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

Wei Yu [a, b, c, *], Baizhan Li [a, b], Runming Yao [b], Di Wang [a], Ketong Li [a]

[a] Joint International Research Laboratory of Green Buildings and Built Environments, Ministry of Education, Chongqing University, 400045, China
[b] National Centre for International Research of Low-Carbon and Green Buildings, Ministry of Science and Technology, Chongqing University, 400045, Chongqing, China
[c] Key Laboratory of Eco-environments in the Three Gorges Reservoir Region, Ministry of Education, Chongqing University, 400045, Chongqing, 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.

1. Introduction

Tibet, located in the Qinghai-Tibet 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 area 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 changes 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

* Corresponding author. Joint International Research Laboratory of Green Buildings and Built Environments, Ministry of Education, Chongqing University, 400045, China.
E-mail address: yuweixscq@126.com (W. Yu).

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on human physiological responses in an artificial chamber, and found significant effects when it decreased to 85/70 kPa. 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 5347 m 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).

The average annual dry-bulb temperature in these typical cities is less than 10 °C, even in the hottest month the highest average temperature is below 17.69 °C. Meanwhile, the annual total solar radiation is more than 5000 MJ/m^2, which represents a very rich solar resource.

2.2. Residential buildings 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.

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 include questions on the basic information about the buildings, residents' demographic information such as gender, age, regional location, occupancy time, living habits, and the present measures regarding the

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

City	Observatory site		Annual average air temperature (°C)	Average temperature of the hottest month (°C)	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