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Heat-transfer characteristics of aluminum-foam heat sinks with a solid aluminum core

Wei-Hung Shih [a], Chin-Chia Liu [b], Wen-Hsin Hsieh [b,*]

[a] Medical Device Section, Medical Devices & Opto-Electronics Equipment Department, Metal Industries Research & Development Centre, Taiwan, ROC
[b] Department of Mechanical Engineering, National Chung Cheng University, Taiwan, ROC

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ABSTRACT

In the convective cooling processes of electronic components with metal-foam heat sinks, the waste heat generated by an electronic component passes through the heat sink wall (abbreviated as HSWALL) in contact with the electronic component and then into the metal foam. In this study, we increased the surface area of the HSWALL by vertically placing a solid aluminum cylinder in the center (i.e., core) of an aluminum-foam heat sink to enhance the cooling performance of the heat sink. The contact ratio (α), defined as the ratio of the surface area of the extended HSWALL to the solid–fluid interface area inside the aluminum-foam heat sink, was varied systematically to experimentally investigate the heat transfer characteristics under impinging-jet flow conditions. The experimental results showed the dominant heat-transfer mechanism changed when the contact ratio increased. When the contact ratio increased from 0 to 0.013, the Nusselt number first increased and then decreased. When the contact ratio was equal to 0.00676, the Nusselt number reached a maximum of approximately 2.2 times that of the sample without a core. The increase in the Nusselt number when $\alpha < 0.00676$ was caused by the increased surface area of the HSWALL and that the core allowed the cooling air to enter immediately the effective heat dissipation region near the surface of the core. On the other hand, the decrease in the Nusselt number when $\alpha > 0.00676$ was due to the fact that the area of the gas–solid interface of the aluminum foam was not sufficiently large to effectively transfer the waste heat from the core to the cooling air. The measured temperature distributions showed the existence of a local thermal equilibrium when α was greater than 0.00676, and a non-local thermal equilibrium when α was less than 0.00676. This change from a local to a non-local thermal equilibrium was caused by the reduced solid–fluid interface area resulting from the reduced aluminum-foam volume at larger contact ratios. The measured Nusselt number was found to increase with increases in both the overall height and the outlet height of the heat sink.

1. Introduction

In recent years, the amount of heat per unit volume that must be dissipated in electronic products has increased substantially because electronic devices are being constantly reduced in volume while performing more functions. Metal-foam heat sinks have an excellent ability to remove waste heat because of their large heat transfer surface area per unit volume and high degree of thermal dispersion due to irregular flow through the pores of the metal foam. In its convective cooling process, the waste heat generated by an electronic component passes through the heat sink wall (abbreviated as HSWALL in this work) in contact with the electronic component and then into the metal foam. Previous research has shown that the heat transfer performance of aluminum-foam heat sinks is better than that of finned heat sinks [1–21]. Most of these studies [1–17,20] investigated the heat transfer performance when the direction of the cooling air was parallel to the waste-heat-generating surface and some of them noted that the heat transfer in metal foam occurs mostly in a thin layer of foam adjacent to the heated surface. The numerical study in Betchen et al. [1] showed that most of the heat transfer occurs in a thin layer of foam adjacent to the heated surface. Only very thin layers of aluminum foam are required. Therefore, finned metal foam heat sink was introduced. Bhattacharya and Mahajan [2] presented experimental results on forced convective heat transfer in finned metal foam heat sinks. The heat sinks were made of 1–4 aluminum fins and aluminum-foams filled between two fins. The forced convection results show that heat transfer is significantly enhanced when fins

* Corresponding author at: Department of Mechanical Engineering, National Chung Cheng University, Chia-Yi 621, Taiwan, ROC. Tel.: +886 5 2720411x23355; fax: +886 5 2720589.

E-mail address: imewhh@ccu.edu.tw (W.-H. Hsieh).

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Nomenclature

D	pipe diameter of the air inlet pipe, mm
D_{in}	diameter of the central solid cylinder, mm
D_p	equivalent spherical diameter, mm
d_p	mean pore diameter, mm
k_e	effective thermal conductivity, W/m-°C
H	overall height of the heat sink, mm
H_{out}	height of the outlet, mm
A_f	specific area per unit geometric volume of the aluminum foam, m^2/m^3
A_{heat}	the total area of the heated surface, base plate and central cylinder, in contact with the aluminum foam, m^2
A_{sf}	contact area between solid and air inside the aluminum-foam, m^2
S_v	specific area per unit solid volume of the aluminum foam, m^2/m^3
Nu	Nusselt number
PPI	pore density
Re	Reynolds number
Q	flow rate, m^3/s
q	waste heat transfer, W
$\dot{q}$	heat flux through the bottom of the aluminum foam heat sink, W/m^2
T	temperature, K
U	fluid velocity, m/s
I	electric current, A
V	volt, V
z	position along the axial direction, mm

