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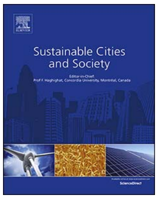

Experimental study on thermal performance improvement of building envelopes by integrating with phase change material in an intermittently heated room

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ABSTRACT

The intermittent heating is frequently used to save the building heating energy consumption. Both the heat storage and release processes of building envelope have coupling influences on the indoor thermal environment during intermittent heating process. In order to make the best of the heat storage and release process to adjust the indoor thermal environment, this paper integrated phase change material (PCM) with the building envelope and experimentally studied the thermal performance improvement under four typical intermittent heating conditions summarized by questionnaires in China. The results show that the inner surface temperature of the PCM wall increased faster after heating, which was more favorable to ensure that the indoor thermal environment recovers to the thermal comfort state quickly. The inner surface temperature of the PCM wall was higher than the reference wall after heating was off, which can maintain a constant indoor air temperature. In the heating process of the four conditions, the inner surface heat flux value was 18.48% lower than the reference wall. Integrating PCM with the building envelope can not only improve the indoor thermal environment, but also reduce the heating time and heating energy consumption.

1. Introduction

In recent years, the building energy sector consumes more than 33% of the total energy in China (National Bureau of Statistics of the People's Republic of China, 2014). People's requirements for indoor thermal comfort have increased with the improving living standards, and the heating line, which is moving southwards, leads to the increase of building energy consumption. It is generally believed that intermittent heating can significantly reduce the heating energy consumption and cost compared with the continuous heating (Badran, Jaradat, & Bahbouh, 2015; Kim, Kim, & Chung, 2010; Liu, Wang & Kong, 2012; Pupeikis, Burlingis, & Stankevicius, 2010; Xu, Hao, Fu, & Di, 2011;). However, in some cases the energy efficiency of intermittent heating is not obvious (Li, Yi, & Da, 2005; Wang, Lin, & Zhu, 2015). Due to the fact that the energy losses of walls accounts for about 25% of the total building energy consumption (The building energy conservation research center of Tsinghua University, 2015), it is very important to improve the wall thermal performance to increase the building energy efficiency during intermittent heating.

The heating equipment starts and stops frequently during intermittent heating, so the building envelopes always stores and releases heat, while the indoor thermal environment is changing. In the intermittent heating process, the thermal inertia of the building envelope is closely related to the indoor thermal environment variation (Peeters, Van der Veken, Hens, Helsen, & D'haeseleer, 2008; Wang et al., 2015). Previous studies on building envelopes have mainly focused on the influence of different wall structures on the intermittent heating energy efficiency and the indoor thermal environment (Barrios, Huelsz, & Rojas, 2012; Tsilingiris, 2006). However, there is few study about using the heat storage of the building envelope's internal part to regulate the intermittent heating process. The building envelope, as a thermal mass, is able to adjust the air temperature by storing heat when the temperature is high and releasing heat when the temperature is low. Ogoli et al. (Ogoli, 2003) found that a wall constructed of heavy materials could reduce the indoor air temperature effectively. Cheng, Ng, and Givoni (2005) comprehensively analyzed the effects of different building heat storage materials, different surface colors of the exterior wall and different building orientations to indoor temperature. During the intermittent heating process, the building energy consumption can be reduced through rationally use of building heat storage to control

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the operation of heating equipment (Wang, 2003).

The phase change material (PCM) is integrated with building envelope for building energy conservation and indoor thermal environment improvement due to its potential latent heat thermal storage (Dutil, Rousse, & Salah, 2011; Khudhair and Farid, 2004). Many scholars have integrated PCM with the building envelope to improve the indoor thermal environment of non-air-conditioned rooms and reduce energy consumption under continuous air-conditioning condition. Kuznik and Virgone (2009) did experiments on the indoor thermal environments of the PCM room and the ordinary room in summer, winter and transition seasons, and their experimental results showed that the phase change wall could reduce the indoor temperature fluctuations. Behzadi and Farid (2011) did computer simulations on PCMs impregnated in building materials, and found that the use of PCMs could effectively reduce the daily fluctuations of indoor air temperature to 4 °C and maintain it at the desired comfort level for a long period without air conditioning. Quanying, Ran, Lisa (2012) studied the thermal performance of PCM walls with different structures and found that the inner surface temperature and heat flux of PCM walls were better than traditional walls. Castell, Martorell, Medrano, Pérez and Cabeza (2010) did comparison experiments on two cubicles integrated with different PCMs, and showed that PCM could reduce the peak temperature by up 1 °C, and the air conditioning energy consumption by 15% in summer. Chan (2011) found that an annual energy saving of 2.9% in air-conditioning system was achieved through integrating PCM with building facades. However, studies on the heat storage and release process of building envelope integrated with PCM during intermittent heating still lacks.

