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Technical Note

A pore-scale visualized study of melting heat transfer of a paraffin wax saturated in a copper foam: Effects of the pore size

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ABSTRACT

In this Technical Note, a visualized study at the pore-scale was carried out to explore the pore size effects on melting heat transfer of a paraffin wax saturated in a copper foam. Three types of copper foams having a pore size of 15 ppi, 30 ppi and 50 ppi were used. The pore-scale visualization of the melting process was enabled using an infrared video camera equipped with a macrolens. Thermocouples were also embedded in the melting system at different locations to monitor the local temperature variations. It was observed that at the wall superheat of 20 °C, the 30 ppi and 50 ppi copper foams lead to almost identical overall melting rates, which are both much faster than that for the 15 ppi one. However, when the wall superheat was increased to 30 °C, the 30 ppi copper foam appears to be the best filler that causes much faster melting than that of the 50 ppi one. In addition, transient evolutions of the pore-scale temperature field were observed through the infrared thermal imaging snapshots at representative time instants during melting. The local thermal nonequilibrium between the paraffin wax and its surrounding copper ligaments was clearly demonstrated to decrease with reducing the pore size. In sum, the use of copper foams with relatively small pores was deemed to be desirable, which may lead to both faster melting and less significant local thermal nonequilibrium effect.

1. Introduction

The involvement of open-cell metal foams has been studied and practiced as an efficient approach to enhancement of heat transfer in phase change material (PCM)-based thermal energy storage systems [1]. In such systems, a PCM is often infiltrated into a highly-conductive metal foam [2], made of copper or aluminum for example, to form a composite PCM with improved effective thermal conductivity [3]. To improve the charging performance of thermal energy storage systems, the melting of metal foam/PCM composites has been studied extensively at the system level. Among the great amount of relevant studies, some of the representative experimental efforts over the last decade can be found in Lafdi et al. [4], Siahpush et al. [5], Li et al. [6], Mancin et al. [7], and Fleming et al. [8], where the emphasis was put on the effects of porosity and/or pore size of the metal foams.

However, in addition to the enhanced heat conduction that is directly related to the improved thermal conductivity, heat transfer during melting of such composite PCM becomes very complicated due to the presence of extra mechanisms associated with the metal foams. For example, natural convection in the PCM melt is confined in the small-sized pores that may offset the enhanced heat conduction. Hence, investigation of melting of metal foam/PCM composites at the pore-scale is deemed to be necessary for getting a deeper insight into the heat transfer mechanisms involved [9][10]. In a recent work by Fan and Jin [11], a visualized study at the pore-scale was successfully conducted, based on the infrared (IR) thermal imaging technique, for observing melting of a paraffin wax/copper foam composite with a single pore size.

In this Technical Note, an extended work is carried out to further explore the influence of pore size on melting heat transfer of the composite PCM. Using the proposed IR thermal imaging method that enables pore-scale visualization [11], the confined natural convection in pores as well as the local thermal nonequilibrium effect are studied both qualitatively and quantitatively.

2. Experimental

The paraffin wax/copper foam composite samples were prepared through vacuum infiltration. The paraffin wax was determined to possess an onset melting point around 46.4 °C and a peak

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melting point around 54.3 °C using a differential scanning calorimeter [11]. In this work, copper foams having a nominal porosity of 95% but with three different nominal pore sizes of 15 ppi, 30 ppi, and 50 ppi were used, while the actual porosity was determined to be 96.1%, 95.3%, and 94.9%, respectively. The composite PCM samples were cut to have dimensions of $20 \times 10 \times 10\ mm^3$, as illustrated in Fig. 1a. The melting test rig, designed and constructed by Fan and Jin [11], was adopted in this work. As shown in Fig. 1b, the test section was a rectangular box made of Plexiglas, which was horizontally arranged to avoid leakage of liquid PCM during melting. The copper block was inserted in the test section to serve as a constant temperature heating boundary by connecting it to a circulation water bath, while the other lateral and bottom walls were covered by insulating materials. The circular window on the cover plate was reserved for exposure to the IR thermal imaging device for pore-scale visualization of surface temperature fields of the composite PCM sample. In addition, two thermocouples (TCs) were installed in the test section. As illustrated by the physical model in Fig. 1c, the TC-0 was embedded in the copper block to measure the heating boundary temperature, while the TC-1 was positioned right underneath the top surface of the composite PCM sample to monitor the local surface temperature variations.

