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Experimental Study on the Influence of Foam Porosity and Pore Size on the Melting of Phase Change Materials

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Experimental study on the influence of foam porosity and pore size on the melting of phase change materials

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Experimental study was carried out to study the phase change heat transfer within a composite of phase change material (PCM) infiltrated high thermal conductivity foam. An experimental setup was built to measure the temperature profiles and capture the melting evolution of the PCM inside aluminum foams. Aluminum foams were used as the porous material, and low melting temperature paraffin wax was used as the PCM. It was observed from the results that the system parameters of the wax/foam composite had a significant influence on its heat transfer behavior. By using higher porosity aluminum foam, the steady-state temperature was reached faster as compared to the foams with lower porosity. Similarly for the bigger pore size foams the steady state was attained faster as compared to the smaller pore size foams. This was due to the greater effect of convection in both the higher porosity and bigger pore size foams. However, for the lower porosity foams the heater temperature was comparatively lower than the higher porosity foams due to greater heat conduction through the foam material. Therefore, an optimal value should be selected for the foam porosity and pore size such that the effects of both conduction and convection heat transfers can be completely utilized to have a greater and improved thermal performance for the wax/aluminum foam composite. © 2007 American Institute of Physics. [DOI: 10.1063/1.2802183]

I. INTRODUCTION

Thermal management is a major issue in the design of small size electronic chips, which are subjected to high heat generation densities. In electronic cooling applications, temperature stabilization requirements typically range from near ambient (20 °C) up to (100 °C). Using active cooling by circulating a coolant fluid to absorb the heat from these kinds of electronic chips is known to consume too much power and add complexity to the system design. In addition to this, the heat generated from these electronic chips may be steady or transient in multichip modules and sensors that operate irregularly or have variable power. Therefore, developing a new generation of electronic devices, which have high capabilities and high mobility, requires using passive cooling systems, which can be achieved using phase change materials (PCMs).

By definition, PCMs are those materials that experience phase change from solid-solid, solid-liquid, or liquid-gas under normal operating conditions. The advantage of this type of material in temperature control stems from their higher heat capacity and the isothermal nature of the phase change process. A negative aspect of PCMs is that most of these materials suffer from inherent low thermal conductivity. The lower thermal conductivity of these materials increases the charging and discharging time for any PCM energy storage. Also, in the case of temperature control of electronic devices, the low thermal conductivity of the PCM makes the temperature shoot up rapidly once the melting interface moves away from the surface subjected to the heat flux.

Use of PCMs in heat protection applications requires a high melting temperature, high thermal conductivity, and high latent heat. Most of the existing PCMs present low thermal conductivity. The lower thermal conductivity of the PCM can be enhanced by using metal filler additives, fins, or metal porous structures. Bogaje[1] performed experimental study to investigate the methods of enhancing the thermal response of paraffin wax heat storage tubes by incorporating aluminum thermal conductivity promoters of various designs into the body of the wax. It was found that the melting and solidification times were reduced significantly due to these promoters. Velraj *et al.*[2] performed a detailed investigation for different heat transfer enhancement methods for thermal storage system using fins and Lessing rings. They concluded that applying these methods was highly suitable for solidification enhancement. Cabeza *et al.*[3] carried out an experimental study for a small energy storage device to study heat transfer improvement in PCM with the addition of stainless-steel pieces and copper pieces. The PCM used was water. They noticed that addition of steel pieces did not increase the heat flux significantly, but adding copper had a significant effect on enhancing the heat transfer process. Uros[4] presented an experimental wok to investigate melting and solidification of paraffin and the time-dependent storage of heat in the PCM with and without steel fins for heat transfer enhancement. Through this study, correlations between Nusselt and Rayleigh numbers were made.

Due to the attractive properties of carbon fibers, Fukai *et al.*[5,6] investigated experimentally two thermal conductivity enhancement techniques for PCM using carbon fibers and carbon brushes. Their results showed that the two methods were useful in enhancing the thermal conductivity, and using fiber brushes was better in enhancing the thermal conductivity in the fiber direction. Hamada *et al.*[7] studied both experi-

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mentally and numerically enhancement of PCM energy storage using carbon fiber chips and carbon brushes as additives. They mentioned that the carbon fiber chips were effective for improving the heat transfer rate, but they found that the thermal resistance near the heat transfer surface was higher than that for carbon brushes.

