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Experimental study on melting/solidification and thermal conductivity enhancement of phase change material inside a sphere☆

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ABSTRACT

In this paper, the melting and solidification processes and the thermal conductivity enhancement of the phase change material (PCM) inside a sphere have been experimentally investigated to facilitate a greater understanding and improvement of the phase change heat transfer of PCM inside a sphere. The experiments are conducted by inserting a sphere filled with organic PCM into a constant temperature bath of hot/cold water. Through measuring and analyzing the temperature field inside the sphere under conditions of various initial and final temperatures, the thermal characteristics of melting and solidification processes of PCM are obtained. To determine the thermal conductivity enhancement effect of aluminum powder, the PCM-aluminum composite material in which the mass fractions of aluminum are 1% and 2%, respectively, is tested. And the experimental data of PCM-aluminum composite material are compared with those of pure PCM. Results indicate that the PCM in the upper part of the sphere melts faster than that in the lower part, and the PCM near the inner wall solidifies faster than that in the center of the sphere. The initial PCM temperature has little effect on the solidification process of the PCM inside the sphere when Stefan number (*Ste*) is small and Rayleigh number (*Ra*) is large. The thermal conductivity of the PCM inside the sphere is enhanced by adding aluminum powder. And the sedimentation of aluminum powder is more beneficial to accelerate the heat transfer of the whole sphere in the melting process, compared with the uniform diffusion of aluminum powder in the PCM.

1. Introduction

The thermal energy storage system using a phase change material (PCM) has good application foreground due to the advantages of high thermal storage density, small temperature swing, and so on [1,2]. The PCM is generally stored in a container which has various shapes, such as spheres and cylinders. The spherical container, which has a favorable ratio of the heat transfer surface area to volume and can be easily packed into the storage system, is most commonly used to store the PCM [3]. Thus, it is of great significance to investigate melting and solidification processes and the thermal conductivity enhancement of the PCM inside a sphere for the design of an efficient thermal storage system [4–6].

The melting process inside a sphere, which is usually accompanied by nature convection, has been frequently studied. Roy and Sengupta [7] discussed a theoretical model of gravity-assisted melting in a spherical enclosure, and analyzed the effects of natural convection on the melting process. Fomin and Saitoh [8] investigated the close-contact melting in a spherical capsule numerically and analytically. An approach, which was developed by Bareiss and Beer [9] for the horizontal cylinder, was applied to establish the numerical model of contact melting in a spherical capsule with a non-isothermal wall. Khodadadi and Zhang [10] presented a computational study of the effects of buoyancy-driven convection on constrained melting of PCMs within spherical containers. Amin et al. [11] conducted an experimental research on the heat transfer through a single sphere subject to varying temperature differences, and developed a computational fluid dynamics (CFD) model which ignored buoyancy of the PCM in a sphere. Assis et al. [12] explored numerically and experimentally the melting process of PCM in spherical geometry. Tan [13] experimentally investigated the constrained and unconstrained melting processes of the PCM inside a sphere. Later, Tan et al. [14] analyzed the role of buoyancy-driven convection during constrained melting of PCM inside a spherical capsule by experimental and computational methods. Rizan et al. [15] studied the melting process of PCM inside a sphere which was immersed in a water tank and subjected to different power-rated heaters.

Compared with the melting process, the heat transfer of the solidification process inside a sphere, which is dominated by thermal conduction, is relatively simple. Experimental works of the solidification process in spheres have been concentrated in the case that the water is used as PCM [16,17], while the investigations on organic PCM are relatively few. Chan and Tan [18] presented an experiment study on the solidification of an *n*-hexadecane inside a spherical enclosure. The research results indicated that the effect of the initial liquid superheats

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Nomenclature

Abbreviation
PCM phase change material

Symbols
c_p specific heat, kJ/kg·K
d sphere diameter, m
L latent heat of PCM, kJ/kg
Ste Stefan number
T temperature, °C
T_m the mean phase change temperature of PCM, °C
Ra Rayleigh number

Greek symbols
ρ density, kg/m^3
β volumetric thermal expansion coefficient, 1/K
ν kinematic viscosity coefficient, m^2/s
α thermal diffusivity, m^2/s

of the PCM on the solidification was insignificant. But so far there have been very few experimental studies on both melting and solidification processes of organic PCM inside spheres.

In addition, the application of organic PCM is limited due to its low thermal conductivity. A lot of methods have been used to improve the thermal conductivity of PCM [19–28], such as adding metal mesh or metal powder, and using the extended surface. Mettawee and Assassa [29] carried out experiments to investigate a method of enhancing the thermal conductivity of paraffin wax by embedding aluminum powder in it. Veerappan et al. [30] studied the phase change behavior of different PCMs inside spherical enclosures to identify a suitable heat storage material. Hosseinizadeh et al. [31] conducted the numerical computation to analyze the melting process of nano-enhanced PCM (NEPCM) inside a sphere using copper particles as nano-particle. The results showed that the NEPCM had a higher thermal conductivity and lower latent heat as compared to the conventional PCM. According to the previous researches on enhancing the thermal conductivity of PCM, it can be seen that the experimental studies on improving melting and solidification processes of PCM inside the sphere by adding high conductive powder are scant.

