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Optimization of thermal performance in a Chinese traditional heating system – Burning cave

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ABSTRACT

Nowadays, inhabitants living in rural areas of northern China still rely on traditional heating methods, such as kangs (bed-stoves), radiators heated by mini stoves, and burning caves in cold winter period. Burning caves are increasingly used due to free fuels from crop wastes, simple structures, and better heating effect than kangs and mini stoves. In this study, field measurements of indoor environment in several rural houses with burning caves designed by local craftsmen and located in northern China were carried out in 2010–2011. The results show that indoor temperatures maintained at above 18 °C and it was felt more comfortable than houses heated by kangs and mini stoves. To solve some existing problems in houses with burning caves built by local craftsmen, a new house integrated with an improved burning cave was built in December 6, 2011. The results from theoretical analysis and field measurements showed that temperature difference between adjacent rooms could be reduced by 4–6 °C, which is 2–5 °C lower than the houses with the burning caves designed by craftsmen, and the thermal efficiency reached 56.7%. In addition, the concentration of CO was reduced to 1/5 of the value in the houses with burning caves by local craftsmen.

1. Introduction

Heating is necessary for more than two thirds of China area in winter. Building energy consumption in 2010 in rural areas was about 316 millions of tons of coal equivalent (tce), which is 1.93 times as much as in urban areas [1]. About 140 millions of tce were consumed from biomass. Large amounts of crop wastes (e.g., straws, corn cobs, corn stalks, etc.) are produced after harvest every year in China. About 46.94% of them are used for cooking and heating, a few percent is recycled, and the residual is disposed by open burning [2]. For example, in Fuxin city, northeast of China, annual planting area of abundant crop straws is about 561.8 hectares, and annual production is more than 1.5 billion kilograms of biomass. About fifty percent of them are collected and centralized to incinerate (open burning) (Fig. 1), which results in energy waste and air pollution. In 2006, open burning of crop wastes in Liaoning Province emitted about 1.5 kilotonnes (kt) of sulfur dioxide, 9.2 kt of nitrogen dioxide and 55 kt of PM 2.5 [2]. Various kangs have been widely used in about 85% of rural houses in northern China. In 2004, about 67 millions of kangs were being used by 175 million people [3]. However, several problems have been observed in rooms heated by kangs: higher indoor temperature difference (>8 °C) between day and night in heating rooms, ice and droplets leaving on the window panes (Fig. 2), and uneven temperature distribution on surfaces of kangs and condensation under the coverings being very harmful to human health. Furthermore, poor air quality has been a serious problem in houses where domestic stoves were using. The concentration of pollutants in the indoor air was still at relatively high levels up to the mid-1980s, especially in winter [4]. A number of investigations between indoor environment and human health have already been completed and discussed based on the multivariate analysis of physically interdisciplinary research. Sustainable energy utilization methods and relevant criteria related to healthy buildings have been carried out, which could lead to a sustainable, healthy, comfortable indoor and outdoor environment [5–10]. Not only indoor-air-quality (IAQ) has been set to standards, but also building energy-saving systems have been applicable for existing buildings [11]. Recent years, burning caves have been attracted much more attention in rural areas of northern China, because of their simple structure, low cost and better heating effect. Demands for houses integrated with burning cave heating systems designed by local craftsmen are increasing day by day. This paper investigated the performance of the burning caves designed by the craftsmen, and proposed an improved burning cave heating system

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Fig. 1. Crops incineration in rural areas of China.

Fig. 2. Frozen window pane.

with optimized structure and heat transfer approach to overcome the problems in burning caves by the craftsmen. Field measurements and theoretical analysis were also conducted to verify the performance.

