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Indoor thermal conditions and thermal comfort in residential buildings during the winter in Lhasa, China

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Abstract

In order to research the indoor thermal conditions and residential thermal comfort in low-pressure plateau climate, a field study was conducted from December 2007 to February 2008 of 20 residential buildings in Lhasa. A total of 44 participants provided 356 sets of physical measurements together with subjective questionnaires that were used to collect the data. By linear regression analysis of responses based on the ASHRAE seven-point thermal sensation scale, the neutral air temperature of the total samples based on thermal sensation was 19.3℃. According to the Probit regression analysis, the lower limit of acceptable air temperature of 80% Lhasa occupants was 13.3℃. The results revealed that Lhasa occupants have adapted to the typical natural environment from physiologically, psychologically, and behaviorally.

Keywords: Plateau climate; Indoor thermal environment; Thermal comfort; Field study

1. Introduction

According to statistics, more than 520 million people worldwide now live on the mountains and plateaus in different altitudes. Figure 1 presents the distribution of Average Mean Sea Level (AMSL) of China, Qinghai-Tibet plateau is known as "the roof of the world" for the mean sea level altitude of over 4,000m. With a population of over 10 millions, it spreads over an area of a quarter of the whole Chinese territory. Therefore, China is one of the biggest plateau countries with the area of plateau. In recent years, with the implementation of China's develop-the-west strategy and the operation of the whole Qinghai-Tibet railway, more and more people work, live, and travel on the plateau, which drives the economic development of Qinghai-Tibet plateau. Demands of improving the indoor thermal environment are strong as people's living levels has been improved significantly.

The research on thermal comfort has been improved greatly in recent years, represented by Fanger's climate chamber study [1] and Humphreys and de Dear's field study [2-3]. Based on those researches, the international thermal comfort standard ISO7730 [4] and ASHRAE55-2004 [5] had been formed. At present, most thermal comfort researches are conducted in the normal air pressure environment. It has been acknowledged that the diffusive transfer of water evaporation increases in the hypobaric conditions whereas dry heat loss by convection decreases [6-7]. Such changes in heat and mass transfer may cause the change of body heat loss, and then affect people's thermal comfort feeling [8].

Thermoregulatory responses in humans exposed to acute hypoxia have been studied extensively with most of researches on thermal perception [9-12] and reaction time [13, 14]. These studies focused on the effect of thermoregulatory responses of hypoxia. Hideo et al. [15] have studied the effect of hypobaric conditions by using decompression chamber to simulate different altitude. Their experiments showed that as altitudes rise, the skin temperatures of face and body are higher than those of extremities, and thermal sensations for the face and body become warmer. Thus, subjects found that it was difficult to express their thermal states. Haiying Wang et al. [16] clarified the effects of barometric on human thermal comfort, and have proved that as the air pressure reduces, the mean thermal sensation votes (MTSV) falls. Under the condition of the same environmental parameters, people tend to feel cooler in hypobaric environment. These studies were made in the decompression chamber to simulate the barometric conditions in 1atm, 0.85atm and 0.75atm, which are equivalent to the altitude of 0m, 1300m, and 2300m respectively. However, what are the real thermal conditions and thermal comfort of people who live in the plateau above 4000m?

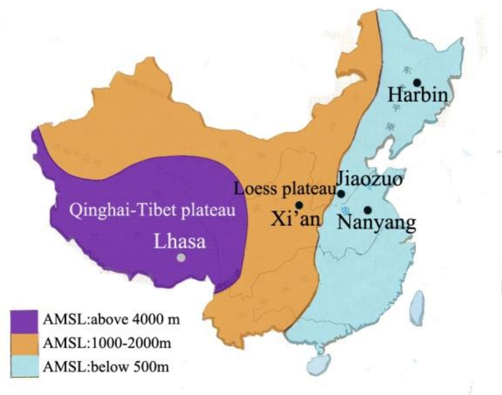


Figure 1. The distribution of Average Mean Sea Level of China and location of Lhasa.

In recent years, many field studies on the thermal comfort performed in China mostly focused on the southeast coastal areas in a normal air pressure conditions [17-25]. Therefore, it is essential to carry out the field study of thermal comfort in the plateau climate. This research was conducted in Lhasa of Qinghai-Tibet plateau. The objectives of this study are to investigate the indoor thermal conditions of the occupants in residential houses in Lhasa in plateau climate, to analyze the subjective responses and thermal comfort for Lhasa context; to compare this study with other field studies, and to find the adaptive opportunities that influence thermal comfort perception in plateau climate.

2. Geography and Climate characteristics of Lhasa

Lhasa, the capital of Tibet in China, is an ancient city with a history of more than 1300 years. It situates at 29°72′ north latitude, and 91°03′ east longitude. With an altitude of 3,650 meters height (11,975 feet), Lhasa is one of the highest cities in the world. The average air pressure (652mbar) of Lhasa is only about two-thirds of normal air pressure (1,000mbar). Lhasa belongs to typical plateau continental climate with cold winter and cool summer, little rain. The annual average temperature is 7.8℃, which is much lower than the regions with the same latitude of the country. The mean temperature of the coldest month (January) is -1.6℃, and the mean temperature of the hottest month (June) is 15.9℃. The city experiences a large temperature difference from day to night, about 13K-15K, however, the annual temperature range of Lhasa is only 17.5℃. Lhasa enjoys the reputation of "sunshine city", because it receives 7,318.0 MJ/m2 solar radiations every year. There are about 3,000 hours in annual sunshine time.