In the present study, a sphere filled with organic PCM is used for the experiment. The temperature field under conditions of different initial and final temperatures is measured to analyze the characteristics of melting and solidification of PCM inside the sphere. Then, the PCM-aluminum composite material in which the mass fractions of aluminum are 1% and 2%, are investigated so as to obtain the effects of adding aluminum powder on the thermal conductivity of PCM. The motivation here is to understand and improve the phase change heat transfer of PCM inside a sphere, which can provide a reference for designing the thermal energy storage that uses the organic PCM inside the spherical container.

2. Experimental setup and procedure

2.1. Experimental setup

The experimental setup consists of two isothermal water baths, a spherical glass filled with organic PCM, several thermocouples and a data acquisition unit, as shown in Fig. 1. The two water baths are internally installed with heater, refrigeration and stirrer, and can maintain a constant temperature. Their working parameters are listed in Table 1. It can be observed that the temperature stabilities of two baths are good enough to meet the test requirements.

Paraffin is used as the PCM, and is filled into the sphere. Its thermal physical parameters are as follows: melting interval: 45.8–50.3 °C, latent heat: 129 kJ/kg, specific heat capacity in solid/liquid state: 2/1.5 kJ/kg·K, thermal conductivity in solid/liquid state: 0.27/0.15 W/m·K, and density in solid/liquid state: 916/776 kg/m^3. Five thermocouples are placed in five measuring points along the centerline of the sphere. The five measuring points are expressed as Tc1, Tc2, Tc3, Tc4 and Tc5 in turn from bottom to top, as shown in Fig. 2. Tc1 is 5 mm away from the bottom of the sphere whose diameter is 100 mm, and the distance between two adjacent measuring points is 15 mm. The temporal temperatures of measuring points are recorded and stored in the computer by the data acquisition unit which is connected with the thermocouples.

2.2. Experimental procedure

In Fig. 1, the left bath, called bath A, is used to make the PCM inside the sphere achieve an initial temperature. And the right bath, called bath B, is used to make the PCM melt or solidify. In the melting test, the PCM is solid initially. The temperature of bath A is less than the melting temperature of PCM, and that of bath B is higher than the melting temperature. In the solidification test, the PCM is liquid initially, and the temperatures of bath A and bath B are higher and less than the melting temperature of PCM, respectively.

The experimental procedure is as follows: first, the temperature of bath A is adjusted to a predetermined initial temperature of PCM, and that of bath B is set to a final temperature. The sphere filled with PCM is submerged into bath A for a long time so as to achieve the uniform PCM temperature and the predetermined initial temperature. Then, the sphere is removed from bath A to bath B quickly to start the melting or solidification test. The melting or solidification test is completed when the temperatures of all measuring points are equal to that of

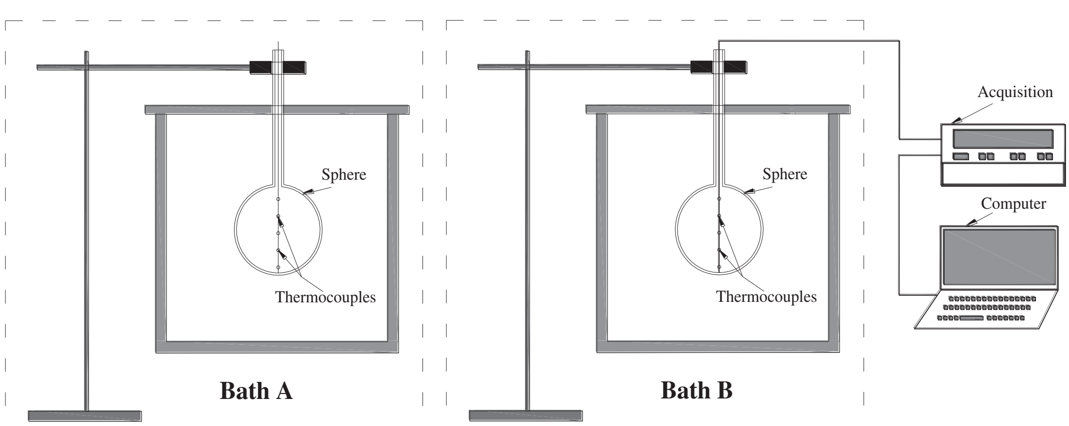

Fig. 1. Schematic of the experimental setup.