2. Chinese traditional heating system – burning cave

Burning caves are based on a process of smoldering of fuels, generally placed under the rooms, to heat houses by radiant floors. The fuels are derived from crop wastes, such as sawdust, rice husks, leaves, wheat, cattle or horse manure, straws, corn cobs, corn stalks, etc. [12]. Because smoldering is a very slow combustion, the frequency of refilling fuels is about 2–3 during heating period. If smoldering is well controlled, the frequency of refilling fuels can be 1 during heating period. There are two ways to discharge flue gas: one is that flue gas is discharged via chimney directly (Fig. 3(a)), the other is that flue gas is discharged by channels to kangs for better heat utilization, then via chimney (Fig. 3(b)). Burning caves integrated into a greenhouse could also bring considerable benefits (Fig. 3(c)). On the one hand, different areas with different radiant temperatures could provide suitable environment for livestock and poultry during different growth stages. On the other hand, the raised temperature of soil surrounding the burning cave can help biogas production and crop growth in cold winter in northern China.

3. Performance of burning caves by craftsmen

3.1. The burning caves designed by craftsmen

Local skillful craftsmen have made every effort to improve the performance of traditional heating systems, including burning caves, kangs, etc. Two houses with burning caves designed by the craftsmen were built in Fuxin city (latitude 42.03N, longitude 121.65E), northeast of China, as shown in Fig. 4. In these houses a north-facing room is elevated to the second floor to build a burning cave under the room. In this way, the bedroom on the second floor is heated by radiant floor, and the rooms around the burning cave are heated by the walls. In addition, all the south-facing rooms can absorb more solar radiation heat.

3.2. Field measurements

To verify the thermal performance of the burning caves by the craftsmen field measurements were conducted in a house with floor area of 199 m^2 in Fuxin (Fig. 5). The burning cave with a diameter of 2 m, a height of 1.5 m, and flue gas was discharged via the kang in bedroom 2. Bedroom 1 was mainly heated by the radiant floor above the burning cave. Bedroom 2 was heated by the kang. Living room was a non-heating region. The indoor/outdoor temperature and relative humidity were measured by thermo recorder TR-72U. The data for heat flux of radiant floor were collected by a data logger SWP-L816. All the measurements were recorded every 10 minutes and saved in a computer. The concentrations of CO, CO_2 and particles were measured separately by an indoor air quality meter TSI7545, and an aerosol monitor TSI AM510, taking averaged test values in 3 minutes as the measured concentration. The surface temperatures of the radiant floor and the kang were recorded by an infrared camera FLIR B250. The test points are illustrated in Fig. 5(b). Test period was from March 11, 2011 to March 31, 2011.

3.3. Results and analysis

3.3.1. Indoor environment

The indoor/outdoor temperature and relative humidity in different rooms are shown in Fig. 6. The ignition time was at 18 PM on March 12, 2011. After igniting, the indoor temperature of bedroom 1 above the burning cave was increased from 10 °C to 21.2 °C gradually, and the relative humidity was decreased from 50% to 10%. When outdoor temperature swung in a range of −7 to −2 °C, the average indoor temperature of bedroom 1 was about 22 °C, which is 10 °C higher than in bedroom 2 with the kang heating during the testing period. The relative humidity of bedroom 1 was below 10%. Bedroom 1 was warmer, but extremely dry environment is harmful to human health. Fig. 6 also gives that the temperature difference between the adjacent rooms in the house was about 8–10 °C. Other field measurements in local houses heated by kangs and mini heating stoves showed that average indoor temperature was about 11 °C, and even below 0 °C in early morning [13]. It is obvious that the heating effect of burning caves is better than the kangs and mini stoves.

The average indoor concentrations of CO and PM10 were about 14.2 mg/m^3 and 0.22 mg/m^3 respectively during the heating period in the house heated by the burning cave by the craftsmen. The results indicated that the concentration of CO was 4.2 mg/m^3 higher than the limits in the indoor air quality standards (GB/T 18883-2002) [14], and the concentration of PM10 was 0.06 mg/m^3 higher than the limits in the standards [14]. Some measurements in rooms with kangs and stoves showed that the concentration of CO and PM10 was about 15.96 mg/m^3 and 0.76 mg/m^3 respectively while cooking. Poor indoor air quality could result from leakage of flue