Thermal performance analysis of PCM wallboards for building application based on numerical simulation

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ABSTRACT

The use of phase change materials (PCMs) in buildings is an efficient way to reduce the building energy consumption. PCM wallboards used in buildings have been widely studied and optimized in many studies; however, further thermal performance analysis needs to be performed. To utilize the PCM more efficiently in practical engineering, five PCM wallboards used in the exterior wall of an air-conditioning room in Beijing were studied using numerical simulation, and four new aspects of the thermal performance analysis of PCM wallboards were presented. It was found that the energy consumption of the building using the PCM wallboard with a higher phase change range was 103 kJ less than the referenced wallboard in June, while 72 kJ more in December. Therefore, the thermal performance of the PCM wallboard might be adverse in different seasons, and the thermal performance analysis during an entire year was necessary. Using the heat ratio, the months in which the phase change had a significant effect on the thermal performance of the wall were found, and only in these months, the optimization of the thermal performance was effective. The heat transfer coefficient of the PCM wall was defined, and it was used to justify that the PCM met the design standard for energy efficiency of buildings. Using relative thermal conductivity, the effective months of the phase change for different areas of China were determined. The optimization of the thermal performance of the PCM wallboard should focus on these months. For Beijing, the months were June and September. For Harbin, the months were July and August. For Shanghai, the months were June, July, and September. For Guangzhou and Haikou, the months were May and April, respectively.

1. Introduction

Excessive energy consumption, which has led to an energy shortage worldwide, is an urgent problem to be solved. As a lot of energy is consumed in the building stock, an essential part of the solution must be found there. The utilization of solar energy is an efficient way of collecting natural energy to meet the demand for thermal comfort of humans and energy conservation (Xie et al., 2016). The use of solar energy includes converting it into electricity and heat (Das et al., 2015; Edgar et al., 2017; Bullich-Massagué et al., 2017; Li et al., 2017; Gill et al., 2016; Vakili et al., 2016; Duomarco, 2015; Nikoofard et al., 2014).

Thermal energy storage (TES) is an important method of converting solar energy to heat. The main advantage of using TES in solar systems for buildings is the success of converting an intermittent energy source in meeting the demand, which may be intermittent and/or have a time shift (Navarro et al., 2016a). Among many TES methods quite often the latent heat storage using phase change materials (PCMs) is more preferable (Kenisarin and Mahkamov, 2016). PCMs can store passive solar energy and other heat gains as latent heat within a specific temperature range, leading to a reduction in energy usage, an increase in thermal comfort by smoothing out temperature fluctuations throughout the day, and a reduction and/or shift in peak loads. In the latent heat storage, much work has been performed. Navarro et al. (2016b), Pomianowski et al. (2013), Akeiber et al. (2016), and Kalnaes and Jelle (2015) reviewed the application methods of PCMs integrated in building components, and classified them depending on their component integration. Ma et al. (2016), Khadiran et al. (2016), Konuklu et al. (2015), and Memon (2014) reviewed the phase change materials used in buildings for effective thermal management and improved energy performance. Dutil et al. (2011, 2014), Al-Saadi and Zhai (2013), and Mirzaei and Haghighat (2012) reviewed the different modeling methods generally used for PCM simulations, including the enthalpy method, heat capacity method, temperature transforming model, and heat source method. Besides, these studies compared and highlighted the advantages, disadvantages, and limitations of these models and methods.

