Energy & Buildings 171 (2018) 196–208

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Experimental study of the thermal performance of combined floor and Kang heating terminal based on differentiated thermal demands

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ARTICLE INFO

Article history:
Received 9 December 2017
Revised 19 April 2018
Accepted 24 April 2018
Available online 3 May 2018

Keywords:
Experimental study
Thermal performance
Floor heating
Kang heating
Differentiated thermal demands

ABSTRACT

To meet the indoor differentiated thermal demands of rural residents in winter, a novel combined floor and Kang heating terminal was proposed. The experimental platform of the combined heating terminal used in this study, was constructed in Shaanxi, China. Five experimental conditions for each of the four cases were investigated during the period January 15-February 21, 2017.

Through testing indoor air temperature and surface temperature of the floor and the Kang, and the comparative analysis of energy consumption and radiant temperature asymmetry, a series of results were obtained. The three above-mentioned temperature parameters could not meet the differentiated thermal demands when the floor and Kang heating worked independently and were higher compared to the comfort temperature range excluding the Kang surface in a sleeping state as long as the combined heating performed concurrently. Compared to the above three cases, the alternative operation of the combined heating terminal could efficiently satisfy the differentiated thermal demands. Both the energy consumption and the radiant temperature asymmetry in case 4 were not much high. The obtained test results of the four cases could provide the basis for the combined floor and Kang heating terminal to become an attractive rural heating approach.

1. Introduction

Winter in the northern China lasts for a long time, resulting in the increased demand of heating for up to 5–6 months [1]. Therefore, domestic heating represents a significant issue for residential buildings. The majority of the urban areas incorporate a thorough heating design, usually including a continuous heating mode to meet the indoor heating demand. Thus, this increased heat energy consumption leads to high operation fees [2]. Compared with the city, the economic level and living standard of rural areas are relatively lower and the settlements of residents are relatively scattered. In particular, due to the lack of central heating measures, most residents use traditional heating measures (such as Chinese Kang and burning cave) to alleviate the cold winter, leaving the poor indoor thermal environment of most rural buildings [3–4]. Kang is a kind of essential home facility similar to the bed in the rural areas of northern China, which corresponds not particularly for domestic heating, but also for sleeping [3,5–6]. Compared to the above-mentioned methods in urban areas, heating methods in rural areas can reduce heating fees during winter to a certain extent. Nevertheless, these may cause thermal discomfort and poor indoor air quality [6].

In recent years, with the improvement of rural living standard, residents pay more attention to indoor thermal environment compared to heating fees. However, the usage of current urban heating design is responsible for causing frequently the sudden increase of heating energy demand and heating cost. Therefore, the selection of the heating methods in rural/urban areas should not exclusively be based on meeting resident's demand for indoor thermal environment but also indistinctively control the rural heating energy consumption and cost.

A similar indoor activity pattern is presented by the rural residents, during winter in Northwest China, which results in the basic conditions for the development of intermittent and local heating [7]. Residents remain in the bedroom for an extended period not only during the nighttime sleep but also for daytime activities [8]. The metabolic rate of human body during sleeping state is significantly lower compared to the awake state, resulting in the differentiated thermal demands (DTD) in the two occasions [9–10]. At present, current design specification in China defines 18°C as the indoor heating design temperature in civil buildings [11]. Never-

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https://doi.org/10.1016/j.enbuild.2018.04.060
0378-7788/

theless, a unified standard of heating leads to failure in meeting the residents' requirement of actual thermal comfort and furthermore causes an increase of heating energy consumption.

The majority of thermal comfort temperatures were collected from different areas and under different conditions [12–13], which can be considered as indoor heating design temperature. By investigation and test during winter under sleeping/awake status in the Northern China, Liu, et al. [8], demonstrated that the suitable temperature in awake-state is equal to 16–18°C and the corresponding temperature during sleeping state is 11–13°C. Therefore, it will be beneficial to deduce energy consumption and costs of building heating for the bedroom in northern rural areas when DTD of these two-activity state are met.

Additionally, there is a direct contact of the residents and the surface of floor and bed in waking and sleeping state, respectively. Thus, the comfortable temperature range of floor and bed should also be considered. The suitable range of average floor surface temperature corresponds to 25–28°C, while it would be inappropriate to exceed 31°C [14]. Wang et al. [15], experimentally indicated that the comfortable temperature during sleep-state ranges from 27°C to 32°C.

Floor heating represents one of the most widely applied terminal forms [16] and Kang serves as the traditional heating system, which is extensively used by up to 85% of rural residents in the northern China [6]. Thus, a novel heating terminal of combined floor and Kang was proposed, which could serve the demands of indoor heating, as long as the heating of floor and Kang surface under different conditions. If heating power is provided according to the DTD, then the energy consumption of building heating can be reduced.

