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A simplified model for dynamic analysis of the indoor thermal environment of rooms with a Chinese *kang*

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ABSTRACT

This paper uses thermodynamics equilibrium theory to develop a mathematical model for dynamic thermal processes pertaining to rooms with a Chinese *kang* (a heatable brick bed). The model is developed through analysis of the dynamic thermal equilibrium of indoor air temperature and the temperature of interior and exterior surfaces of the building envelopes of rooms with a *kang*. It is developed and solved using a thermal reaction coefficient. Based on data from a field test, a simplified mathematical model of thermal processes in such a room is presented. The model only takes into account the radiation heat transfer between the exterior surface of the *kang*'s faceplate and the other interior surfaces of the building envelope, while ignoring the reciprocal radiation heat transfer between all other interior surfaces. A simplified mathematical model pertaining to the Chinese *kang* is also put forward. This model does not take into account the reciprocal radiation heat transfer between the interior surfaces of the Chinese *kang*. By combining these two models, the hourly values pertaining to indoor air temperature and exterior temperature of the *kang*'s faceplate can be predicted for different burning modes of the Chinese *kang*. MATLAB was used for calculating the target temperatures and solving the thermal reaction coefficient. The model was validated by error analysis and correlation analysis, the result of which shows that this mathematical model can accurately predict various characteristics concerning the temperatures in a room with a Chinese *kang*.

1. Introduction

At present, energy usage in northern rural areas in China are mainly for cooking and heating, of which heating energy usage is the most prominent in winter. Overall, the energy for space heating was 131.3 million tce (3.8×10^9 GJ), which accounts for 41.5% of total rural energy consumption in China [1]. With the improving living standards and urbanization, the prospects of the traditional commercial heating method are not optimistic in rural areas in China. Since the 1980s, the commercial energy resources (i.e. commercial coal, electricity and natural gas) used in the rural areas have gradually increased. In accordance with this situation, there bound to be heavy pressure on economic and social sustainable development of China. If the residential heating in rural areas goes through the same way as that in urban areas, it is neither economic nor realistic. Thus, on basis of the unique characteristics of the rural areas in northern China, seeking a proper heating method to improve the indoor thermal environment without heavy energy consumption is an important issue for building energy conservation.

There are many kinds of conventional bioenergy in northern rural areas which is easy to be obtained, especially those remainders from harvesting (i.e. the straws and other crop residues). According to the statistics, the total bioenergy produced every year in rural areas of China is approximately 6 million tons, of which

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about 60% is used as fuel for heating and cooking [2]. Therefore, the heating methods using the bioenergy are more in line with the rural lifestyle, including the Chinese *kang*. Meanwhile, it is a more scientific and rational way to ensure energy heating requirements in rural areas.

The *kang* is a traditional long platform made of bricks or other forms of fired clay and more recently of concrete in some locations. Its interior cavity, leading to a flue, channels the exhaust from wood or coal cooking fire, usually the fire would be fed from a stove of the adjacent room which serves as a kitchen. A separate stove may be used to control the amount of smoke circulating through the cavity of the *kang* for maintaining comfort. Typically, a *kang* occupies one-third to one half the area of the room, and is used for sleeping at night and for other activities during the day, such as general living, working and entertaining [3].

According to the statistics from the Ministry of Agriculture of the People's Republic of China, there were about 66.85 million *kang*s existed in China in 2004, used by nearly 43.64 million rural families (approximately 175 million people) [4], namely every two families have 3 *kang*s. Therefore, the Chinese *kang*, which is the most widely used heating method in rural areas of northern China, deserves further study. Similar heating systems also existed in other counties, such as the *ondol* in Korea and hypocaust in ancient Rome [5–7].