Our research team conducted the tests to measure the solar radiation in Lhasa in the typical d summer day of 2006 and the typical winter day of 2007, as shown in Figure 2. During the survey days, the sunshine duration in Lhasa in summer was 12-13hours, the average intensity of the total solar radiation of the sunshine time was 0.75kW/m^2, and the peak value of 1.2kW/m^2 appeared at about 14:00. The sunshine duration in winter was 10-11hours, the average intensity of the total solar radiation of the sunshine time was 0.45kW/m^2, and the peak value of 0.75kW/m^2 also appeared at about 14:00. The direct solar radiation of winter and summer accounts for about 90% and 85% of the total solar radiation intensity, respectively, which reflects the rich solar radiation resources in Lhasa area [26].

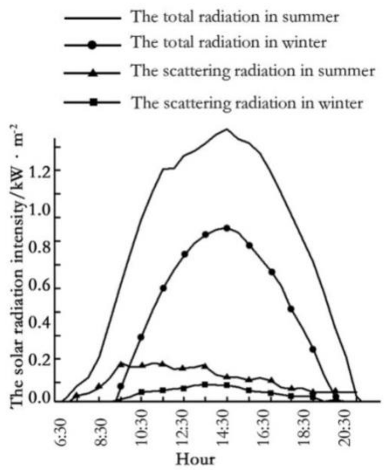


Figure 2. Solar radiation in survey day.

Obviously, the characteristic of outdoor climate in Lhasa are larger diurnal temperature range, smaller annual temperature range and intense solar radiation, which are different from inland cities. Thus, it's likely to result in different thermal sensations in Lhasa.

3. Methodology

The survey was carried out from December 2007 to February 2008, the coldest period of one year. The survey was conducted in two levels: transverse and longitudinal [27]. Transverse survey（sampling without replacement）was to select different subjects randomly. Every subject was interviewed thrice a day, in the morning, afternoon and evening between 7 a.m. and 11 p.m.. Each interviewer was to ask to fill in the questionnaires, and the environment parameters were also measured simultaneously. Longitudinal survey（sampling with replacement）, was to make repeated observations on the same group of subjects for a long-time. In this study, the subjects were interviewed under the transverse survey for one day and in longitudinal survey for the next two days. All the subjects were briefed about the survey, prior to the interview in all the transverse surveys. No briefing was necessary in longitudinal surveys as they were conducted, the day after the transverse survey.

3.1. Objective and Subjective measurements

The outdoor environmental data was procured from the local meteorological station. The air temperature and relative humidity were measured by using wet and dry bulb thermometer in every family. The instruments were positioned at the height of 0.6-1.1m above the floor, close to the subjects.

The subjective questionnaires and a description of the experimental work procedure had been translated carefully into Chinese so that the occupants could follow and understand them. The subjective questionnaires included four main sections:

- Background and personal information: age, gender, height and weight.
- Building details: construction year, building style, floor area of apartment, heating system or apparatus, window form.
- Clothing and activity checklists: The checklists include different types of clothing and activities that occupants can choose from.
- Thermal, humidity and air movement sensation survey: The thermal sensation scale is the ASHRAE seven-point scale of warmth ranging from cold (-3) to hot (+3) with neutral (0) in the middle. Similarly, the seven-point scale is also used in the humidity and air movement sensation investigations.

The operative temperature (the average of air temperature and mean radiant temperature) is regarded as the evaluation index of thermal comfort in many field studies. Limited by the instruments, the globe temperature and air velocity have not been measured in this study. Therefore, the air temperature is adopted as the evaluation index in spite of its limitation without considering the effect of radiation. All the data are statistically analyzed by Excel and Statistic Package for Social Science (SPSS) software. Linear regression analysis is then applied to determine the Actual Mean Vote (AMV) for thermal sensation as a function of air temperature (t_i). The neutral temperature defines that people vote to zero and feel neither cool nor warm. The obtained linear regression equations are then solved for neutrality (AMV=0) to determine the neutral temperature. The acceptable temperature range of 80% occupants is determined with Probit regress by using the SPSS and Excel software.

3.2. Clothing and activities description

Tibetans with nomadic life prefer to the clothing style which is convenient for riding and travelling. In addition, the clothing should not only have a good thermal insulation property, but also can dissipate heat easily for the unique local climate condition with a large temperature difference between day and night, which is an obviously characteristic of the inland plateau. The style of Tibetan robes meeting the features mentioned above are shown in Figure 3 (a), the features of Tibetan robes can be summarized as follows: wide waist, long sleeves, the left front of the robe cover the right front, and laces in the right oxter. The Tibetan robe is long, straight, loose, thick, and full of still air to decrease the heat loss. Moreover, the opening design of the front and the sleeve can play the role of heat dissipation. The material of Tibetan robe is mainly cotton or woolen with good air permeability. The robe usually has interlining, and the air of the fillings becomes a static insulating layer to increase the heat preservation of clothing [28].

