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Numerical and experimental research of cold storage for a novel expanded perlite-based shape-stabilized phase change material wallboard used in building

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ABSTRACT

Phase change material (PCM) used in building can enhance the thermal inertia of building and improve the indoor thermal comfort. A novel shape-stabilized phase change material wallboard (PCMW), in which paraffin was as the PCM and expanded perlite (EP) was the supporting material, has been prepared through a horizontal vacuum absorption rotate roller (HVARR) in this study. Its melting point and freezing point were measured to be 27.60 °C and 23.56 °C, respectively, and the melting and freezing latent heats reached to be 67.13 J/g and 67.06 J/g, respectively. PCMW was experimentally and numerically studied to analyze the thermal performance. The experimental result in 5 days, which was a demonstration in a container subject to weather conditions typical for the north China, showed that PCMW used in the building can maximally reduce the indoor temperature of 2.53 K. For the numerical study, based on the equivalent heat capacity method, a one-dimensional heat transfer model of PCMW was developed and combined with TRNSYS. This model was validated by the experimental data, and the numerical data agreed well with the experiment data. Under the summer condition, the numerical study of PCMW used in a typical office building during two months showed PCMW can averagely reduce the temperature of 9.22 K in the building operation time (7:00–18:00). Besides, according to the numerical model, an optimal configuration of PCMW in the cold zone of China has been obtained. The studied method provides a comprehensive guide to the PCMW design and application.

1. Introduction

With the total quantity and area of buildings rapidly growing, building energy consumption has been increased, which can lead to a further increase in emissions of greenhouse gases. Recently, it was reported that buildings accounted for about 40% of the global energy consumption and contributed over 30% of the CO_2 emissions in the world [1]. For solving this issue, the energy efficiency technologies applied in buildings have been focused on. Among these technologies, phase change materials are widely studied as a type of material for thermal energy storage. PCM can absorb/release the heat from/to the indoor environment, when the environmental temperature was higher/lower than its phase change point. The building application for PCM can be divided into two parts, i.e., PCM combination with cooling/heating systems for energy storage[2–6], and PCM incorporation with building envelope, including PCM walls, PCM floors, PCM roofs and so on[7–9].

Due to the large latent heat storage capacity, PCM has been used to store the surplus heat in the building to prevent heat loss from building envelope, and enhance the indoor thermal comfort [10–12]. The combination of PCM and building envelope mainly included four methods: direct incorporation, immersing incorporation, shape-stabilized method and encapsulation. For PCM direct incorporation and immersing incorporation, the leakage problem of liquid PCM is the main obstacle for long-term use [13–15]. Shape-stabilized method is that PCM is uniformly dispersed into supporting materials (high density polyethylene, ethylene-vinyl acetate, cellular material, and so on) [16–18]. Generally, supporting materials have the microstructure of three dimensional frameworks, such as micropores or grooves. Even in the liquid state, PCM molecules can also be enclosed in the micropores and grooves, due to the capillary action and surface tension. Thus, in appearance, the shape-stabilized phase change material shows a solid-solid transition in

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Fig. 1. Image of the EP.

the phase transition process. Because of the advantages, including relatively large latent heat, suitable thermal conductivity, the shape-stabilized ability especially in the phase change process, as well as very low performance degradation in multiple applications, the shape-stabilized PCM has been extensively researched. Besides, the shape-stabilized PCM wallboard, without premixing with building materials (such as mortar or concrete), can be conveniently used in existing buildings retrofit [19].

Several studies have been conducted to develop the shape-stabilized PCM and research their performances. Krupa et al. [20] have used two soft and hard paraffin wax to blend with isotactic polypropylene (PP) to prepare shape-stabilized PCM, and found that PP matrix structure kept PCM in a compact shape. Besides, the structure and properties of composite PCM were measured through DSC, DMA, TGA and SEM. Chen et al. [21] have successfully prepared a novel shape-stabilized composite phase change material based on lauric acid and polyethylene terephthalate (1:1, wt/wt), and characterized the performance. Mehrali et al. [22] fabricated a form-stable composite phase change material that was composed of paraffin and graphene oxide. The largest absorbing ratio of paraffin in composite PCM was 48.3%. Trigui et al. [23] have solved the immiscibility of PCMs (waxes) and low-density polyethylene (LDPE) by the melt mixing method. Sarı [24] used capric acid, polyethylene glycol, dodecanol and heptadecane to immerse into bentonite clay to produce form-stable composite phase change materials, which included 40 wt% capric acid, 43 wt% polyethylene glycol, 32 wt % dodecanol and 18 wt% heptadecane, respectively. Deng et al. [25] have developed a shape-stabilized composite phase change material, in which a high-melting-point inorganic salt, potassium nitrate (KNO_3), was incorporated with diatomite by the mixing and sintering method, and the KNO_3/diatomite PCM has showed the potential in solar energy storage.