Recent studies on the enhancement of the thermal conductivity of PCMs have focused on use of a porous matrix. Hoogendoorn and Bart[8] reported that the low thermal conductivity of the PCMs can be greatly enhanced by embedding a metal matrix structure in them. Erk and Dudukovic[9] utilized low-density additives such as porous silica catalyst, while Eltouney et al.[10] used metal screens/spheres placed inside the PCMs. Mauran et al.[11] used a solid matrix made of graphite as a support for low thermal conductivity reactive salts. This support presented several advantages such as achieving a high external heat transfer coefficient, very low bulk density, good mechanical properties, and chemical inertness.

It was obvious from the literature review that phase change processes (melting and solidification) inside high thermal conductivity porous media did not receive extensive research. All the research which has been conducted in this field is concentrated on heat conduction in multiphase systems with free and forced convection in porous media. Melting and solidification of PCM inside packed beds has been studied using simple models based on the assumption of local thermal equilibrium. This can be accepted when the thermal properties of the two phases are close to one another. These studies are mainly concentrated on testing the enhancement in the effective thermal conductivity of the PCM-based composites. They did not take into account the phase change process, the molten liquid flow motion, and the parameters that affect the performance of such composites in thermal management applications.

The aim of this study is to investigate experimentally the phenomenon of phase change of PCMs inside high thermal conductivity foams. Aluminum foams with different physical properties were infiltrated with paraffin wax. An experimental setup was built to measure the temperature field and to capture the liquid-solid interface motion during the melting of PCM inside the foam structure. Effect of different parameters like foam porosity and pore size on the melting of paraffin wax and heat transfer through the composite system was analyzed. The practical use of the current study could appear in a number of thermal management applications, such as energy harvesting, active and passive cooling of electronic devices, and energy storage systems.

II. EXPERIMENT DETAILS

A detailed experimental study was carried out to study the heat transfer and phase change processes inside high thermal conductivity foams saturated with PCM. Before performing the experimental investigation, different measurements were carried out for the foam and PCM properties so that system parameters required for the analysis are accurately known. The well-known guarded plate technique was used to measure the thermal conductivity of different porous

TABLE I. Aluminum foam properties. All the samples dimensions are $4 \times 4 \times 2$ in., with tolerances: thickness ± 0.01 in., length and width ± 0.03 in.

Sample no.	Pores per inch (PPI)	Pores per meter (PPM)	Foam density (1.0-porosity)	Pore diameter $(d_p)[m]$
1	5	197	6.3%	0.0042
2	10	394	6.6%	0.0033
3	20	787	6.1%	0.0027
4	40	1575	6.3%	0.0019
5	0	394	3.4%	0.0033
6	10	394	11.6%	0.0034

foam materials. All PCM properties such as viscosity, thermal conductivity, melting point, specific heat, and latent heat of fusion were measured using a rheometer and a differential scanning calorimeter (DSC), respectively. Some of these properties such as PCM viscosity and thermal conductivity were obtained as a function of temperature.

A. Samples

Cubic high porosity aluminum samples of dimensions $4 \times 4 \times 2$ in. were used in this study. Different samples with different porosity and pore size selected for aluminum foam. Two quantities, the porosity and the pore density, are used to describe this type of foam, where the latter is expressed in units of pores per inch (PPI). The properties of the aluminum foam as delivered by the manufacturer, ERG (Energy Research and Generation Corp.) are listed in Table I

The measurement results for aluminum and thermal properties of PCM are summarized in the tables below. Table II gives the thermal conductivity values of the aluminum foams for different PPI and porosity; also, the thermal conductivity of solid aluminum is listed in the bottom row.[12] The values showed that the effective thermal conductivity is mainly related to foam porosity because it changed from 2.9 to 7.5 when the porosity decreased from 96.6% to 88.4%. Also, a lower thermal conductivity value was obtained for the smaller pore size foam with 40 PPI. This could be attributed to the increase in the tortuous path of the heat as the pore size of the foam decreases.

The PCM used in the experiments was a low melting temperature paraffin wax. It is an alkyl hydrocarbon k-18 paraffin wax. This type of wax was selected because its melting temperature is very close to the ambient temperature, so the losses in the experimental setup would be minimal.

TABLE II. Measured thermal conductivity of aluminum foam.