With the process of urbanization, international exchange and cooperation in Lhasa are also developing. The clothing of the public is more and more modern, and becomes similar to other cities. The men over 60 years old and individual middle-aged men dress in traditional clothes, while, the little boy and young adult men were jackets or suits, which are very similar to the western style. Generally speaking, the women carry more traditional obligations in the dress than the men do, it is common that the women over 40 years old wear the traditional clothes, and the elder women mostly wear the traditional clothes. The women under 30 years old with traditional clothes only account for small part. Basically, younger girls do not wear the traditional clothes (Figure 3).

The individual insulation of western garment is determined according to ASHRAE55-2004 [8], while the insulation value of Tibetan robe is similar to that described “long-sleeve long gown (thick) (0.46clo)” and “long-sleeve long wrap robe (thick) (0.69clo)” in ASHRAE55-2004 [8], and then the entire ensemble is calculated by the following equations (1clo=0.155m^2·k/W)[29]:

$$\text{Male: } I_{cl}=0.113+0.727\,\Sigma I_{comp}$$

$$\text{Female: } I_{cl}=0.05+0.77\,\Sigma I_{comp}$$

a. The style of Tibetan robe

b. The Tibetan robe

c. Dressing in Lhasa in winter

d. Dressing indoor in Tibetan family

e. Toast each other in the Festival day in Tibetan family

Figure 3. Dressing costume of the Tibetan.

ISO7730 [30] specified that the metabolic rates of relaxed seated and sedentary activity (office, dwelling, school, laboratory) are 1.0 met and 1.2 met, respectively, and that of standing, light activity and medium activity(domestic work) are 1.6 met and 2.0 met, respectively. When the occupants filled in the questionnaires, they were asked to engage in light activity movement (such as sitting or watching TV). The metabolic rate value used in this study is estimated to be 1.2 met as recommended by ISO7730.

4. Results and analyses

4.1. Description of residential buildings and heating equipments

The majority of existing residential buildings are low-rise in Lhasa [31]. Most of the investigated residential buildings are between 2 or 3 stories（Figure 4）, being made of brick and concrete structure. Wall is mainly made of concrete block; however, the brick and stone are little used. Most of the windows are with single-layer glass and the aluminum alloy frame. 42.8% of floor area of residential buildings investigated in Lhasa is 80-120 m^2, below 80 m^2 and above 120 m^2 are both 28.6%, respectively. About 90% of the balconies of the residential building are enclosed. Lhasa belongs to the cold climate zone and, requires heating in the cold season. Due to lack of conventional energy (such as coal, natural gas, and oil), energy in urban areas mainly depended on hydroelectric power and geothermal power. Therefore, there are no central heating systems in Lhasa. 40% of the investigated houses do not have any heating systems or apparatus, while 60% of the houses are equipped with individual space heating units by electric heaters, stove heaters or air conditioners which are intermittence used. Therefore, 24.6% of all the recorded samples data is for heating, 75.4% without heating. 61.1% of hot-water which is used for bath or cooking in winter is heated by solar energy, but in part of houses, the hot-water is heated by electric or liquefied petroleum gas.

Figure 4. Residential building in Lhasa.

4.2. Description of occupants

44 subjects from 20 residential buildings in Lhasa were surveyed in this field study. The occupants participating in the study consisted of 25 (56.8%) males and 19 (43.2%) females. A total of 356 sets of physical measurements and questionnaires were collected, of which 203 sets from males (57.2%) and 152 from females (42.8%). The occupants' ages ranged from 7 to 70 years old with an average of 32.5 years old, and 70% of the occupants are of 25-40 years old. The average height of occupants is 160.6cm, and the average weight is 56.8kg. A summary of the background characteristics of the occupants is given in Table 1.

Table 1. Summary of the subjects.

Sample size	Age	Height/cm	Weight/kg
Mean	32.5	160.6	56.8
Standard deviation	14.0	20.1	14.7
Maximum	70	190	81
Minimum	7	120	24

4.3. Clothing

In Table 2 and Figure 5, they show that the average thermal insulation of clothing for Lhasa females is 1.63clo with the standard deviation of 0.34, however, it is 1.47clo for Lhasa males with the standard deviation of 0.29, and the mean clothing insulation for total is 1.54clol. Their clothing insulation is bigger than that of Harbin residents (1.42clo for the Harbin females, 1.33clo for the Harbin males) [14], because Harbin residences are serviced by central heating system which is more stable and higher than that of Lhasa residences in a cold season.

We divided all the data into two groups; one is in heating condition, while the other is no heating condition. The average clothing insulation of the samples in heating condition is 1.48clo, while that of the samples without heating conditions is 1.59clo. Whether female or male, and in heating or no heating conditions, the difference of clothing insulation is significance between them at the 95% confidence level by one-sample T Test (gender: $F=1.599$, $p=0.207>0.05$; $t=-4.746$, $p=0.001<0.05$. Heating means: $F=0.094$, $p=0.760>0.05$; $t=-2.845$, $p=0.005<0.05$).

