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Experimental study on the melting and solidification of a phase change material enhanced by heat pipe☆

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ABSTRACT

In the present paper, the effect of using a heat pipe on the melting and solidification behavior of a phase change material (PCM) in a vertical cylindrical test cell was experimentally studied. The experiments were performed using a constant temperature thermal reservoir to provide constant temperatures above and below the melting point for heating and cooling. The melting and solidification experiments were run in test cells with and without heat pipes. The experimental results indicate that utilizing a heat pipe in PCM test cell dramatically enhance the melting and solidification rate. Heat pipe surface temperature was measured during experiments. It shows heat pipe isothermally transmits heat very well. By applying different reservoir working temperature, it is concluded that a 15 °C increase in reservoir temperature in melting experiment with heat pipe almost decreases the melting time by 53% and a 10 °C decrease in temperature in solidification reduce the solidification time by 49%. The growth of solid layer and solid–liquid interface in PCM during solidification was experimentally investigated.

1. Introduction

The use of latent heat of phase change materials (PCM) is one of the promising techniques for storing thermal energy in sustainable heating and cooling applications because of their isothermal operation during charging and discharging process (melting and solidification) and their large heat storage capacity. Choosing a PCM and designing an appropriate heat exchanger are two factors in performance of a latent heat thermal energy storage system [1]. Due to low thermal conductivity of PCMs, the thermal resistance near the heat transfer surface increases during phase change of PCM and consequently the surface heat flux decreases. Several studies have been conducted to study heat transfer enhancement methods in PCMs include using fins with different configurations [2], insertion of a high conductance matrix into the PCM [3], using PCM dispersed with high conductivity particles [4] and so on.

A heat pipe, a thermal conductor sealed tube with a wick inside the tube wall, relatively isothermally transfers heat from the heat source to the heat sink through the latent heat of vaporization of its working fluid, so they can be combined with a PCM to increase heat exchange rate between heat transfer surface and the PCM during melting and solidification. Heat pipes have received attention recently in thermal energy storage systems because of their great potential in heat transfer enhancement. For example, US patent 5386701, assigned to Cao Yiding and published in 1995, describes a system for human body cooling using a suit with heat pipe in it which had been connected to a PCM module, or, an aircraft company utilized heat pipes to extract heat from electronic equipment into a PCM (n-heptadecane proposed for 20 °C) [5]. Etheridge et al. [6] combined a PCM module and heat pipes in a free cooling system of a building. In their model building, heat pipes transfer heat into or out of PCM. They demonstrated that the system reliably performs in the freezing of the PCM during the night and melting during the day. The performance of the charging, the discharging, and simultaneous charging/discharging operation modes of the heat pipe heat exchanger with latent heat storage is experimentally studied by Liu et al. [7,8]. They investigated influence of hot and cold inlet temperature and flow rate of fluid flow on the melting and solidification time of PCM. For instance, melting completion time reduces by 52% when inlet temperature of hot flow increases from 70 °C to 90 °C, or as the flow rate increases from 0.83 to 3.33 kg/min, the solidification completion time indicates a reduction of 17.5%. Tardy and Sami [9] developed a mathematical model to predict the thermal behavior of heat pipes with thermal storage during an ice cooling cycle. The thermal behavior of heat pipes has also been studied experimentally and analyzed under different conditions. Shabgard et al. [10] developed a thermal network to analyze heat transfer in a high temperature latent heat thermal storage system for two configurations. They showed that addition of HPs always accelerated charging or discharging rates. Liu et al. [11] simulated the dynamic characteristics of a heat storage device with heat pipe during charging process. The effects of inlet temperature of heat pipe medium and initial temperature of the PCM on the thickness and temperature of the PCM, outlet temperature of

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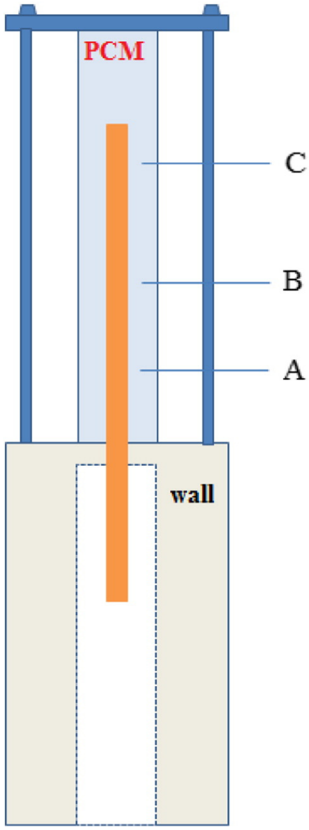

Fig 1. Schematic diagram of test cell.

