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Investigation on winter adaptive thermal comfort in university buildings in underdeveloped areas in hot summer and cold winter zone of China

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Abstract: Current findings show that an appropriate indoor thermal environment in educational buildings benefits both the learning efficiency and the building energy performance. These findings emphasize the importance of providing comfortable indoor thermal conditions within these buildings. However, research on thermal comfort in educational buildings is mainly conducted in developed areas rather than in underdeveloped areas. To fill the gap in the understanding of indoor thermal environments and thermal comfort of university buildings in underdeveloped areas, a field investigation was performed in naturally ventilated university buildings in underdeveloped area (Zunyi) within the hot summer and cold winter zone (HSCW) of China during the wintertime. The influence of non-physical factors (e.g., economic level, past thermal experience and thermal expectation) on thermal comfort is also explored. The results show that due to the poor winter indoor thermal condition, 38.3 % of subjects feel "cool" or "cold". The neutral temperature and the 80% acceptable temperature range are 17.36 ℃ and 14.97-20.69 ℃, respectively, which is lower than that predicted by the PMV-PPD model. The comfortable temperature mean value derived by applying the Griffiths′ method is 16.88 ℃. The impact of non-physical factors on thermal comfort is demonstrated by the lower values of both the neutral temperature and the lower limit of 80% acceptable temperature zone, comparing with that in developed area cases of HSCW zone. Therefore, it clarifies that passive strategies can be considered when improving winter indoor thermal environment in naturally ventilated university in Zunyi.

Keywords: hot summer and cold winter zone; underdeveloped area; university buildings; adaptive thermal comfort

夏热冬冷气候区欠发达地区高校建筑冬季适应性热舒适研究

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摘　要:现有研究表明,良好的室内热环境不仅有助于学习效率的提升,还有利于建筑节能。因

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此,为学校建筑提供舒适的室内热环境具有重要意义。但是,目前对学校建筑热舒适的研究主要集中在经济发达地区,对经济欠发达地区的研究相对匮乏。为了填补经济欠发达地区高校建筑室内热环境和人体热舒适研究的空白,对中国夏热冬冷气候区经济欠发达地区(遵义)的自然通风高校建筑进行实地调查,并对非物理因素(如经济水平、过去的热经历、热期望等)对人体热舒适的影响进行探讨。结果表明:该地区自然通风高校建筑冬季室内热湿环境较恶劣,38.3%的受试者感到“凉”或“冷”。实测热中性温度为17.36 ℃,80%可接受温度区间为14.97~20.69 ℃,均比PMV-PPD预测模式下相应数值偏低。Griffiths模型预测的平均舒适温度为16.88 ℃。在非物理因素的作用下,该地区热中性温度和80%可接受温度区间均较夏热冬冷区发达地区低。所以,遵义地区自然通风高校建筑在改善冬季室内热环境时可考虑能耗低的被动式措施。

关键词:夏热冬冷区;欠发达地区;高校建筑;热舒适

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1 Introduction

Compared with residential and office buildings, university buildings have high population density, periodic use and limited environmental control measures[1]. As a result, occupants' indoor thermal conditions and thermal comfort requirements in univeristy buidlings may be different. Meanwhile, the indoor thermal environment's quality impacts students' physical and mental health as well as learning efficiency[2]. Therefore, it is essential to perform field investigations on the indoor thermal environment and thermal comfort in university buildings.

Recently, numerous field studies on thermal comfort in university buildings have been performed covering various continents (e. g. , Europe[3], America[4] and Asia[5]), climate regions including temperate[6], tropical[7], dry and continental climates[8], seasons[9], educational stages in terms of primary[10], secondary, high school, university levels[11], building types with respect to naturally ventilated[12], air-conditioned[11], and mix modes[13]. As a result, the environmental variable recommendation values representing a comfortable indoor thermal environment are specified via various international standards, such as ASHRAE 55 standard and ISO7730. However, these recommendations are not applicable for cases in China due to little consideration of datasets collected from the region[14].

In China, the surge in the number of students due to the expansion of college enrollment attracts more attention to the indoor thermal environment in university buildings in the recent two decades. Numerous field studies on the indoor thermal environment and thermal comfort have been carried out, particularly in the HSCW zone. Li et al. [15] proposed that the thermal neutral temperature and temperature ranges for 80% acceptability are 19.12 ℃ and 14.04-24.20 ℃, respectively, by conducting field investigations on winter thermal comfort in naturally ventilated classrooms in Chongqing. Similar research was also performed by Zhuge et al. [16], Li et al. [17], Yang et al. [18] and Cao et al. [19] in Nanjing, Changsha and Shanghai, respectively. Li et al. [20] and Wu et al. [21] performed thermal comfort field investigations and quantified preferred temperatures for university buildings in Chongqing and Changsha, respectively. It is found that subjects preferred cooler versus the neutral thermal environment in summer and warmer versus the neutral thermal condition in winter. The thermal comfort of college dormitories [22-23] has also been explored in the HSCW zone. By comparing the results in terms of thermal neutral temperature, temperature ranges for 80% acceptability, and thermally preferred temperature, it is evident that they are different, even if all the experiments are carried out in a similar building type with the same climatic characteristics. It implies that the environmental criteria representing indoor thermal comfort may not be the same, even in the same climate zone.

