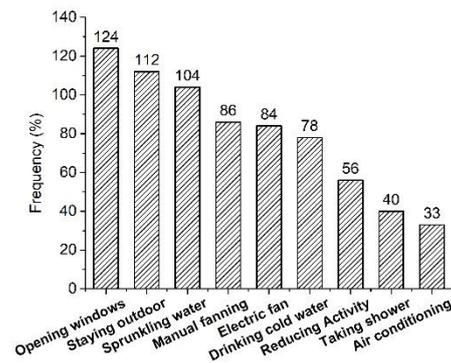


Figure 12. Frequency of thermal adaptation behavior

3.6.2. Living habits. Continuous records of air temperatures and humidities in both semi-open and interior spaces show that the interior spaces possess a good thermal stability, while air temperatures in the semi-open spaces vary greatly with solar radiation on a typical summer day. High temperatures of the day mainly occur from 2pm to 8pm in the semi-open spaces, and the hottest time is around 5pm. According to a survey of the residents' living habits (Table 6), for the time periods of 9am-2pm and 8pm-12am, the residents mainly stay in the semi-open spaces (such as courtyard and Supa) where temperatures are lower than those indoors, while for the period of 2pm-8pm when temperatures in the semi-open spaces are high, the residents would move to the interior spaces (such as bedroom and reception room). It illustrates that the local residents have developed a habit of transferring living spaces over time to adapt to the thermal environment.

Table 6. Daily behaviour pattern of the inhabitants on a typical summer day.

Time	Location		Behaviour
	Interior space	Semi-open space	
12am-9am	Bedroom		Sleep
9am-10am		Supa	Cook, have a breakfast
10am-2pm		Courtyard	Labour
2pm-3pm	Reception room		Cook, have a lunch
3pm-4pm	Bedroom		Take a nap
4pm-8pm	Bedroom		Rest
8pm-9pm		Supa	Cook, have a supper
9pm-12am		Courtyard	Labour

3.6.3. Frequency of Thermal Adaptation Behaviour. Figure 12 summarizes the frequencies of the residents' thermal adaptation behaviours. It can be seen that the residents' adaptation to the hot summer climate includes opening window, staying outdoor, sprinkling water, manual fanning, electric fan, drinking cold water, reducing activity, taking shower, air conditioning. Among them, the frequencies of passive behaviours such as opening window and staying outdoor are higher than those of active behaviours such as electric fan and air conditioning. This indicates that the residents of

Kashgar old City mainly employ passive behaviours for thermal adaption, implying an energy-saving pattern.

4. Conclusions

From the investigation of the residents' summer thermal comfort and adaptive behaviors in the residential buildings of Kashgar old City, the following conclusions can be drawn:

4.1 The local residents feel slightly warm in summer, and the overall thermal satisfaction is good, indicating that the residents have a good psychological adaptation to the local climate.

4.2 The residents' actual thermal neutral temperature is lower than that from prediction, and the slope of the AMV line is lower than that of PMV line, indicating that their thermal tolerance and sensitivity in summer are both lower than those being expected.

4.3 The upper limit of the acceptable temperature range in summer for 80% of the residents in Kashgar old City is close to those in other locations of the Cold Region, but is lower than that in Turpan, indicating that the residents in Kashgar old City have worse thermal adaptability in summer than those living in rural Turpan.

4.4 Among the residents' adaptive behaviors in Kashgar old City, the frequencies of the passive behaviors are much higher than those of the active ones, which can greatly reduce energy consumption from air conditioning and other active cooling devices.

In a word, this study shows that the existing comfort standard in the Cold Region of China (the evaluation standard for indoor thermal environment in civil buildings GB/T 50785-2012) is generally applicable in Kashgar old City. However, differences have been identified between urban and rural residents in regards to their thermal responses to the summer climate, therefore it is recommended that the corresponding thermal comfort standards should be established respectively. The benefit of passive behaviors in terms of energy saving should be considered in the design of thermal environment of local dwellings. It should be noted, there are a couple of limitations with the survey, such as the sample size and the time scale. Further detailed investigation on the resident's thermal comfort in Kashgar old City will be carried out for the other seasons in order to obtain more comprehensive conclusions.

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