Clothing level adjustment is an important adaptation process to maintain the comfort at different temperatures. Figure 6 represents the occupants' clothing level against indoor air temperature in Lhasa, each point represents the average clothing level within a temperature range of 0.5℃. Eq. (1)-(3) show the above relationship of all the samples, the male and the female. In the findings by de Dear [32] and Mui [33], the regressed equation between clothing insulation and operative temperature is Eq. (4) and (5), respectively. Heidari [34] showed the relationship between average indoor air temperature and clothing value (Eq. (6)).

$$CL = 1.875 - 0.035\, t_i \quad (R^2 = 0.547) \quad \text{(Total)} \qquad (1)$$
$$CL = 1.710 - 0.024\, t_i \quad (R^2 = 0.296) \quad \text{(Male)} \qquad (2)$$
$$CL = 2.086 - 0.037\, t_i \quad (R^2 = 0.396) \quad \text{(Female)} \qquad (3)$$
$$CL = 1.730 - 0.04\, t_o \quad (R^2 = 0.18) \qquad (4)$$
$$CL = 1.760 - 0.04\, t_o \quad (R^2 = 0.21) \qquad (5)$$
$$CL = 1.868 - 0.047\, t_i \quad (R^2 = 0.38) \qquad (6)$$

Where CL is clothing insulation value (clo), t_i is indoor air temperature (℃), t_o is indoor operative temperature (℃).

By comparing with the above equations, the results of this study are similar to that of other field studies. The changing of the females clothing with the indoor air temperature variation in this study is more sensitive than the males', that is to say, the females adjust their clothing in time with the change of indoor air temperature.

Table 2. Statistics of clothing insulation for different groups.

Clothing /clo	Female	Male	Heating	No heating	Total
Mean	1.63	1.47	1.48	1.59	1.54
Standard deviation	0.34	0.29	0.31	0.31	0.33
Maximum	2.46	2.19	2.39	2.46	2.46
Minimum	0.69	0.71	0.69	0.71	0.69

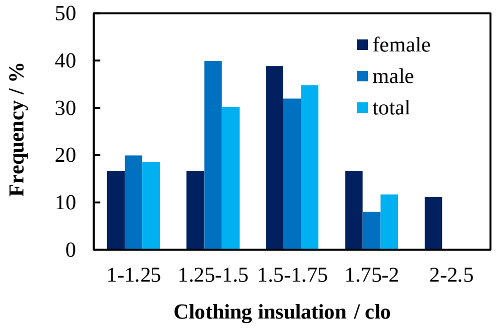


Figure 5. Frequency distribution of clothing insulation.

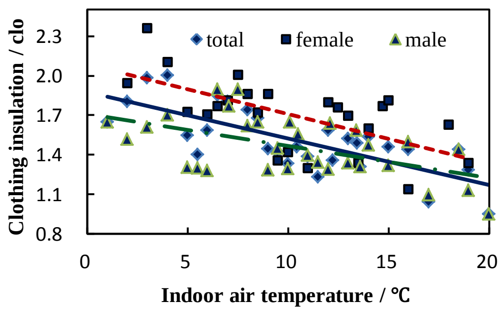


Figure 6. The relationship between indoor air temperature and clothing insulation.

4.4. Outdoor and indoor temperature

As shown in Figure 7, during the survey period (from December 2007 to February 2008), the outdoor daily mean air temperature ranged from -6.1℃ to 8.3℃, with an average of 1.7℃. But the air temperature of a single day (took 28-29, December 2007 as a typical day) fell within -5.7℃ and 15.5℃ (Figure 8). It is possible to observe that the temperature difference in a single day is 21.2K, nevertheless, the daily mean air temperature is relatively low.

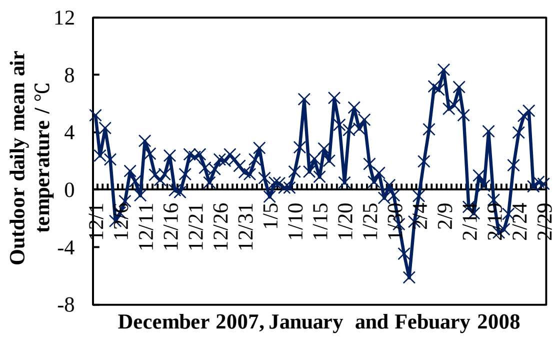


Figure 7. Frequency distribution of outdoor daily mean air temperature.

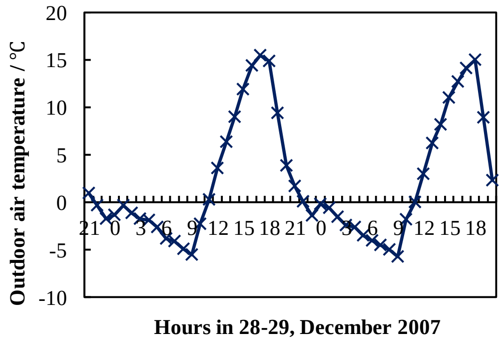


Figure 8. Frequency distribution of outdoor air temperature in typical day.

The frequency distribution of the indoor air temperatures to which the subjects were exposed is shown in Figure 9. The indoor air temperature of residential buildings in Lhasa fell within 0.6℃ and 21℃, with an average value of 10.9℃, and standard deviation of 3.95. Meanwhile, 64.2% indoor air temperature distributes from 10℃ to 15℃, and the maximum proportion (54%) fell on 11℃. It indicates that the range of indoor air temperature is wider, and unstable indoor air temperature in residential buildings in winter has an adverse effect on occupants' thermal comfort.

