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Article

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A study of thermal comfort in residential buildings on the Tibetan Plateau, China

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Abstract: Tibet is located on the Qinghai-Tibetan Plateau in China, the highest and largest plateau in the world. It is in the *Cold* and *Severe Cold* zones according to the Chinese climatic division for building design and has unique climatic characteristics and traditional cultural background. In order to obtain a comprehensive understanding about the real indoor thermal environment and the residents' thermal comfort status in Tibet, a field investigation of residential buildings was conducted in the Tibetan Alpine region with on-site environmental parameter measurements and a simultaneous survey using a subjective thermal comfort questionnaire. Based on the analysis of the data collected from the field study, the value of the adaptive coefficient λ in the adaptive thermal comfort model $aPMV=\frac{PMV}{1+\lambda PMV}$ suitable to the Tibet area has been obtained as -0.34; and thus the acceptable thermal comfort temperature range for residential buildings in this area has been produced. The research findings provide comprehensive knowledge and a useful reference for the development of a design and evaluation standard for indoor thermal environments in the Tibet region.

Key Words: Tibetan Plateau; indoor thermal environment; thermal comfort; residential buildings; field investigation.

1. Introduction

Tibet, located in the Qinghai-Tibetan Plateau China, the highest and largest plateau in the world, has distinct climatic characteristics [1] and unique traditional living styles [2]. The main climatic characteristics of Tibet can be summarized as hypobaric hypoxia, low average temperature and relative humidity, high wind velocity and solar radiation, and low rainfall. Many internal thermal environment investigations of traditional dwellings have been conducted in this area [3-14] and some other adjacent areas, including western China [15, 16], India [17] and Nepal [18-20]. This research has shown that the residents had formulated their own lifestyle and measures adapted to the severe thermal environment.

Research on thermal comfort conditions and human adaptation in high altitude areas has attracted many scholars due to their unique climatic conditions. Some [21] studied the physiological adaptation of the original inhabitants of an area. Some others [22-28] focused on the building technologies or designs that improve thermal comfort whilst others dealt with the effect of the special thermal environment on occupants' thermal comfort in these areas. The majority of Tibet lies within the 'cold' and the 'severe cold' zones of China [29], which, according to several studies in these climate zones, have a lower comfort temperature range than those in warmer zones, [10, 30-32]. The comfort temperature varied because of thermal adaption [33-35], and also related to buildings styles [4, 36, 37] and seasons [38]. Besides that, the significant impacts of hypobaric hypoxia on physiological and subjective responses to the thermal environment were also recognized [39].

In order to study the effects of hypobaric conditions on people's thermal responses, Ohno H *et al.* [40] conducted experiments to clarify the interactive effects between barometric and thermal events on people's thermal comfort under hypobaric conditions (pressures about 30% below that at sea level) and the results showed that some physiological features change when the altitude increases which leads to subjects finding it difficult to express their thermal state. Cui *et al.* [41] studied the effect of low pressure on human physiological responses in an artificial chamber, and found significant effects when it decreased to 85/70kPa. Wang, H. *et al.* [42] conducted an experiment in a decompression chamber to simulate the hypobaric conditions, and found that people become more sensitive to draught and expect lower air movements. It was concluded that the hypobaric environment tends to make people feel cooler. Studies on the thermal environment in high altitude areas are limited, Liu, Y. *et al.* [34] carried out a field study of the thermal comfort conditions in residential buildings in high-altitude regions with sub-atmospheric pressure in China. They found that the neutral temperature in winter is much higher than the mean indoor air temperature. Wang, D. *et al.* [43] investigated the indoor thermal environment of residential buildings in Lhasa in winter and found that the low indoor humidity has a negative impact on thermal comfort. As to the strategies to improve the thermal environment, Chang and Santee [44] studied the clothing insulation in a hypobaric environment and revealed that evaporation was the dominant process at the skin surface, while convection dominated at the outer clothing surface. This resulted in the skin temperature being found to be lower than it is at sea level, but the clothing temperature was found to be higher than it is at sea level. In order to study the strategic planning of the architecture design, Luo [45] carried out a field study on the existing buildings at an altitude of 5,347m on a mountain in Tibet and found that the solar house is an effective way to improve the thermal environment.

However, very little previous research has studied the adaptive thermal comfort model for indoor thermal environments in this area. The theories of adaptive thermal comfort are widely used to evaluate indoor thermal environments in 'real world' buildings [46-48] due to human thermal adaptation, and are incorporated in most current thermal comfort standards worldwide [49-51]. It is known that indoor thermal environments and the characteristics of human thermal comfort differ between different areas [52] due to cultural, climatic, and social differences and personal experience and preferences [53, 54]. Yao *et al.* [55] proposed a theoretical adaptive model of thermal comfort (aPMV), which has proved to be useful in similar geodetic latitude regions in India [56] and China [57]. However, due to its high altitude on the Qinghai-Tibetan Plateau, the region's unique climatic characteristics have distinct impacts on indoor thermal environments compared to the other regions in the same climatic zone. Therefore, the open questions remaining are: what is the real situation of the indoor thermal environment and how do the local residents respond to it in order to achieve 'thermal comfort'?

In summary, there are many studies for Tibet residential buildings focused on different aspects, but little comprehensive study on indoor adaptive thermal comfort based on the theoretical adaptive models. Unique characteristics do exist in terms of local climate and its impact on the indoor thermal environment and building design. Therefore, the existing thermal comfort and indoor environment design standards may not be suitable to this area. In order to fill the gap, the aim of this research is to gain a comprehensive understanding of the indoor thermal environment and the occupants' thermal comfort in order to develop a thermal comfort model suitable to this area. Such research findings will provide information and knowledge for indoor environmental design, operation, and evaluation in this specific region.

2. Background information

2.1 Climatic characteristics

Due to the high altitude, Tibet has higher annual solar radiation and lower annual average air temperature compared to the other cities in the same climate zone. Table 1 shows meteorological parameters for the outdoor climate of the typical cities in the Tibetan Plateau area（Lhasa and Sining）.

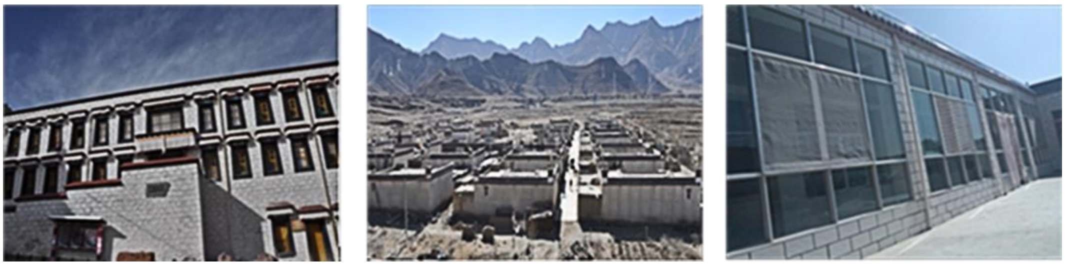
Table 1: A comparison of the meteorological parameters of typical cities on the Tibetan Plateau [58].

City	Observatory site		Annual average air temperature (℃)	Average temperature of the hottest month (℃)	Annual total solar radiation (MJ/m^2)	Altitude (m)	Pressure （KPa）
	North latitude	East longitude					
Lhasa	29.67	91.13	8.30	16.40	7331.20	3648.9	65.24
Sining	36.72	101.75	5.93	17.69	5601.00	2295.2	77.41
Changdu	31.15	97.17	7.45	15.40	6078.63	3306.0	68.16
Nyingchi	29.67	94.33	9.00	15.82	6359.40	2991.8	70.73

The average annual dry-bulb temperature in these typical cities is less than 10℃, even in the hottest month the highest average temperature is below 17.69℃. Meanwhile, the annual total solar radiation is more than 5,000MJ/m^2, which represents a very rich solar resource.

