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Effects of PCM on power consumption and temperature control performance of a thermal control system subject to periodic ambient conditions

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HIGHLIGHTS

- Phase change thermal control with under periodic ambient condition was studied.
- Influences of PCM on thermal control effects were explored.
- The simulated results agreed well with the experimental results.
- Conditions of achieving the optimal thermal control effects were proposed.
- An optimal phase change range can be obtained according to TMY data.

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ABSTRACT

Thermal control systems operating under periodic outdoor ambient conditions have numerous important applications in industrial fields. Reducing system energy consumption and enhancing temperature control effects are crucial to improving the performance of these systems. To this end, the application of phase change material (PCM) in the envelope of a thermal control system was investigated through experiment and simulation. A simulation model of an active ventilated thermal control system was constructed and verified with experimental results, and the influences of PCM incorporated in the envelope on the power consumption and temperature control effects were discussed in two time scales. The results for typical meteorological days indicate that excellent thermal control effects can be achieved when the phase change range of PCM brackets the temperature control setpoint and is consistent with the fluctuation range of the ambient temperature. The results for a typical meteorological year (TMY) demonstrate that an optimal phase change range can be determined according to TMY data to realize the optimal thermal control effects of PCM. When the required temperature control setpoint is not within the optimal phase change range, the phase change range bracketing the temperature control setpoint is recommended.

1. Introduction

Due to high latent heat and an isothermal phase change process, the principal applications of PCM are thermal energy storage and thermal control. Latent heat storage using PCM not only efficiently reduces the disparity between supply and demand in space and time but also improves the performance and reliability of energy systems [1]. Presently, most research on PCM has focused on the latent heat storage [2–6]. Nevertheless, PCM also has another outstanding feature, i.e., the temperature change of PCM is minimal during melting and freezing processes [7]. This characteristic can be utilized to control the temperature of an object (i.e., phase change thermal control) when properly designed [8]. Many studies have investigated temperature control with PCM that are involved in electronic device cooling [9–12], battery thermal management [13–15] and other areas. To improve the performance of temperature control, various methods have been proposed to enhance the heat transfer rate in and out of the PCMs. These methods include the use of fins [16–18], nanomaterials dispersed in PCM [19,20]

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and the application of low melting point liquid metal [21,22]. All of the above investigations belong to the short-term temperature control.

In reality, there are many objects subject to periodic boundary conditions, such as solar irradiation and air temperature. The temperature of these objects will change with periodic ambient conditions. To maintain the stability of these objects, temperature control with PCM (i.e., periodic phase change thermal control) is an approach worthy of consideration. As opposed to short-term phase change temperature control, periodic phase change thermal control focuses on an object subject to periodic ambient conditions or intermittently generating heat and can considerably decrease the amplitude of temperature fluctuation of the object [23] into a desired region.

The investigations on periodic phase change thermal control are seldom reported. A few researchers devoted to energy saving buildings have investigated the thermal performance of PCM wallboard subject to periodic boundary conditions. Neeper [24] and Koo et al. [25] found that maximum diurnal energy storage occurs when the melting temperature of PCM is close to the average room temperature. The same phenomenon was also found by Zhou et al. [26,27], who further concluded that the stored heat of PCM wallboard depends on both the inside and the outside environment, without elucidating how to choose the phase change temperature according to the inside and outside environments simultaneously. Furthermore, most of these studies evaluated the thermal performance of PCM in terms of energy storage, not from the angle of thermal control effects. Finally, these studies only focused on a passive single PCM wallboard in a single day, which cannot reveal the energy saving and thermal control characteristics of a whole year for PCM.

In this paper, the thermal control performance of PCM incorporated in the envelope of a thermal control system with active ventilation was investigated under periodic boundary conditions for time scales of an entire year as well as a single day. The impacts of PCM on power consumption and temperature control effects were discussed. The background of this work is for thermal protection of an object or device that requires precise temperature control in industry. The object or device is usually placed in a thermal protection envelope exposed to outdoor periodic ambient conditions in operation processes or transportation, and a thermal control facility is necessary to strictly control the temperature of the object and ensure reliability. The envelope, which is an essential part of the thermal control system, has crucial influence on the system performance. Therefore, to reduce the energy consumption of the system and improve temperature control effects, the influences of the envelope on system performance need to be studied thoroughly. To do this, a simulation model of the thermal control system was created and verified with data from an outdoor experiment system. Comparative analyses of thermal control effects of PCM and thermal insulation material (TIM) were performed for two time scales, the typical meteorological day (TMD) and the typical meteorological year (TMY). Finally, the conditions to achieve optimal thermal control effects for PCM were proposed, and a new method for determining the optimal phase change range was suggested.