4.5. Thermal sensation vote

Figure 10 shows frequency distribution of overall actual thermal sensation vote of selected buildings. The mean thermal sensation vote of residential building in winter in Lhasa is -1.27, a heavy bias towards the "cold" section of the seven-point scale. 21.9% of the respondents feel cool (-2) in their home, while 14.5% feel very cold (-3), and only 24.9% feel neutral (0). 62.8% of the votes recorded range from -1 (slightly cool) to +1 (slightly warm).

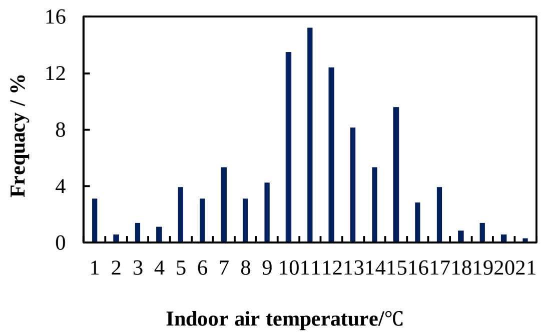


Figure 9. Frequency distribution of indoor air temperature in residential buildings in Lhasa.

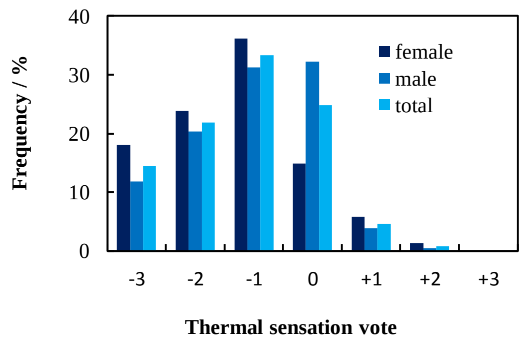


Figure 10. Distribution of overall actual thermal sensation vote.

By using decompression chamber to simulate up to 2300m altitude, Haiying Wang et al. [16] reported that, in the normobaric environment, thermal sensations for males and females were almost the same. As air-pressure decreased, females were more prone to feel cooler than males do. When the air-pressure is 0.75 atm, the mean thermal sensation vote (MTSV) of females is averagely 0.15 lower than that of males. In low-pressure plateau climate of Lhasa (above 4000m), it is also observed that the proportion of the votes between the "very cold" and "slightly cool" regions from the female occupants is higher than that of the male occupants. The result is accordant to Haiying Wang's studies. The difference of thermal sensation votes between the female and male is significant at the 95% confidence level by T test (F=0.050, P=0.824; T=3.522, P=0.001).

4.6. Thermal Neutral temperature

The fitted lines, the linear regression equations and neutral temperature in the present study are shown in Figure 11-12 and Table 3. The neutral temperature of all the occupants is 19.3℃, as shown in Table 3. The linear regression equations in Table 3 are significant at the 95% confidence level by F test (P＜0.001), indicating strong linear correlation between AMV and indoor temperature. the regression coefficients of those linear regression equations are significant at the 95% confidence level by T test (P＜0.001), suggesting that the developed regression equation could give good indications for estimation of thermal sensation.

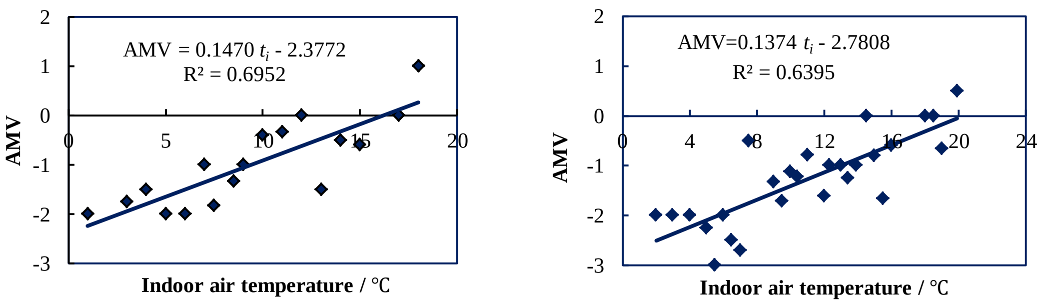
The slope (gradient coefficient) of the regression line can be used to evaluate the sensitivity of the occupants to the air temperature variation. Some studies [35, 36] have found that females are more sensitive and tend to be cooler in cold environment for the same clothing insulation level. In our study, it is found to be 0.1090/℃ for the Lhasa females, 0.1378/℃ for the Lhasa males, which shows that thermal sensation of Lhasa females changing with the temperature variations were less sensitive than that of Lhasa males. We think that one possible reason is that the females adjust their clothing levels more swiftly according to the indoor temperature shown in Figure 6, resulting in insensitivity to indoor temperature changes.