2.2 Residential building types

The research team carried out a large number of surveys by visiting local residential buildings in Tibet. Three typical types of residential buildings are identified; namely, traditional buildings, new buildings and solar houses (see Fig.1). Residential buildings are usually one- to three-story, low-rise buildings. External walls are usually composed of stone or rammed-earth, load-bearing walls coated with plaster on one or both sides. The internal supporting beams and columns are composed of timber. Due to the abundant solar energy, the south-facing wall is usually glazed to provide passive solar heating in winter. Based on such a construction type, the thermal properties of external walls for the three typical residential building types are listed in Table 2. From this table we can see that the traditional residential building has the highest thickness.



(a) Three-story stone-wall (b) One-story rammed-earth wall (c) One-story solar house

Fig. 1: Typical Tibetan residential buildings

Table 2: Thermal properties of external walls of typical residential buildings in Tibet

Building Type	Index	Thermal Conductivity (W/m·k)	Thermal Capacity (W/m²·k)	Thickness（m）	Thermal Resistance (m².k/w)	Thermal Transmittance (w/m².k)	Thermal Inertia Index（D）
Traditional Tibetan Dwelling	Lime Gypsum plaster	0.70	7.56	0.02	0.839	1.192	6.450
	Stone wall	1.28	12.54	0.6			
	Gypsum plaster	0.23	4.11	0.02			
New Tibetan Dwelling	Rubble masonry	1.28	12.54	0.24	0.478	2.091	2.705
	Calcium sulphate plaster	0.23	4.11	0.02			
South-facing Direct-gain Passive Solar House	Glass	0.88	12.56	0.02	0.186	5.367	0.284

3. Research Methodology

In this research, primary data on the subjective evaluation of indoor thermal comfort and outdoor environmental parameter data were collected through onsite measurements and subjective questionnaire surveys. The monitored environmental parameters and the surveyed data have been subjected to statistical analysis. The existing adaptive thermal comfort model – aPMV - has been applied to study the characteristics of indoor thermal environments in residential buildings in Tibet.

3.1 Onsite subjective survey

A questionnaire survey on occupants' thermal sensation and onsite physical environmental parameter measurements was conducted in 527 residential buildings. The questionnaire survey aimed to obtain residents' thermal sensation and included questions on the basic information about the buildings, residents' demographic information such as gender, age, regional location, occupancy time, and living habits, and the present measures regarding the regulation of the indoor thermal environment. Respondents' subjective thermal sensation vote (TSV) was evaluated using the 7-point scale suggested by ASHRAE Standard 55 [51]. The thermal sensation scales are listed in Table 3.

Table 3: The scale of thermal, humidity and draft sensation

Sensation	Temperature	Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold
	Humidity	Very humid	Humid	Slightly humid	Neutral	Slightly dry	Dry	Very dry
	Draft Sensation	Very stuffy	Stuffy	Slightly stuffy	Neutral	Slightly breezy	Breezy	Very breezy
Scale points		+3	+2	+1	0	-1	-2	-3

Onsite surveys were conducted from 5th July to 25th August in 2013, from January 13th to 22nd February 2014, and 10th July to 29th August 2014. The surveys and measurements were conducted during the daytime between 8:30 and 19:30. The thermal sensation and environmental parameters were recorded at one-hour intervals. A total of 1,741 copies of a questionnaire were distributed through field studies in 7 districts in the Tibet region, including the three cities of Lhasa, Shigatse and Lhoka, during the two seasons of summer and winter. A total of 1,258 completed questionnaires were received, of which 1,182 were valid. Among the 1,182 completed valid questionnaires, 609 were from the summer survey and 573 were from the winter one. The distribution of the valid questionnaires over the main regions is: 351 from Lhasa, 196 from Shigatse, and 103 from Lhoka. Fig. 2 shows the geographic location of the surveyed areas.

Note: Spots represent the towns investigated

Fig. 2: The investigated Tibetan cities and the survey scene

Of the 1,182 respondents, 579 were male and 603 were female. The subjects' ages range between 68 years (the oldest) and 16 years (the youngest). The respondents' basic information is presented in Table 4.

Table 4: Respondents' basic information

Total sample	1,182 （609 in summer, 573 in winter）	
Gender	Male	579(49%)
	Female	603(51%)
Age [Years]	Maximum	68
	Minimum	16
	Average	33
	16-30	**42.70[Average, %?]**
	30-50	**43.07[Average, %?]**
	50-70	**15.73[Average, %?]**

3.2 Onsite parameter measurement

The measured environmental parameters include indoor and outdoor air temperature, humidity, globe temperature, and air velocity. The following instruments have been used to measure the physical environmental parameters: a Dwyer 485-2 digital temperature and humidity meter, a Testo 425 Hot-wire Anemometer, and a SWEMA Black Ball temperature instrument. The measuring range for each instrument is given below:

- Dwyer 485-2 digital temperature and humidity meter:
  Temperature range: -30 ~ +85℃; Accuracy: ± 0.5℃;
  Humidity range: 0~100%, Accuracy: ± 2%
- **RH Testo 425** Hot-wire Anemometer:
  Velocity Range: 0-20m/s, System Accuracy: ± 0.03m/s
- SWEMA Black Ball temperature instrument:
  Temperature Range: -20～+50℃, Accuracy: ±0.3℃.

Due to the constraints and complications of measuring radiant temperature, the globe temperature was measured instead in this study. Many other researchers popularly use the globe temperature to estimate radiant temperature, particularly in studies of residential buildings [59].

The onsite measurement is based on the method recommended in ASHRAE 55-2013 [51]. More specifically, for the indoor environment parameters, the center of the room and the people's occupancy areas were selected as the representative points for measurement. The measurements of temperature, humidity, and air speed were conducted on the height of 1.1m because the occupants were usually in a sitting position at home. For a few subjects in standing postures, the measurement point was set at 1.6m above the floor. As to the outdoor environment parameters, the measurements were conducted on the open ground near to the tested house. The instruments were settled out of direct sunlight at a height of 1.1m. The recorded air velocity was the average over a 2-minute period.

3.3 Operative temperature and neutral temperature

The indoor operative temperature (t_{op}) can be calculated as the average value of the indoor air temperature (t_a) and indoor mean radiant temperature (t_r) when metabolic rates are between 1.0met and 1.3met, not in direct sunlight, and not exposed to air velocities greater than 0.20m/s. The indoor thermal environments of the surveyed homes fall into this category.

The indoor operative temperature can be calculated using the following formula:

$$t_{op} = (t_a + t_r) / 2 \qquad (1)$$

The parameter air temperature t_a was directly measured and the mean radiant temperature t_r was assumed to be approximately equal to the globe temperature t_g [59] which can be measured directly. The neutral temperature can be regarded as the temperature at which the occupant's thermal sensation vote is 'neutral'.

3.4 The aPMV model

Yao *et al.* [55] established a theoretical adaptive model based on the thermal comfort-adaptive Predicted Mean Vote (aPMV) using the "black box" theory. It reveals the relationship of the lab-based, steady-state Predicted Mean Vote (PMV) [60] and the actual mean vote in the real environment taking into account occupants' psychological and behavioral adaptations and so on.

The aPMV model is presented as follows:

$$\text{aPMV} = \frac{PMV}{1+\lambda\times\text{PMV}} \qquad (2)$$

"λ" is the adaptive coefficient.

The aPMV model has been adapted in the Chinese national standard "Evaluation standard for the indoor thermal environment in civil buildings" GB/T50785-2012 [50].

The aPMV model can be used to predict the actual thermal sensation in dynamic environmental conditions. The determination of the value of "λ" is based on field studies considering the local climate, culture, and social background.

