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Heat transfer characteristics of aluminum metal foam subjected to a pulsating/steady water flow: Experimental and numerical approach

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ABSTRACT

The microminiaturization of electronic components has led to an increase in the heat dissipation rate (per unit area) of electronic chips. This paper presents the results of an experimental and numerical study of the use of aluminum foam as a heat sink for the Intel core i7 processor. The aluminum foam was subjected to a pulsating water flow with a frequency range between 0.04 and 0.1 Hz, an amplitude range between 297 and 1353, and a heat flux range between 8.5 and 13.8 W/cm^2. The distributions of the cycle average local surface temperature over the heater representing the electronic surface and cycle average local Nusselt number were measured and compared with the numerical data obtained using the finite element method. The numerical results were in good agreement with the experimental data for different flow amplitudes and heat flux within a maximum relative error of 0.75% for the local temperature and 1.8% for the local Nusselt number. The pressure drop across the aluminum foam heat sink was measured and the effects of the dimensionless flow frequency and the flow amplitude on the heat transfer characteristics of the pulsating flow through the aluminum foam were analyzed. An empirical correlation of the average Nusselt number as a function of the dimensionless flow frequency and flow amplitude was developed. A comparison between the heat transfer characteristics of the steady and pulsating water flows was also conducted. The experimental results revealed that the cycle average local temperature decreases along with decreasing heat flux, increasing the pulsating flow frequency and amplitude. The local temperature distribution shows a convex profile due to the reversing flow and development of a boundary layer. Results also revealed a 14% increase in the average Nusselt number for pulsating flow when compared to the steady flow. Lastly, the thermal performance of the aluminum foam heat sink was evaluated. The experimental result revealed a 73% decrease in the uniformity index for pulsating flow when compared to the steady flow, indicating that the pulsating water flow leads to a more uniform temperature distribution. This finding is very important to the field of electronic cooling since the reliability of transistors and the operating speed are dependent upon temperature uniformity along the surface.

1. Introduction

Electronic devices are part of our everyday lives, from toys and appliances to high speed computers. The overall efficiency of electronics is controlled primarily by the efficiency of particular electronic components. The recent acceleration in the design of modern high speed computers has led to a demand for new and more effective methods of electronic cooling. Electronic components depend on electrical currents passing through resistance in order to perform their duties. This is accompanied by heat flux dissipation. The continuous developments in the design of electronic chips have resulted in an increase in the amount of heat generated per unit of volume. These days, it is not unusual to see a 3 cm × 3 cm chip with several million components. The international technology road map for semiconductors reported that the heat flux of chips reached 520 W/cm^2 in 2011 [1]. The failure rate of electronic devices increases exponentially with increases in temperature. In addition, the high thermal stress on the solder joints of electronic component mounted on the circuit boards resulting from temperature variations is one of the major causes of electronics failure. Traditional free or forced convention cooling methods are only capable of removing small amounts of heat flux, making it imperative to search for new methods of cooling high-speed electronic components.

In order to enhance the heat transfer rate of modern high speed electronic devices, researchers have conducted extensive investigations using different shapes and arrangements (single or multiple square, rectangular and circular modules (rods)) mounted on

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Nomenclature

q''	heat flux (W/cm^2)
Nu_x	local Nusselt number
$Nu_{,avg}$	average Nusselt number of pulsating flow
Re_w	kinetic Reynolds number
U	velocity fields (m/s)
K_b	permeability (m^2)
k_f	thermal conductivity of fluid
d_f	ligament diameter (m)
k_s	thermal conductivity of solid (W/m K)
K_{eff}	effective thermal conductivity (W/m K)
T_x	local surface temperature (°C)
$f_{friction}$	fanning friction factor
T_{in}	inlet water bulk temperature (°C)
h_x	local heat transfer coefficient (W/m^2 K)
A_o	pulsating flow amplitude
$Nu_{,avg,s}$	average Nusselt number of steady flow
F	body force (N)
D_e	hydraulic diameter (m), $D_e = \frac{4 * Cross\ section\ area}{Wetted\ perimeter}$
T^*	dimensionless temperature $\left[T^* = \frac{T - T_{in}}{q'' * \frac{D_e}{K_{eff}}}\right]$
x^*	dimensionless flow direction axis, $x^* = \frac{x}{D_e}$
ΔP	pressure difference (Pa)
$I_{efficiency}$	thermal efficiency index