Sample	$K_{eff}[W/mK]$
5 PPI, 93.7% porosity	5.0
10 PPI, 93.4% porosity	5.2
20 PPI, 93.9% porosity	5.0
40 PPI, 93.7% porosity	4.5
10 PPI, 96.6% porosity	2.9
10 PPI, 88.4% porosity	7.5
Solid aluminum	236
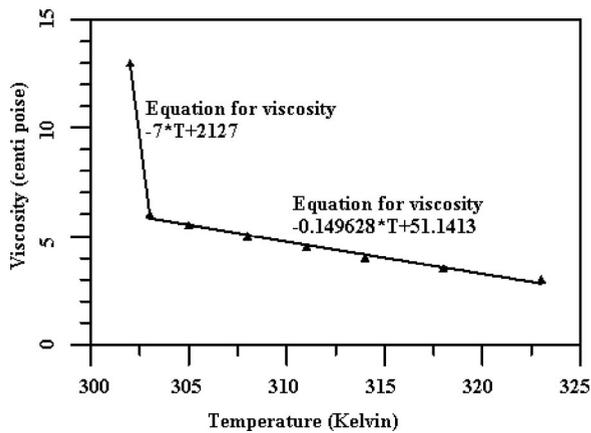
FIG. 1. Variation of pure wax viscosity with temperature.

FIG. 2. (Color online) Experimental setup for phase change analysis of composite samples (front view).

To find out the behavior of the PCM during the melting and freezing processes DSC measurements were performed using thermo-analysis equipment with a liquid nitrogen cooling system. From the measurements, it was possible to determine the latent heat of fusion, the melting point, and the specific heat of the wax. It was found that the wax melting temperature ranged from 25.4 up to 28.9 °C.

The viscosity of the molten liquid of the wax was measured with the programmable rheometer. The viscosity was measured at different temperatures.

Figure 1 shows the viscosity change of pure wax with temperature. The viscosity changed linearly with temperature when it was in the purely liquid state. At temperatures near melting, when the wax started to solidify, the viscosity increased suddenly due to the formation of solid nucleates inside the wax. All the properties of the paraffin wax used as PCM are tabulated in Table III.

B. Enclosure design and measurement details

The experimental setup built for the study consisted of PCM-foam composite was held inside an enclosure as shown in Fig. 2. The details of the setup are described below. The setup was used to measure the temperature field and capture the liquid-solid interface motion during the melting process. To hold the PCM saturated foam sample and to prevent leakage during melting, a container was manufactured from plexiglas and aluminum sheets. The four side walls, front, rear, top, and bottom of the container, were made of 7/16 in. thickness plexiglas sheets to allow visual access to the phase change process within the container as shown in Fig. 2. An aluminum plate of thickness 3/16 in. was glued to the left
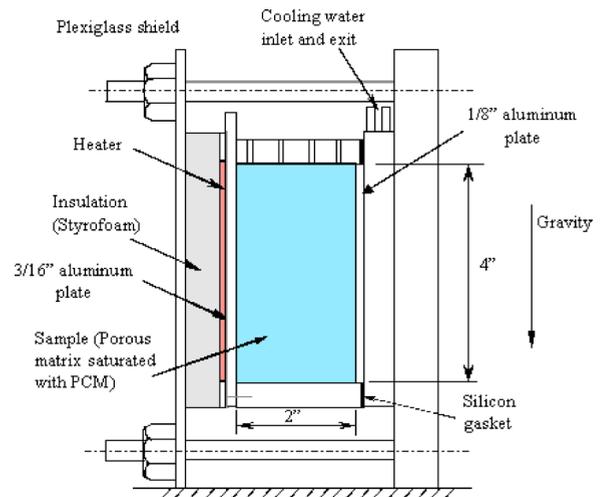
TABLE III. Thermophysical properties of paraffin wax.

Property	Value
Density [kg/m³]	740–820
Latent heat [kJ/kg]	155–157.5
Specific heat [kJ/kg K]	2.0–3.0
Melting temperature [°C]	25.5–28.9
Thermal conductivity [W/mK]	0.15–0.25
Viscosity at 50 °C [cp]	3.0
Thermal expansion coefficient [1/K]	0.000 12

side of the sample using a very thin silicon layer and tightened using screws. Another aluminum plate of thickness 1/8 in. was used to cover the container from the right side.

