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Field measurements, assessments and improvement of Kang: Case study in rural northwest China

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ABSTRACT

Many residents in northwest rural China use a traditional system of Kang to heat their houses during the winter. Kang as a simple and regionally cultural technique has been widely used in vast rural areas in northern China with a perpetual history. In fact, the current Kang system is inefficient and requires high levels of fuel consumption. Then, how to improve both the thermal performance and energy efficiency is of great importance to the construction and development of the new-type Kang. In this paper, the Kang widely used in northwest rural areas surrounding Xi'an of China has been taken as the test object. The tests were conducted in detail under different operating conditions of stoves (stove 1 and stove 2, separately or both combined). A series of evaluation indexes about Kang such as average surface temperature, standard deviation of surface temperature, instantaneous thermal efficiency, and indoor air temperature have been analyzed. An improved layout model for Kang flue has been developed to assist in designing and optimizing the domestic Kang heating system. Based on the numerical simulation, the improved layout model was demonstrated to lead to substantial improvement of Kang thermal environment characteristics.

1. Introduction

Chinese Kang has been used over two thousand years and is still being widely used in the vast rural areas of northern China [1]. The Kang usually made from masonry, adobe and cement acts as a traditional bed platform and a heating system for residents in rural areas of China. The earliest Kang can trace its history back to the Zhou dynasty (722–483 BC) [2]. A report on investigation of rural energy in Northern China in 2006 showed that Kangs were found in nearly 85% of rural homes in northern China [3]. The climate in northern China regions is cold and dry during most time of the winter with an average temperature below −10 °C and a minimum of less than −20 °C [4]. So a domestic heating system is indispensable there and Chinese Kang as an effective way of using locally-produced biomasses or wasted is just the most typical one.

Rural building heating constitutes 25% of total building energy consumption in China [5]. Improvement of living conditions and continuing urbanization of rural China will aggravate the national energy crisis. Hence, there is an increasing urgency in improving rural building energy efficiency. The traditional Kang heating systems efficiency (with energy efficiency under 20%) is relatively low and requires lots of fuel consumption [6]. How to improve the thermal performance and energy efficiency is of great importance to the construction and development of the new-type Kang. Numerous studies of Chinese Kang have been conducted to improve the heating efficiency. The review paper [6] discussed the basic heat transfer and airflow principles of Chinese Kang, as well as described the traditional grounded Kang and the relatively new elevated Kang. On the bases of field surveys [7,8], Li proposed the scientific and engineering problems of Kang from the aspects indoor thermal comfort. Commonly used control technology of indoor environment has been integrated with the traditional Chinese Kang, such as forced convection, solar energy [9,10] and so on. Wang et al. [11] developed a new full-scale Chinese Kang with forced convection that the CKFC (a Chinese Kang with forced convection) has satisfactory performances. Yang et al. [12] developed a new Kang system that integrates a low-cost, easily maintained solar air collector into the convectional Chinese Kang system.

As computational science has extensively been developed, it has become possible to research the building performance of Kang accurately by simulation tools [13,14]. Cao et al. [15] established a set of models to simulate the energy performance of the Kang heating system to collect practical parameters in a newly constructed

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Nomenclature

A	total area of the Kang surface (m^2)
A_i	equally divided area of the Kang surface (m^2)
m	number of measurements
n	number of measurement points
R	thermal resistance of Kang structural layer material ($m^2 K/W$)
S	coefficient of thermal storage of Kang structural layer material ($W/(m^2 \cdot K)$)
T_h	heating time (h)
t_0	surface average temperature of the initial (°C)
$t_{j,i}$	instantaneous average temperature of the ith measurement point on the Kang surface (°C)
$t_{j,av}$	instantaneous average temperature of the Kang surface at the jth measurement (°C)
t_{inlet}	smoke temperature of the flue inlet (°C)
t_{outlet}	smoke temperature of the flue outlet (°C)
t_{in}	indoor air temperature (°C)
$\bar{u}$	average velocity of selected points (m/s)
u_i	is the velocity of the ith selected point (m/s)
σ	standard deviation of the Kang surface temperature
η_k	instantaneous thermal efficiency of Kang
σ_u	root of mean square error

house. Wei et al. [16] presented a mathematical model of solar Chinese Kang to study its thermal performance and energy consumption based on the evaluation of sleeping environment thermal comfort with predicted mean vote (PMV) value.

