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Study on improving thermal environment and energy conservation of quadrangle adobe dwelling

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ABSTRACT

In China, more than 100 million people live in earth-based dwellings currently. However, there have been few studies on measures for improving indoor thermal environment and decreasing energy consumption of adobe buildings systematically. So, this paper studied the measures mentioned above. Firstly, parameters such as indoor thermal environment, PMV, thermal properties and thermodynamic disfigurement of building envelope were measured and analyzed on a quadrangle adobe dwelling in Gansu, China. Then, three optimization schemes (transforming layout only, transforming external walls only and changing the two simultaneously) were put forward. Finally, the thermal environment and energy consumption of the optimization schemes were analyzed by numerical simulation, and the cost benefit analysis of them was carried out. Among those schemes, scheme of changing layout and external walls simultaneously leads to the best performance in both the two respects mentioned above, while scheme of transforming layout only gives the worst performance. But, when both taking consideration of economy and energy saving, the preferred plan is scheme of changing layout only, and the worst is scheme of transforming layout and external walls simultaneously. This study has been conducted to give guidance when constructing or reconstructing quadrangle adobe dwelling, which is distinctive and historical in China.

1. Introduction

Earth building refers to the construction mainly structured with original raw soil, in which the material is simply processed without roasting. Adobe building and rammed earth building are both earth buildings. It has been reported that approximately 30% of the global population live in earth-based dwellings currently [1]. In China, more than 100 million people live in earth buildings [1], which is one of the most common architecture forms in rural area [2].

Early studies on earth buildings were mainly focused on structural safety. With energy crisis and environmental pollution becoming focus of attention, studies on earth buildings were gradually related to indoor environment [3–5] and energy saving [6–12].

Researchers agreed that the indoor thermal environment of earth buildings ought to get improved, especially in winter. Taylor et al. [3] compared thermal comfort in a rammed earth building to that of a cement building by spot test. They found that the thermal comfort of the rammed earth building was not so good and was worse in the winter. During their measurement in winter, thermal comfort of offices in the second floor reached 70% while that in the ground floor only stayed at 13%. Therefore, two key points must be focused on the improvement of the earth buildings. They are winter and ground floor. Li et al. [4] measured and analyzed thermal environment and air quality of an earth building in China. They discovered that the average satisfaction with the overall environment in it was higher than that in normal brick rural buildings: 0.84 versus 0.63 in summer, and 0.78 versus 0.51 in winter. In 2013, Alhaddad and Zhou [5] found that annual comfort of adobe building was 67.8%, but total discomfort reached 464.9 h, including 385.8 h of excessively cold period and 79.1 h of excessively hot period. The extreme cold period was four times longer than the extreme hot one. Therefore, in this paper, we focus on the thermal comfort of adobe buildings in winter only.

Researchers hold the consensus that earth buildings consumed less energy and its external wall's thermal performance should get improved. According to Houben [6], energy consumption by con-

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crete construction outnumbered about 100 times of that by earth construction. However, the energy consumption he referred to was not just energy consumption of building cooling and heating, but included production and transportation of building materials, construction process, management of environmental pollution and so on. Taylor [7] carried out in-situ measurements of a rammed earth building in Australia for a whole year. He found earth building has a 25% heat diffusion during the process of absorbing heat. The heat absorbed by internal walls stayed close to that released by external walls. Yan et al. [8] studied on the thermal and moisture properties of a rammed earth building in China by experiment, and quantitatively examined the thermal properties including density, conductivity and specific heat capacity. Taylor et al. [3] compared energy consumption of a rammed earth building in Australia with a concrete office building in the same location. Experimental results showed that the rammed earth building used more energy for heating. Results of computer modeling indicated that it was needed to increase the R-value of the external walls by external insulation. Li [9] tested a rammed earth building in QinLing Mountains in northeast China. The results showed that the thermal environment of earth building in winter had been better than that of brick building, though it still can't meet the comfort requirement. He put forward a proposal of adopting internal insulation for rammed earth wall. Taylor et al. and Li had different opinions of using heat preservation materials for external insulation or internal insulation. In addition, they did not only refer to the structure of insulation layer but also the kind of insulation materials. Shi [10] studied thermal performance of various earth buildings by calculation based on parameters from standards. However, there are differences between the calculation values analyzed by her and the measured values tested by other researchers. Reddy and Sreeram [11] compared energy consumption between a cement stabilised rammed earth school and a conventional brick building. The former stayed less energy than half of the latter. It shown that rammed earth building was of low embodied energy. Chel and Tiwari [12] developed model of earth building integrated with earth to air heat exchanger (EAHE). The results showed that annual energy saving potential of the building after integration of EAHE could move up over 5375 kWh/year. In conclusion, different types of architecture have been studied, including dwellings, office buildings and schools, and they are all rammed earth buildings. In addition, few studies put forward methods of energy saving for earth dwelling. Besides that, those methods are merely quantitative analysis. When it comes to practical application, there is a lack of operational details.