We divided all the samples data into two groups according to heating and no heating in the houses, and analyzed it by liner regression. The results are shown in Figure 11 (a, b) and Table 3. The neutral temperature of samples with heating is 16.2℃, and that of samples without heating is 20.2℃, as shown in Table 3, which indicates that the neutral temperature of occupants in houses without heating devices is higher than that of houses with heating devices.

Table 3. Regression equation and neutral temperature.

	Regression Equation	Correlation coefficient (R)	Neutral temperature /℃
Heating	AMV = 0.1470 t_i − 2.3772	0.8338	t_i =16.2
No heating	AMV = 0.1374 t_i − 2.7808	0.7997	t_i =20.2
Total	AMV = 0.1292 t_i − 2.4953	0.8357	t_i =19.3

Where: AMV is actual mean vote of thermal sensation and t_i is the indoor air temperature.



a. Heating

b. No heating

Figure 11. Linear regression calculation based on AMV versus indoor air temperature.

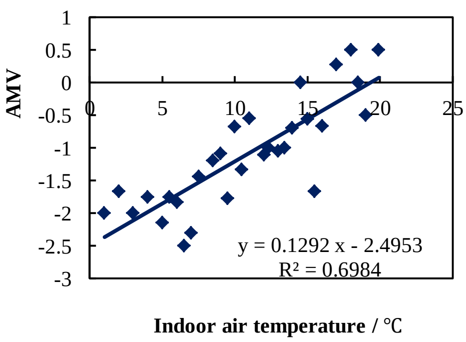


Figure 12. Linear regression calculation based on AMV versus indoor air temperature for total.

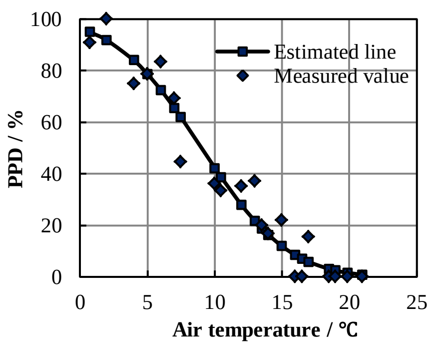


Figure 13. Thermal acceptability.

4.7. Thermal acceptability

ASHRAE Standard 55 specifies the conditions in which 80% or more of the occupants will find the environments thermally acceptable. It is a common assumption that a vote outside the three central categories (-1, 0, 1) of the ASHRAE scale is an expression of dissatisfaction (unacceptable). Therefore, the resulting percentage of people's dissatisfaction （PPD） from occupants' votes (-2, -3, +2, +3) in each 0.5℃ bin was plotted as a function of indoor air temperature. The Probit regression percentage curve of thermal unacceptable on air temperature in winter is depicted in Figure 13. When the percentage of people's dissatisfaction is equal to 20%, the lower limit of acceptable air temperature of 80% occupants can be calculated as 13.3℃. This finding indicates that occupants in Lhasa could accept wider temperature range. The Probit regression equation is as follow:

$$\text{Probit}=\Phi(1.784-0.198t_i)$$

5. Discussion

5.1. Comparison with other cities

In order to understand the winter indoor thermal environmental conditions in China well, five cities are chosen to compare in terms of thermal comfort investigation. They are Lhasa, Xi'an, Nanyang, Jiaozuo and Harbin. The five cities are in different typical climate regions of China (Figure 1). Although the summer climates in these cities are quite different, but cold and dry conditions in winter is their common characteristics.

Central heating systems and individual heating units are usually used by occupants in cold season. Table 4 demonstrates that the percentages of houses equipped with central heating systems in Harbin, Xi'an, Jiaozuo and Nanyang are 100%, 96.5%, 78.7% and 41.3%, respectively. Houses in Lhasa use individual space heating units such as electric heater. Because the majority of houses of Harbin and Xi'an used the central heating systems, we find that the mean indoor air temperature in the two cities is over 20℃, which is the highest one among the cities. On account of intense solar radiation in Lhasa, although the mean outdoor air temperature in Lhasa is 1.4℃, about 4.5K lower than that of Nanyang and Jiaozuo during investigation, but the mean indoor air temperature in Lhasa is 10.9℃, which is similar to that of Nanyang and Jiaozuo which used individual heating units to warm their houses in winter. However, the mean indoor temperature in Lhasa is lower than that of houses which equipped with central heating system. It reveals that the indoor air temperature is affected not only by outdoor climate and space heating system or apparatus, but also by solar radiation level.

5.2. Comparison with previous field studies

Table 4 and table 5 show the findings of different field studies of thermal comfort in winter. The neutral temperature of Lhasa occupants is 19.3℃, which is similar to that of Jiaozuo and Harbin, higher than Xi'an and Nanyang's results.

The slope between the actual thermal comfort vote and the air temperature is 0.1292/℃, which is lower than that of the San Francisco, Montreal, Kalgoorlie, and

Harbin, higher than Xi'an's and Jiaozuo's results. The slope presents the subjects' thermal sensitivity to air temperature variations. In general, the subjects with the Chinese cultural background have lower neutral temperature and are less sensitive to air temperature variations than those of the other cultures with higher neutral temperature, possibly due to the heavier clothing insulation level in winter.