To seal the enclosure from the right side upon tightening, a thin silicon gasket was placed between the cold plate and the plexiglas. The composite sample was heated from the left side using a heater with heat being dissipated from the right side using an aluminum plate cooled by flowing water (heat sink). A sufficient space was allowed at the top, and some holes were made at the top plexiglas plate to allow the expected volume change during melting, and to insert the thermocouples from the top plate into the foam material.

The heater and the heat sink were attached to the left and right aluminum plates, respectively, using thermal paste to minimize the thermal contact resistance. A highly conductive silicon paste (thermal conductivity=2.5 W/mK) was used as the thermal paste. While conducting the experiments, the side walls of the container were insulated by Styrofoam plates. The insulation from the front side was removed for about 30 s for taking photos at different times through the test.

A total of 24 k-type thermocouples were used. Seven thermocouples were attached to the left side of the heater using thermal tape, while five thermocouples were attached in the thermal paste layer between the right aluminum plate and the heat sink. The rest of the thermocouples were attached inside holes made in the foam material using fine plastic tubes to prevent their expected motion during the test. The thermocouples used to monitor the temperature inside the foam material were arranged in three levels; four at the top 0.66 in. from the top surface of the foam, four in the middle plane, and four at 0.66 in. from the bottom surface. The locations of all the thermocouples and their numbers, which will be used throughout this thesis, are shown in Fig. 3.

An interface visual basic program was developed to acquire the data from thermocouples and record it in spreadsheet format on the computer. The thermocouple readings were sampled by a rate of 100 samples per second per channel and averaged to record a single reading. Time intervals of
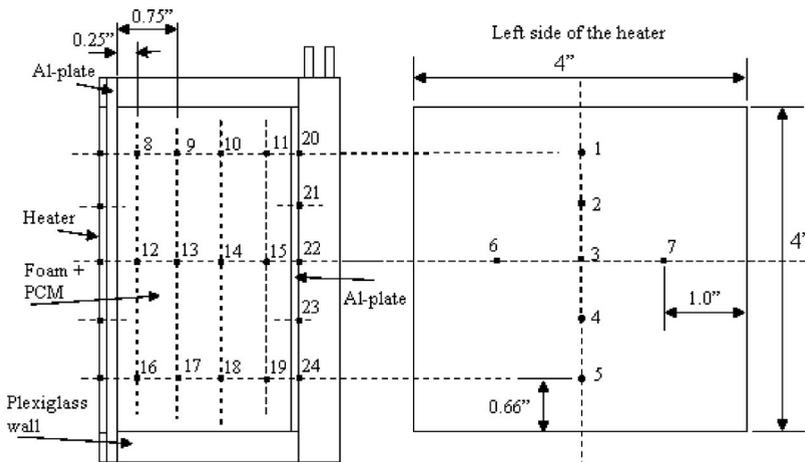
FIG. 3. Thermocouple locations.

three seconds were set for all the data acquisition. The thermocouple readings were calibrated against a mercury thermometer and it was found that the thermocouple readings were accurate within ±0.2 °C in the temperature range from 0 to 100 °C.

Before the experiment, the thermocouples at the lower plane of the foam were fixed inside the foam, and the foam was placed inside the enclosure. Then, the enclosure was slowly filled with molten PCM. In all the experiments, the heater power supply was set to 50%, which produced about 28.9 W.

C. Experimental results

The liquid-solid interface was traced by direct observation through the transparent plexiglas sides. A high-resolution digital camera was fixed in a suitable position in front of the test rig. After the highest temperature recorded by the thermocouples reached the melting point of the PCM, a photo shot was taken every certain time interval.

The experimental results were extracted in terms of temperature-time history at different locations of the experimental setup as well as snapshots of the liquid-solid interface

at selected time intervals. The liquid-solid interface for different aluminum foam porosity and with the same pore size is shown in Fig. 4.

At the beginning of the melting process, a thin layer of PCM melted and this layer grew thicker with time. Due to the temperature buildup in the vicinity of the heated wall, the hotter layer near the wall moved upward due to buoyancy effect and turned to impinge on the solid-liquid interface in the top region. This accelerated the melting process at the top more than at the bottom region. The lower thermal conductivity and the higher permeability of the lower density foam increased the temperature buildup near the hot surface and decreased the liquid motion resistance inside the porous structure, respectively. Due to these two effects as observed from the shape of liquid-solid interface, the effect of convection motion was more pronounced for the higher porosity foam [Fig. 4(a)]. Conversely, for lower porosity foams the convection motion of the liquid phase became very small and the interface shape remained nearly straight [Fig. 4(b)].