The field investigations mentioned above were mainly conducted in developed areas in the HSCW zone, such as Shanghai, Hangzhou, Changsha and Chongqing. The HSCW zone mainly refers to the middle and lower reaches of the Yangtze River, including 16 provinces and a population of 550 million people covering an area of 1 800 000 km^2 [24]. In addition to the developed areas, the HSCW zone also includes several underdeveloped areas. They are different from the developed areas concerning the economic level, cultural background, subjects' living habits, past thermal experiences and thermal expectations. According to the adaptive thermal comfort theory, the achieved thermal comfort in a real environment is affected by multi-factors comprising of an individual's behavior, thermal expectations, and past thermal experience[25-28]. Following the same line of thought, the question of whether the comfortable requirements of students living in underdeveloped areas within the HSCW zone are different from those in developed areas is subsequently raised. Particularly under the circumstance that installing air-conditioners in university buildings in developed area of the HSCW zone is becoming more and more popular. Unfortunately, no relevant findings can be used to answer this question directly because similar research is seldomly performed in this area.

A comprehensive literature review search reveals some useful clues to help us with experimental design and the ability to carry out on-the-spot investigations to address the question. In theory, the real thermal environment, particularly in non-air-conditioned buildings, is unlikely to achieve a uniform steady state due to the influences of both internal and external climatic and human factors. Consequently, people are active in interacting with their surrounding environment to restore thermal comfort. These interactions are usually regarded as adaptations in physiological, behavioral and psychological aspects[25]. Physiological adaptation, also known as "thermoregulation"[29], is normally embodied by utilizing physiological responses, such as vasoconstriction, vasodilation and sweating, in response to physical environmental fluctuations, therefore, changing their thermal perception based on cold and heat adaptations. The conscious or unconscious behaviors conducted in daily life, which induce a change in the heat exchange between people and the environment, are viewed as behavioral adaptation. Occupants employ behavioral adaptations with respect to personal, technological, and cultural responses to alleviate thermal discomfort. Brager et al. [25] concluded that behavioral adaptation could be viewed as an immediate and conscious feedback loop, where the discomfort was the starting point rather than end point.

Psychological adaptation is usually defined as an altered perception of and a reaction to sensory information of subjective past thermal experiences and expectations[29]. Based on the literature review, the research on the psychological adaptation of the human body in the context of the built environment has focused on the effects of thermal expectation and perceived environmental control levels[25]. There is an agreement that repeated exposure to certain thermal conditions, and a higher level of perceived control over the ambient thermal environment would benefit from forming relaxed thermal expectations and being more tolerant of undesirable thermal stimuli[30].

In practice, Gagge et al. [31] carried out experiments with three unclothed human subjects in a climate chamber in the 1960s, aiming to identify the physiological responses at various ambient temperatures. They found with an increase in ambient temperature (12 ℃ to 48 ℃) that the mean skin temperature kept rising proportionally from 25. 5 ℃ to 36 ℃. However, the skin has a tendency to become fairly uniform in temperature when the ambient temperature exceeded 28 ℃ . Many subsequent chamber experiments have verified this tendency for skin temperature to vary with the ambient thermal environment[32-33]. In other words, long-term exposure to specific thermal conditions would trigger the increase or decrease of core body heat generation to compensate for heat loss or to enhance the dissipation of heat and subsequently change the subjects' thermal perceptions accordingly. A 3 ℃ discrepancy in preferred temperature between Malaysian subjects and London subjects was obtained in a climate-chamber-based experiment[34]. In university buildings, the thermal sensation changes as a result of acclimatization and has been identified and verified in investigations in China[35], Indonesia[36] and Malaysia[37]. Concerning adaptive behaviors, MacFarlane's experiment[38] in the humid tropics of Australia was one of the early examples of behavioral adaptation. It is concluded that wearing light clothing and lowering physical activity levels helped local residents achieve acceptable comfort. Emmerich et al. [39] concluded that due to adaptive behavior, people in naturally ventilated buildings tolerated a larger range of temperatures than subjects in air-conditioned buildings. Baker et al. [40] observed 273 adjustments to environmental controls or other environmental aspects among a total of 864 observed subject hours during the first monitoring studies of the 1993 PASCOOL comfort task. As a result, reduced local temperatures are often obtained when comparing the average room temperature. Indraganti[41] conducted a field investigation on environmental controls usage in apartments in India and indicated that people would like to use different environmental control measures. The use frequencies of fans, air coolers, and air conditioners increased with rising temperature. Also, the effects of cultural dress codes[42-43] and the posture of the human body[44] on thermal comfort have been confirmed. Humphreys[42] noted that "characteristically, people seek to be comfortable, and take actions to secure thermal comfort, the motivation to do so is powerful". Chatonnet et al. [45] stated that "behavioral thermoregulation is well-developed in man becoming preponderant and tending to supplant other forms of thermoregulation". Thus, the occupants' behavioral adaptation plays a significant role in enabling subjects to achieve thermal comfort. However, obstacles for the selection and usage of environmental control measures in the process of behavioral adaptation cannot be overlooked. A field study conducted in India's apartments during the summer and monsoon seasons revealed that apart from the efficacy, the use of those control measures was also impeded by subjects' economic status and attitudes[41]. Chen et al. [46] also attributed the unique characteristics of local people's thermal sensations and adaptive behaviors to economic levels and local climate. Therefore, in theory, occupants' adaptive actions in different cities within the HSCW zone would vary. Subsequently, the corresponding thermal perceptions would also be different. McIntyre[47] was one of pioneers studying the role of expectation in thermal comfort and stated that "a person's reaction to a less than perfect temperature will depend very much on his expectations, personality, and what else he is doing at the time". By comparing the occupants' thermal preference between the two groups with and without long-term exposure to air-conditioned space, a noticeable difference of 20% in the fraction vote for a cooler thermal condition is attributed to the different expectations[48]. Rajkovich et al. [49] studied thermal responses of subjects in transitional spaces and found that thermal expectation influences thermal sensation significantly. Williams[50] obtained a positive relationship between perceived control and thermal satisfaction levels in her study of office environments in England. Rowe et al. [51] concluded that people were more tolerant of variations in ambient environmental parameters if they can take control of them. These have been proven from both the theory and the practice aspects that non-physical factors are significant enough to incur changes in thermal perceptions.

