



Development of graphite foam infiltrated with MgCl₂ for a latent heat based thermal energy storage (LHTES) system[☆]



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ABSTRACT

Thermal energy storage (TES) systems that are compatible with high temperature power cycles for concentrating solar power (CSP) require high temperature media for transporting and storing thermal energy. To that end, TES systems have been proposed based on the latent heat of fusion of the phase change materials (PCMs). However, PCMs have relatively low thermal conductivities. In this paper, use of high-thermal-conductivity graphite foam infiltrated with a PCM (MgCl₂) has been investigated as a potential TES system. Graphite foams with two porosities were infiltrated with MgCl₂. The infiltrated composites were evaluated for density, heat of fusion, melting/freezing temperatures, and thermal diffusivities. Estimated thermal conductivities of MgCl₂/graphite foam composites were significantly higher than those of MgCl₂ alone over the measured temperature range. Furthermore, heat of fusion, melting/freezing temperatures, and densities showed comparable values to those of pure MgCl₂. Results of this study indicate that MgCl₂/graphite foam composites show promise as storage media for a latent heat thermal energy storage system for CSP applications.

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1. Introduction

If concentrated solar power (CSP) is to be a viable technology for producing cost-effective grid electricity, thermal energy storage (TES) will be needed to generate electricity during nighttime and cloudy days and thereby improve the overall plant efficiency. With increased plant efficiency, the leveled cost of electricity would be reduced. One of the approaches for increasing plant efficiency is to deploy higher temperature power cycles, such as use of supercritical steam. The inlet temperatures for the heat transfer fluids (HTFs) for supercritical steam is 540–620 °C. This temperature range implies that the TES systems would need to operate such that during the system discharge the outlet temperature of the HTF is > 650 °C [1,2].

Recently, various researchers have proposed TES systems for CSP based on the latent heat of phase change materials (PCMs). However, PCMs have relatively low thermal conductivity [3], which leads to long times to charge/discharge the storage system. In addition, PCMs are not fully utilized during the desired 8 h of charging time. Therefore, several studies have focused on enhancing the heat transfer characteristics of the PCMs. Finned tubes and heat pipes have been proposed to reduce the thermal resistance between the HTF and the PCM [4–13], while particles and metal foam structures with high thermal conductivities have been suggested to reduce the thermal resistance of the PCM itself [14–20].

Recent development of graphite foams with extremely high bulk thermal conductivities [21] has led to several investigations on using them for improving the thermal performance of low thermal conductivity materials [22–28]. Zhong et al. [24] showed that the thermal diffusivity of a paraffin/graphite foam composite was 570 times higher than that of pure paraffin wax. Warzoha et al. [25,26] used a simple submersion technique combined with a vacuum infiltration technique to infiltrate the foam with paraffin wax. Their results showed that the vacuum infiltration technique was better as compared to the simple submersion technique, and it can fully infiltrate the foam with paraffin wax. Xiao and Zhang [27]

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compared the infiltration rates for the cases with and without vacuum assistance, and their results showed that the infiltration process with vacuum assistance was superior to that without it. Further, they reported that the thermal conductivity of the composite was higher compared to pure paraffin. The phase change behaviors of the composite were also investigated with a differential scanning calorimeter (DSC). The presence of the porous carbon foam did not affect the phase change behavior of pure paraffin wax.

Recently, Sedeh and Khodadadi [28] investigated the effective thermal conductivity of composites of graphite foam infiltrated with cyclohexane as the PCM. Their results indicated an improvement in the effective thermal conductivity of composites compared to that of the pure PCM at temperatures up to 70 °C. Their numerical simulation and experimental results were in good agreement. They also found that the role of natural convection within the pores was negligible.

There are only a few studies on the use of high conductivity foams with high melting point PCMs [29–31]. Kim et al. [29] conducted a parametric study of latent heat thermal energy storage (LHTES) systems using graphite foams and high temperature PCMs. They found that the use of the graphite foam and the turbulent flow could significantly reduce the number of heat transfer fluid pipes. Zhao et al. [30] investigated the exergy efficiency in LHTES systems using the MgCl₂-graphite foam composite. They found that the graphite foam could significantly improve the heat transfer performance as well as the energy efficiency in the LHTES system. Recently, Jianfeng et al. [31] developed a high temperature energy storage material using silicon carbide (SiC) ceramic foam as matrix and Na₂SO₄ as phase change material with melting point of 884 °C. In this work, sodium sulfate was infiltrated into the silicon carbide foam via the melt infiltration method. The resulting composite thermal conductivity was found to be ~6 W/m-K, and the thermal energy storage density was 161 kJ/kg as the composite was cycled between 800 °C and 900 °C. Further, thermal cycling did not degrade the composite performance.