3.5 The statistical methods

After the raw data was collected from the field study, several data processing methods were used for analyzing the results [61]. Using different questionnaires in the same room produces the bin method in section 4.1, **whilst being** plotted as every **questionnaire** in other sections. Occupants' clothing insulation was calculated using the clo-checklist method, according to ISO7730: Annex C: 'Estimation of thermal insulation of clothing ensembles' [62]. The indoor operative temperature bins are created for every 1°C, and used to build linear regressions with the value from thermal comfort models. **Coefficient R^2 values were determined and** used to assess the power of the regression models. A confidence level of 95% was adopted in the statistical analysis in this paper.

4. Results and Analysis

4.1 Comparison between globe temperature and air temperature

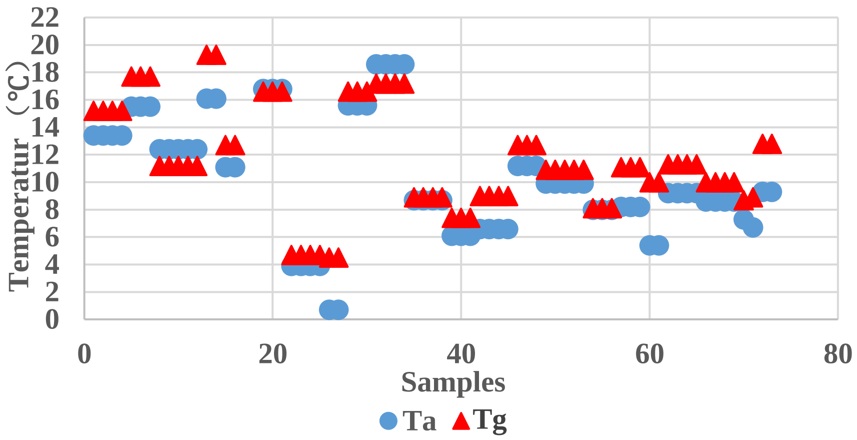


Fig. 3: A comparison between globe (Tg) and air temperatures (Ta)

Based on the data obtained, we compared the indoor globe temperature and indoor air temperature as simultaneously measured (see Fig. 3). The proportion of samples for which the globe temperature is higher than the air temperature is up to 83.10%. The average value of the difference between the globe temperature and air temperature is 1.3℃. It is thus clear that the globe temperature is higher than the air temperature due to the high solar radiation intensity. Therefore, the operative or globe temperature is used instead of the indoor air temperature in this study.

4.2 Annual indoor environmental parameters

According to the measured data, the outdoor air temperature in Tibet ranges between -20 to 32.5℃, and the indoor air temperature between 0.5℃ to 30℃. Fig. 4 shows the relationship of the indoor and outdoor air temperatures. In order to compare the relationship of the indoor and outdoor temperatures, a reference line of $t_{out} = t_{in}$ is drawn in Fig. 4. For the purpose of explanation, we **categorize** three zones according to the outdoor air temperature. These are Zone A (lower than 0℃), Zone B (between 0 and 20℃) and Zone C (greater than 20℃). In Zone A, indoor air temperatures fluctuate greatly within a range of 0℃ - 26℃. This is due to the diversities in the use of heaters. In Zone B, the indoor air temperatures are **almost always** greater than the outdoor air temperatures. This is because the internal heat gains, including the heat gains from solar radiation and residents' activities, keep the indoor temperature higher than that outdoors. Furthermore, in this temperature range, the windows were almost always kept closed for warmth. In Zone C, the indoor temperatures are **almost always** lower than those outdoors. This is because the building envelope plays the role of thermal insulation to prevent the fenestration of outdoor heat into the room.

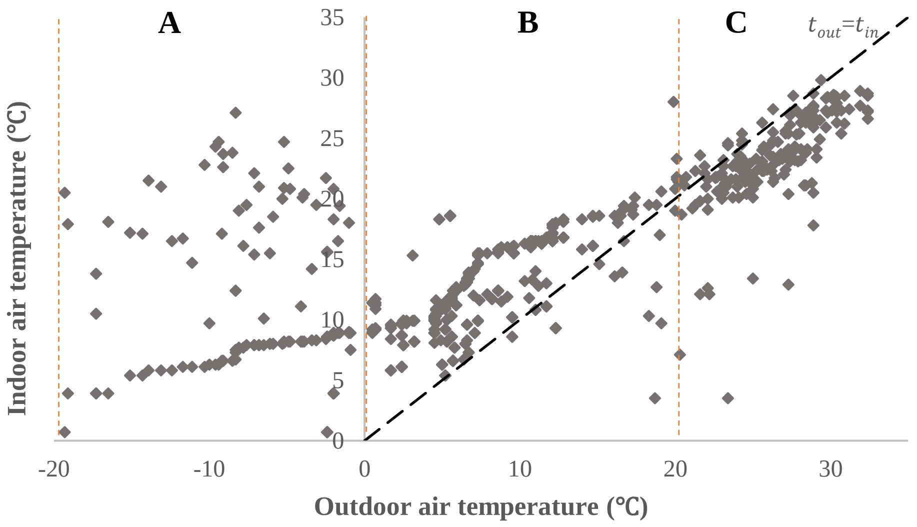


Fig. 4: Relationship between indoor and outdoor temperatures in Tibet

According to the survey, the indoor air temperature range is between 13.5℃ and 30.0℃ in the summer (June, July and August) and between 0.5℃ and 24.0℃ in winter (November, December, January and February). Fig. 5 shows the indoor air temperature frequency distribution. From the figure we can see that the frequency of the temperatures between 21℃ and 24℃ is about 25%, and the temperatures under 18℃ account for about 37% all year round. Fig. 6 shows the frequency distribution of the indoor air relative humidity. From the figure we can see that that the periods when relative humidity is lower than 40% account for nearly 55% all year round.