Past research mainly focused on the heat dissipation characteristics of terminal forms and indoor thermal environment construction [17–18]. The floor temperature and heat flow represent two parameters, which are usually adopted in floor heating thermal performance analysis. Shin et al. [19] classified the design parameters of coil pipe for floor radiant heating system and determined the main parameters affecting the heat flux and the floor surface temperature. Additionally, they analyzed the relationship among the parameters of heat flux and floor surface temperature, since their relevant research limited the floor radiant heating design in practical engineering.

Residents contact directly on Kang's surface and experience its corresponding temperature [20]. Thus, Kang is responsible for the establishment of a comfortable local thermal environment [21]. However, there are important disadvantages since the indoor temperature is still not satisfactory, while the indoor pollution is significant [22]. Furthermore, Duanmu et al. [23] indicated that traditional Kang presented many drawbacks, such as uneven temperature distribution, unheated combustion and low heat efficiency.

The adoption of Kang heating system has been reduced in the modern buildings. However, the rural residents in China has been ordinarily accepted Kang as a heating system, due to culture and societal reasons during the time evolution. Therefore, an efficient solution to the problem would be to retain the body of Kang and simultaneously ameliorate the above-mentioned drawbacks. He et al. [24] proposed a solar Kang in which coil pipe applied on Kang surface and solar energy was adopted as heating source. The results showed that the Predicted Mean Vote (PMV) of sleeping environment is acceptable, while the solar heating fraction varies from 74.3% to 52.6% with a corresponding solar Kang inlet water temperature of 35°C–55°C.

Currently, the majority of the scientific research focused on the single heating terminal, while limited research concerns the combined heating terminal. Zhao et al. [25] investigated the solar Chinese Kang and the solar air heating system (a combined heating system) by adopting experiment and simulation. The corresponding temperatures of indoor air and Kang surface in different operation modes were analyzed. Although the thermal performance of combined heating system under DTD was not considered, the study still provided reference for the combined heating terminal analysis.

The experimental platform of combined floor and Kang heating terminal (CFKHT) system was constructed in Shaanxi, China. A long-term test was conducted to establish the heat dissipation characteristics and the heating effect of indoor thermal environment by using the CFKHT. The flow and inlet water temperature of the CFKHT were distributed in four operation cases to meet the DTD. In addition, the contrastive analysis of energy consumption and the radiant temperature asymmetry were also conducted in the four cases. The analysis results of the tests can provide a reference for the CFKHT to become an attractive rural heating approach.

2. Experiments

2.1. Experiment system

As illustrated in Fig. 1, the experimental system includes the following four parts: the heat source, the transmission-distribution system and the heating terminal. An electric boiler was selected to serve as the system heat source and the transmission and distribution system were composed of a circulation pump, a double head distributor and a collector. The CFKHT system was consisted of two parts: a floor heating sub-system and a Kang heating sub-system.

According to the floor and Kang surface comfort temperature range [14–15], the initial design of the heating terminal was carried out based on the existing design code. The reconstructive of the floor heating terminal was processed based on the plain soil. Over the plain soil, the following were fixed in the appropriate sequence: the supporting layer, the insulating layer, the reflecting film, the coil pipe, the filling layer and the leveling layer. For the Kang heating terminal, the following were arranged according to the original Kang body in the appropriate sequence: the insulating layer, the reflecting film, the coil pipe, the filling layer and the leveling layer. The material data-sheet and detail dimensions of the CFKHT used in current experiment are presented in Table 1. The diameter of the coil tube made of cross-linked polyethylene (PEX) corresponded to DN20 and the tube spacing equaled 200 mm.

According to the initial design of the CFKHT, the experimental platform was built in a rural household which was located in Baoji, Shaanxi province on December 1, 2016. At the early stage, the original brick floor was removed. The soil was dug at 50 mm depth and then was compacted. The structure of the CFKHT was identical to that referred in Table 1. Fig. 2 illustrates the construction process of the CFKHT. The system was connected to the pump and the electric boiler according to the schematic of Fig. 1 and commissioning was completed.

When the floor is exclusively required for heating, the Kang surface loop system is turned off and vice versa. As long as both of the floor and the Kang systems are required for heating demand, the two loops are turned on. Heat transmission to the floor and Kang occurs through convection. Through convection and conduction, the indoor temperature, as long as floor and Kang surface temperature would finally increase.

The electric boiler and circulating system were set up in the room. The indoor circulation pipeline was short and installed including insulation layer. Thus, the effect of pipe heat dissipation on the room temperature was neglected. The electric boiler with capacity of 3 kW was used to set coil pipe inlet water temperature. The circulating water pump was normally set on turn-on mode to analyze the experimental data.