Over the years, a systematic review of latent heat storage in building
elements was conducted by Mavrigiannaki and Ampatzi (2016). Evidence was collected, which showed that with appropriate design, PCM elements could contribute to reducing loads and achieving energy savings in buildings, while securing a comfortable indoor environment. Key design factors to this end were found to be the climate and target season, the design of appropriate controls for active and passive systems used in combination with the PCM elements, and cost-related factors. Kenisarin and Mahkamov (2016) analyzed the state of the art on integration of PCMs into building structures for their passive thermal control. The results of comparative tests on fifteen full-size buildings containing elements with PCMs were summarized. Experiments conducted by many researchers on passive solar buildings demonstrated that the application of phase change heat storage materials decreased the variation in the air temperature in the rooms, shifted the peak energy consumption for heating and cooling of lightweight buildings by several hours, and decreased energy consumption for maintaining comfortable temperature levels in buildings. Yuan et al. (2014) summarized the preparation and characteristics of fatty acid composites as PCMs and analyzed the thermal reliability and stability of fatty acids as PCMs and their heat transfer characteristics in a unit. In addition, they pointed out the future research direction of fatty acids as PCMs as a solution of the insufficiency and flaws of current studies. In the research of Mi et al. (2016), the effect of PCMs on the energy consumption of a typical multistory office building located in five different cities of China, was simulated for a whole year. Test results showed that the energy savings resulting from PCM application were more prominent for office buildings located in cold regions as well as in hot summer and cold winter regions. The application of PCMs in Shenyang, Zhengzhou, and Changsha proved to be economically beneficial. Lee et al. (2015) placed the thin PCM layer into the wall via a thermal shield, whereby the PCM was contained in thin sealed polymer pouches, arranged in sheets laminated with aluminum foil on both sides. The optimal location for the PCM layer in the wall was obtained and the peak heat flux reductions of the south wall were 51.3%. Álvarez et al. (2013) presented innovative solutions to overcome the drawbacks of the night cooling ventilation using PCMs. Compared with existing solutions, innovative solutions proposed increased the contact area between the PCM and air by a factor of approximately 3.6, increased the convective heat transfer coefficient significantly, and improved the utilization factor owing to the inclusion of active control systems. In the study of Barzin et al. (2015a) on PCM underfloor heating in combination with PCM wallboards for space heating, an experimental study was carried out using two identical test huts at the Tamaki Campus, University of Auckland. Results using a price-based method showed electricity savings in both consumption and cost of up to 35% and 44.4%, respectively. In another study of Barzin et al. (2015b), the application of night ventilation in combination with PCM-impregnated gypsum boards for cooling purposes was experimentally investigated. Two identical test huts equipped with “smart” control systems were used for testing the concept. An air conditioning (AC) unit, without night ventilation, was used in both huts to charge the PCM during the low peak period, showing very little savings in electricity. However, when night ventilation was used to charge the PCM instead, a weekly electricity saving of 73% was achieved.

The essential way to reduce the building energy consumption effectively is the reasonable design of the PCM wall. The key point is the selection of the wall material, which depends on the comprehensive thermal performance analysis of the PCM. Although the performance of the PCM used in walls has been widely studied and optimized, further thermal performance analysis needs to be performed. In current studies, for the PCM used in the wall of an air-conditioned room, the comprehensive effect of the thermal resistance, thermal capacity, and phase change of the material on energy saving is shown through the calculation of the heat transferred from the PCM wall to the indoor air. However, the single role of the factors mentioned has never been showed. Some researchers pointed out that many studies regarding the applications of PCMs in building envelope just focused on their thermal performance in a specific season, and the whole-year performance should be analyzed (Cheng et al., 2014). However, the method for the year-round thermal analysis of PCMs has never been presented. The focus of the application effect of PCMs used in the air-conditioned room is always the reduction in energy consumption, and meeting the design standard for energy efficiency of buildings in the studied period or the other seasons has never been considered. Furthermore, the application effectiveness of PCMs should be evaluated in different areas, and that can help the researcher to find the proper area and period to apply the PCM.

Considering the four points mentioned above, a numerical simulation was conducted using the software MATLAB, and thermal performance of PCM wallboards used in the exterior wall of an air-conditioned room in Beijing was analyzed considering four aspects: (1) difference of the thermal performance in different seasons; (2) the period in which the phase change significantly affects the thermal performance; (3) the satisfaction of the design standard for energy efficiency of buildings by the PCM; and (4) the thermal performance of the same PCM wallboard in different climate regions. Further, the convective heat transferred from the wall to the indoor air, heat ratio, and relative thermal conductivity was calculated and defined for the thermal performance analysis.

2. Model of the PCM wallboard

2.1. Building description

The PCM wallboard is used in the exterior wall of an air-conditioned room in Beijing. The room studied is on the second floor of a building with dimensions of 5 m × 5 m × 3 m. Only the south wall is the exterior wall. The construction of the PCM wall is shown in Fig. 1. From outdoors to indoors, the wall layer is the insulation layer, followed by the brick layer and the PCM wallboard, and thicknesses of the three layers are 4 cm, 30 cm and 3 cm respectively. Five PCM wallboards with different thermal properties are studied for the thermal performance analysis. PCM wallboard I is made with the mixture of the PCM and building material (Castell and Farid, 2014). The difference among I, II, III, and IV is the phase change temperature, and the difference between I and V is the latent heat capacity. To study the effect of the phase change, a gypsum board (Yahay and Ahmad, 2011) with the same dimensions as the PCM wallboard is chosen as the compared wall layer. Physical property parameters of wall layers are given in Table 1.

The boundary conditions of the PCM wall are shown in Fig. 1. The external wall surface is affected by solar radiation and convective heat transfer. The internal surface is affected by convective heat transfer and the radiation heat transfer is neglected. The convective heat transfer coefficients for the external and internal wall surface are respectively 18.6 W/(m²·C) and 8.7 W/(m²·C) (Zhang et al., 2008). Indoor air...
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