Phase change composite based on porous nickel and erythritol

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ABSTRACT

We developed a phase change composite (PCC) using a porous metal with a thermal conductivity that is two orders larger than that of the original phase change material (PCM). A PCC of erythritol/porous nickel was prepared by vacuum impregnation, and its thermophysical properties such as effective thermal conductivity, latent heat, and melting temperature were measured by the laser flash method and differential scanning calorimetry (DSC). The effect of the porous structure was also examined. Results showed that the latent heat of the PCC could be simply explained by the impregnation ratio of the PCM, not by the pore size. The largest effective thermal conductivity, $11.6 \, \text{W} \, \text{m}^{-1} \, \text{K}^{-1}$, was recorded for PCC with 15 vol% of porous nickel having a pore size of 500 μm and 85 vol% of PCM; this value is 16 times higher than that of pure erythritol, i.e., 0.733. The developed PCC offers many benefits, including a high heat transfer rate and enhanced cost-effectiveness, and it will also contribute to the efficient utilization of solar heat and industrial waste heat.

1. Introduction

The increasing gap between the global demand for energy and the supply of energy is becoming a major problem. This problem underscores the need to store excess energy that would otherwise be wasted as well as to the bridge the energy gap. Thermal energy storage is one of the most effective approaches to realizing high energy efficiency, energy saving, and effective use of available resources and renewable energies [1–6].

For practical use, however, two problems need to be resolved. The first problem is the slow rate of heat transfer. The transfer rate between the PCM and the heat transfer fluid is generally unacceptably low owing to the low thermal conductivities of PCMs [7–10]. It has been proposed that the thermal conductivity of a PCM can be increased by mixing it with a high-thermal conductivity material [11–13]. The second problem is that PCMs cannot be used in high-temperature applications. PCM encapsulation for high-temperature applications (above 100 °C) has not been realized thus far because of technical difficulties [14–16]. Liquid PCM tends to leak through cracks generated by volumetric expansion upon melting [17]. For this reason, the thickness of the capsule layer is required to be high, but this leads to a decrease in the heat storage density of the capsule beds.

Porous materials with a high thermal conductivity are promising candidates for solving these two problems simultaneously. It is considered that porous materials can assume a stable shape that prevents the leakage of liquid PCM owing to the capillary and surface tension forces of a porous structure. Thus far, many researchers have focused on the production of a PCM composite [18–20]. In a previous paper, the impregnation of a porous material with a PCM was studied; erythritol was selected as the PCM, and expanded perlite (EP), diatom earth (DE), and gamma-alumina (GA) were selected as the porous materials. Such materials are quite attractive from an economic perspective, although their thermal conductivity is still low. In addition, porous materials with a high thermal conductivity should be studied in order to increase the overall rate of heat transfer [21–25].

In light of the above, the purpose of this study was to prepare phase change composites using porous nickel as a support for increasing the thermal conductivity. The composites can be used to efficiently store heat in the form of latent heat. In our experiments, composites were produced by filling porous nickel with liquid erythritol as a PCM with a melting point of 118 °C. Impregnation treatment was performed under the conditions of high temperature and vacuum. The thermophysical properties of the composites—thermal conductivity, latent heat, and melting temperature—were measured by the laser flash method at room temperature and differential scanning calorimetry (DSC). The effect of the porous structure on the melting point, latent heat, effective thermal conductivity, and stability of the PCM was also examined.

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Table 1
Specifications of erythritol used in study [28].

Melting point [°C]	Latent heat [kJ kg^{-1}]	Density [kg m^{-3}]		Specific heat [kJ(kg K)$^{-1}$]	
		Liquid	Solid	Liquid	Solid
118	354.7	1280	1450	2.66	1.68

Table 2
Specifications of porous material used in study.

Component	True density [kg m^{-3}]	Bulk density [kg m^{-3}]	Bulk thermal conductivity [W m^{-1} K^{-1}]	Porosity [–]	Average pore diameter [μm]
Ni	8908	1247–1425	90.3	0.85 ± 0.01	100, 300, 500

The results confirmed the feasibility of using a new phase change composite with a high thermal conductivity for high-temperature applications, thus contributing to the efficient use of solar energy and industrial waste heat.