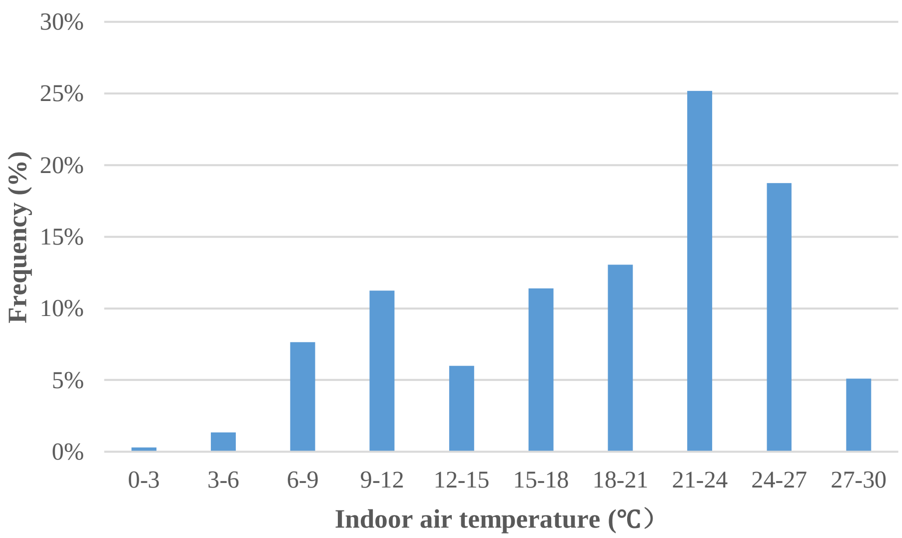


Fig. 5: Frequency of the indoor air temperature all year round

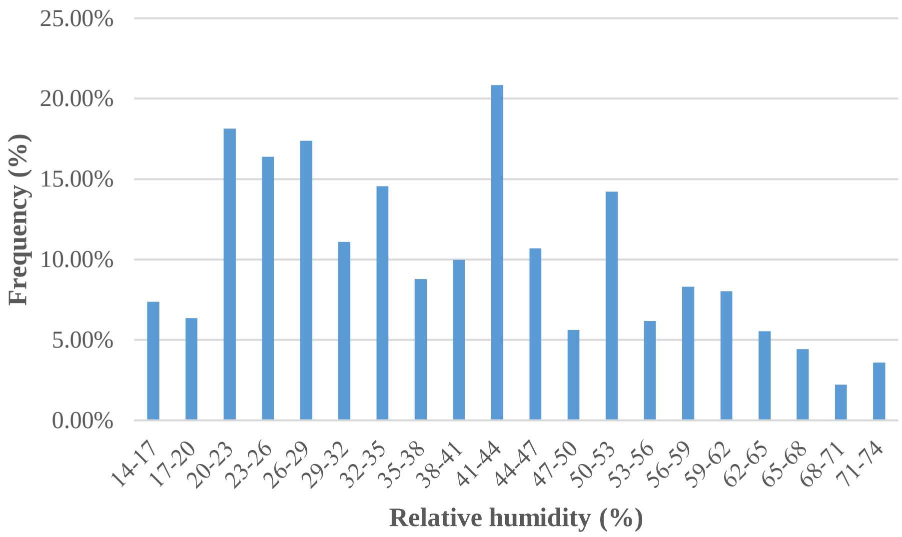


Fig. 6: Frequency of the indoor air relative humidity all year round

4.3 Adaptive behavior of residents

Tibet residents have a unique traditional lifestyle and adaptive measures to secure their thermal comfort. In summer, residents use natural ventilation to improve warm/hot indoor conditions; while in winter, they usually wear more clothes, drink butter and sweet tea, or use a stove/fire heater to keep warm as their homes lack central heating systems. Butter tea is a kind of high-calorie hot drink which not only replenishes their daily energy requirements, but also enables people to keep warm in winter. Therefore, drinking a cup of warm butter tea or sweet tea has become a feature of the residents' lifestyle and an integral part of daily life for the families in Tibet, as shown in Fig. 7.

Tibetan dress in summer.

Small areas of windows and doors.

Indoor stove heating.

Drinking sweet tea or butter tea.

Fig. 7: Adaptive measures in summer and winter

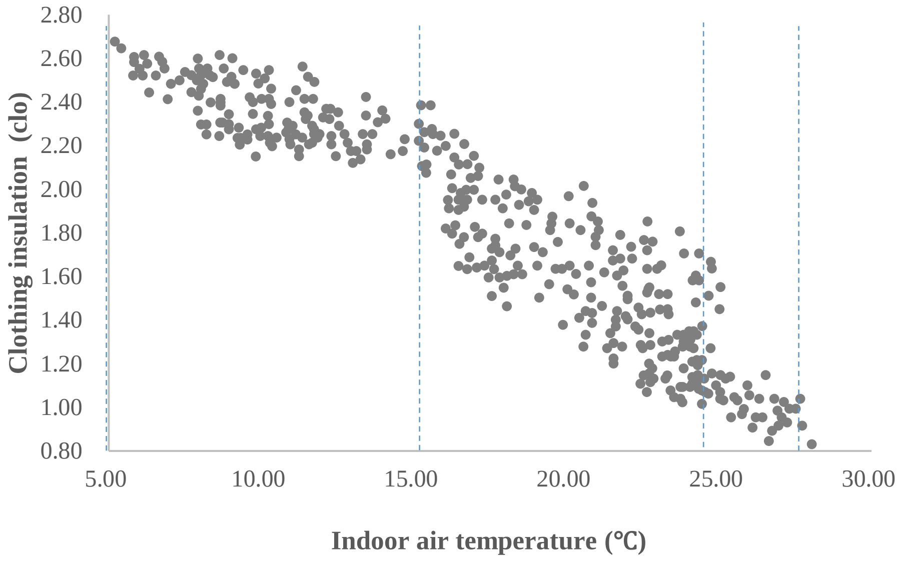


Fig. 8: Correlation between residents' annual clothing insulation with indoor air temperature

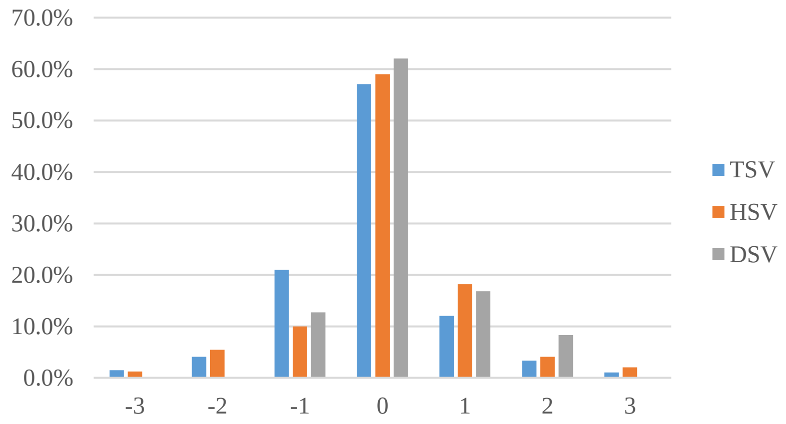
Fig. 8 shows a linear correlation between the residents' clothing insulation and indoor temperature. It can be seen that the clothing insulation levels decrease when the indoor temperatures increase. This phenomenon reflects the residents' lifestyle of changing clothing levels to keep themselves thermally comfortable. When the indoor temperature is lower than 16℃, the clothing insulation changes slightly according with the indoor air temperature. When the indoor air temperature ranges between 16℃ - 25℃ the fluctuation of clothing levels is more significant within the range between 2.3clo to 1.0clo and the gradient is much steeper. When the indoor temperature is higher than 25°C, the clothing insulation changes slightly with a gentle slope, which is mainly within the range between 1.1clo and 0.8clo. Tibetan residents have a variety of traditional dress ranges all year round, such as the 'Chuba', the Tibetan-style robe, which is characterized by long sleeves, a loose waist, and large lapels.

4.4 Indoor thermal environment

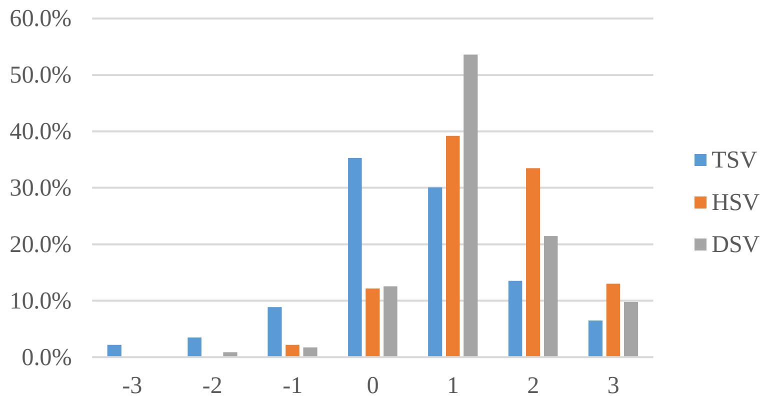
The thermal sensation votes (TSV), humid sensation votes (HSV), and draft sensation votes (DSV) are shown in Fig. 9. From Fig. 9 (a) it can be seen that most residents felt comfortable in summer. 91.35% of the votes for 'slightly warm', 'comfortable' and 'slightly cool' fall within the range -1 to +1 and, among those, the vote for 'comfortable' accounts for 57.57% (TSV = 0). The proportion of people having an acceptable humid sensation accounts for 87.88% (HSV -1 to +1), from which 59.68% (HSV = 0) vote for 'comfortable'. The proportion of people having an acceptable draft sensation accounts for 91.58% (-1 to +1), among which the vote for 'comfortable' accounts for 62.3% (DSV = 0) in summer.