2. Experimental system

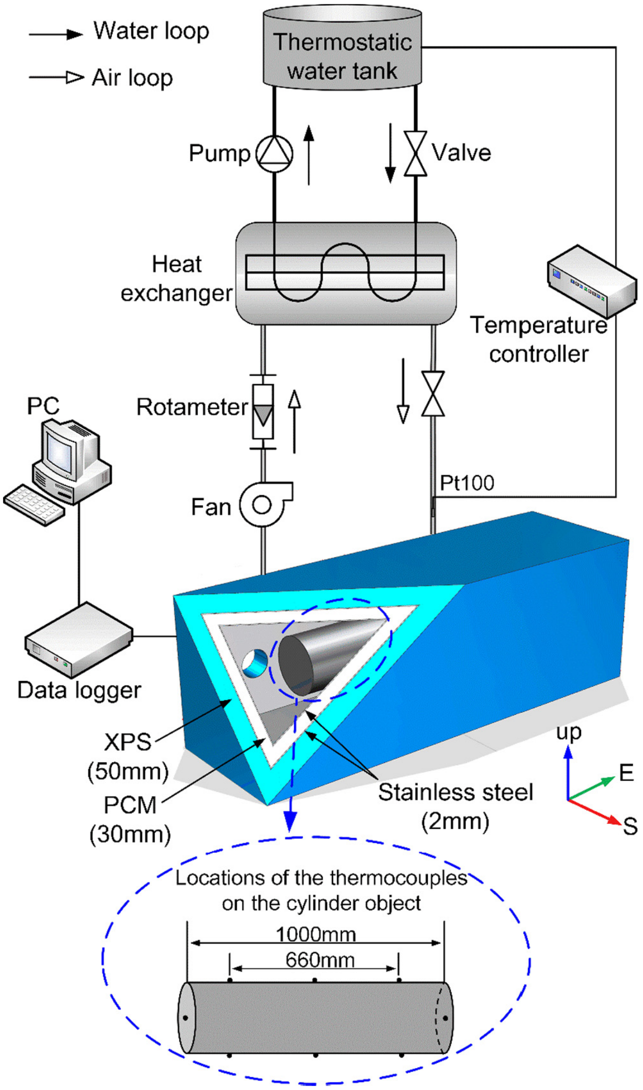

Fig. 1. Schematic of the thermal control system.

As shown in Fig. 1, the experimental system consists of the main body and two peripheral loops. The main body is composed of an envelope and an internal object. The object is a cylindrical shell filled with paraffin wax with a melting point of 54 °C. The cylindrical shell is made of 2-mm thick stainless steel and has an outside diameter of 218 mm and a length of 1000 mm. There are two sets of envelopes, one set with PCM and the other without PCM. The external dimensions of both envelopes are 1570 mm (length) × 500 mm (width) × 670 mm (height). All walls of the envelope without PCM are composed of 80-mm thick extruded polystyrene (XPS) and 2-mm thick stainless steel from outside to inside. Because the top, southern, eastern and western walls of the envelope with PCM are directly irradiated by solar radiation, PCM is incorporated into the four walls. The walls are all composed of 50-mm thick XPS, 2-mm thick stainless steel, 30-mm thick PCM and 2-mm thick stainless steel from outside to inside. There are two vents with a diameter of 100 mm on the north wall. In the following discussion, the system incorporated with PCM is called the PCM system, and the other one is called the TIM system. A paraffin mixture is selected as the PCM due to it characteristics of high latent heat, no phase separation, a low degree of undercooling, non-corrosiveness and compatibility with stainless steel containers [28].

The principal role of the peripheral loops, which are air and water loops, is to provide constant temperature airflow for the main body. The air loop comprises a heat exchanger, centrifugal fan, rotameter and valve. The water loop consists of a thermostatic water tank, pump and water valve. The air from the main body is blown into the heat exchanger, where it exchanges heat with the