Applied Thermal Engineering 128 (2018) 966–972

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Transient performance of a PCM-based heat sink with a partially filled metal foam: Effects of the filling height ratio

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HIGHLIGHTS

- A metal foam was partially filled to improve performance of a PCM-based heat sink.
- Transient performance of the heat sink was tested in terms of filling height ratio.
- Pore size and heating power effects were also examined as two influencing factors.
- Filling effectiveness was defined to assess trade-off between performance and cost.
- Better comprehensive performance can be attained using partial filling strategy.

ARTICLE INFO

Article history:
Received 6 August 2017
Revised 1 September 2017
Accepted 10 September 2017
Available online 11 September 2017

Keywords:
Heat sink
Metal foam
Partial filling
Phase change material
Thermal management

ABSTRACT

In this Short Communication, the transient performance of a phase change material (PCM)-based heat sink filled with a copper foam was experimentally studied. Attention was paid to revealing the influence of filling height ratio of the copper foam on the performance. The effects of pore size of the copper foam and the heating power were also studied parametrically. The results showed that the PCM-based heat sink could inhibit the temperature excursions during the heating period, and that the performance could be improved almost monotonously with increasing the filling height ratio. However, the performance improvement was found to become saturated approaching the full-filling case, regardless of the pore size and heating power. A new parameter, i.e., the filling effectiveness, was defined to help make a trade-off analysis between the performance gain and cost saving. As can be assessed by the filling effectiveness, the 2/3 partial filling was demonstrated to be more economical than full filling because the save in cost of materials and system weight is obvious with only a negligible sacrifice in the gain of performance improvement. The results suggested that the partial filling strategy can be applied to attain a better comprehensive performance of PCM-based heat sinks.

1. Introduction

The integration of a phase change material (PCM) into traditional heat sinks has long been studied and implemented as a passive thermal management technology for microelectronics [1]. By taking advantage of the latent heat thermal energy storage (LHTES) during melting of PCM, such passive technology is suitable for cooling of electronic devices working under transient modes, i.e., damping of oscillatory temperature variations upon a periodic heat load and inhibition of temperature extrusions upon a pulsed heat load. The application of this technology has already been extended to the areas of cooling of Li-ion batteries and photovoltaic modules [2].

A great number of experimental and numerical efforts have been dedicated to improving and optimizing the performance of PCM-based heat sinks under specific conditions [3–10]. The effects of various factors have been investigated parametrically, including heating mode [3], geometric design [5], PCM selection [6] and filling [7], system orientation [8], and so on. Due to the low thermal conductivity of the pertinent PCM candidates, e.g., paraffins, in the temperature range of interest, thermal conductivity enhancement (TCE) has always been the major concern for PCM-based heat sinks [11] and general LHTES scenarios [12]. Among the variety of

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http://dx.doi.org/10.1016/j.applthermaleng.2017.09.047
1359-4311/

Nomenclature

h	height of the metal foam (mm)
H	height of the composite PCM (mm)
t	time (s)
T	temperature (°C)
R	ratio
Greek symbols	
ε	filling effectiveness
Subscripts	
0	case with filling height ratio of 0
1	case with filling height ratio of 1
f	filling height
i	improvement
p	protection

TCE schemes available [12], the introduction of extended surfaces like metal foams [4] and fins [6,7] as well as discrete particles like carbon nanotubes and graphite nanoplatelets/nanofibers [4,9], has been attempted for PCM-based heat sinks. A direct comparison suggested that the use of metal foams is preferred due to their more effective performance improvement when compared to discrete enhancers [4]. Upon embedding a metal foam into the heat sink, heat transfer during melting of the PCM is enhanced to a great extent [13,14], with a pronounced growth in effective thermal conductivity of the composite PCM [15]. When fins are used in PCM-based heat sinks, geometric parameters such as shape, thickness, height and spacing could be optimized for heat transfer enhancement [7]. Similarly, an optimization problem is posed while using metal foams because the heat transfer enhancement is strongly dependent on the material [16], porosity and pore size of the metal foams adopted [17]. Although metal foams can enhance the effective thermal conductivity of PCM, Qu et al. [17] pointed out that the presence of porous metal skeleton and the confinement of PCM in small pores would weaken significantly the natural convection during melting of PCM at the same time. Moreover, increasing the amount of metal foam will decrease unfavorably the LHTES capacity of PCM-based heat sinks [15].