From Fig. 9 (b) it can be seen that the proportion of the votes from 'slightly warm', 'comfortable' and 'slightly cool' within the range of -1 to +1 accounts for 74.37% and among them the vote for 'comfortable' and 'slightly cool' accounts for 35.29% (TSV = 0) and 30.25% (TSV = +1) respectively. The proportion of people having an acceptable humid sensation accounts for 53.44% ($-1 \leq HSV \leq +1$), among which the votes for 'comfortable' and 'slightly dry' account for 12.15% (HSV = 0) and 39.27% (HSV = -1) respectively. The proportion of people having an acceptable draft sensation accounts for 87.65% (-1 to +1), among which the proportion of people feeling comfortable accounts for 53.39% (FSV = 0). Based on the analysis above, the indoor thermal sensation vote (TSV) is more dispersed compared to the other two thermal comfort sensations (HSV and DSV). This is because residents actively adjust the thermal environment by moving around for sunbathing, drinking hot drinks, **moving**

closer to the stove, adding layers of clothing, and turning on electric heaters and other heating appliances. When HSV = 0, the acceptable draught was the highest and the acceptable humid environment was the lowest with only 12.15% of residents feeling comfortable.



(a)



(b)

Fig. 9: TSV, HSV, DSV in summer (a) and winter (b)

4.5 Comparative Analysis of PMV and AMV

By using regression analysis, the correlation between the Actual Mean Vote (AMV) and indoor operative temperature in winter and summer has been obtained in addition to the correlation between the Predicted Mean Vote (PMV) and the measured indoor operating temperature in winter and summer. Fig. 10 shows the correlation of PMV and AMV with the operative temperature in summer (i.e. months June, July and August). This can be expressed in Equation **3**

$AMV=0.1923\ T_o-4.1907$ ($R^2=0.8657$) (3)

When $AMV=0$, then $T_o=21.79$ ℃

This means that the actual indoor thermal neutral temperature of Tibetan dwellings in the summer is 21.79℃.

$PMV=0.2794T_o-6.6438$ ($R^2=0.9916$) (4)

When $PMV=0$, the predicted thermal neutral temperature of Tibetan dwellings in summer is 23.77℃.

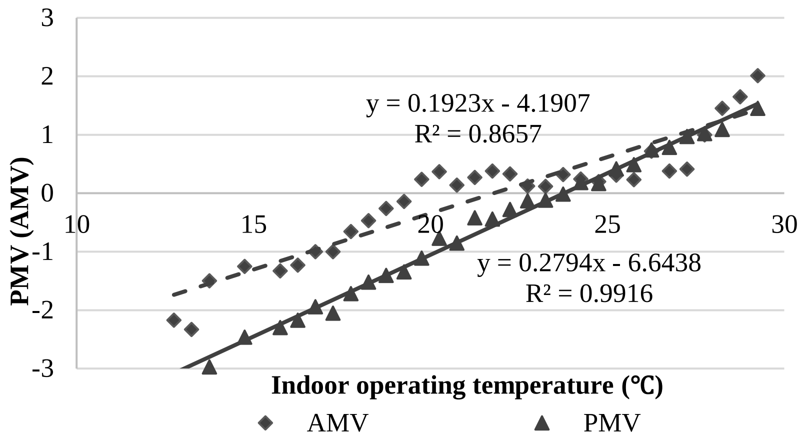


Fig. 10: The linear relationship between AMV/PMV and indoor operating temperature in summer

The actual thermal neutral temperature in this region is lower than that derived from the PMV model. In particular, within the temperature range 13℃ to 19℃, the AMV was higher than the PMV. This indicates that in summer the Tibet residents are more tolerant of the ‘cold’ conditions. This may be explained by the local residents **having become adapted** to living in the high altitude climate for many years. Besides, the low barometric pressure at high altitudes shows that the air density is low; hence the increased clothing insulation performance is possibly due to the reduced convective heat transfer coefficient between the clothing and air compared to the **conditions in which** the PMV model **was** developed. Furthermore, local residents are very active in taking adaptive measures to improve thermal comfort.

However, within the temperature range 25℃ - 28°C, the AMV is slightly lower than the PMV. This indicates that the residents can also tolerate hot conditions compared **to those predicted by the PMV.** But when the temperature exceeds 28℃, the residents feel hot. This is because they wear thick clothing (also called the Tibetan cloak) even in the summer, leading to higher clothing insulation. Besides, the measured parameters show that the residential indoor air velocity is low, which **contributes to the occupants feeling hot.**

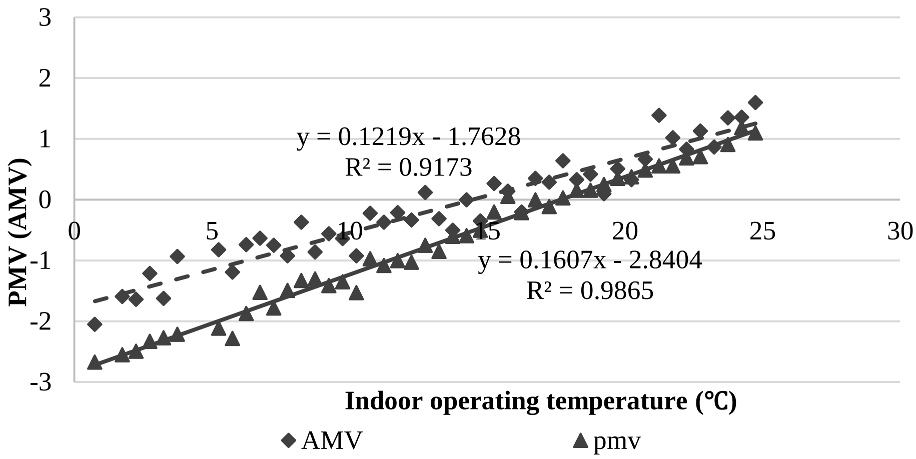


Fig. 11: Linear relations between AMV/PMV and indoor operating temperature in winter

Fig. 11 shows the correlation of PMV and AMV with the operative temperature in winter (i.e. December, January and February). This can be expressed in equation **5**

$AMV=0.1219\ T_o-1.7628$ $(R^2=0.9173)$ (5)

When AMV = 0, the actual indoor thermal neutral temperature T_o (actual) in winter is 14.46℃.
PMV=0.1607 T_o-2.8404 (R^2=0.9865) (6)
When PMV = 0, then the predicted thermal neutral temperature T_o (predicted) is 17.68℃. The actual indoor thermal neutral temperature in this region is lower than the predicted thermal neutral temperature. Especially, within the range 0 to 10℃, the AMV was higher than the PMV value. This can be explained as follows. In winter the residents normally wear heavy clothing and keep the windows closed. Beside the high indoor mean radiant temperature due to the high solar radiation makes the thermal sensation **less** cold than the predicted one. Furthermore, the residents have been living in the area for a long time and formed low expectations due to their economic **circumstances**. The adaptive measures for thermal comfort include putting on more layers of clothes, preventing infiltration from the doors and windows, drinking hot drinks, and using stoves in kitchens in extreme cold conditions. It is noted that the indoor operative temperatures were sometimes higher than 20℃, even in winter, due to the strong solar radiation. In this case, the residents need to adjust their clothing or open the windows to prevent them from feeling hot.

5. Adaptive thermal comfort

5.1 Obtaining the adaptive coefficient *λ*

In the adaptive thermal comfort model $aPMV=\frac{PMV}{1+\lambda\times PMV}$, the coefficient λ for Tibet's cold environment can be obtained using the least squares method[13]. Using this method, the value of the adaptive coefficient was calculated as follows:

$$Q=\sum\left(y-y_c\right)^2= \text{ minimum} \quad (7)$$

Since $y_c = a + bx$, equation (7) becomes:

$$Q=\sum(y-a-bx)^2= \text{ minimum} \quad (8)$$

Then solving the partial derivatives for *Q*, and letting it be equal to 0, gives:

$$\frac{\partial Q}{\partial a}=\sum 2(y-a-bx)\,(-1)=0 \quad (9)$$

$$\frac{\partial Q}{\partial b}=\sum 2(y-a-bx)\,(-x)=0 \quad (10)$$

This leads to the following:

$$\sum y=na+b\sum x \quad (11)$$

$$\sum xy=a\sum x+b\sum x^2 \quad (12)$$

Substituting the measured data (*x*, *y*) into equation (8), the parameters *a* and *b* can be calculated, as follows:

$$b=\frac{n\sum xy-\sum x\sum y}{n\sum x^2-(\sum x)^2} \quad (13)$$

$$a=\frac{\sum y}{n}-b\frac{\sum x}{n} \quad (14)$$

Finally, y_c can be obtain by substituting *a* and *b* into the equation $y_c= a+bx$

In the adaptive model with x representing $x=\frac{1}{PMV}$ and y representing $x=\frac{1}{aPMV}$

and substituting into the adaptive model equation (2), then:

$$y=x+\lambda, \{y=f(x)\} \quad (15)$$

That is when *b* = 1, the value of *a* that we applied is λ.