The Chinese *kang* has been extensively studied, both experimentally and computationally. Many of the studies have focused on particular elements of the *kang* system itself, i.e. stove efficiency, smoke flow, and how to make *kang* model accurately by observed data. Chen [8] conducted two field surveys in three residences to investigate the indoor thermal environments of rural residences with a coupled Chinese elevated *kang* and passive solar collecting wall heating system. Li [9] presented preliminary results from field measurements and mathematical modeling, and discussed the development of Chinese *kang*s as related to future energy consumption in rural homes. Zhuang [4] reviewed the basic heat transfer and airflow principles of Chinese *kang*, and did field surveys to show the thermal performance of the *kang*. A thermal and airflow model for an elevated *kang* was also developed by Zhuang [10] with a simply consideration of the heat transfer in building envelope. It was observed by them that the increase of the plate time constant and the heat source frequency with continuous firings and equally distributing the firings and adding the number of firing with intermittent firings can effectively decrease the fluctuation of *kang* plate temperature and indoor air temperature. Zhuang [11] also investigated thermal storage in *kang*s and incorporated transient heat transfer effects into the system model. Zhuang [12] and Cao [13] used complex modeling methods to simulate the smoke within the *kang* and both verified the rate of smoke flow which was calculated in the model. A comprehensive study concerning the heating performance of the *kang* was also conducted by Cao [13], who simulated the dynamic performance of the *kang* using the IDA-ICE software and found that the comfortable temperature range for the bedroom of a rural home is 12–16 °C. Wang [14] developed a new Chinese *kang* with forced convection, which adopted hot water as the heat transfer medium and added in a small fan to enhance convective heat transfer. Experimental data showed that the new type of *kang* retained the merits of a traditional *kang* by providing local thermal comfort. Zhai [15,16] researched the *kang* system by creating a simplified and modular system modeling program with the aim to assist in accurate real-time design and optimization of the domestic *kang* heating system. It was found that the addition of a room radiator system, consisting of a heat exchanger, water tank, thermostat controls and a panel radiator, delivered the most economical solution in regards to the increasing the resident's comfort per dollar invested. A Chinese *kang* with two stoves was studied in detail to evaluate the thermal performance by Li [17]. An improved layout model for *kang* flue was developed to assist in designing and optimizing the domestic *kang* heating system.

Existing research mainly focused on the *kang* itself and individual possible solutions, i.e. improved building envelope insulation, coupling with passive solar systems, and the use of phase change materials, etc. There is little concern about the surrounding thermal environment of the *kang*, namely the indoor thermal environment of the room where the *kang* placed. To understand such an issue requires a simplified and modular model of the room with the *kang* that can evaluate and measure the effectiveness of possible technical solutions to improve the thermal environment, with less but meaningful inputs, besides the model of the *kang* itself. Developing a simplified model of the room with the *kang* and the *kang* itself is to create a tool that can quickly evaluate possible improvements without requiring sophisticated technical data. The previous literature was used intensively as a guide while constructing the framework for the simplified system model. Research data from the field tests were employed to construct and validate the system model. Informal interviews of residents were also carried out to provide background information regarding cultural practices and habits in rural northwest China.

2. Outline of thermal process

Chinese *kang* is not only a heating facility, but also can be thought as a part of the building. The thermal environment of the room with a Chinese *kang* is determined by the dynamic thermal process of itself. Thus, according to the systematic research on dynamic thermal process of the room and the *kang*, the influence that the *kang* acts on the indoor thermal environment can be quantitatively analyzed in practice.

The heat transfer ways that influence the indoor thermal environment include convection between each interior surface and the indoor air, radiation between the surfaces, and conduction from the building envelopes. The exterior surface temperature of the *kang*'s faceplate is much higher than the indoor air temperature and the interior surface temperatures of the building envelopes. Therefore, calculation of heat dissipation from the exterior surface of *kang*'s faceplate should include convection with the indoor air, and radiation with interior surfaces of the building envelopes.

The research of indoor thermal environment of the room with a *kang* is more complex than that of the room with normal convective heating method, because radiation is involved in every interior surface of the room. As shown in Fig. 1, the core of the thermal process of the room with a *kang* contains the elements as the indoor air, interior surface of the building envelopes and exterior surfaces of the *kang*, which can form the core of the system model. The completed system model also includes control channel and interference channel. It is shown in Fig. 1 that, in the control channel, the heat transfers from the heat medium to the air inside the *kang*, then transfers to the interior surface of the *kang* by convection, after that transfers to the exterior surface of the *kang* by conduction; and in the interference channel, the heat transfers from the exterior ambient to the exterior surface of the building envelopes by convection and radiation, then transfers to the interior surface of the building envelopes by conduction.

2.1. Heat transfer of kang (core)

Basically, the Chinese *kang* is the only indoor heating device to improve the indoor thermal environment, making full use of the residual heat from the smoke exhausted by the stove. During the cooking time, the air in the kitchen is driven into the stove by