Moreover, the thermal comfort field experiments which have been performed in university buildings of the HSCW zone mainly focus on summer rather than winter cases. To make up for the lack of winter data and understand indoor thermal conditions and thermal requirements of occupants in university buildings, and particularly to explore the influence of non-physical factors on thermal perceptions in addition to physical environmental stimuli, it is necessary to carry out on-the-spot investigations in university buildings within the underdeveloped areas of the HSCW zone. Therefore, this paper presents a thermal comfort field study in naturally ventilated university classrooms during the wintertime in underdeveloped areas of the HSCW zone with the aim at addressing the influences of both physical and non-physical factors on thermal comfort. The findings concluded in this paper help with extending and supplementing the database of thermal comfort for the HSCW zone.

Meanwhile, it also provides a reference for improving the indoor thermal condition in university buildings as well as building energy-saving refurbishment with passive design strategies.

2 Research objects and methods

2.1 Research objects

2.1.1 The weather conditions in Zunyi. Zunyi is located in northern Guizhou and is adjacent to Chongqing city. It is a typical city with hot summer and cold winter climatic characteristics. The annual average temperature is 12.6-13.1 ℃. January is usually the coldest month with a monthly mean temperature of 2-8 ℃. The annual frost-free period and precipitation are 270-300 d and 1 000-1 300 mm, respectively.

2.1.2 The surveyed building. The surveyed buildings in this study are naturally ventilated and are located at a university in Zunyi. The buildings have between 4-5 floors with south-north orientation, flat roof, reinforced concrete frame structure, and double glass with a plastic steel single frame. No air-conditioners and central heating system are installed. To guarantee the a fair representation of the experimental data, the field investigation covers all floors of the surveyed buildings.

2.2 Methodology

2.2.1 Physical environmental variables measurement. Environmental parameter collection includes indoor and outdoor environmental variables. Indoor air temperature (T_a), air velocity (V_a), relative humidity (RH), and globe temperature (T_g) constitute indoor thermal variables. Mean radiant temperature ($\overline{T_r}$) and operative temperature (T_o) are calculated according to the equations of $\overline{T_r}=T_a+2.44V_a^{0.5}(T_g-T_a)$ and $T_o=AT_a+(1-A)\overline{T_r}$[52], respectively. The value of A can be determined by referring to Table 1.

Table 1 The values of *A*

$V_a/(\mathrm{m \cdot s^{-1}})$	A
<0.2	0.5
0.2-0.6	0.6
>0.6	0.7

Outdoor climate parameters consist of outdoor air temperature, air velocity, relative humidity and globe temperature. Hot-wire anemometer (TESTO 425) and a black bulb temperature and humidity meter (AZ8778) are employed in this study to measure indoor T_a, V_a, T_g and RH, respectively. All indoor environmental parameter measurements last at least 3 min at 1 s intervals. The indoor thermal environmental variable collection will not be applied until the instruments are stabilized. The instruments and method used in this study are in accordance with the requirements specified in GB 50785-2012[53] and ISO 7726-2001[54].

2.2.2 Questionnaire survey. A questionnaire survey is conducted simultaneously with the physical environmental parameter measurements. The questionnaire applied in this investigation comprises three parts. The first part is used to collect subjects′ basic information, such as age, gender, living years in Zunyi, activity and clothing levels. Part two, the respondents′ thermal sensation, thermal preference and thermal satisfaction are quantified by employing ASHRAE′s 7-point scale (−3 cold, −2 slightly cold, −1 cool, 0 neutral, +1 slightly warm, +2 warm and +3 hot), thermal preference scale (−2 want much cooler, −1 want slightly cooler, 0 no change, +1 want slightly warmer and +2 want much warmer) and thermal satisfaction scale (−3 very dissatisfaction, −2 slightly dissatisfaction, 0 just ok, +1 slightly satisfaction, +2 satisfaction and +3 very satisfaction). Part three, the information on adaptive behaviors utilized by occupants is recorded. To guarantee the accuracy of the collected data, the subjects who stay indoors less than 30 minutes or are engaged in non-sedentary activities are not considered in this survey.

