Experimental study on the thermal performance of underground cave dwellings with coupled Yaokang

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1. Introduction

Seeking climate responsive characteristics of vernacular dwellings is one of the most effective ways for sustainable development. As a traditional dwelling form, cave dwellings, called “Yao Dong” by the natives, have been widely experienced on Loess Plateau of Northern China for thousands of years. Even now there are still about 40,000,000 people living in this kind of ancient buildings [1]. By utilizing local materials and fitting topography, cave dwellings are mainly divided into three types, namely, cliff-side, stand-alone and underground ones. The underground cave dwelling is completely built under the ground, which is widely distributed in the northeast of Gansu province, south of Shanxi province and west of Henan province, respectively. Using the stability of loess, a closed quadrangular courtyard is formed by digging vertically into the ground, and then the cave rooms in four sides are built by the excavation along the horizontal direction (as shown in Fig. 1). Compared with the cliff-side and freestanding cave dwellings, the advantage of underground is reflected by the courtyard with the function of reducing cold air infiltration in winter and preventing sun exposure in summer. Therefore, it is the courtyard creating a micro-climate to improve the thermal environment. Cave dwellings are mostly located in cold area of China, and thus, how to get heat in winter becomes a main concern. As an ancient traditional heating system, Kang, called “Yaokang” by the natives is widely accepted in cave dwellings. Yaokang takes use of the surplus heat of hot smoke from the stove, which is heated by biomass, such as straw and stalk. By means of the improvements of chimney and flue, most of the resulting flue gas can be discharged, accordingly, the effect of undesirable gases on indoor air quality can be decreased effectively. Generally speaking, the function of Yaokang is not only to provide an important place for rest as a bed, but also maintain the home feeling, including eating, chatting and entertaining guests, etc. It plays a significant role for building energy efficiency and resident life. Similar heating systems also exist in other countries, such as ondol in Korea [2,3] and hypocaust in ancient Rome [4,5].

Studies on thermal performance of Chinese Kangs and indoor thermal environment of Kang buildings have been performed, which can be divided into two categories. One is focused on simulation analysis for combustion and heat transfer of Kang [6,7], the other is related to the thermal environment of rural residences with coupled Kang heating by onsite monitoring [8,9]. Zhuang [10] outlined the construction of a mathematical model of Kang system. Based on the model, thermal storage and smoke flow characteristic of Kang have been obtained. A simplified and modular system modeling program was created by Zhai John [11,12], which assisted...
in optimization of Chinese Kang heating system. Despite lack of investigations into thermal response of cave dwellings under Yaokang heating, there are a few studies on the thermal environment of rural brick/concrete residences with coupled Kang heating. Literature [13,14] indicated that the indoor air temperature was around 10 °C in the rooms heated by the Kang system. Chen [15] investigated the thermal environments of three rural residences in Dalian, which integrated different Kang heating systems, and obtained the optimization model for rural residences. Liu [16,17] presented an energy performance evaluation for new Yaodong dwellings and analyzed the thermal transfer through the wall using the energy simulation program Energyplus.

According to research review, the existed work was mainly focused on individual optimization of Kang, or the thermal environmental monitoring for brick or concrete buildings under Kangs. However, the discussion about indoor thermal performance of cave dwellings with coupled Yaokang heating has not yet been found with the author’s knowledge. Yaokang has the different construction technologies and materials in comparison with other Chinese Kangs. Meanwhile, the facade thickness of cave dwellings can reach to 3 m. Such massive envelope plays a significant role in thermal response. However, studies about cave dwellings are mainly connected with their architectural form, culture and construction techniques [18,19]. Although some have touched its thermal environment aspects, they are mostly qualitative [20,21].

Therefore, a quantitative study about the thermal responsive characteristics for underground cave dwellings with coupled Yaokang heating is initiated by the authors. In this paper, a short-term field experiment (from January 21, 2015 to January 28, 2015) and a long-term remote monitoring (from July, 2015 to December, 2016) has been performed in cave dwellings in Miaoshang village of west Henan province. Based on the experimental data, thermal performance of Yaokang is analyzed firstly, and then the results of thermal environment monitoring are shown. Finally, energy efficiency rate of Yaokang under various climates is evaluated by the Kang heating potential coefficient proposed. This work can provide some information about the indoor thermal environment of traditional underground cave dwellings in winter in Northern China.

2. Design issues of Yaokang

2.1. Layout

The firstly considered factor in function and disposition of cave dwellings is the location of Yaokang. Usually speaking, with consideration of the natural lighting, convenient ventilation and smoke discharge, etc., there are mainly two ways to layout the location of Yaokang. The first one, which is also commonly used, is placing Yaokang near a window and close to the facade (see Fig. 2(a)), with the advantage of good lighting and ventilation. The second one is to arrange it in the deepest position of a cave room, which will decrease the heat loss in winter (see Fig. 2(b)).

According to the location of Kang body, there are two design ways for chimneys. As shown in Fig. 2, the chimney is at the edge of facade for Yaokang located near the window, while it is in the back wall for Yaokang located in the deepest room.

2.2. Construction

The building material used for Yaokang, named adobe, is made of immature soils by manufacture molds. The adobe is completed after soaking, mixing, tedding, kneading, going into the mold, forming, form removal, drying and other processes, etc. To increase the strength of adobe, straws are added during mixing sometimes. The unified size of adobe is 0.4 m long, 0.25 m wide, and 0.05 m high.

Adobe is made of raw soil, which has not been fired, with larger porosity. The hot air can be kept longer in the pores of adobe. Therefore, compared to other materials, adobe is more beneficial to heat storage. Adobe where Yaokang stores heat during cooking time can maintain heat for several hours, creating a comfort thermal environment inside. In addition, using adobe as Kang materials is also a custom. Among the local villagers, there is a saying of “ground air”, which means that people expect to maintain zero distance from the soil when sleeping at night.

The masonry method of Yaokang contains a wealth of scientific experience. Fig. 3 illustrates a typical ground Yaokang, including a stove, a Kang body and a chimney. The bottom of Kang body is paved with adobe, about 5 layers of height. The stove always locates in the middle of Kang front wall, which is more convenient to add fuel.

The upper layer of adobe cushion platform is adobe flue, which is consisted of several channels with 25 cm height and 15 cm or 30 cm width. As shown in Fig. 3(a), the flue layout of Yaokang belongs to the mixed flue [9]. That is to say, at the smoke inlet, the adobe pillars are perpendicular to the smoke inflow direction with a smoke leading flue. On one hand, by adding the leading flue of Kang’s width, the inlet smoke is led directly into the tail of the flue. On the side near the chimney, the flue is parallel to the smoke inflow direction, which forms the smoke damper (see Fig. 3(b)). The inlet hot smoke can be taken to the turn-around flue and then to the exhaust flue chimney so as to avoid smoke back flow. The flow path design contributes to the thermal diffusion and uniformity of surface temperature. On the other hand, adobes placed in rows in the flue are used as pillars to bear the upper faceplate. The adobe-faced faceplate is smoothed by straw mud, as shown in Fig. 3.

![Fig. 1. A typical underground cave dwelling, its photo and elevation (a) photo (b) elevation.](image-url)
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