The above studies have laid emphasis up on the manufacture method and materials performance testing. Another important study method for composite PCM applied in building is the numerical modeling. The solidification/melting process of PCM was usually numerically studied with enthalpy method and equivalent heat capacity method, both of which have their advantages, such as the high precision of enthalpy method [26] and large applicability of equivalent heat capacity method [27]. In enthalpy method, PCM was assumed to be a porous medium, and its porosity (value 0–1) was increased in the melting process and decreased in the freezing process. The porosity represented the liquid fraction in mushy region (solidified/liquid region). So it can precisely describe the melting/freezing process of PCM. However, because of the combination of binary materials (PCM and supporting material), it is difficult for the shape-stabilized PCM to be defined as the mushy region. The equivalent heat capacity method is that the latent heat of PCM was treated as a great heat in sensible form during the whole phase transition temperature period, without concerning on the mushy region changes [28,29]. Therefore, it is applicable and convenient for the equivalent heat capacity method used in the numerical modeling of shape-stabilized PCM. According to the indicators of thermal energy storage and time shift, Koo et al. [30] have investigated the effects of several parameters of PCM through enthalpy method, and they found phase change point should be close to the average indoor temperature. Zhou et al. [31] have discussed the influences of factors that included the melting temperature, melting range, latent heat, thermal conductivity and surface heat transfer coefficient on the PCMW, based on the equivalent heat capacity method.

The previous studies have proved the feasibility of shape-stabilized PCM in thermal storage application, and mainly focused on the preparation and characterization analysis [32,33]. However, the performance study of shape-stabilized PCMW in real building was lack. In this study, a novel expanded perlite-based shape-stabilized PCMW was prepared with a new method, a horizontal vacuum absorption rotate roller. A heat transfer model of PCMW has been developed using equivalent heat capacity method, and then this model has been coupled with TRNSYS software. Meanwhile, the experiment of PCMW incorporated with the wall and the roof was conducted to validate the model. The thermal performance and optimization of PCMW were numerical investigated based on this model.

2. PCMW preparation and experimental study

2.1. Materials and preparing process

The following two principles are generally utilized in the selection of PCM [34]: (a) the suitable melting temperature range according to indoor temperature change; (b) economical efficiency, non-toxicity and non-corrosiveness. As a common kind of PCM, paraffin is in conformity with all the principles above, thus being widely used in the building energy storage research [35,36]. Therefore, a low-temperature paraffin (25#, produced in Sinopec Nanyang Branch) is chosen as the PCM used in the experiment.

EP, an inorganic porous material, is used as the supporting material to absorb paraffin. As shown in Fig. 1, the perlite whose particle size is 3–6 mm is from the perlite mining area in Xinyang, Henan Province. Before the absorption, the perlite is heated with high temperature to remove the moisture inside EP. Under the effects of the capillary absorption and surface tension of the micro pores, the liquid PCM can be absorbed to the micro pores and encapsulated firmly.

The absorption method based on the vacuum flask is adopted in the previous research process [16,24,37], but the number of PCMs used to fabricate PCMW is limited at a time. Therefore, a horizontal vacuum absorption rotate roller has been prepared based on the absorption principle to fabricate composite PCM, as shown in Fig. 2. It can simultaneously satisfy the conditions of vacuum, heating and uniform mixing, and can produce 4 Kg's PCMs a time, significantly enhancing the production efficiency of PCM. The horizontal vacuum absorption rotate roller is composed of hexagon vacuum roller, heating box and