3 Results and analysis

3.1 Basic information of subjects

The field survey on winter indoor thermal environment and thermal comfort was carried out in university buildings in Zunyi from December 2018 to January 2019. In total, 329 subjects participated in this study, comprising of 137 males and 192 females. Since most of them were enrolled as full-time undergraduate students, the largest proportion of respondents were under the age of 21, accounting for 87% of the respondents that filled out the questionnaire. All occupants have lived in Zunyi for 4 years on average, which implies that subjects have physiologically acclimatized to the local climate. This study's mean value of clothing insulation is 1.03 clo which is slightly greater than 1.0 clo recommended in the ASHRAE55 standard. More details will be analyzed in Section 2.7. Since all people were engaged in sedentary activities in terms of reading, watching TV and typing, the metabolic rate of occupants was determined to be 1.2 met.

3.2 Indoor and outdoor thermal conditions

The variations of outdoor temperature and relative humidity during the survey period are presented in Fig. 1. It shows that the daily mean temperatures vary significantly in winter from −2.5 ℃ to 16.5 ℃ with a mean value of 4.83 ℃. The relative humidity level is greater with an average value of 82.4%. It agrees with cold and humid climatic characteristics of the HSCW zone in the winter[55].

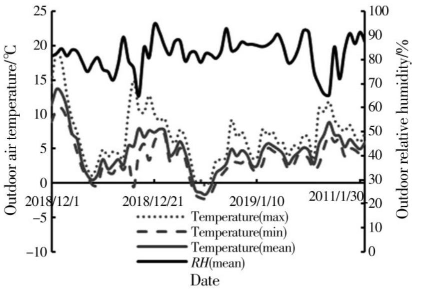

Fig. 1 Outdoor air temperature and relative humidity

The indoor thermal environmental parameters are shown in Table 2. The average indoor air temperature is lower at 13.93 ℃. Fig. 2 illustrates the distribution of indoor operative temperature of winter in Zunyi. The indoor operative temperatures which are most frequently observed are in the range of 14-15 ℃, accounting for 65.2%, with a mean value of 14.57 ℃. The indoor mean radiant temperature is 14.72 ℃, which is slightly higher than the average indoor air temperature. The mean value of indoor relative humidity is 72.5%. Concerning indoor air velocity, the average level of indoor air velocity is 0.18 m/s, which is much lower than that of outdoor air velocity (0.71 m/s).

Table 2 Indoor environmental parameters in winter

Statistical variables	Air temperature/℃	Relative humidity/%	Air velocity/(m·s^{-1})	Operative temperature/℃	Mean radiant temperature/℃
Max	19.80	88.51	0.26	21.20	20.90
Min	11.57	65.00	0.03	11.82	11.77
Mean	13.93	72.50	0.18	14.57	14.72
S.D.	2.35	8.37	0.07	2.72	2.69

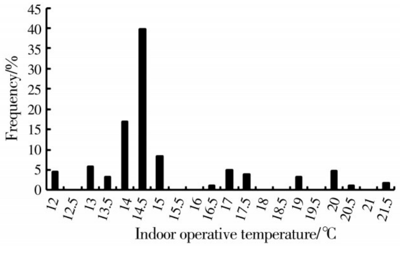

Fig. 2 Distribution of indoor operative temperature

3.3 Thermal sensations and thermal neutral temperature

Fig. 3 demonstrates the distribution of actual mean votes (AMV). More than half (57.9%) of subjects' AMV are within the central three categories of the ASHRAE's 7-point scale (AMV=−1,0,+1). Among them, the occupants whose AMV=0 accounts for 29.2 %. Meanwhile, 18.4% and 19.8% of respondents reported their thermal sensations as "cold" and "cool", respectively. Only 3.9% of subjects regarded the current thermal environment as "warm", and no one felt hot in the winter. The mean value of AMV during the survey period is −1.11, which indicates that without effective environmental controls, people within the university buildings tend to have a cooler thermal sensation in the winter due to lower indoor temperatures.

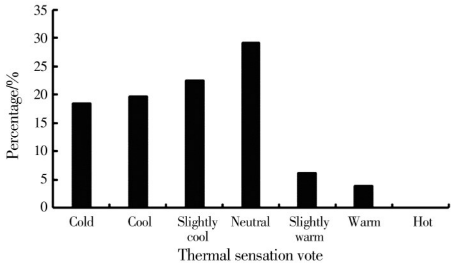

Fig. 3　Distribution of thermal sensation votes in winter

In order to identify the relationship between AMV, predicted mean vote (PMV) and T_o, the average values of AMV and PMV in each 0.5 bin are plotted as a function of indoor T_o, as shown in Fig. 4. The linear regression equations are $AMV = 0.4633T_o - 8.0438$ ($R^2 = 0.941$) and $PMV = 0.2813T_o - 5.9727$ ($R^2 = 0.8639$), respectively.