The least squares calculation of f(*x*) gives:

$$\prod = \sum_1^n \left[y_i - f(x_i)\right]^2 = \sum_1^n \left[y_i - (x_i+\lambda)\right]^2 = \min \quad (16)$$

$$\text{Let } \frac{\partial \Pi}{\partial \lambda} = 0 \quad (17)$$

$$\text{Then, } \frac{\partial \left[y_i - (X_i+\lambda)\right]^2}{\partial \lambda} = 2\sum_1^n \left[y_i - x_i - \lambda\right] = 0 \quad (18)$$

In the case of a cool environment i.e. when PMV <0, the results for 34 groups were obtained by processing the data using the bin method. Therefore,

$$\lambda = \frac{\sum_1^{34}(y-x)}{34} = -0.34 \quad (19)$$

Hence, the aPMV model for Tibetan dwellings can be written as follows:

$$aPMV = \frac{PMV}{1-0.34\times PMV} \quad \text{(cold environment)} \quad (20)$$

In order to compare the actual Predicted Mean Vote (aPMV) derived from the aPMV model and the actual thermal sensation vote (TSV), the aPMV and TSV are plotted in Fig. 12 **as follows:**

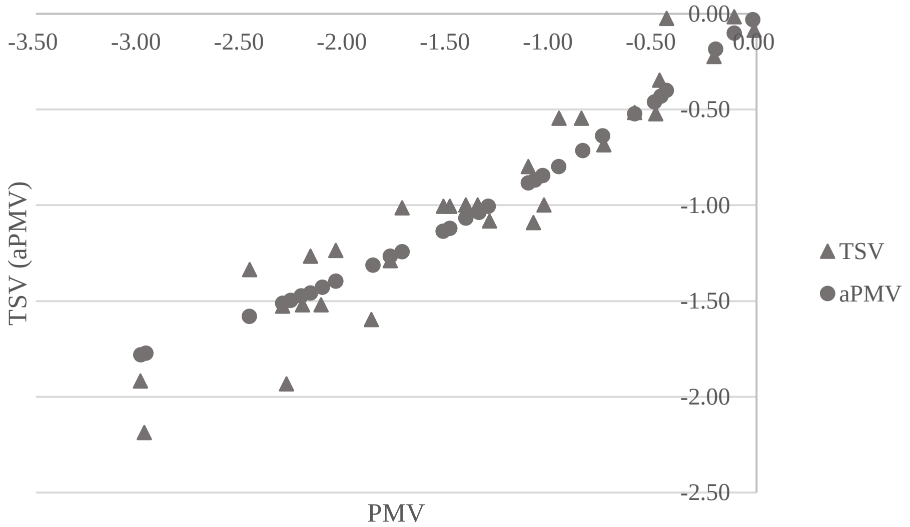


Fig. 12: Correlation between PMV, aPMV and TSV

The coloration of the two groups of data has a high degree of agreement with RMSE=0.1853.

5.2 Acceptable thermal comfort range

1） Acceptable indoor relative humidity range

In accordance with the Chinese regulations GB/T 50785 'Evaluation standard for indoor thermal environment in civil buildings' [50], the acceptable relative humidity range for the indoor thermal environment is 30% to 60% in winter, and 40% to 80% in summer. Most of the areas in Tibet are in the *Cold* and *Severe Cold* climatic zones of China. Based on the meteorological parameters of the major cities in China, the outdoor relative humidity range for this area is as follows: the monthly average of the coldest month in winter is 28%, and the monthly average of the hottest month in summer is 54%. In summary, the range of the suitable indoor relative humidity is within the 30% to 80% range in Tibet.

2） Thermal comfort zone

The requirement for a thermal comfort temperature under non-artificial heat and within a cold environment is described in GB/T 50785 which identifies three grades of indoor thermal environment in residential buildings: Grade I in which aPMV ranges between -0.5 and 0.5; Grade II between -1 and -0.5 or 0.5 to 1; and Grade III with aPMV < -1 or aPMV> 1. In Figure 15, the zone within the dashed grey line demonstrates the Grade I thermal comfort zone according to the GB/T 50785. Based on the adaptive thermal comfort model and using the adaptive thermal comfort coefficient λ= -0.34, the aPMV can be calculated under different humidity levels, using the formula $aPMV=\frac{PMV}{1+\lambda\times PMV}$. It is worthy of note that in the calculation the velocity and clothing level are adjusted to the local residents' actual situation which is different to the one used in GB/T 50785. The indoor air velocities are 0.03 and 0.02m/s for the aPMV values greater and less than zero respectively, clothing levels are 1.2clo for summer and 2.2clo for winter. The people's average metabolic rate is 1.2met for sitting or light physical activity representing the **occupants'** activity in these residential buildings, which remains the same as that in GB/T 50785. Accordingly, the acceptable operating temperatures under the different humidity levels can be calculated (see Table 5).

Table 5: Acceptable operating temperature under different humidities for the Tibet area (℃)

Φ / aPMV	30%	40%	50%	60%	70%
0.5	22.91	22.61	22.31	22.02	21.74
-0.5	10.18	9.97	9.75	9.56	9.36

Under the following conditions: Air velocity =0.03m/s, clothing insulation = 1.2clo when aPMV > 0, Air velocity =0.02m/s, clothing insulation = 2.2clo when aPMV < 0; activity level=1.2met

Note: Φ represents the relative humidity indoors.

The thermal comfort zone for the Tibet area based on Table 5 is represented by the red dashed line in Fig. 13. From the figure, we can see that, compared to the Grade I thermal comfort zone described in the GB/T 50785, the thermal comfort zone for the Tibet area is shifted down towards the lower temperature range. The dots represent the status of the air measured in the field study. About 28.6% of the dots fall within the comfort zone for the Tibet area.