The purpose of this paper is to apply practical measures for builders when constructing or reconstructing quadrangle adobe dwelling. On the one hand, based on measurements of thermodynamic disfigurement and heat transfer coefficient, thermal property of the building is clearly understood. On the other hand, based on measurements of temperatures and PMV, thermal comfort of the building is figured out. Problems are discovered through the testing results. Urgent problems are improving thermal comfort and reducing energy consumption of adobe building. At the same time, three specific schemes are proposed to solve those above problems. In order to clarify the effect of these three schemes, simulations are carried out. On the one hand, the indoor air temperature of these schemes is simulated by FLUENT and analyzed. On the other, energy consumption of these schemes is simulated by DEST and analyzed. At the end, the economy of the three schemes is compared, and evaluation of these schemes in energy saving and economy is done. In conclusion, the paper provides technical and economic guidance for practical application in construction or reconstruction of quadrangle adobe dwellings, which is distinctive and historical in China.

2. Methodology

2.1. Tested building

Quadrangle adobe dwelling in Gansu province is endowed with traditional material and typical spatial pattern in Chinese buildings. It has been featured by thick wall and shed roof here. Before 1980, quadrangle dwellings were mainly constructed to be rammed earth. Currently, quadrangle dwellings with adobe wall have developed into the major domestic architectures in rural Gansu. Fig. 1 shows characteristics of the tested building in this paper, which is located in Gansu province, China. It is clear that the tested building is a quadrangle dwelling from its general view and plan. There are rooms on the east, south, west and north side of the yard. The west room and the north room are used for residence with *Kang* set inside. A *Kang* is a heatable brick bed, which is a typical type of heating equipment used widely in northern China. The south room and the east room are used for storaging of cereal, agricultural implements, etc. The building consists of adobe earth walls and timber roofs. The adobe wall's structure is also shown in Fig. 1, and all the rooms are covered with shed roofs, with 30° slope and 300 mm overhanging eave. The roof is designed to collect rainwater into the courtyard, because the building locates in water-starved area.

2.2. Measurements and data processing

The heat flow meter was used to monitor the heat transfer coefficient of the walls and roof. Thermodynamic disfigurement of the building envelope was checked by infrared thermal imaging technique. The predicted mean vote (PMV) value was directly measured by thermal comfort meter. Temperature auto-loggers were used to monitor indoor and outdoor temperature. Information about main instruments was shown in Table 1.

The heat flow meter was calibrated onsite before use to reduce potential measurement errors and uncertainty. The thermal comfort meter and temperature auto-loggers were placed inside the west room, kitchen and north room in the middle of the room at 1.5 m height. Temperature auto-loggers for outdoor measurements were put in a shady location of the courtyard. The test period is from Dec. 8, 2012 to Dec. 30, 2012.

All above parameters were tested according to Chinese building industry standard JGJ132-2009 [13]. Formula of thermal resistance is shown in Eq. (1) [13].

$$R = \frac{\sum_{j=1}^{n}(\theta_{Ij} - \theta_{Ej})}{\sum_{j=1}^{n} q_j} \quad (1)$$

where R is thermal resistance of building envelope ((m^2 °C)/W), θ_{Ij} is the jth test value of inside surface temperature on the building envelope (°C), θ_{Ej} is the jth test value of outside surface temperature on the building envelope (°C), q_j is the jth test value of heat flux (W/m^2).

Formula of the heat transfer coefficient is shown in Eq. (2) [14].

$$K = 1/(R_i + R + R_e) \quad (2)$$

where K is the heat transfer coefficient of the building envelope (W/(m^2 °C)), R_i is the inside surface heat resistance ((m^2 °C)/W) and R_e is the outside surface heat resistance ((m^2 °C)/W). According to Chinese national standard GB50176-93 [14], the latter two are 0.11 m^2 °C/W and 0.04 m^2 °C/W respectively.