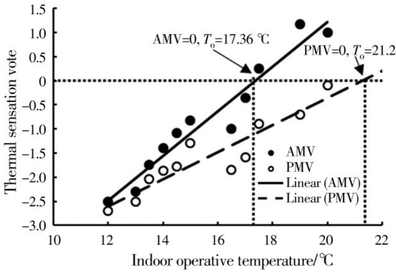

Fig. 4　Linear regression of T_o, AMV and PMV

As shown in Fig. 4, PMV values are lower than AMV values in the whole variation range of indoor operative temperature during the survey period. That is to say, at the same temperature, people are likely to have more warmer thermal sensations than predicted ones. This phenomenon could be attributed to the following reasons. Due to not having effective environmental controls in the surveyed buildings, people here are already accustomed to experiencing lower temperatures and a higher relative humidity in the winter. Yielding a psychological hint that the indoor thermal condition should be cold and humid in the winter without air-conditioning and heating devices. A more tolerant thermal expectation is consequently formed. Meanwhile, living in Zunyi for a long periods, four years on average, helps residents acclimatize to the local climate physiologically. With the assistance of adaptations in terms of physiological and psychological dimensions, together with clothing adjustments, subjects have warmer thermal sensations in winter. On the contrary, PMV is a result of climate chamber-based experiments and derived by Fanger based on heat balance theory[56]. The adaptations of the occupants in a real environment are rarely considered. The PMV consequently overestimates the influence of lower temperatures on thermal sensations and predicts the occupants feel a cooler thermal sensation. As a result, the differences between AMV and PMV values are observed as a "scissor" phenomenon[57]. Thus, PMV is not suitable for prediction of occupants′ thermal sensations directly in naturally ventilated university buildings in Zunyi.

3.4　Actual percentage of dissatisfaction (APD) and acceptable temperature range

The actual percentage of dissatisfaction (APD) is defined as the ratio of thermal sensation votes outside the central three categories of the thermal scale. Similarly, the average values of APD and predicted percentage of dissatisfaction (PPD) in each 0.5 ℃ bin were plotted as a function of indoor operative temperature, as shown in Fig. 5.

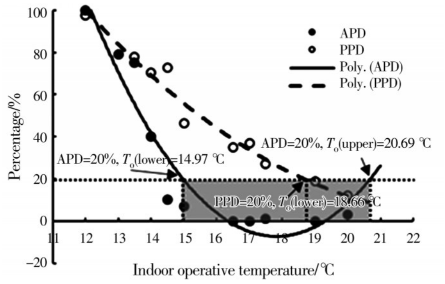

Fig. 5　Non-linear regression of percentage of dissatisfied and indoor operative temperature T_o

It can be seen that the PPD values are more significant than the APD values. In response to thermal dissatisfaction of 20%, the acceptable temperature range in which 80% of respondents perceived the thermal environment they occupied as acceptable could be determined. Thus, the 80% acceptable temperature zone under the APD model is 14.97-20.69 ℃. The lower limit is less than that under the PPD model by 3.69 ℃. It implies that under the PPD model, the thermal satisfaction percentage of 80% would require higher indoor temperature in the winter. It also confirms that the PPD model underestimates adaptations of the occupants and consequently overestimates the percentage of dissatisfaction.

Referring to Fig. 3, the frequency of indoor operative temperatures during the survey period within the 80% acceptable temperature zone is 29.4%. Without heating devices, the respondents' thermal comfort requirements from the university buildings with natural ventilation in the winter can not be met. The phenomenon also confirms such a statement that the mean value of AMV in this study is −1.11. The indoor operating temperature of 14.5 ℃ accounts for 50% of the total sample size and is very close to the lower limit of the 80% acceptable temperature range (14.97 ℃). It indicates the possibility of applying passive design measures to improve the indoor thermal environment in university buildings in Zunyi during the wintertime.

3.5 Thermal preference and preferred temperature

Fig. 6 depicts the distributions of thermal preference votes. Up to 83.7% of the occupants want the indoor thermal environment in winter to be "slightly warmer" and "much warmer". Subjects who do not want to change the current thermal condition account for only 11.8%. Even though the indoor temperatures in the surveyed buildings are lower, 4.5% of the respondents prefer a slightly cooler indoor thermal environment. Therefore, people from the university buildings with natural ventilation prefer a warmer thermal environment in the winter.

Fig. 6 depicts the voter distribution of thermal sensation across thermal preference. In response to the variation of thermal preference vote changing from "cool" to "warm", the proportions of "hot" and "warm" thermal sensation votes decrease gradually. Conversely, the percentages of thermal sensation votes in terms of "cool" and "cold" are gradually increasing. In other words, the colder the occupants feel, the stronger they prefer a warmer indoor thermal environment. It also indicates that the respondents' thermal preferences are to a great extent related to their thermal sensations. When subjects do not want the indoor thermal condition to change, the fraction of occupants who regard the current thermal environment as "slightly warm" is higher than people who sense it as "slightly cool". It confirms that the respondents in this study prefer warmer indoor thermal conditions in the winter.