Another important point to be noted is, for higher density foam with a porosity of around 88.4%, the interface region became very thick [Fig. 4(c)]. This could be noticed from the color change between the pure liquid region and the pure solid region. This happened due to the high thermal
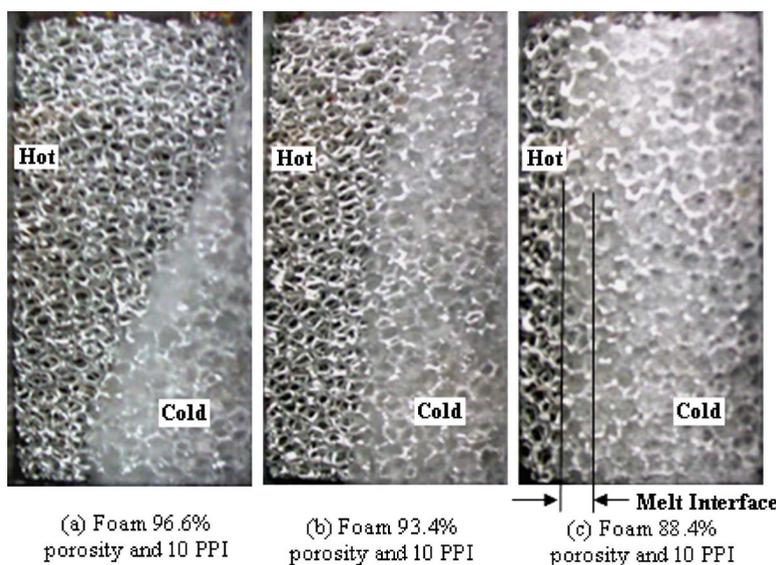

FIG. 4. (Color online) Liquid-solid interface at time =75 min from applying the heat for different porosity aluminum foam.
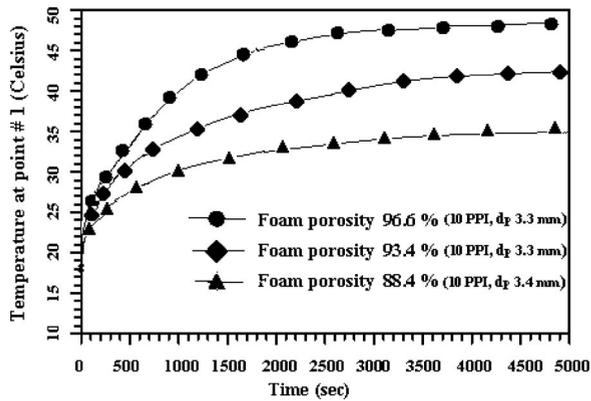
FIG. 5. Heater temperature-time history for different porosity Al foam.

FIG. 7. Temperature-time history for different pore size foams.

conductivity of this foam, so the heat diffusion inside the foam material became faster than the heat exchange with the PCM. By examining the temperature-time history of the heater, it was found that using lower porosity foam lower heater temperature were obtained as shown in Fig. 5 but, for the higher porosity foam, the steady-state temperature was reached faster due to the higher effect of liquid phase convection motion.

As defined in the literature,[13] permeability is the fluid conductivity of the porous material and is roughly a measure of the mean square pore diameter in the foam material. Peak *et al.*[14] has shown that for a fixed porosity permeability of foam material increases with the increase in its pore diameter. Due to this reason, it was observed that the liquid-solid interface became more flat as the pore size decreased as shown in Fig. 6.

