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The impact of LEG roof on indoor hydrothermal environments and thermal comfort in summer: A case study in Chongqing

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Abstract: Nowadays, green roof is considered as a good strategy to improve the indoor hydrothermal environment. In order to investigate the influence of a light extensive green (LEG) roof on indoor temperature, humidity and human thermal comfort in summer in Chongqing, comparative experiments on two kinds of roofs, namely LEG and the common one, were carried out at two similar six-floor naturally ventilated residential buildings. The results showed that the room with LEG roof was characterized with a lower indoor temperature compared with the room with ordinary roof in summer. During the study period of July, monthly average indoor temperature of the tested room with LEG roof was 5.8 ℃ lower than outside and 4.9 ℃ lower than that of the room with ordinary roof at 14:00. On 24th July, the hottest sunny day in the study period, there was an obvious difference on indoor and outdoor temperatures of the room with LEG roof, which could reach as high as 7.6 ℃ at noon, while the indoor thermal environment had no significant temperature stratification. The humidity inside the room with LEG roof was relatively higher compared to that of the room with an ordinary roof. Assessed results from both PMV-PPD model and thermal sensation vote (TSV) indicate that LEG roof can significantly improve indoor thermal comfort. Higher level of indoor thermal comfort and lower indoor thermal dissatisfaction can be realized by the application of a LEG roof.

Keywords: light extensive green roof; hydrothermal environment; PMV-PPD model; TSV index; thermal comfort

LEG 屋顶对夏季室内热湿环境和热舒适的影响

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摘　要:绿色屋顶被认为是改善建筑物热湿环境和室内热舒适性的技术。为研究轻型绿色(LEG)屋顶对重庆市夏季室内温度、湿度和人体热舒适度的影响,对两栋自然通风的 6 层住宅内相似房间、不同类型的屋顶(LEG 和普通型)进行了对比试验。结果表明,与普通屋顶建筑相比,夏季 LEG 屋顶室内温度较低。下午 14:00,LEG 屋顶的 7 月份室内月平均温度比室外低 5.8 ℃,比普通屋顶室内月平均温度低 4.9 ℃。7 月 24 日,研究期间最炎热的晴天,LEG 屋顶室内外温度明显不同,在

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中午时温差达到7.6 ℃,室内没有明显的温度分层。与普通屋顶相比,LEG屋顶的建筑内部湿度相对较高。PMV-PPD热舒适模型和热感投票(TSV)都表明,LEG屋顶可显著提高人体热舒适性。利用LEG屋顶可以实现更高的室内热舒适度和更低的室内热不满意度。

关键词:轻型绿色屋顶;热湿环境;PMV-PPD模型;TSV指数;热舒适性

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1 Introduction

With the acceleration of global warming and the development of urbanization, it has been promoted to a new level regarding the use of energy in a more sustainable and effective way[1-3]. It is reported that the energy consumption of buildings accounts for approximately 40% of the urban energy consumption[4]. Green roof is playing an important role in saving energy, increasing urban green area, absorbing noise and improving the urban ecological environment [5-6]. Green roof is defined as a roof covered with vegetation and cultivation medium. Green roof can be divided into three categories, namely extensive, intensive and semi-intensive green roofs. Intensive green roof is a roof planted with small trees, shrubs, bushes, and other tall plants by using thick substrate layer (usually above 200 mm). It requires frequent maintenance such as watering, weeding and fertilizing. Extensive roof only requires thin substrates to support plants growth with a few maintenance. Unique CAM photosynthetic plants are always chosen for this kind of green roof. CAM,here,refers to a plant having a sedum natural acid metabolic pathway, and is mostly a multi-slurry plant. Semi-intensive roof is an intermediate type between the other two. Due to the light weight (usually less than 1.8 g/m^3) of the LEG roof and strong adaptability of the green plants on the LEG roofs[7-8], a LEG roof planted with *Sedum lineare* was studied in this study.