In spite of the higher neutral temperature of Lhasa occupants, the acceptable temperature range is relatively wider. The lower limit of 80% occupants in Lhasa can accept the air temperature of 13.3℃, which is lower than that of Xi'an (16.4℃) and Harbin (18.0℃), but higher than that of Nanyang (11.2℃) and Jiaozuo (11.6℃).

Table 4. Statistics of environmental parameters among different cities in China.

City		T_{in}		T_{out}	Clothing (clo)		Air pressure (mbar)	Space heating	Climate type
		CH	IH		CH	IH			
Lhasa	Mean		10.9	1.4		1.50	650	IH	Plateau climate
	Standard deviation		3.95	5.5		0.29			
	Maximum		21	15.8		2.20			
	Minimum		0.6	-12.7		1.03			
Xi'an[37]	Mean	20.3		-2.5	0.89		978.7	96.5% CH	Cold climate
	Standard deviation	2.3		3.8	0.24				
	Maximum	24.3		-14.9	1.65				
	Minimum	12.8		3.8	0.45				
NanYang[38]	Mean	16.2	9.9	5.7	1.14	1.41	1010	41.3% CH 58.7% IH	Hot in summer and cold in winter
	Standard deviation	1.97	3.2	-	0.12	0.28			
	Maximum	21	17.5	-	1.66	2.2			
	Minimum	12.5	4	-	0.86	0.86			
JiaoZuo[24]	Mean	18.5	10.6	5.5	1.15	(1.5)	1017	78.8% CH 21.2% IH	Cold climate
	Standard deviation	2.6	2.2	4.3	0.38	0.24			
	Maximum	24	17.1	17.3	2.60	2.37			
	Minimum	9.9	6.0	-2.2	0.45	0.92			
Harbin[17]	Mean	20.1		-9.9	(1.4)		1001	100% CH	Severe cold climate
	Standard deviation	2.43			0.28				
	Maximum	25.6			2.08				
	Minimum	12.0			0.81				

Note: The insulations of the chairs (0.15clo) are included in parenthesis. CH and IH are the space heating pattern of residential building. CH refers to central heating system, and IH refers to individual space heating devices or no heating apparatus.

Table 5. Statistical results of field studies in winter.

	Actual Mean Vote equation	Correlation Coefficient (R)	Neutral temp. **t_o** (ET*)	Preferred temp.	80% acceptable temp.	Clothing (clo)
Shiller[40] San Francisco	**AMV = 0.26 × *ET***− 5.83**	0.9274	(22.0)		20.5-24.0	0.58
Donnini[41] Motreal	**AMV = 0.49×** t_o **− 11.69**	0.9899	23.1 (22.6)	22	21.5-25.5	0.87
Cena[42] Kalgoorlie	**AMV = 0.21×** t_o **− 4.28**	0.8426	20.3		-	0.7
de Dear[43] Brisbane	-	-	24.2			0.41-0.52
	-	-	23.8			0.37-0.53
	-	-	22.6			0.46-0.62
Lhasa	**AMV = 0.13 ×** t_i **– 2.4953**	0.8357	19.3(t_i)		≥13.3	1.50
Xi’an[37]	**AMV = 0.06 ×** t_o **− 1.092**	0.2306	17.0	17.4	16.4-24.0	0.89
NanYang[38]	**AMV = 0.15 ×** t_o **− 1.976**	0.7166	13.6	14.5	11.2-16.8	1.14-1.41
Jiaozuo[24]	**AMV = 0.09 ×** t_o **- 1.822**	0.8526	19.4	21.0	11.6-24.2	1.15-1.51
Harbin[17]	**AMV=0.30 ×** t_o **- 6.506**	0.8722	21.5	21.9	18.0-25.5	1.37

Notes: AMV refers to actual mean vote. **ET*** is the new effective temperature, t_o is operative temperature, t_i is air temperature.

5.3. Thermal adaptation

In conclusion, the thermal comfort of Lhasa occupants is more different from the findings of other field studies. The possible reasons are local unique plateau climate and the adaptation of local people. When adaptive opportunities are available and effective, occupants will be able to achieve thermal comfort in terms of psychological and behavioural adaptation [29]. People who live in free-running buildings can have more opportunities to control over their environment to suit themselves [39].On account of living in the plateau for thousands of years, Lhasa occupants have adapted to the typical natural environment psychologically, physiologically, and behaviourally.

5.3.1. Psychological expectations

The occupants of Lhasa have higher thermal expectation. The possible explanation may be as follows. Yanfeng Liu reported that, when the outdoor average air temperature of Lhasa was -0.6℃, the indoor mean daily air temperature of southern and northern space without heating devices were 18.0℃ and 7.4℃, respectively [44]. A relatively warm environment in southern space in Lhasa was built due to the intense solar radiation in winter. As a result, people who stay in the southern space are satisfied with their thermal environment. But when they go into or out of northern space such as a kitchen or a toilet with lower temperature, it is possible to produce heavier cold stress physiologically and psychologically caused by the temperature difference between southern and northern space, and as well as the psychological expectations caused by the thermal experience in the southern space. Therefore, when people move out of the warm south-side or sun-spaces, they feel cold discomfort in the other colder regions of the house, and are likely to be more critical of those.