The focus of this work is to develop a graphite foam/PCM composite that could be used in an LHTES system that will be compatible with a supercritical steam power cycle. In this regard, we selected magnesium chloride (MgCl₂) as the PCM, which has a melting point of 714 °C, and infiltrated it into the graphite foam preform. Various physical and thermal characterizations were performed on the fabricated composite to validate its use for the LHTES system.

2. Experimental procedure

2.1. MgCl₂ PCM

In the present study, magnesium chloride (MgCl₂) was chosen as the PCM for the infiltration experiments because of its melting temperature range, high volumetric heat of fusion, small undercooling temperature, and low vapor pressure [32]. The physical and thermal properties of MgCl₂ are summarized in Table 1.

For the experimental work, MgCl₂ was obtained from a commercial source (98% purity, ACROS Organics). The as-received MgCl₂ powders and the foam/PCM composites were characterized for weight loss as a function of temperature, melting point, and heat of fusion by means of a differential scanning calorimeter-thermogravimetric analyzer (DSC-TGA, Model SDT-Q600, TA Instruments).

2.2. Graphite foam

Two kinds of commercial graphite foams that have different

porosities were used in the present study: POCO-HTC (high density) and Graftech (low density). From here on, the POCO-HTC and Graftech foams will be referred to as high density (HD) and low density (LD) foams, respectively. The as-received graphite foams were characterized for density (gas pycnometer, Model Ultrapyc 1200e, Quantachrome Instruments). The microstructure of the graphite foam samples, both as-received and after infiltration, was examined by scanning electron microscopy (SEM) and energy dispersive x-ray analysis (EDX). Due to the processing of the graphite foams, their properties are anisotropic. They are the same in the x-y plane but different in the out-of-plane z direction, which is the rise direction of the foams. The manufacturer-provided thermal conductivities of the HD and LD foams are 245 W/m-K and 50 W/m-K in the z direction, and 70 W/m-K and 25 W/m-K in the x-y directions, respectively.

2.3. Infiltration of graphite foam with MgCl₂

A pressure-assisted melt process was used to infiltrate MgCl₂ into the graphite foams. The graphite foam samples and MgCl₂ powder were placed in separate chambers, as shown schematically in Fig. 1. The graphite foam chamber was evacuated while the PCM salt was heated to >800 °C in an argon gas cover. Once the salt was completely melted, the valve separating the two chambers was opened to allow the melt to infiltrate the graphite foam. In addition, gas pressure was used to ensure complete infiltration of the foam with PCM. Post infiltration, any excess PCM was gently wiped off. Typical dimensions of the infiltrated samples were 15.2 cm × 7.6 cm × 1.9 cm.

2.4. Measurements of thermal diffusivity and thermal conductivity

Thermal conductivity is related to thermal diffusivity, density, and specific heat capacity at constant pressure as per the following equation:

$$k = \alpha \rho c_p \quad (1)$$

where k is thermal conductivity, α is thermal diffusivity, ρ is density, and c_p is specific heat capacity. Therefore, to determine the thermal conductivity of a material system, its thermal diffusivity, density, and specific heat need to be measured independently.

For this paper, thermal diffusivity was measured by applying an energy source on one face of the sample, and the temperature rise was recorded as a function of time. A commercial unit (Model DXF-900, TA Instrument) that employs a xenon flash was used for the thermal diffusivity measurements. These measurements provided accurate thermal transport properties of the baseline graphite foam and post-infiltration composite as a function of temperature.

The density and specific heat capacity of the composites were calculated from the following equations:

$$\rho_{\text{composite}} = \varphi_{\text{foam}} \rho_{\text{PCM}} + (1 - \varphi_{\text{foam}}) \rho_{\text{foam}} \quad (2)$$

$$c_{p, \text{composite}} = \frac{\varphi_{\text{foam}} \rho_{\text{PCM}} c_{p, \text{PCM}} + (1 - \varphi_{\text{foam}}) \rho_{\text{foam}} c_{p, \text{foam}}}{\rho_{\text{composite}}} \quad (3)$$

where φ_{foam} is porosity of the graphite foam. Density and specific heat capacity of PCM and foam were determined as a function of temperature from data in Ref. [32] and used for the calculation of the thermal conductivity of the composites with Eq. (1).

The thermal diffusivities of MgCl₂/graphite foam composites were measured for both the z direction and x-y directions because

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