In the past several years, impacts of extensive green roof on indoor hydrothermal environments have been widely investigated. Measurements and simulations have been carried out by researchers in different regions. The results show that the effects of extensive green roofs on indoor thermal environments depend on several factors, which are solar radiation, wind speed, rainfall, temperature, humidity, plant species and subsequent management. Considering the different experimental conditions, there are consensus and controversy in the results of green roofs' influences on indoor temperature and humidity. In recent years, most of the research on green roofs has been focused on the energy conservation[9-11]. Ugai[12] studies the advantages of water collection, sound insulation and carbon emission reduction in green roofs. In terms of temperature, Teemusk *et al*[13] found that during summer, a green roof with 100-mm-thick substrate layer significantly decreased temperature fluctuations in comparison with a bituminous roof surface. The average difference between the temperature amplitude under the substrate layers of the planted roofs and the surfaces of the conventional roofs was 20 ℃. A 100-mm-thick substrate layer entirely covered by plants successfully mitigates the influence of weather conditions on the roof membrane[14]. He's results[15] showed that the indoor temperature could be cooled down as much as 5 ℃ in buildings with a green roof in Shanghai. Huang's research[16] on green roof in Taiwan also presented similar results. However, their research mainly focused on the temperature changes in substrate layers of the planted roofs. There is rarely research on the indoor temperature that directly affects the living quality of occupants. On the other hand, the impact of a green roof on humidity varies. Luo's result[17] showed that, in Shenzhen, the humidity of a common building was higher than that with a green roof. However, Wu's findings[18] in Chongqing were opposite to the result in Shenzhen.

The relationship between the indoor hydrothermal environment and human thermal comfort is an important focus. Thermal comfort is an essential evaluation indicator for building site selection, architectural design as well as built environment design. At present, dynamic simulation analysis on indoor thermal environment and energy consumption by using computer software becomes a reality. The micro-climate of three different urban forms were simulated using the software ENVI-met in the study of Li *et al*[19]. By comparing and analyzing air temperature, solar radiation, mean radiation temperature and wind speed, the micro-climate performance in three cases were presented. However, it is found that defined gaps exist between simulations and on-site measurements. Chen *et al*[20] explored the gap between the DeST-h building energy simulation results and on-site measurements. Gao *et al*[21] used PMV-PPD to predict the indoor thermal comfort at the design stage of a building, which was taken as a tool to adjust design details such as window orientation. Liu *et al*[22] compared the effects of PMV-PPD on the thermal comfort of local residents and tourists constituted of mixed gender in semi-enclosed spaces. They found that females and tourists were more sensitive to humidity and wind speed. Gilani *et al*[23] used thermal sensation vote(TSV) to optimize the design of a building. In his opinion, TSV was superior to PMV index in terms of quality and the information range of prediction. Location may have critical impact on the experimental results. The so-called "mountain city", Chongqing, is famous for its rugged terrain. Although the existence of mountain-valley wind, natural ventilation in the morning and evening, local residents are still in dire need of improving indoor hydrothermal environment.

The influence of a green roof on indoor temperature and humidity has been widely studied. However, little attention has been paid in Chongqing regarding the effects of the LEG roof on indoor hydrothermal characteristics and thermal comfort. In order to investigate the effects of an ordinary roof and a LEG roof on indoor temperature, humidity, temperature distribution and indoor thermal comfort in the context of Chongqing′s unique geoclimatic environment, the inner and outer temperature and humidity of buildings with two different kinds of roofs were studied and compared with each other under the same meteorological conditions. The results of PMV-PPD and thermal sensation vote (TSV) of two roofs were also analyzed.

2 Experimental method

2.1 Case conditions

The experiment was conducted in Beibei District, Chongqing City, where two similar rooms with the same orientation in two similar Six-floor residential buildings were chosen for this study. The southern one of the two buildings is applied with a LEG roof (Fig. 1), while the northern one is applied with ordinary roof. The tilts of these two buildings' roofs from the middle to the four angles are both about 5 degrees with well-designed drainage. For the LEG roof, there are eight layers in total from top to bottom, namely, substrates (with the thickness being about 120 mm), filter layer (with the thickness being about 3 mm), drainage layer, waterproof layer, support panel, insulation gas barrier and concrete floor (Fig. 2). For the ordinary roof, there are waterproof layer and ordinary concrete floor. Testing was carried out from July 1, 2016 to July 31, 2016. During the period of the experiment, the windows and doors of both rooms were kept being closed, and air conditioners were kept being turned off.