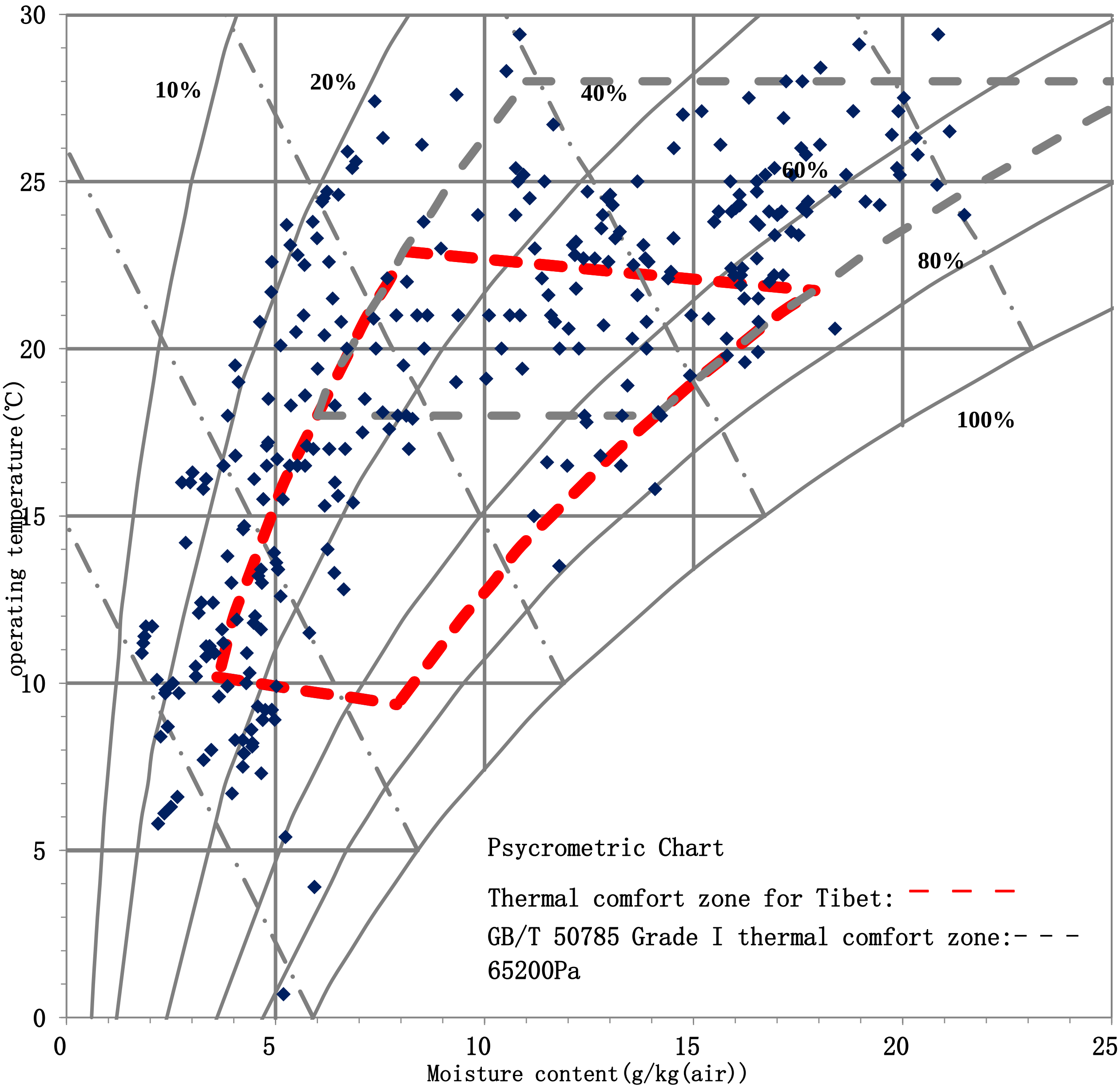


Fig.13: Thermal comfort zone for residential buildings in Lhasa

6. Conclusions

Tibet, located on the Qinghai-Tibetan Plateau in Southwest China, has distinct climatic characteristics and local residents who have a unique lifestyle. There is little in-depth understanding of the indoor thermal environment and local residents' living habitat. This paper presents a study of simultaneous indoor and outdoor thermal environmental measurements and a subjective questionnaire survey which was conducted in an area covering Lhasa, Shigatse, Qamdo, Nagqu, Nyingchi, Lhoka and Ngari. The research findings are summarized as follows:

1) According to the Thermal Design Code for Civil Buildings GB50176-93, the majority of areas in Tibet are classified in the 'severe cold' or 'cold' zones. However, the indoor thermal environment in Tibet is severe, particularly in winter, yet there are no central heating systems in residential buildings. Indoor air temperatures in residential buildings fluctuate greatly within the range 0 to 26℃ during the daytime when the outdoor temperature is between -20 and 0℃.

Thus, the indoor thermal environments are highly variable due to the great variety of heating measures that are in use.

2) Tibetan people have a unique lifestyle in terms of thermal adaptation. They wear heavy clothing (1.19 – 2.67clo) and drink butter-sweet tea to protect themselves from cold at home in winter. The summer clothing level is between 0.43 and 1.71clo due to the traditional dress of Tibetan-style robes such as the Chuba. They adjust the thermal environment using shading and open windows. The indoor temperature is higher than the outdoor temperature when the outdoor temperature is between 0 to 20℃; while the indoor temperature is mostly lower than the outdoor temperature when the outdoor temperature exceeds 20℃. This phenomenon reflects the active behavioral adaptation.
3) By applying the adaptive thermal comfort model (aPMV model), the adaptive thermal comfort coefficient (λ) value of -0.34 has been obtained and validated for residential buildings in Tibet. The acceptable thermal comfortable zone for the indoor environment of residential buildings in Tibet has been **identified** within the temperature range between 10.18℃ and 22.91℃ under a low relative humidity of 30% and between 9.79℃ and 21.74℃ under a high relative humidity of 70%.
4) Compared to the thermal comfort range recommended by the "Evaluation standard for indoor thermal environment in civil buildings" (GB/T 50785-2012), the acceptance range of the Tibet acceptable comfort range is shifted towards the lower temperature. From this study we can see that Tibetan people **are well adapted to** the cold environment. This is mainly because they have distinctive life-styles that involve wearing heavy traditional clothing and drinking **butter-sweet tea**. However, they are more sensitive to warm/hot environments due to their traditional dress code (0.4-1.7clo) in summer.

To summarize, the acceptable temperature range is far below that recommended in the *Evaluation Standard* GB/T 50785-2012. In the severe cold conditions, fires/stoves are commonly used for heating, which could cause poor indoor air quality and consequently affect people's health and wellbeing. Therefore they urgently need appropriate solutions to the heating of residential buildings in the region to meet occupant health and wellbeing demands. There is abundant solar energy which could be exploited for space heating in order to improve indoor thermal environments, for example, the passive solar house and solar energy storage systems. This research provides a comprehensive understanding of the indoor thermal environment of residential buildings in Tibet which could be referenced for the development of local thermal comfort standards and building design.

Acknowledgments

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Appendix A

Questionnaire of Indoor Thermal Environments for Summer Survey

The field survey is supported by the National Science & Technology Support Project of China, aiming to lay the foundation for governments to make national policies of energy-saving and emission-reduction as well as human well-being improvement. Please fill in the questionnaires during the survey with much patience, and all the information would be kept absolutely secret except for research only. We appreciate it very much for your participation and support for our projects.

The First Part (for respondents)

Sex：Male□ Female□， Age:_____， Height:_____，Weight:______，Occupation：_______
Length of residence: _______year (s)

1. Built time for present building:		Before 70s□, 70s□， 80s□, 90s□, new buildings□
2. Present dressing:		**upper**：shirt□，T-shirt□，a suit and tie□，thin coat□，none□ **lower**：trousers□，shorts□，dresses□，skirts□， **shoes**：sneaker□，leather shoes□，sandals□，slipper□， **socks**：socks(thin)□，silk socks□，none□， **others**：_________________________
3. Time spending in this room:		morning□, noon□, afternoon□， evening□， all day□ total hours：__________________
4. Feeling at present：	**temperature:** hot□，warm□，slightly warm□，neutral□，slightly cool□, cool□, cold□ **humidity :** very humid□, humid□, slightly humid□, neutral□，slightly dry□, dry□, too dry□ **air movement:** too stuffy□, stuffy□, slightly stuffy□, neutral□, slightly breezy□, breezy□, very breezy□	
5. Thermal satisfaction presently：		dissatisfied□, slightly dissatisfied□, acceptable□, slightly satisfied□, satisfied□
6. If dissatisfied，the reason is：		none□，cold□，hot□，humid□，dry□，stuffy□，draught□， others：________________
7. Thermal expectation for indoor thermal environments:		**temperature**： upper□, no change□, lower□ **humidity**： upper□, no change□, lower□ **air velocity**： upper□, no change□, lower□
8. Which ways would like to improve individual thermal comfort：		comfortable，no change□，using air-conditioning□, opening window for ventilation □，closing window □,add clothing, take off clothing, hot drinks, cool drinks, light activities, changing postures□, others：______
9. The habit, time and reason for window opening：		habits： frequently□, occasionally□, seldom□； time： morning□， noon□， afternoon□， evening□； reasons：smoking□， stuffy□， ventilation□， lighting□