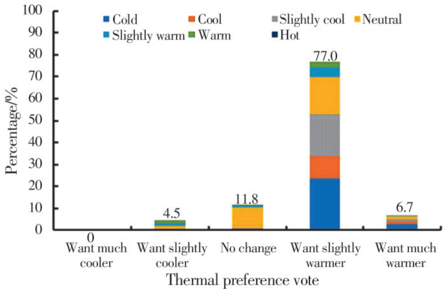

Fig. 6 Thermal preference votes

Those who voted for "want slightly cooler" and "want much cooler" are classified into the "want cooler" category. Conversely, the "want warmer" category comprises of the people who voted "want slightly warmer" and "want much warmer". The percentages for "want cooler" and "want warmer" are calculated for each 0.5 ℃ indoor T_o bin. The intersection of these two regressive curves is defined as the preferred temperature[58]. As illustrated in Fig. 7, preferred temperature of this study is 19.92 ℃, which is higher than the thermal neutral temperature by 2.56 ℃. It indicates that the thermal environment corresponding to thermal neutrality sometimes can not satisfy occupants with their thermal comfort requirements.

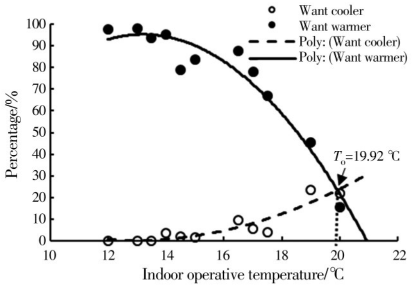

Fig. 7 Preferred temperature

3.6 Griffiths' method

The comfort temperature for university buildings with natural ventilation in Zunyi in winter is further determined by applying Griffiths' method. In this method, comfort temperature (T_{comf}) is expressed as a function of indoor temperature (T_{in}) and AMV by introducing Griffiths coefficient G [59], as below.

$$T_{\mathrm{comf}}=T_{\mathrm{in}}+\frac{(0-\mathrm{AMV})}{G} \tag{1}$$

Humphreys et al. [60] suggested there are three options for G, 0.25, 0.33 and 0.5, respectively.

By substituting collected data into Eq. (1), the results are presented in Table 3. When $G=0.5$, the corresponding comfort temperature varies within the narrowest range. The G value in this investigation is thus determined to be 0.5. The average comfort temperature of 16.88 ℃ calculated using Griffiths′ method is close to the thermal neutral temperature of 17.36 ℃ determined by the linear regression equation of both the indoor temperature and AMV.

Table 3　Comfort temperature in Griffiths′ method

G value	Comfort temperature (S. D.)/℃
0.25	19.10 (5.81)
0.33	18.02 (4.49)
0.50	16.88 (3.16)

3.7　Adaptive behaviors

Clothing adjustment is one of the most popular personal adjustments in response to the indoor thermal environment changes. The mean value of clothing insulation in the current study is 1.03 clo covering the range of 0.67-1.90 clo. By averaging the clothing insulation values in each 0.5 ℃, the tendency of clothing insulation values to vary with T_o is plotted in Fig. 8. The linear regression equations of clothing insulation values, indoor operative temperature $T_{\text{o-in}}$, and outdoor operative temperature $T_{\text{o-out}}$ are obtained as follows.

$$\mathrm{clo}=-0.033T_{\text{o-in}}+1.575\,6\ (R^2=0.832\,1) \tag{2}$$

$$\mathrm{clo}=-0.023\,9T_{\text{o-out}}+1.351\,8\ (R^2=0.570\,8) \tag{3}$$

It can be seen that, in general, with increasing operative temperature, the mean values of clothing insulation decrease gradually. It is consistent with the findings of other scholars[16,22,28]. Also, the greater the value of R^2 indicates that clothing insulation values have a better correlation with indoor T_o rather than with outdoor T_o. Meanwhile, the changes in clothing insulation values with indoor T_o appears to occur in two stages with a turning point at 16.5 °C. With increasing indoor T_o, the mean values of clothing insulation decrease gradually from 1.25 clo to 1.0 clo until the indoor T_o reaches 16.5 ℃ after which they fluctuate around 1.0 clo.

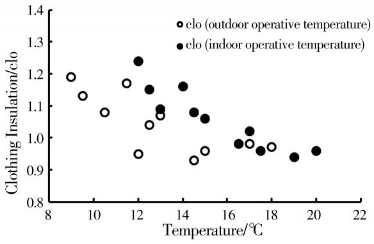

Fig. 8　Clothing insulation values against operate temperature

By linking the values of clothing insulation with each category of the thermal sensation scale, Fig. 9 is obtained. Generally, the higher the mean value of clothing insulation, the warmer occupants feel. It can be seen that adding clothes is an effective way of improving thermal sensations in university buildings with natural ventilation without a heating supply in winter.

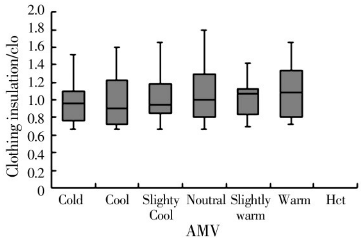

Fig. 9　The relationship between clo and AMV

4　Discussions

4.1　Comparative analysis

To further clarify the influence of non-physical factors on occupants′ thermal comfort, the results gathered from the current study are compared and analyzed with findings obtained from other cases under the same conditions in other cities inside the HSCW zone. The details are shown in Table 4.