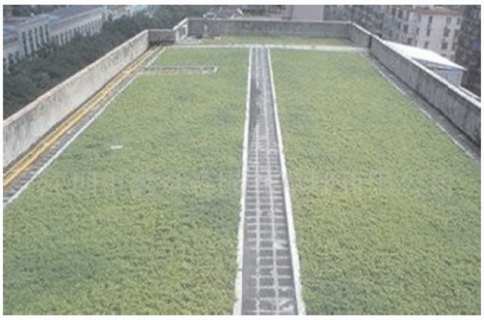


Fig. 1 LEG roof applied in this case

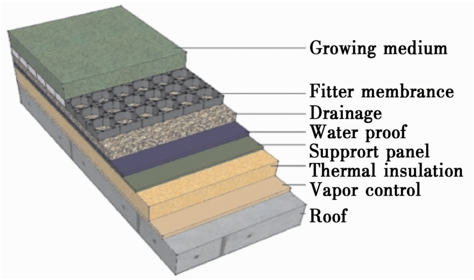


Fig. 2 The structure of LEG roof

2.2. Instrumentation and measurement

During the period of the experiment, a portable weather station was installed next to the roof to record local meteorological data, including air temperature, relative humidity, solar radiation, wind speed and precipitation. Considering the effect of temperature stratification on human thermal comfort, six different T-type thermocouples for each room were mounted along the vertical direction of the room, and the humidity sensor was mounted at the center of each room at the height of 1500 mm above the ground (Fig. 3). The TSV test was carried out simultaneously based on the measured values of temperature and humidity. All the sensors used in this experiment are listed in Table 1.

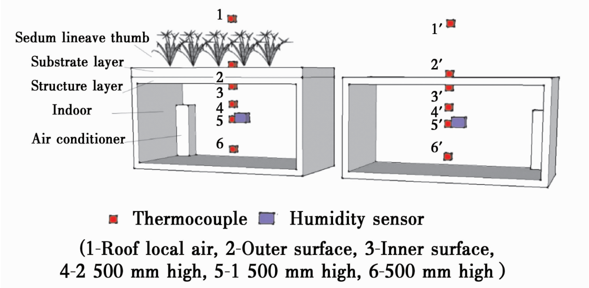


Fig. 3 Sketched drawing to show the set up of the experiment

Table1 Instrumental specifications

Equipment	Type	Range	Resolution
Thermocouple	T	－200 ℃～100 ℃	0.1 ℃
12-bit thermometer	DS18B20	－40 ℃～100 ℃	<0.03 ℃
Data acquisition meter	Agilent 3499A		
Weather station	NHQXZ602		
Humidity Sensor	HR202		±5%RH

2.3 Analytical methods

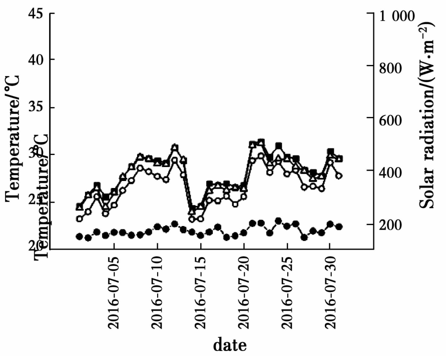
Predicted Mean Vote (PMV) is a thermal comfort index which considers the effects of human activity degree, cloth thermal resistance, outdoor temperature, average radiation temperature, air flow and relative humidity. It assesses human comfort degree in 7 grades: cold (－3), cool (－2), slightly cool (－1), comfortable (0), slightly warm (1), warm (2) and hot (3)[16].

Predicted Percentage of Dissatisfied (PPD) is an indicator for the percentage of human dissatisfaction toward thermal environment, which makes the satisfaction degree of the indoor thermal comfort reflected more directly and vividly.