10. Do you use air-conditioning frequently in summer：	YES□,NO□； if it is no, please choose the reason: ①comfortable, no need□，②unlike, draught□，③poor air circulation□，④power saving□，⑤using other regulation methods□，⑥without devices in rooms□
11. What are you feelings indoor for a long time?	Fatigue and drowsiness□，nausea and dizzy□，hot and upset□，eyes irritation□，sore throat□，nose discomfort and shortness of breath□，tinnitus □，impaired concentration□，dry, itchy and rash of skin□，none□
12. The overall thermal acceptability for thermal environments：	absolutely unacceptable□, unacceptably□, slightly unacceptable□，slightly acceptable□，acceptable□, absolutely acceptable□

The Second Part (for testers)

City: _________Building name: _____________Types of community：residences□，downtown□； others□
Dates：______**yy**____**mm**_____**dd** **Time**：__________ **Weather**（sunny□ cloudy□ rain□ snow□）
Tester name：________________

1. Building structure：	Masonry-concrete structure□，Reinforced Concrete Structure□， others□
2. Building location:	Along the street□， away from street□；suburb□
3. Total layers and floor：	Floor:______，total:_____ （basement excluded）
4. Window orientation for measuring room：	east□，south□，west□，north□，southeast□，northeast□，southwest□，northwest□
5. Type of rooms：	Living rooms:____ Bedrooms:____
6. Room areas：	areas:____ m^2， window（overall：___ m^2，opening areas___ m^2）
7. Types of windows：	Single frame with single glass□, single frame with double glass□, double frames with double glass□
8. The number of people presently in room:	Number:_________
9. Activities for respondents：	reclining□, sitting□, standing□, walking□
10. The window condition at present：	open□， close□
11. The regulation method for indoor thermal environments at present:	Air-conditioning□, household central air-conditioning□，central cooling□，air conditioning fan□，electric fan□，naturally ventilation, without regulation measures□，others：____________________
12 . Is the air-conditioning opened？if so, the set-point is :	Yes□，No□ Under 20oC□, 20oC□， 21oC□，22oC□，23oC□，24oC□, 25oC□，26oC□，27oC□，≥28oC□， unclear□

The Third Part (environmental parameters)

1. Test instrument type： Temperature and humidity meter：__________ Anemometer：______________

2. Instrument accuracy: Temperature and humidity meter：___________Anemometer：__________

3. Recording table ：

Outdoor air temperature oC：		Indoor air temperature oC：	
Outdoor relative humidity %：		Indoor relative humidity %：	
Outdoor air velocity m/s：		Indoor air velocity m/s：	

Appendix B

Questionnaire of Indoor Thermal Environments for Winter Survey

The field survey is supported by the National Science & Technology Support Project of China, aiming to lay the foundation for governments to make national policies of energy-saving and emission-reduction as well as human well-being improvement. Please fill in the questionnaires during the survey with much patience, and all the information would be kept absolutely secret except for research only. We appreciate it very much for your participation and support for our projects.

The First Part (for respondents)

Sex：Male□ Female□， Age:_____， Height:_____，Weight:______，Occupation：_______
Length of residence: _______year (s)

13. Built time for present building:		Before 70s□, 70s□， 80s□， 90s□, new buildings□
14. Present dressing:		**upper**：underwear: shirt□，T-shirt□，long sleeves□，warm underwear□ sweater: thin□， thick□ coat: thin□， thick□, down Jackets□, suit+tie □ **lower**：underwear: long johns□, warm underwear□ woolen trousers: thin□， thick□ trousers: jeans□，straight trousers□ **shoes**：sneaker□，leather shoes□，sandals□，casual□ **socks**：socks(thin)□，silk socks□ **others**：_________________________
15. Time spending in this room:		morning□, noon□, afternoon□， evening□， all day□ total hours：__________________
16. Feeling at present：	**temperature:** hot□，warm□，slightly warm□，neutral□，slightly cool□, cool□, cold□ **humidity :** very humid□, humid□, slightly humid□， neutral□，slightly dry□, dry□, very dry□ **air movement:** very stuffy□, stuffy□, slightly stuffy□， neutral□, slightly breezy□, breezy□, very breezy□	
17. Thermal satisfaction presently：		dissatisfied□, slightly dissatisfied□, acceptable□, slightly satisfied□, satisfied□
18. If dissatisfied，the reason is：		none□，cold□，hot□，humid□，dry□，stuffy□，draught□， others：________________
19. Thermal expectation for indoor thermal environments:		**temperature：** upper□， no change□， lower□ **humidity：** upper□， no change□， lower□ **air velocity：** upper□， no change□， lower□
20. Which ways would like to improve individual thermal		comfortable，no change□，using air-conditioning or heater □, opening window for ventilation □，closing window □, add clothing□, take off

comfort:	clothing□, hot drinks□ , light activities□, changing postures□, others: _
21. The habit, time and reason for window opening:	habits: frequently□, occasionally□, seldom□; time: morning□, noon□, afternoon□, evening□; reasons: smoking□, stuffy□, ventilation□, lighting□
22. Do you use air-conditioning and other devices frequently for heating:	YES□,NO□; if it is no, please choose the reason: ①comfortable, no need□, ②unlike, draught□, ③poor air circulation□, ④power saving□, ⑤using other regulation methods□, ⑥without devices in rooms□
23. How are you feelings in the room for a long time?	Fatigue and drowsiness□, nausea and dizzy□, hot and upset□, eyes irritation□, sore throat□, nose discomfort and shortness of breath□, tinnitus □, impaired concentration□, dry, itchy and rash of skin□, none□
24. The overall thermal acceptability for thermal environments:	absolutely unacceptable□, unacceptably□, slightly unacceptable□ , slightly acceptable□, acceptable□, absolutely acceptable□

The Second Part (for testers)

City: _________**Building name:** _____________**Types of community**：residences□ downtown□ others□

Dates：______**yy**____**mm**_____**dd** **Time**：__________ **Weather**（sunny□ cloudy□ rain□ snow□）

Tester name：________________

12. Building structure：	Masonry-concrete structure□，Reinforced Concrete Structure□， others□
13. Building location:	Along the street□， away from street□；suburb□
14. Total layers and floor：	Floor:______，total:_____ （basement excluded）
15. Window orientation for measuring room：	east□，south□，west□，north□，southeast□，northeast□，southwest□，northwest□
16. Type of rooms：	Living rooms:____ Bedrooms:____
17. Room areas：	areas:____ m^2， window（overall：___ m^2，opening areas___ m^2）
18. Types of windows：	Single frame with single glass□, single frame with double glass□, double frames with double glass□
19. The number of people presently in room:	Number:_________
20. Activities for respondents：	reclining□, sitting□, standing□, walking□
21. The window condition at present：	open□， close□
22. The regulation method for indoor thermal environments at present:	heater fan□, electric furnace□, air-conditioning□, household central air-conditioning□，central heating□，electric heater□, naturally ventilation□, without regulation measures□，others：____________________
12． Is the air-conditioning opened？if so, the set-point is :	Yes□，No□ Under 20oC□, 20oC□， 21oC□，22oC□，23oC□，24oC□, 25oC□，26oC□，27oC□，≥28oC□， unclear□

The Third Part (environmental parameters)

1. Test instrument type： Temperature and humidity meter：__________ Anemometer：______________

2. Instrument accuracy: Temperature and humidity meter：___________Anemometer：__________

3. Recording table ：

Outdoor air temperature oC：		Indoor air temperature oC：	
Outdoor relative humidity %：		Indoor relative humidity %：	
Outdoor air velocity m/s：		Indoor air velocity m/s：	