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A simplified calculation method for predicting the thermal performance of a burning cave in rural houses of Northern China

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ABSTRACT

Burning cave is becoming more and more popular in rural areas of northern China. It also has some disadvantages such as uneven temperature distribution, partial higher temperature and lower thermal efficiency. In order to research the heat transfer performance of the burning cave, an unsteady heat transfer model has been established, and a theoretical calculation formula has been deduced and verified by experimental data. It shows that both the thermal characteristic of the radiant floor on the burning cave and the heat generated from different biomass fuels inside the burning cave have a large impact on the surface temperature and heat transfer of radiant floor. Moreover, while the heat transfer coefficient of the radiant floor was a constant, the surface temperature of the radiant floor changed with the heat released from different fuels was consistent with exponential variation form. However, as using the same biomass fuel, the thermal resistance of the radiant floor was increased by 0.5(m^2 K)/W, the heat transferred from the burning cave to the heating room could be reduced to 0.67 times of the original heat before optimized. Therefore, the valid theoretical analysis calculation formula could provide theoretical support for reasonable design on a burning cave, and predict thermal performance on different types of burning caves more easily.

Contents

1. Introduction

Burning cave is a conventional heating system, and becoming more and more popular in rural areas of northern China. Because there are four keys in heating process, such as taking crop wastes as

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biomass fuels, continuous heating like a radiant floor heating, providing a comfortable indoor environment, and easy to be integrated with a house. Through a field of measurements in a room heated by a burning cave, the average indoor air temperature could be maintained at about 15.5 °C, and the temperature difference between day and night could be reduced to 6 °C [1]. However, at present, the heating problems of the burning cave are as follows: (1) the smoldering process of fuels is not easy to control. (2) The phenomenon of uneven temperature distribution and excessive higher temperature on partial surface of the radiant floor is very common. (3) The heat utilization efficiency is nearly about 30% and the heat loss is very serious. In the process of application, the structure of burning cave has been effectively improved by craftsmen in rural areas. But the thermal performance of the optimized burning cave should be tested.

In foreign countries, a number of experimental and theoretical studies have been carried out in respects of smoldering characteristics and control approaches. However, the application effect of burning cave was barely studied by foreign scholars. The study hotspot was on the smoldering mechanism and heat transfer process of fibrous matter before the fire started. Since 1983, the heat and mass transfer laws of energy wave has been gained through theoretical and experimental research on the propagation velocity and direction during the smoldering process by Ohlemiller [2]. In 1990, the propagation principle of smoldering in horizontal layers has been analyzed and the empirical formula of heat transfer process has been carried out by Ohlemiller [3]. From 1991 to 2000, the multi-factors (including oxygen demand, gas flow rate, combustion rate, and the weight) influencing on the smoldering process have been studied by some famous scholars [4–12]. In 2001, a mathematical model for describing the heat and mass transfer inside different fibrous matters under the status of spontaneous combustion has been established, which could be used for predicting different thickness of ashes impacting on smoldering process by Krause and Schmidt [13]. In 2003, the combustion status and influencing factors on biomass fuels burning inside the heating equipment have been researched through experimental study, and the wood burning directly impact on the indoor air quality of a modern rural house by Boman et al. [14]. Besides, while biomass fuels burning in the small furnace, particle diffusion process has been discussed through experimental study by Johansson et al. [15]. Until 2008, while biomass fuels were burning from normal combustion to smoldering, the processes of gas diffusion and secondary combustion have been analyzed through the experimental study Tissari et al. [16,17].

Domestic famous scholars have taken some detailed studies on smoldering and application technology of burning cave. Sun et al. [18–21] have taken experimental measurements and theoretical simulations on the forward and reverse smoldering process of combustible fibrous materials. Moreover, the impacts of air velocity, ignition area, the size of porosity and particle on smoldering process have been discussed. The utilization status and heating characteristics of the burning cave have been researched by experiments, and the thermal efficiency of burning cave was only up to 30% [21]. The lose rate and productive efficiency of the heat generated from smoldering biomasses under different bulk density and different filling types have been studied by experimental research by He et al. [22,23].

Through discussions all above, the research on the thermal performance and the heat transfer process of the burning cave has been researched barely by theoretical analysis. The intensity of the heat resource, materials of the cover plate influencing on the surface temperature of the radiant floor heating has not been discussed.

2. Design mode and measured methods

To discuss the thermal performance of the burning cave, a house integrated with an optimized burning cave and kang has been built with the floor area of 199 m^2 in Fuxin of northern China (as shown in Fig. 1(a)). The burning cave was designed as a cylinder under the second floor, the diameter was 2 m, and the height was 1.5 m. During the testing period, corn cobs have been taken as biomass fuels, whose stacking density was about 97 kg/m^3. The construction materials are listed in Table 1. On the one hand, most of the heat has been transferred from the burning cave into the bedroom on the second floor through the cover plate (which is also named as the radiant floor, used in the following parts of this paper). The working principle of the burning cave heating is as the same as the radiant heating floor. Besides, the flue gas exhausted from the burning cave was discharged via the kang in the bedroom on the second floor. On the other hand, only a few of heat released from the burning fuels has been transferred to the bedroom on the first floor through the wall between the burning cave and the bedroom, which was similar to the hot flue gas heating wall.

A field of measurements has been taken in this ordinary farmhouse. The temperature distribution in the burning cave has been tested by the high-temperature multi-circuit monitoring system (measured error is ±1 °C). As a result of combustion status of fuels and construction materials of the burning cave, the temperature distribution has been taken divided into two parts for discussion (as shown in Fig. 1(b)). The heat transferred from the burning cave and kang was measured by data logger SWP-L816 (measured error is ±1 $W/(m^2\,K)$), and there were 2 test points on the kang and 9 test points on the floor. The inner surface temperatures of the building envelopes have also been measured by SWP-L816 (measured error is ±0.1 °C). The indoor and outdoor air temperature and relative humidity were respectively measured by thermo recorder TR-72U (measured error is ±0.1 °C). The radiant temperature was tested by black radiant thermometer JTR-04 (measured error is ±0.5 °C). All the measurements were recorded every 10 min and saved in a computer. The test points are illustrated in Fig. 1(b). Test period was from March 12, 2011 to March 26, 2011.

3. Results discussions

3.1. Temperature distribution inside the burning cave

Fig. 2 shows that the surface temperature of the burning fuels was between 480 °C and 510 °C inside the burning cave. In part I, the time for the burning fuels to reach to the highest temperature is 3–5 h longer than which in part II. The temperature in part I is 34–40 °C higher than which in part II. The temperature difference between the two parts is the main factor influencing on uneven temperature distribution on the radiant floor. Based on the highest surface temperature of the burning fuels was correspond to the time for burning, the average burning velocity in each part is about 6.2 mm/h, 5.6 mm/h respectively by calculation. Therefore, the oxygen infiltrated into the burning cave and the burning velocity is 1.1 times more than the values in the reference [24], which illustrates that the status of the burning fuels inside the burning cave is flaming combustion. Therefore, taking some appropriate methods to control the burning velocity is significant for controlling the surface temperature of the radiant floor. Such as reducing the oxygen infiltration and equipped with automatic sprinklers.

By radiation heat transfer calculation [25], the radiation heat exchanged from the burning fuels to the radiant floor was reduced from 41.25% to 20.82%, as the height of the burning fuels was decreased from 1.0 m to 0.3 m. Besides, the radiation heat exchanged from the burning fuels to the around wall is increased