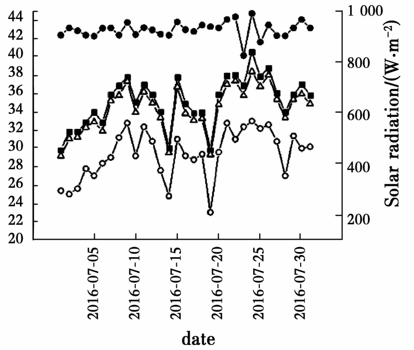
3 Results

3.1 Indoor temperature analysis

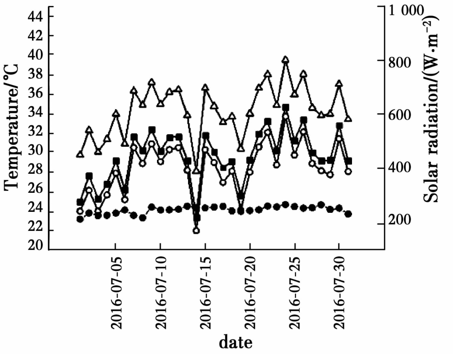
3.1.1 Average monthly and daily indoor temperature variations Solar radiation is an important factor affecting indoor temperature, and the amount of solar radiation varies with seasons and the time of the day. July is the hottest month in Chongqing in a year. During this month, the sunrise and sunset times are normally at 6:00 and 20:00, respectively. Therefore, measurements were conducted at 7:00, 14:00 and 18:00 per day to observe the changes of indoor temperature. The average value of the temperature measured at a height of 1500 mm and 2500 mm was taken as the indoor temperature. The testing results are presented in Fig. 4 and Fig. 5. Fig. 4 showed that indoor temperatures of the two rooms were slightly lower than the outdoor temperature, and the indoor temperature of the room with the LEG roof was lower than that of the room with the ordinary roof at 7:00. At 14:00, the indoor temperature of the room with the ordinary roof was still slightly lower than the outdoor temperature, however, the cooling effect of the LEG roof was obviously better than that with the ordinary roof. In the 31 days, the average indoor temperature difference between the LEG roof and the ordinary roof was as much as 4.9 ℃, and the average indoor temperature of the room with the LEG roof was obviously lower than the outdoor temperature by 5.8 ℃ (Fig. 5). At 18:00, the indoor temperature of the room with the LEG roof was still lower than the outdoor temperature, while the indoor temperature of the room with the ordinary roof was higher than outdoor temperature. It could be seen that the outdoor temperature dropped with the reduction of the



(a) 7:00



(b) 14:00



(c) 18:00

Fig. 4　Temperature variations of the considered sites (inside of the room with the LEG roof, inside of the room with the ordinary roof, and outdoor) in specific days

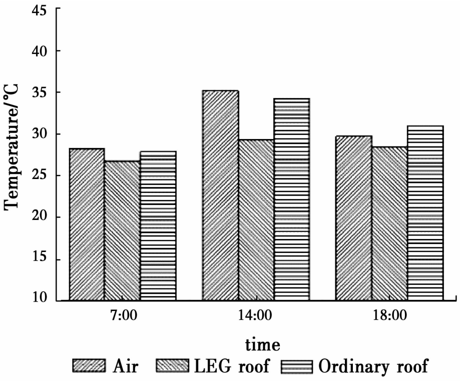
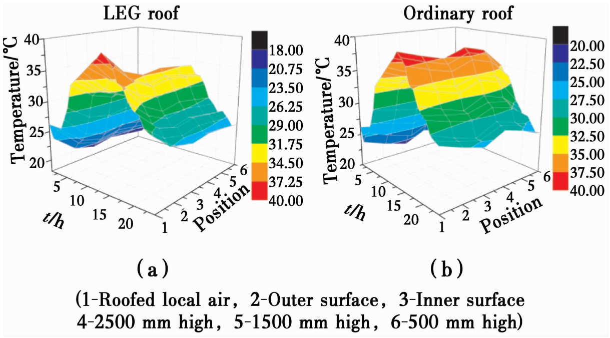


Fig. 5　The average temperature comparison of the considered sites (inside of the room with the LEG roof, inside of the room with the ordinary roof, and outdoor) in July

solar radiation. However, the indoor temperature of the room with the LEG roof was slightly decreased. The indoor cooling of the ordinary roof was also less than the outdoor air cooling. This indicates that the indoor temperature reduction of both rooms either with the ordinary roof or the LEG roof has an obvious time lag. This is because the amount of solar radiation is reduced, there is still solar radiation that provides a source of heat for stabilizing the room temperature. At 14:00 and 18:00, Jian's study[24] revealed that the indoor temperature with a bare roof, the indoor temperature with a green roof, and the outdoor temperature were consistent with ours' findings; but different results were given at 7:00. In Jian's study, the indoor temperature with the bare roof was highest; while in our study, the outdoor temperature was the highest among the three. This is due to the rapid change in solar radiation in the morning, which causes a rapid change in outdoor temperature.