2. Methods

2.1. Experimental

2.1.1. Materials
2.1.1.1. PCM. Table 1 shows the specifications of erythritol (C$_4$H$_8$O$_4$). In the experiments, erythritol with a melting point of 118 °C, latent heat of 473 MJ m^{-3}, and thermal conductivity of 0.733 W m^{-1} K^{-1} [26] at room temperature was selected as the PCM. The high latent heat and melting point render erythritol suitable for the storage of industrial waste heat. In fact, erythritol is used for the recovery of waste heat. Further, it is a type of sugar alcohol and is completely safe.

2.1.1.2. Supports. Porous nickel with pore sizes of 100, 300, and 500 μm was selected to serve as a support in the impregnation process. Porous nickel with a cylindrical shape having a 10-mm diameter and 10-mm thickness was prepared according to the manufacturing method described in Ref. [27]. The cylinder was cut into cylindrical disks with a thickness of 2.0 mm and a porosity of 85% (±1%). Table 2 shows the specifications of porous nickel used as a support in the impregnation process. We prepared three samples with different pore sizes in order to examine the effect of pore size on the latent heat and thermal conductivity of the composite.

#### 2.1.2. Impregnation experiments
Porous nickel was impregnated with the PCM under vacuum conditions to remove the air from the pores [28]. Fig. 1 shows a schematic of the impregnation treatment under vacuum. First, solid PCM and porous nickel disks were placed in an electric furnace with a vacuum pump. The pump was used to remove the air from the furnace. Then, the furnace temperature was maintained at 150 °C in order to liquefy erythritol. The porous nickel disks were then physically placed in the liquid PCM for 3.6 ks. Next, the vacuum pump was turned off in order to fill the furnace with air. The PCM-filled porous nickel disks were removed from the liquid PCM bath using a stainless mesh. To remove liquid PCM that had not penetrated the pores, the disks were kept in a heated furnace at 150 °C. Finally, the disks were removed from the furnace and dried.

2.1.3. Characterization techniques
Following impregnation, the latent heat and melting point of the disks were estimated using a scanning electron microscope (SEM) and a differential scanning calorimeter. The thermal conductivity of the composite was measured at room temperature by the laser flash method. In this study, the effect of pore diameter on the melting point, latent heat, effective thermal conductivity, and stability of the PCM was our chief area of investigation.

2.1.3.1. Differential scanning calorimetry (DSC). The melting and heat storage behaviors of the composite were studied by DSC under an argon atmosphere (Thermo plus DSC 8230, Rigaku, Japan). The data were collected at a scan rate of 2 K min^{-1} up to a temperature of 140 °C. Measurements were made by placing 5–10 mg of the composite sample on the calorimeter sample cell made of aluminum.

2.1.3.2. Thermal conductivity measurement. The thermal diffusivities of all the disks at room temperature were measured by the laser flash method. In this method, a very short and uniform laser pulse was directed at the sample (TC-7000, Rigaku, Japan). The radiation energy of the pulse was absorbed on the front surface, which resulted in an increase in the temperature on the back surface of the sample. A thermal detector was used to measure this temperature increase as a function of time. The thermal diffusivity of the sample in the direction perpendicular to the front and back surfaces at room temperature was determined by measuring the thickness of the sample, L, and the half time $t_{1/2}$, which was the time required for the temperature of the back surface to reach 50% of its maximum value, as given by the following relationship [29]:
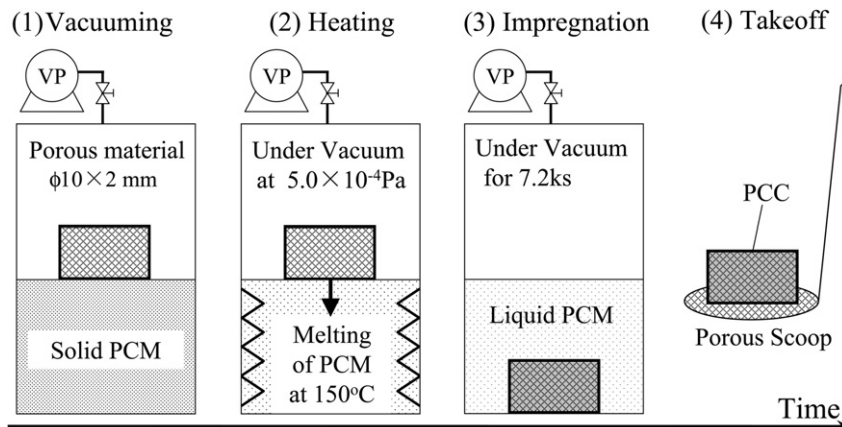
Fig. 1. Procedure of *the vacuum impregnation treatment* for the production of phase change composite (PCC).