3. Results and discussion

3.1. Overall melting rate

The melting experiments were conducted under two constant boundary temperatures, i.e., the wall superheat of 20 °C and 30 °C in relative to the measured onset crystallization point of 50.9 °C of the paraffin wax [11]. The local temperature variations, as recorded by TC-0 and TC-1, in the melting system during typical runs for the various cases are plotted in Fig. 2. The constant temperature boundary conditions are clearly confirmed by the nearly flat temperature variations of TC-0, except for the short temperature rising periods in the beginning. In Fig. 2, the band bounded by 46.4 °C and 54.3 °C represents the temperature range where melting occurs. For this reason, the temperature rise curves experience a small and continuous slope change while passing through the nearly 8 °C band, instead of the presence of a plateau on the melting curves of a single-component PCM having a well-defined melting point. If the local temperature reaches 54.3 °C, it means that the melting front (i.e., solid-liquid phase interface) has moved to the location of TC-1. The time elapsed can be used as a measure for the overall melting rate by assuming flat phase interfaces. At the lower wall superheat of 20 °C, as shown in Fig. 2a, the composite PCM melts faster when the 30 ppi and 50 ppi copper foams were used. This suggests that the copper foams with smaller pores are preferred at a nearly constant porosity, possibly due to the more remarkable thermal conductivity improvement. It is also noted that at this wall superheat, the melting rates are nearly consistent between the 30 ppi and 50 ppi samples.

As expected, the melting rates all become faster than those in the previous case, when the wall superheat was increased to 30 °C. However, in this case the 30 ppi sample stands out to become the fastest among the three samples. The 30 ppi sample melts even much faster than the 50 ppi one at this higher wall superheat, while the latter only melts a little faster than the 15 ppi one. Natural convection is inherently more intensive in this case, suggesting that the confined natural convection in very small pores (i.e., the 50 ppi case) can offset or even overweigh the enhanced heat conduction. Although small pores may be desirable for thermal conductivity enhancement, a trade-off consideration should be taken to avoid heat transfer deterioration because of the confined natural convection if the pores are too tiny.

3.2. Local thermal nonequilibrium

The thermal imaging snapshots showing the pore-scale temperature fields, which were taken at representative time instants during melting at the wall superheat of 20 °C, are plotted in Fig. 3a. It is noted that the effective diameter of the circular view window is 5 mm, and that the spatial temperature resolution is 50 μm. The color bars are fixed between 40 °C and 60 °C, as represented by blue and red colors, respectively. Hence, the green color in the thermal images represents the presence of solid-liquid phase interfaces. In most of the cases, large interface spans are seen instead of sharp interfaces due to the wide range of melting point. The progresses of melting can be clearly illustrated by temporal evolutions of the temperature field, and the comparison of overall melting rates among the various pore sizes is found to be consistent with that observed previously by the TC readings.

Owing to the high thermal conductivity contrast between the paraffin wax and copper, the presence of copper ligaments is clearly observed and identified on the thermal images, as confirmed by comparing with the optical images given in the very left column in Fig. 3a. It is obvious that the presence of copper foams results in nonuniform temperature distributions, especially for the two cases with smaller pore sizes. The color contrast between the paraffin wax and its surrounding copper ligaments demonstrates the presence of local thermal nonequilibrium. To further quantify the local thermal nonequilibrium at the pore-scale, the temporal evolutions of the temperature difference at two select

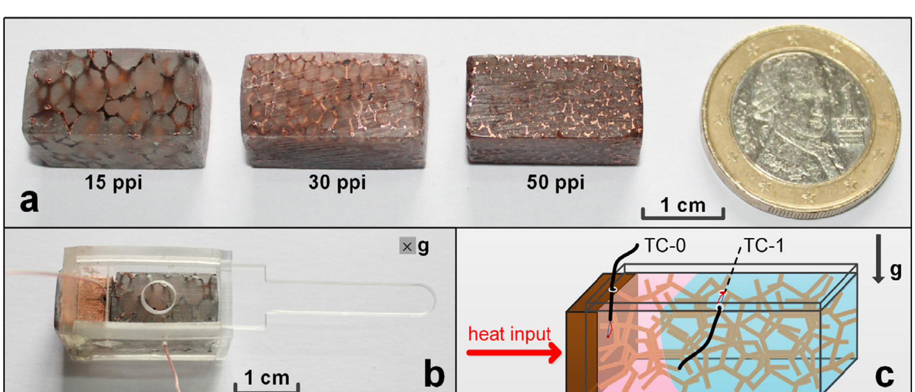

Fig. 1. Photographs showing (a) the composite PCM samples prepared by impregnating a paraffin wax into copper foam of three pore sizes, and (b) the test section of the melting setup, as well as the schematic diagram showing the physical model of melting of the composite PCM.