In Fig. 4, July 24 was the hottest sunny day during the experimental period, which had a maximum solar radiation of 25.54 MJ/m^2 and a highest peak temperature of 40.5 ℃. On that day, the average indoor temperature with the LEG roof was 2.8 ℃ lower than that with the ordinary roof, and was 3.7 ℃ lower than outdoor temperature (Fig. 5). At 14:00, temperature difference between indoor and outdoor of the room with the LEG roof was 7.6 ℃. July 14 was a rainy day with a lowest temperature. Fig. 4 indicated that indoor temperatures of the two room were similar, which further indicated the cooling effect of a LEG roof would be influenced by weather conditions. Li[25] studied the cooling effect of green roofs in extreme summer weather in Chongqing and found that the indoor temperature of green roofs was 1.7 ℃ lower than that of common rooms. This temperature difference was 2 ℃ lower than ours's results. This was because Li's research was conducted in an extreme weather condition. The plant died due to the extreme weather, resulting in the reduction of the roof thermal insulation performance. He also compared the difference of the indoor temperature between the green roof and the ordinary roof during a summer rainfall period, the findings matched with our conclusions very well.

3.1.2 Vertical temperature distribution in the two rooms in a typical summer day Weather conditions significantly affect indoor thermal environment. In order to reduce the influences of weather change (e.g. sunshine to rain) on the experiment results, July 24, 2016, a continuous sunny day, was selected for multi-point continuous observations along the holistic vertical temperature profile. As shown in Fig. 6, surface temperature $T(3')$ of the ordinary roof increased quickly from 33.3 ℃ to 37.4 ℃ since 9:00 to 14:00, but surface temperature $T(3)$ of the LEG roof was almost constant at about 33 ℃ within the whole day. This comparison means that a LEG roof can effectively improve indoor thermal environment. The trend of the vertical temperature distribution of the room with an ordinary roof was like a hump. It can be seen that indoor temperature $T(4')$ at the height of 2500 mm was higher than inner surface temperature $T(3')$ of the roof; there was an obvious indoor temperature differences among $T(4')$, $T(5')$ and $T(6')$. This indicates that indoor temperature of the building with ordinary roof has an obvious stratification, which will decrease indoor thermal comfort. In contrast, there was no obvious thermal stratification at different heights in the room with LEG roof (Fig. 6(a)). It suggests that LEG roof makes contributions to designing an even indoor temperature distribution.



(a) (b)

(1-Roofed local air, 2-Outer surface, 3-Inner surface 4-2500 mm high, 5-1500 mm high, 6-500 mm high)

Fig. 6 Temperature distributions of LEG roof and ordinary roof on a typical summer day

3.2 Indoor relative humidity analysis

3.2.1 Daily variation of indoor relative humidity of the two buildings Indoor relative humidity of the two rooms at 14:00 are shown in Fig. 7. It was clear that there was a consistent variation trend for indoor relative humidity of the two rooms, but indoor relative humidity of the room with LEG roof was generally higher than that of the room with ordinary roof. Similar results were obtained from the research conducted by Feriadi *et al*[26]. The better the cooling effect performed by the green roof, the lower the indoor temperature and the higher the relative humidity of the room. This is because the LEG roof reduces the indoor temperature while the indoor air moisture content remains unchanged. It can be seen from the enthalpy chart that under the condition of the same moisture content, the relative humidity increases with the decrease of the temperature.

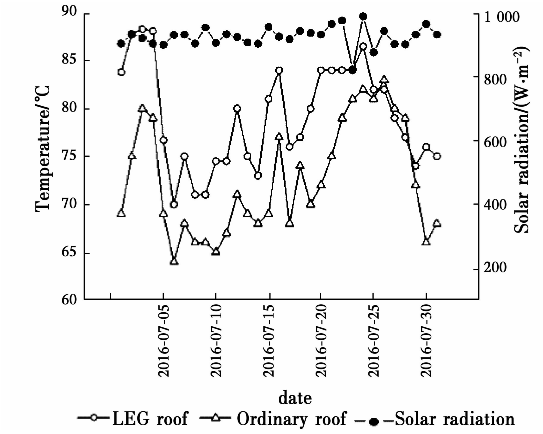


Fig. 7 Relative humidity of the room with the LEG roof and the room with the ordinary roof in July