As presented in Table 4, the thermal neutral temperatures under 20 ℃ exist in the Chongqing and Zunyi cases. However, the thermal neutral temperature in the Zunyi case is 1.76 ℃ lower than that of the Chongqing case. Considering the impact of the clothing insulation value on thermal sensation, the winter thermal comfort temperature in naturally ventilated university buildings in Chongqing would exceed 20 ℃. Since all cities listed in Table 4 are within the HSCW region and share similar macro-climates, the reasons leading to the differences in the thermal neutral temperature and the 80% acceptable temperature zone are discussed from the following aspects.

Table 4 Results of comparison of thermal comfort investigations in winter university buildings in HSCW zone of China

Location	Year	Sample size	Building type	Thermal neutral temperature/°C	Acceptable temperature range/°C	Clothing insulation/clo	References
Chongqing	2007	3 621	classroom	19.12	14.40-24.20	1.39	[15]
Changsha	2006	1 273	classroom, dormitory	21.73	12.86-30.59	0.94	[18]
Shanghai	2012	230	classroom	21.00	13.68-28.34	1.04	[19]
Wuhan	2007	1 725	classroom	21.70			[61]
Zunyi	2018	329	classroom	17.36	14.97-20.69	1.03	This study

Firstly, one of the critcal indicators to judge whether a region is developed or not is the economic level. In the context of built environment, the availability and diversity of environmental control measures are mainly determined by economic status. Humphreys et al. [62] stated that economic issues would impose restrictions on adaptive behaviors regarding the availability, diversity and efficiency of environmental controls and personal adjustments measures. Although Chongqing and Zunyi are located in the traditional western underdeveloped areas of China, as a municipality, Chongqing's GDP and per capita disposable income have jumped to the country's forefront in recent years[63]. Chongqing can then be viewed as a developed city when compared to Zunyi. Under such circumstances, in theory, the "adaptive opportunity"[64], which is used to describe the extent to which the occupied environment could provide subjects with a level of control over the space they occupy, will be more signifigant in the case of Chongqing. However, all surveyed buildings in each city in Table 4 are naturally ventilated with similar structure, function and layout. Also, no environmental control measures are equipped for space heating. Therefore, the "adaptive opportunity" in this case is mainly referred to as the diversity of personal adjustment. Personal adjustments of this study include using clothes with light and warm characteristics, heating pads, feet warmer pads, and various portable hand warmers. The efficiency and user experience of these personal adjustment strategies are also closely related to their price, availability and diversity of each occupant's personal adjustment in the developed area are not comparable with that of underdeveloped areas. Consequently, personal adjustments with more diversity, higher efficiency and better user experience properties enhance the warmer thermal preference of subjects in developed areas during winter time, therefore, producing a higher thermal neutral temperature and upper limit of 80% acceptable temperature range.

Secondly, there is an agreement demonstrated in previous research that thermal expectations impose signifigant effects on subjects thermal satisfaction and thermal acceptance[65]. According to Auliciems[29], Humphreys[66], Nikolopoulou et al. [67], past thermal experience, particularly long-term exposure to a specific thermal environment, plays a key role in helping occupants form specific thermal expectations. In this study, due to the differences in diversity and efficiency of personal adjustment measures resulting from economic status, the occupant's past thermal history would vary from place to place. The formed criteria for thermal comfort assessment for similar thermal conditions are therefore different. Specifically, in Zunyi, the subjects' thermal expectations are not as high as those in other cities. Because of a decreased diversity of personal adjustment approaches, this makes occupants in Zunyi have a psychological notion that there are not sufficient strategies to adapt to the ambient thermal environment. Therefore, lower and relaxed thermal expectations enable them to accept a relatively lower indoor temperature in the winter. On the contrary, the higher thermal neutral temperatures and greater upper limits of acceptable temperatures are subsequently required by occupants from developed areas to achieve thermal comfort. This finding is also following statements that people have when they sense that they can control their thermal environment or cope with environmental variables′ and fluctuations. The space′s expectations will rise and result in a lower tolerance to the cold and warm thermal environments[68].

Finally, the effect of each non-physical factor within the building environmental context is not independent of each other but may overlap thermal comfort. For example, in a given climate region, economic status determines the diversity and efficiency of environmental control measures, which also constitutes the unique physical environment forming the occupants′ past thermal experiences. The past thermal experiences further contribute to the established physiological acclimatization and thermal expectations, which usually are benchmarks for thermal environmental evaluations. Furthermore, the greater the discrepancy between the thermal expectations and the actual thermal condition, leads to a decline in the thermal comfort of the occupants[65]. Also, the thermal expectation is dynamic rather than a steady-state variable, and it varies with people′s thermal experience (short-term and long-term exposure) as well as the degree of physiological acclimatization[69]. Brager′s statement that people′s thermal perception in a real environment was influenced by the complexities of past thermal history, cultural, and technical practices also confirms that the influences of non-physical factors on thermal comfort are comprehensive effects of a complex interaction among non-physical factors like the physical, environmental and social-economic-cultural factors[70].