During the intermittent heating, the heat storage and release processes of building envelope have coupling influences on indoor environment variation, and the rational use of building heat storage can significantly improve the indoor thermal environment. In this paper, PCM is integrated to building envelope to improve the thermal performance. PCM with latent heat storage allows phase changing to reduce the wall load during the heating time and regulate the indoor air temperature during the heating suspension time. Experimental building with the PCM wall unit and the reference wall unit are built in this paper to study the thermal performance improvement of building envelope by integrating with PCM. The transmission and attenuation of temperature and heat flow in walls integrated with PCM are assessed under four typical intermittent heating conditions which are summarized by questionnaire.

2. Experimental set-up

2.1. Intermittent heating operation conditions based on questionnaire

The intermittent heating conditions were determined based on residents' living habits in many studies (Kim et al., 2010; Li et al., 2005; Wang et al., 2015; Xu et al., 2010; Xu et al., 2011). However, the intermittent heating operation mode is greatly influenced by the occupants, and an accurate determination of heating equipment operation modes can provide basic research for the room's dynamic thermal response mechanism and building envelope optimization. In December 2015, the authors conducted an online questionnaire survey on heating equipment operating time in residential buildings and office buildings located in the south of China. 420 questionnaires were issued and 420 were returned. The results show that in residential buildings the main operating time of bedrooms heating is 21:00–7:00, while that of living rooms is 19:00–23:00. For office buildings, the heating equipment operation time is 9:00–17:00, which is the same as the working hours. However, some respondents go home to rest from 12:00 to 14:00, which leads to a cessation of the heating time. Based on the respondents' heating equipment usage habits and the research focus of intermittent heating, this paper choses four typical intermittent heating operating conditions through the results of the questionnaire. The operation conditions of intermittent heating are shown in Table 1.

Table 1
Operation conditions of intermittent heating.

Operation condition	Heating time	Test period
Condition 1	19:00–23:00	1.10–1.11
Condition 2	21:00–6:00	1.12–1.14
Condition 3	9:00–12:00, 14:00–17:00	1.15–1.16
Condition 4	9:00–17:00	1.17–1.18

2.2. Experimental methodology

The experiment was carried out in the wall dynamic test experimental building. There are two rooms in the experimental test building, as shown in Fig. 1, and the size of the rooms are both 3.5 m (length) × 3.0 m (width) × 2.2 m (height). The building is located in Chengdu, southwest China. This location is a hot summer and cold winter area, with an average temperature of 5.6 °C, and an extreme temperature of −3.9 °C in winter. A split air conditioner (KFR-35GW/HFJ + 3) is installed on the south wall of Room 1 to achieve the intermittent heating.

The experimental wall with the PCM wall unit and the reference wall unit are embedded in the north external wall of Room 1 (Fig. 1(b)). The two wall units with size of 600mm × 600mm × 260 mm are in the same indoor and outdoor environment, which makes the test results more comparable. Supported by steel frames, the two wall units are surrounded by 80 mm EPS to reduce the heat transfer between units, ensuring one-dimensional heat transfer in the central area of each one. Fig. 2 presents the schematic structures and measurement arrangements of walls, and Fig. 3 shows the test wall units during construction process. From the inner side to the outer side, the PCM wall consists of one layer of cement mortar of 10 mm, one layer of PCM of 20 mm, one layer of solid brick of 220 mm and one layer of cement mortar of 10 mm. From the inner side to the outer side, the reference wall consists of one layer of cement mortar of 10 mm, one layer of solid brick of 240 mm and one layer of cement mortar of 10 mm. The physical properties of each layer of material are shown in Table 2. The PCM in this paper is the Natural TCM Energy Saver (Anonymous, 2018a) produced by Tri-Y Enterprises Limited from Canada (Anonymous, 2018b). The phase-transition temperature range of the PCM is from 18 °C to 26 °C, which has phase change latent heat of 178.5 kJ/kg.

For the test wall units, thermocouples are arranged at the center of the inner and the outer surfaces to measure the surface temperatures, and heat flux meters are arranged at the center of the inner surfaces to measure the heat flux of the inner surfaces. One thermocouple is located 20 cm from the wall inner surface to measure the indoor air temperature near the wall, while another sensor is arranged 20 cm from the wall external surface and 1.5 m above the ground to measure the outdoor air temperature near the wall. In addition, there are thermocouples on the center of both sides of PCM layer. The detailed measurement arrangements are shown in Fig. 2.

T-type thermocouples (with test error less than 0.5 °C) and heat flux meters (JTC08A with accuracy of 5%) are used to measure the temperature and heat flux. All measurement data are recorded by a JTRG-II building thermal temperature automatic tester. The measurements of temperature and heat flux under different intermittent heating conditions were carried out every 10 min from 18:00 on 10th January 2016–24:00 on 18th January 2016. For each of the four working conditions in the questionnaire, two cycles of experiment were carried out. The test time is shown in Table 1. Because the phase-transition temperature range of the PCM is from 18 °C to 26 °C, the heating thermostat setting was adjust to 30 °C for winter space heating to ensure the phase change of PCM.