3.2.2 Relative Indoor humidity of the two buildings on a typical summer day The alternation of sunny and rainy weather is one of the key factors affecting indoor humidity. Thus July 24, 2016 was chosen as a typical day for humidity analysis. Fig. 8 indicated that indoor relative humidity of the room with LEG roof was higher than that of the room with ordinary roof within 24 hours. Before the sunrise, indoor relative humidity for each room was similar; then, indoor relative humidity of the room with ordinary roof decreased quickly with the increase of outdoor temperature. However, indoor relative humidity of the room with LEG roof decreased slightly due to the higher aqueous vapor pressure inside. It concludes that the relative humidity in the room decreases with the increase of solar radiation as well as the weakness of the solar radiation. The relative humidity in the room maintains high humidity in the absence of solar radiation. However, in Fig. 7, the relationship between solar radiation and indoor relative humidity couldn't be obtained because the difference in solar radiation was relatively small as well as the effect on indoor relative humidity, and the relative humidity in the room does not change significantly. At 17:00, indoor relative humidity of the two rooms attained the minimum value, and the maximum difference between them reached 10%. High indoor relative humidity will affect the human thermal comfort significantly. Due to the relatively high indoor relative humidity, natural ventilation will be a good strategy if outdoor weather conditions are suitable.

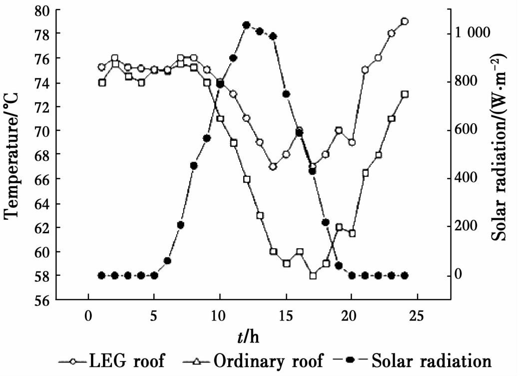


Fig. 8　Relative humidity of the two rooms on a typical summer day

3.3　Effects of LEG roof and ordinary roof on human thermal comfort

The factors affecting the human thermal comfort include the thermal resistance of clothing, individual physical and mental conditions as well as humidity and thermal parameters. The recognized and most widely used methods for assessing human thermal comfort are predicted mean vote (PMV), predicted percentage of dissatisfaction (PPD) and thermal sense voting (TSV).

3.3.1　The PMV-PPD assessment method　To investigate indoor thermal environmental quality with the applications of a LEG roof and an ordinary roof, a comparative analysis of PMV-PPD was carried out in July. Fig. 9 indicated that the PMV-PPD result of LEG roof significantly differentiated from that of ordinary roof. The indoor PMV values of LEG roof varied in the range of 1 and 2, and PPD values varied from 40% to 67%. While the PMV values of ordinary roof varied between 2 and 3.5, and PPD values ranged from 75% to 99%. It suggests that a better indoor thermal comfort and lower thermal dissatisfaction can be obtained with the application of a LEG roof.

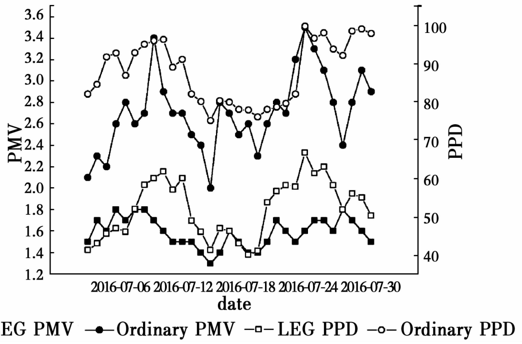


Fig. 9　The PMV-PPD values of the rooms with LEG roof and ordinary roof

3.3.2　The analysis of thermal sensation vote (TSV)　TSV was obtained by questionnaires on the typical 7-point scale and calculated as a mean value of the votes to the environment [27]. The questionnaire was carried out by the participation of 50 persons including 26 males and 24 females. Their age distributions are shown in Table 2[28]. The initial distinct thermal environments will influence participants' thermal expectations and thermal sensation. Thus, participants are not allowed to enter temperature transition spaces until they have stayed in a buffer room with a constant temperature of 26 ℃ for at least 30 min. Considering indoor temperature difference of the rooms with different roofs, participants stayed in the room with the ordinary roof for at least 30 min for thermal sensation test, following the test in the room with the LEG roof. Fig. 10 indicated that 60% of the participants were satisfied with indoor thermal environment in the room with the LEG roof, 26% even felt cool, and only 6% felt hot. In contrast, 84% of the participants felt hot or quite hot, and only 6% of them were satisfied with the indoor thermal environment in the room with ordinary roof. Therefore, it is clear that participants fell more comfortable in a naturally ventilated room with a LEG roof.