4.2 Suggestions on passive design strategy to improve the winter thermal environment of existing university buildings in the HSCW zone

Compared with the cold or severe cold zone, the thermal neutral temperature and preferred temperature in winter are relativly lower in the HSCW zone[71-72], which lays a foundation for improving winter indoor thermal conditions in this area by applying passive design strategies. In this section, the feasibility of applying passive design approaches to improve the winter indoor thermal environment within university buildings in the HSCW zone is qualitatively discussed. Passive design, sometimes called "bio-climatic design", is defined by Olgyay et al. [73] and Givoni[74] as "to heat, to cool and light buildings using ingenious design techniques and materials by reducing or even without using any energy system". Orientation, thermal insulation, window to wall ratio, external/internal shading devices, airtightness, and natural ventilation are common passive design solutions[75]. Particular attention should be paid using such measures in buildings in the HSCW zone since both heating and cooling are of concern in this area. Yao et al. [75] employed a simulation method and identified the optimal combinations of passive design solutions for residential buildings located in Chongqing, Changsha and Shanghai, all within the HSCW zone. It provides a reference to select proper passive design strategies for university buildings in Zunyi. Similar to other cities in the HSCW zone, the winter in Zunyi is cold and humid, with average values of dry bulb temperatures and relative humidity at 5.98 ℃ and 80.87%, respectively. Therefore, the measures which provide building protection from heat loss in winter should be considered. Generally, enhancing the thermal insulation of exterior walls and roof by adding insulation layers are popular measures to reduce heat loss. Also, double or triple glazed windows equipped with a thermal cut can significantly decrease heat loss. The ratio of window to wall is another issue needed to be addressed, particularly in the HSCW zone, since it influences heat loss and heat gain through the window. Based on the global horizontal radiation in Zunyi during the winter and referring to the window-wall ratio recommendation specified in *Design standard for energy efficiency of public buildings* (GB 50189-2015), the window-wall ratio of 0.5 is appropriate. Moreover, the south-north orientation guarantees heat gains through the southern-oriented windows during the winter. Based on the figures shown in Table 2, there is nearly a 3 °C deviation between thermal neutral temperature and the mean value of the indoor operative temperature. The habit of opening windows in this area combined with the increasing frequency of freezing weather will inevitably weaken the indoor thermal environment and cause an increase of thermal discomfort. Therefore, to ensure indoor thermal comfort in extreme weather conditions, heating systems are still needed. However, in such circumstances, the air source and ground source heat pump systems should be considered as a first priority in order to achieve building energy target reduction.

The combined effects of these passive design solutions on winter indoor thermal condition improvement are not in the scope of current research. It will be simulated and analyzed in further investigations.

4.3 Limitations

This paper has attempted to understand the winter indoor thermal environment and adaptive thermal comfort in university buildings in underdeveloped areas of the HSCW zone and explore the influences of both the physical and non-physical factors on thermal comfort. Some points need to be considered to improve future research. Firstly, since the current study was conducted in a typical university in Zunyi, the number of female students was dominant. Previous thermal comfort studies that considered gender as a factor revealed that females were more likely to feel discomfort under the same thermal environment[76] and be more sensitive to the cold when compared to males subjects[77]. Therefore, the sex ratio needs to be equal in future research to exclude any potential effect of a gender difference on thermal perceptions. Secondly, only winter cases were considered in this study. In order to fully understand the indoor thermal environment and thermal comfort in university buildings in underdeveloped areas of the HSCW zone, future studies should take the summer season and transitional seasons (e.g., spring and autumn) into account. Thirdly, this study mainly discussed the influence of non-physical factors on thermal comfort concerning economic level, past thermal experience and thermal expectation. The scope of non-physical factors should be expanded in the following research. Finally, the selection and reliability of passive design measures should be verified from a quantitative aspect.

5 Conclusions

1) The mean values of indoor air temperature and relative humidity are 13.93 ℃ and 72.5%, respectively. As a result, more than one-third (38.2%) of the occupants regard indoor temperature in the winter as "cool" or "cold". The AMV value on average for this study is −1.11.

2) The values for AMV are generally more significant than the PMV values. The AMV model′s thermal neutral temperature is 17.36 ℃, which is 3.86% lower than the PPD model. The actual 80% acceptable temperature ranges from 14.97 ℃ to 20.69 ℃. The lower limit is also less than the predicted value of 18.66 ℃. This indicates that people tolerate lower temperatures in the winter due to adaptations.

3) The preferred temperature in this study is 19.92 ℃. Subjects prefer a warmer-than-neutral thermal environment in the winter.

4) Griffiths′ method yields a comfort temperature of 16.88 ℃, which is close to the actual neutral temperature of 17.36 ℃. A lower comfort temperature is due to the adaptabilities of the occupants.

5) The clothes adjustment of subjects is predominantly determined by the indoor operative temperature and demonstrates a two-stage tendency. Also, clothing insulation levels are relevant for the mean thermal sensations of the occupants. Under

non-extreme weather conditions, without heating systems, adding clothes is thus an effective way of improving overall thermal sensation in the winter in university classrooms with no heating devices.

6) The non-physical factors (e. g., economic level, past thermal experience and thermal expectation) positively influence thermal comfort. It is possible to apply passive design solutions in university buildings in Zunyi.

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