Greek

α	contact ratio
μ	viscosity, $N\text{-}s/m^2$
ε	porosity
Δ	difference

Subscripts

air	air properties
e	estimate
f	fluid
outlet	outlet condition
inlet	inlet condition
s	solid
∞	ambient condition

are incorporated in metal foam. DeGroot et al. [3] showed a numerical study to explore the details of forced convection heat transfer in finned aluminum foam heat sinks with local thermal non-equilibrium condition. These works [1–3] on the finned metal foam heat sinks were concerned with the overall heat transfer performance under the conditions that the flow direction was parallel to the waste-heat-generating surface.

On the other hand, several studies [19,18,21–33] have shown that the cooling performance of a metal foam heat sink is enhanced when the direction of the cooling air flow is perpendicular to the waste-heat-generating surface (referred to as the impinging-jet flow condition in this paper). In the investigation of the overall heat transfer performance, Jeng and Tzeng [26] experimentally studied heat transfer associated with a cooling air jet impinging on a rotating heat sink. Hsieh et al. [27] experimentally investigated the Nusselt number for an impinging jet using six different aluminum-foam heat sinks, and they found that the Nusselt number increased as the porosity, or pore density, increased. The local thermal non-equilibrium condition became less prevalent as the Reynolds number and the distance from the heated surface increased.

Similar to these works [1–3] on the finned metal foam heat sinks under the conditions that the flow direction was parallel to the waste-heat-generating surface, some numerical [28–32] and experimental [33,34] investigations on the metal foam heat sinks under the impinging-jet flow conditions also noted that most of the waste heat dissipated in a convective manner into the cooling air flowing in the region near the HSWALL [28–34]. Numerically, Fu and Huang [28] investigated the heat transfer characteristics of porous blocks of various shapes (rectangular, convex and concave) under impinging-jet conditions. Saeid and Mohamad [29] simulated impinging-jet cooling of a porous medium under mixed-convection conditions assuming local thermal equilibrium, rectangular coordinates and constant wall temperature. Sivasamy et al. [30,31] presented two numerical cases in the mixed convection regime under impinging jet: a constant heat flux horizontal surface immersed in a confined porous channel and an isothermal horizontal surface immersed in an unconfined porous medium. Jeng and Tzeng [32] numerically investigated the confined slot jet impinging cooling of porous metallic foam heat sink with local non-thermal equilibrium model. The results of the above numerical studies all showed that the isotherms had higher negative gradients near the heat source and the heat transfer was strongly affected by the fluid flow near the heated region.

In the experimental study of Shih et al. [33], the effect of the height of the aluminum-foam heat sink was investigated. The authors discussed the two conflicting effects of height on the cooling performance of aluminum-foam heat sinks. Their results indicated that decreasing the height of the aluminum-foam heat sink caused its cooling performance to first increase and then decrease. The increase in cooling performance was caused by the increased percentage of cooling air reaching the upper surface of the waste-heat-generating block because of the reduced flow resistance. The decrease in the cooling performance was primarily caused by the reduction in area for heat transfer to occur between the cooling air and the solid portion of the aluminum-foam heat sink. Subsequently, Shih et al. [34] experimentally investigated the enhanced cooling performance of aluminum-foam heat sinks achieved by reducing the area of the flow outlet under impinging-jet flow conditions. By varying the height of an annular, flow-restricting sleeve surrounding the foam, the outlet area for the flow through the aluminum-foam sink could be controlled. Their results showed that the Nusselt number increased as the height of the flow outlet was decreased, which forced more cooling air into the effective heat dissipation region near the HSWALL. These studies [33,34] both implied experimentally more information by measuring the z-axial air velocity, solid- and fluid-temperature distributions near the perimeter of the aluminum foam, and their results indicated that the effective heat dissipation region of the aluminum-foam heat sink under impinging cooling was also limited to the region near the HSWALL.

In order to enhance the cooling performance of an aluminum-foam heat sink under impinging-jet flow conditions, one can enlarge the effective heat dissipation region by increasing the surface area of the HSWALL and guide as much cooling air as possible to the effective heat dissipation region. In this study, the surface area of the HSWALL was increased by vertically placing a solid aluminum cylinder in the center of an aluminum-foam heat sink