Other than China, there are also many similar domestic heating systems such as Ondal system [17,18] of South Korea and Hypocaust [19] of Rome. South Korea Ondal system uses the hot smoke from the stove that located inside or outside the kitchen into the space under the indoor floor for heating. Jeng [20] analyzed the factors that affected the Ondal system's efficiency and proposed some reasonable optimization suggestions. Rome Hypocaust system is easy to be combined with the building and can be used for both heating and cooling system [21]. Bansal [22] once carried out a series of research, drawing a conclusion that Hypocaust was such a good heating system that it could be applied to modern architecture.

Generally speaking, a Chinese Kang with one stove has been taken as the test object in most previous studies. The layout of two stoves (such as one for meal, the other for dishes) is more aligned with the lifestyle of local residents in rural northwest China. A Chinese Kang with two stoves is studied in detail in this paper to evaluate the thermal performance.

Currently the construction of Kang is mostly based on the experience of craftsman, lacking the scientific guidance. There are series of disadvantages such as low heating efficiency, waste of energy, thermal non-uniformity on the Kang surface and so on. Nowadays with the increasing energy consumption of the building, the promotion of high energy efficient Kang in vast rural areas is of both social and economic significance. Complex and detailed models of improved Kang has existed. However the practical use is often limited and restricted. The improved Kang that meets technical, social and environmental needs should be investigated further. This paper evaluated the thermal performance of a traditional Chinese Kang with two stoves and proposed an optimized model by taking the representative Kang of rural areas in northwest China as the research object. The aim of the optimized model is to assist in designing and optimizing domestic heating systems in rural northwest China.

2. Evaluation indexes of performance

A typical Chinese Kang is shown in Fig. 1. Performance evaluation indexes, such as mean temperature rise of Kang surface, have been suggested for years. After years of improvement, a series of evaluation indexes of Kang Performance was adopted by the Chinese national ministry of agriculture and developed as industry standard [23]. These metrics can be included as the following.

2.1. Processing method of testing data

2.1.1. Instantaneous average temperature of the Kang surface

Arithmetic mean that of each surface point's instantaneous temperature at a certain time during the heating stage.

2.1.2. Average temperature of the Kang surface

Arithmetic mean that of each instantaneous average temperature during the heating stage.

2.1.3. Average heating rate of the Kang surface

Temperature difference between the surface average temperature and that of the initial in a unit time during the heating stage.

2.1.4. Non-uniformity of the Kang surface temperature

Arithmetic mean value of the difference between each surface point's maximum and minimum temperature in every measurement during the heating stage.

2.1.5. Cooling rate of the Kang surface

The instantaneous average temperature difference between the moment of the end of heating and the end of cooling stage in a unit time after withdrawing fuel.

2.2. Instantaneous thermal efficiency

To determine the instantaneous thermal efficiency of Kang, Zhuang [24] developed the following equation:

$$\eta_k = \frac{t_{inlet} - t_{outlet}}{t_{inlet} - t_{in}} \tag{1}$$

where, η_k is instantaneous thermal efficiency of the Kang body, t_{inlet} is the smoke temperature of the flue inlet, t_{outlet} is the smoke temperature of the flue outlet, and t_{in} is room air temperature.

2.3. Kang evaluation indexes

2.3.1. The maximum and minimum temperatures of the surface

The range of surface temperature is one of the important indexes to determine the thermal comfort. Based on the point of human body's comfort and physiology, the temperature should be kept in 24–40 °C [24].

2.3.2. Average temperature of the Kang surface

Refer to related rules of floor radiation heating system, and the surface average temperature is in a range of 24–35 °C.

2.3.3. Standard deviation of the Kang surface temperature

The temperature oscillations exist both in space and time, which can be represented by surface temperature standard deviation σ.

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{n} A_i (t_{j,i} - t_{j,av})}{A}} \tag{2}$$