Greek Symbols

ρ	density (kg/m^3)
C_p	specific heat (J/kg °C)
ε	porosity
υ	kinematic viscosity (m^2/s)
β_f	Forchheimer coefficient
μ	dynamic viscosity (Pa s)
$\eta_{uniformity}$	uniformity index

the heated surface in order to attempt to increase the surface to volume ratio of heat sinks. Buller and Kilburn [2] investigated the convective heat transfer using a single rectangular module (rectangular rod). Sparrow et al. [3,4] used different arrangements of square modules and studied the effect of missing modules. They found that the heat transfer coefficient increased by 40% when the missing module located upstream. Sparrow et al. [5] then investigated the heat transfer characteristic using different module heights. Jubran et al. [6] conducted an experimental investigation of the effect of module size and the presence of cylindrical modules or missing modules on heat transfer and pressure drop across the array.

Igarashi et al. [7] used circle modules mounted on the walls of parallel channels. They found that the separation of the flow caused a 10% reduction in the Nusselt number in the first row compared to the second to fifth rows. Iwasaki and Ishizuka [8] calculated the optimum value of fin spacing or the fin thickness of plate fins for a notebook personal computer heat sink and developed an empirical equation for the average Nusselt number. As one can see, many studies have been conducted using various types of heat sinks for electronic cooling, either extending the surface area or increasing the fluid flow. Despite this research, there still exists a demand for more effective electronic cooling methods. Gochman et al. [9] reported that the heat dissipation of desktop and mobile processors is 100 W and 30 W, respectively.

The use of metal foam as a heat sink is a new technique used to enhance the heat transfer rate of the surface of electronics. Metal foam is a class of porous material with a low density and novel thermal, electrical, mechanical and acoustic properties. Many studies have investigated the effect of microstructure properties such as porosity, relative density, pore density, pore size, ligament diameter, and permeability on the heat transfer characteristics of metal foams [10–15]. Boomsma and Poulikakos [16] studied the thermal conductivity of ERG aluminum foams. Klett et al. [17] compared the heat transfer characteristics of the foam radiator with the fin radiator. They found that foam radiators transfers heat an order of magnitude better than fin radiators. Kim et al. [18] compared the aluminum metal foam heat sink with the conventional parallel plate heat sink. They observed an increase in the heat transfer when using the aluminum metal foam heat sink.

Mahajan and Bhattachatya [19] introduced the high porosity metal foam into the air gap between two longitudinal fins. In their research, Ding et al. [20] and Bai and Chung [21] studied the heat transfer characteristics of copper foam. They found that the use of copper foam as a heat sink greatly increases the heat transfer coefficient. In their study, Tzeng et al. [22] and Fu et al. [23] determined the local and average heat transfer characteristics of sintered bronze bead and aluminum foam subjected to forced air flow and observed that the wall temperatures increase with increasing axial flow direction distance.

Boomsma et al. [24] observed that the thermal resistance of the compressed foam heat exchanger is two to three times lower than that of other heat exchangers using water flow through metal foam. Noh et al. [25] conducted an experimental study of non-Darcy water flow in an annulus filled with high porosity aluminum foam and presented the correlations for the average Nusselt number and friction factor. Hetsroni et al. [26] conducted an experimental study of the transmission window cooling technique of an accelerator using aluminum foam.

The local temperature over the surface is more important than the average temperature for electronic cooling applications. Fu et al. [23] observed a 60 °C surface temperature difference when using steady air flow through ERG aluminum foam. This indicates that a steady flow through metal foam yields a high local surface temperature. For modern high speed computers, the operating speed and reliability of transistors depend not only on average surface temperatures, but also on temperature uniformity over the surface. Hot regions can affect the performance of electronics due to prolonged gate delay.

It is conceivable that the pulsating flow will produce a more uniform surface temperature than the steady flow due to the reversing flow (there are two entry regions). Khodadadi [27] solved the problem of pulsating flow through porous media analytically under the assumption of creeping flow. They found that the pulsating flow depends on the shape parameters of the porous media and the stokes number. Leong and Jin [28,29] and Fu et al. [23] conducted an experimental investigation of the heat transfer characteristics of aluminum metal foam subjected to pulsating air flow. The researchers measured the surface temperature distributions, pressure drop across the metal foam, and flow velocity inside of the foam. They also analyzed the effects of the dimensionless amplitude and frequency. They observed a higher average Nusselt number for pulsating flow when compared to the steady flow. The results also revealed that the heat transfer enhancement of the pulsating flow increases as the dimensionless amplitude and dimensionless frequency increase.

Paek et al. [30] conducted an experimental study of pulsating flow through packed spherical beads. They observed a small effect