In a recent work, a partial filling method has been proposed for the optimization of melting performance of a LHTES system filled with metal foam, where the PCM is encapsulated in a concentric-tube type unit [18]. As inspired by such partial filling strategy, this Short Communication is concerned with the transient performance of a PCM-based heat sink in the presence of a partially filled metal foam. A comparative study will be conducted in terms of the filling height ratio of the metal foam, allowing a trade-off evaluation between the performance gain and cost saving.

2. Experimental

2.1. Experimental setup

An experimental setup for testing the transient performance of a PCM-based heat sink was designed and constructed. As schematically shown in Fig. 1, the test rig mainly consists of an aluminum heat sink, an integrated heating unit and other auxiliary components. The rectangular container had inner dimensions of $70 \times 70 \times 25\ mm^3$ and a wall thickness of 5 mm. A PCM was enclosed in the heat sink to reach a height $H = 20$ mm. The container was not fully filled to reserve a space for accommodating volume expansion of the PCM upon melting. A commercially-available paraffin (RT40), supplied by Hangzhou Ruhr New Material Technology Co., Ltd, was chosen as the PCM in this study. Using a differential scanning calorimeter, the peak melting point and latent heat of fusion of the paraffin were determined to be ~46 °C and 121 kJ/kg, respectively.

As illustrated in Fig. 1, two types of copper foams having nominal pore sizes of 15 ppi and 30 ppi, supplied by Suzhou Jiashide Metal Foam Co. Ltd, were adopted as the TCE. The porosity of both

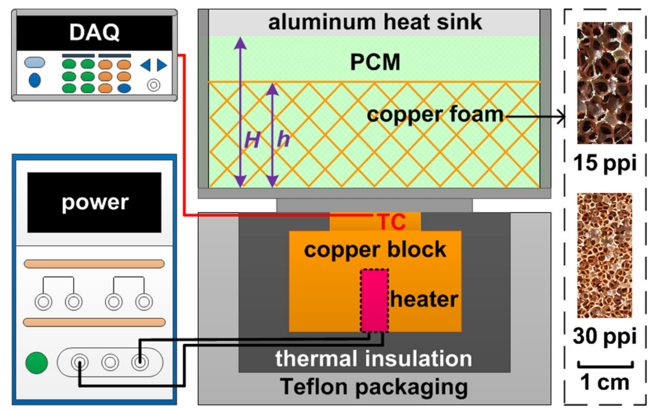

Fig. 1. Schematic diagram of the test rig of the PCM-based heat sink with a partially filled metal foam.

copper foams was almost constant at ~96% [19]. The copper foam samples were trimmed to have a cross-section of $70 \times 70\ mm^2$, allowing a match to the rectangular container. The copper foam samples were always positioned at the bottom of the container, and their height h was varied between 0 mm (no foam) and 20 mm (height of the PCM sample). The filling height ratio was defined by $R_f = h/H$.

The assembly of the integrated heating unit, which was placed underneath the heat sink, can be clearly seen in Fig. 1. The core is a cylindrical copper rod having a diameter of 40 mm and a height of 60 mm, with inserted heaters. There is an extended neck (diameter of 20 mm) on top of the copper rod to provide a relatively high heat flux from this small surface area. A good thermal contact between the bottom surface of the aluminum box and the copper surface of the heating unit was ensured by applying a thermal grease. The copper rod was wrapped by a heavy insulation jacket to minimize heat losses. The entire heating unit was finally packaged in a Teflon shell.

Two levels of heating power were able to be generated by this heating unit, i.e., 40 W and 80 W, leading to nominal heat fluxes of $12.6\ W/cm^2$ and $25.3\ W/cm^2$, respectively, through the heating surface. As shown in Fig. 1, a type-T thermocouple (TC), which was mounted 0.5 mm below the heating surface of the copper rod, was used to represent the surface temperature of the heat source, i.e., the cooling target. The TC was calibrated to have an accuracy of ±0.2 °C prior to use, which was connected to a data acquisition system to record the temperature histories at a frequency of 1 Hz for all experiments.

2.2. Experimental procedure

Before running the experiments, the copper foam samples were cleaned in sequence with water, ethanol and acetone, followed by vacuum drying for 6 h at 105 °C and then natural cooling to the ambient temperature. The PCM/copper foam composite samples