The quantity of the molten wax seemed to be greater for smaller pore sizes, which means that the ability of smaller pore size foams to reject the heat generated inside the heater to the cooling plate is lower than that for larger pore size foams. Hence, it was observed that for a fixed porosity the steady-state temperature was reached faster in case of the bigger pore size foams as shown in Fig. 7. Increasing the wax viscosity or decreasing foam pore size showed the same results. Reducing the pore size as mentioned before is reduc-
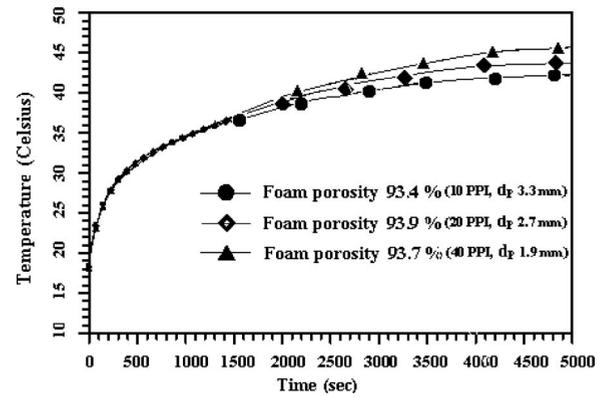
ing the permeability of the foam and consequently the liquid phase convection motion. Also, increasing the viscosity of the wax liquid phase increases the viscous resistance to the liquid phase motion.

Based on the results from Figs. 4–7, the following conclusions can be made. In order to have a wax/foam composite which can dissipate heat quickly and at the same time have lesser heat accumulation on the heater side, a balance needs to be reached regarding the selection of foam porosity and pore size. From the different porosity and pore size foams analyzed in this study, it can be said that an optimal aluminum foam would be corresponding to a foam porosity of 93.9% and 20 PPI. By selecting such a foam with optimum parameters, maximum advantage of both conduction (due to high thermal conductivity of foam material) and convection (due to greater melting of wax within pores) effects can be utilized. The wax/foam composite with optimized foam and wax properties can prove to be extremely efficient as a heat sink for thermal management applications.

III. CONCLUSIONS

Experimental investigation was carried out to study the heat transfer phenomena and solid-liquid PCM phase transition inside high thermal conductivity foams. A test rig was
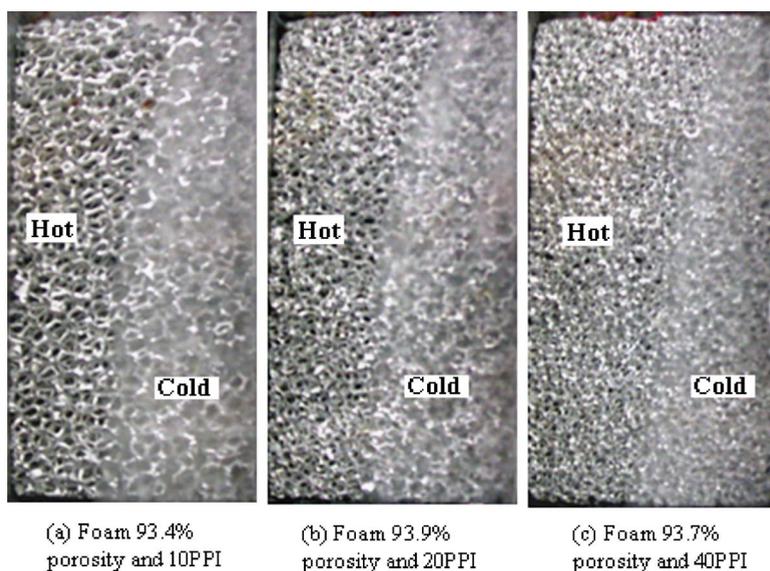

FIG. 6. (Color online) Liquid solid interface at time =80 min from applying the heat for different pore size aluminum foams.

(a) Foam 93.4% porosity and 10 PPI

(b) Foam 93.9% porosity and 20 PPI

(c) Foam 93.7% porosity and 40 PPI

built to analyze the PCM/foam composite phase change process. Aluminum foams were used as the porous material, and low melting temperature paraffin wax was used as the PCM. It was observed from the results that the system parameters of the wax/foam composite had a significant influence on its heat transfer behavior. By using higher porosity or bigger pore size aluminum foams, the steady-state temperature was reached faster as compared to foams with lower porosity or smaller pore size. This was due to the greater effect of convection in both higher porosity and bigger pore size foams. However, for the lower porosity foams the heater temperature was comparatively lower than the higher porosity foams due to greater heat conduction through foam material. Thus, an optimal value should be selected for the foam porosity and pore size to utilize maximum advantage of both conduction and convection effects in wax/aluminum foam composites. The current work will be extended into a detailed parametric study using a numerical procedure based on the requirements of a specific thermal management application.

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