The distribution of indoor air temperature between heating and no heating is shown in Figure 14. It demonstrates that the indoor air temperature in the houses between heating and no heating is significantly different by T test ($P=0.001<0.05$).

The mean indoor air temperature in the houses with the heating devices is lower than that of houses without heating devices. The possible reason is that the number of samples with heating devices is much less. However, the neutral temperature of the occupants in the heating houses (16.2℃) is lower than that of the occupants without heating (20.2℃). It is possible that the psychological factor plays a role in the process of thermal sensation. When there are space heating units with electric heaters or stove heaters in the houses, although there is little function on improving the indoor air temperature, it alleviates the thermal expectations due to environmental control equipments installed in houses.

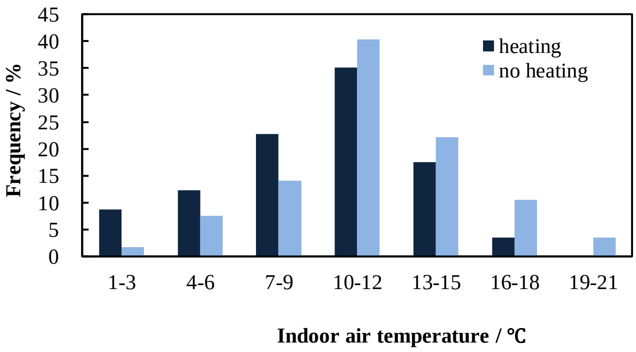


Figure 14. Frequency distribution of indoor air temperature in the houses between heating and no heating.

5.3.2. Acclimatization

The air pressure in Lhasa is two-thirds of the standard air pressure. At low air pressure condition, the increment of evaporative heat transfer was larger than the decrement of convective heat transfer. Radiant heat transfer between human body and environment was not affected by hypobaric exposure, while the respiratory heat transfer changed little [16]. Therefore, compared with the normal air pressure, the heat loss of human body in low air pressure obviously increased. The lower air pressure, the greater the heat loss. It explained why people tended to feel cooler under lower air pressure. Thus they expected a warmer thermal environment.

5.3.3. Behavioural adaption

Firstly, the indoor air temperatures in southern spaces in Lhasa could meet the requirements of human thermal comfort even without the heating system because of the rich solar radiation (Figure 2)[44]. Therefore, the daily living activities of Lhasa residents are concentrated on the southern space (the living room). Moreover, the living room also possessed other functions such as the dining room or the bedroom in some traditional houses.

Secondly, the Lhasa residents wear heavier clothing to resist cold; it can be found that the clothing insulation of Lhasa occupants is the maximum one in comparison with other field studies. Simultaneously, to adapt to the varying thermal regimes, Tibet robes offer a lot of flexibilities to change the micro-climate around the body. For example, on the sunny day, people usually wear the left sleeve, and drape the right sleeve from the shoulder to the front of the chest. Until the sunset, and they wrap tightly the robes. Thus a unique dressing habit of Tibetans is to take off the right sleeve (Figure 3), and the occupants have adaptively used clothing in response to the temperature change.

Thirdly, affected by nomadic life style and alpine climate, the Tibetans develop their dietary custom based on beef and mutton, buttered tea and barley liquor. The high-calorie and high-protein diet can maintain a higher metabolic, so that people can produce more heat to resist cold.

6. Conclusions

The main objectives of this study were to investigate the indoor thermal environment conditions and occupants' thermal comfort sensation in residential building in China. A total of 356 sets of physical measurements and questionnaires were collected from 44 occupants in 20 houses located in Lhasa with the plateau continental climate zone from December 2007 to February 2008. The main results of the study are as follows:

- Most of the residential buildings investigated were between 2 or 3 stories. Due to lack of conventional energy (such as coal, natural gas and oil), there were no central heating systems in Lhasa. About 60% of the houses investigated were equipped with individual space heating units by electric heaters stove heaters or air conditioners which were intermittence used, while 40% without any heating systems or apparatus.
- The average thermal insulation of clothing was 1.63clo for Lhasa females, 1.48clo for Lhasa males, and with a mean clothing insulation of 1.54clo for total sample. The average clothing insulation of the samples with heating devices was 1.48clo, while that of the samples without heating devices was 1.59clo. Whether female or male, heating or without heating, the clothing insulation difference between them was significant at the 95% confidence level by SPSS analysis.
- The indoor air temperature of residential buildings in Lhasa fell within 0.6℃ and 21℃, with an average value of 10.9℃. Meanwhile, 64.2% indoor air temperature distributed from 10℃ to 15℃. The range of indoor air temperature was wider, and unstable indoor air temperature in residential buildings in winter had an adverse effect on occupants' thermal comfort.
- The neutral temperature of samples with heating was 16.2℃, that of samples without heating was 20.2℃, and that of the total samples was 19.3℃.
- The lower limit of acceptable air temperature for 80% occupants in Lhasa was 13.3℃. This finding indicates that occupants in Lhasa who have acclimated to the plateau cold climate could accept wider thermal environments.

- Lhasa occupants have adapted to the typical natural environment from psychological expectation, physiological acclimatization, and behavior adaption.

The results of this field survey and measurement study can be used to design a low energy consumption system with consideration of occupant thermal comfort in plateau climate zone of Lhasa.

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