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Constrained and unconstrained melting inside a sphere ☆

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Abstract

The melting of the phase change material (PCM) inside a sphere using *n*-Octadecane for both constrained and unconstrained melting is investigated. In constrained melting, the solid PCM is restrained from sinking to the bottom of the sphere. For unconstrained melting, the solid PCM would sink to the bottom of sphere due to gravity. The experiments are carried out at three different wall temperatures of 35 °C, 40 °C and 45 °C with a sub-cooling of 1 °C for the unconstrained melting and three different initial sub-cooling of 1 °C, 10 °C and 20 °C at a constant wall temperature of 40 °C for the constrained melting.

Keywords: Constrained melting; Unconstrained melting; Melting inside sphere; Heat transfer; Solid–liquid phase front

1. Introduction

Solidification and melting has great influences on nature and modern technologies for example, in the thermal energy storage (TES) system. The system utilizes the phase change material (PCM) to maintain a constant temperature over a period of time. The TES system is to provide heating or cooling from a thermal energy storage reservoir in the system. The heating or cooling process add heat to or extract heat from the reservoir respectively. The heating effect can be found in the use of solar collector to store thermal energy from the sun to be used later at night whereas the cooling effect is to store thermal energy storage at a low temperature at night to be used in air conditioning during the day. The TES system can enhance the efficient usage of energy with a reduction in the cost of electricity.

In TES system, a spherical container is most commonly used for storing PCM. This is mainly due to its low volume to heat transfer surface area ratio [1]. There are also alternative storage devices such as plates, cans or cylindrical shapes with or without fins. Spherical shape is preferred because it can be easily packed into the storage system. The freezing process has been investigated in various geometrical configurations [2–4] such as slab, cylinder and sphere. Ismail et al. [5,6] presented a numerical solution based on finite difference approximations that are either subjected to convection boundary conditions or a constant surface temperature. Investigation on the thickness of the wall, diameter of sphere, surface temperature and initial PCM temperature were performed. They concluded that different spherical size, thermal conductivity of material and surface temperature had effect on the time taken for complete solidification.

The first to study the unconstrained melting of the PCM within spherical container both experimentally and numerically was Moore and Bayazitoglu [7] where *n*-octadecane was used as the PCM. The mathematical simulation

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was developed by assuming that the liquid remains at the fusion temperature at all times and solved using perturbation method. The solid–liquid interface positions and the temperature profiles were determined for various Stefan and Fourier numbers. The experimental data agreed well with the simulation results. Roy and Sengupta [8] performed a similar study and found an analytical solution for the melting rate at the lower surface of the solid PCM in contact with the heated surface. Following that, Roy and Sengupta [9] performed another study on the unconstrained melting process inside a sphere. They noted two zones of melting: a thin melting layer at the bottom and a thicker layer at the top of the sphere. It was observed that natural convection effect played an important role in the results as large amount of melting was found to be at the upper portion of the sphere. Bahrami [10] observed that the movement of the melting PCM caused by the presence of gravity has a great impact on the rates of melting and heat transfer.

Experimental and numerical analysis of melting of PCM inside a plexiglas spherical container was conducted by Felix et al. [11], where paraffin wax was used as the PCM. Investigation on the effect of the sphere radius, Stefan number, molten fraction and time for complete melting was carried out. The results for both the experimental and numerical were quite identical. It was found that Stefan number and the sphere radius had significant effects on the complete melting time of phase change material.

The constrained melting of PCM within a spherical bulb was presented by Khodadadi and Zhang [12]. They numerically studied the effects of buoyancy-driven convection. They had the same prediction as Roy and Sengupta [9] where the conduction mode of heat transfer was dominant in the earlier stage of the melting process. At a later stage, the melting rate increased as the buoyancy-driven convection inside the liquid PCM became more significant. There is no other work found on the constrained melting inside the sphere to the best knowledge of the author.

This paper is to investigate the differences in the constrained and unconstrained melting of phase change material inside the sphere under several constant surface temperature boundary conditions at several initial sub-cooling conditions. The motivation of the work here is to understand better the melting rate of phase change material inside the sphere with or without restraining of the solid PCM inside the sphere. This would have useful applications to the thermal design of thermal energy storage that uses phase change material inside spherical container.

2. Experimental setup and testing

The schematic of the experimental setup is shown in Fig. 1. The experimental setup consists of a water tank, a spherical glass, several Type K thermocouples, refrigerated bath and the HP data acquisition unit. The hot water from the refrigerated bath flows through the outlet valve into the water tank. The water in the tank is maintained at a uniform temperature through constant stirring (electric stirrer not shown in the schematic). The water then flows out of the tank and back into the refrigerated bath through an inlet

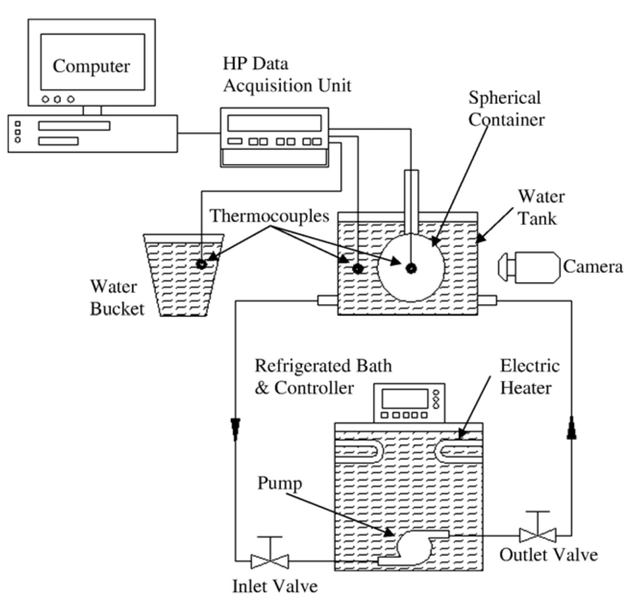

Fig. 1. Schematic diagram of the experimental setup.