heat pipe medium, total heat storage capacity, and heat storage rate of heat storage device were discussed. Their results indicate that total heat storage capacity and heat storage rate increase when the inlet temperature of heat pipe medium increases or the initial temperature of heat storage material decreases. The thermal performance of a heat pipe with PCM for electronic cooling was experimentally investigated by Weng et al. [12]. Their experiments showed that the cooling module with tricosane as PCM can reduce fan power consumption up to 46% and 12.3 °C average heater temperature as compared with no thermal storage material. Nithyanandam and Pitchumani [13] investigated a thermal resistance network model of a shell and tube latent heat thermal energy storage system with embedded heat pipes. A numerical optimization method was utilized to identify the design and operating parameters of the heat pipe embedded latent heat thermal energy storage system that maximizes energy transferred energy transfer rate and effectiveness. Robak et al. [14] experimentally investigated melting and solidification rates of PCM in a latent heat thermal energy storage system utilizing heat pipes or fins. An increase of 70% in melting rate was reported for heat pipe-assisted melting relative to benchmark. In the case of solidification, heat pipes can double the solidification rate. A numerical model has been developed by Sharifi et al. [15] to determine the augmentation of PCM melting associated with use of embedded, vertically oriented heat pipes, solid rods, or hollow tubes. They showed that melting rates are enhanced as either the condenser length or the diameter of the heat pipe is increased. The heat pipe is particularly effective in augmenting melting in configurations involving PCM heating from above.

Although several studies have been conducted on combination of PCM and heat pipe, a constant temperature boundary condition in melting and solidification process as well as heat pipe performance in PCM medium has not been investigated experimentally. In this study, melting and solidification experiments were performed by applying a constant temperature thermal reservoir to provide constant temperature boundary condition. The effect of temperature on heat pipe performance in PCM was also investigated.

2. Experimental procedure

An organic PCM with melting point of 28 °C, i.e., n-octadecane ($CH_3(CH_2)_{16}CH_3$) of 99% purity from Alfa Aesar ® Company, was used in this study. High latent heat storage capacity (243.5 kJ/kg) over a narrow temperature range can be obtained by this paraffin, but its low thermal conductivity (0.358 W/m·K in solid phase and 0.148 W/m·K in liquid phase [14]) impacts on melting and solidification rate of PCM and consequently on performance of latent heat thermal energy storage system.

A copper heat pipe with water as working fluid and sintered wick, made by Thermacore®, was used in this experiment. The diameter and length of heat pipe was 6.35 mm of 150.00 mm, respectively.

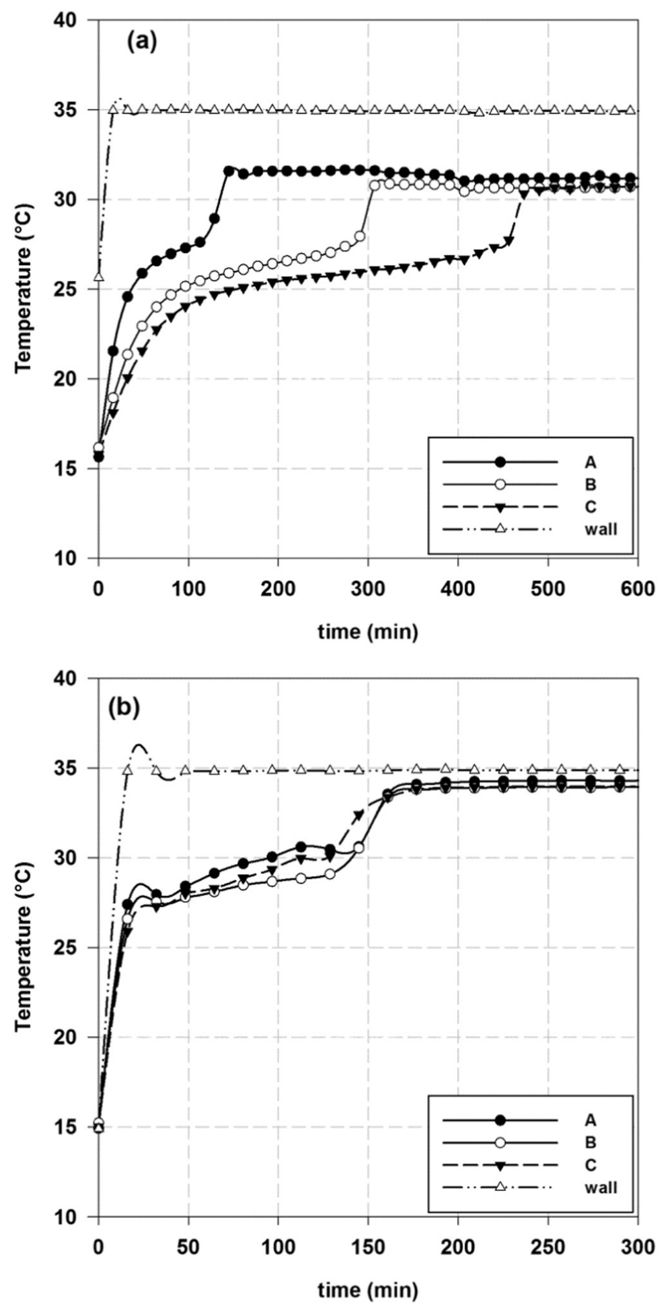

Fig. 2. Temperature variation in PCM during melting at $T_w = 35$ °C. (a) PCM test cell, (b) PCM-HP test cell.