Table 2 Age distribution of thermal sensation vote

Age	Number	Age	Number
≤10	1	31～40	7
11～20	18	41～50	5
21～30	18	≥50	1

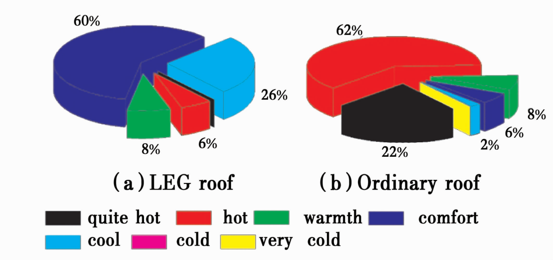


Fig. 10 The TSV results of LEG roof and ordinary roof

4 Discussions

Indoor temperature is of close adherence to solar radiation. Due to the barrier layer formed by vegetation, only a very low ratio of the heat absorbed by the roof releases into indoor space. Thus, cooling benefits of LEG roof is obvious, especially for the strongest solar radiation at noon. In comparison with LEG roof, the reinforced concrete of ordinary roof has a larger heat conductivity coefficient, which leads to a larger amount of heat entering into the room at noon and fewer escape away from the room at night, resulting in time lag of indoor temperature reduction at 18:00.

High indoor relative humidity can seriously affect the human thermal comfort degree. The results of indoor thermal comfort with the use of green roof were different when assessed by PMV-PPD model and TSV. The acceptable thermal comfort range assessed by TSV was larger than that of PMV-PPD model. Taking indoor thermal comfort evaluation of the LEG roof as an example, under the same indoor thermal condition, the result of PMV-PPD index indicated that the majority of participants felt warm and no one felt comfortable. The results of TSV index were that 60% of participants felt comfortable and only 8% of the participants felt warm. Even 25% of the participants felt a little cool. Feriadi *et al* found that, for naturally ventilated buildings located in the tropical regions, thermal comfort prediction based on PMV standard has shown some deviations from the observed results[26]. The main reason of this difference is that PMV-PPD model has the following limitations in the analysis of indoor thermal sensation. First of all, the PMV-PPD models were originally established in European, which may not really reflect the indoor thermal sensation of Chinese; secondly, PMV-PPD models are often used to assess human thermal comfort in steady and moderate environments such as air conditioning environment, while the environment of real thermal comfort such as naturally ventilated space is dynamic. Therefore, when analyzing the actual indoor thermal sensation, especially in naturally ventilated spaces, PMV-PPD index would has a certain deviation. Thus, TSV was used to supplement the indoor thermal comfort analysis of the room with the using of LEG roof. It need to be noted that whichever method was adopted, the results showed that indoor thermal comfort with the use of a LEG roof was significantly improved. The cooling effect of the LEG roof was significant. Due to the function of green plants, it could keep a relatively stable indoor temperature even though solar radiation was strong. However, indoor relative humidity of the room with LEG roof was high. In order to achieve a better indoor thermal comfort, indoor natural ventilation is required to be enhanced to reduce the indoor humidity. The design of operable windows and building orientation should be considered in combination of wind of mountain and valley with the unique geographical and climatic characteristics in Chongqing.

5 Conclusions

In this work, the effects of a LEG roof on indoor temperature, humidity and thermal comfort in summer were investigated. Much research has been done on the difference between the inner surface temperature and the outer surface temperature of a green roof and a ordinary roof. However, there are few researches on LEG roofs for human comfort in summer.

This study measured indoor temperature and relative humidity. Based on the measured data，the influences of the LEG roof on human comfort were analyzed with the use of the PMV-PPD model and TSV. At the peak temperature (at 14：00) of a day in July，the monthly average indoor temperature of the room with the LEG roof was 4.9 ℃ and 5.8 ℃ lower than that of the room with the ordinary roof and the outdoor temperature，respectively. On July 24，the hottest day of the testing period，the temperature difference between indoor and outdoor of the room with the LEG roof was 7.6 ℃ without obvious temperature stratification. Compared with the ordinary roof，the indoor thermal environment of the LEG roof had a relatively high humidity，and the maximum humidity difference reached to 10% at 17：00 on a typical day. Results drawn from PMV-PPD model and TSV indicated that a better indoor thermal comfort and lower thermal dissatisfaction could be achieved with the applications of LEG roof and natural ventilation in summer.

However，the climate in Chongqing is exceptional，which has a high temperature and high humidity in summer. It may not be widely representative. In addition，the author will continue to conduct research on the correlation between solar radiation and ceiling surface temperature.

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