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Hotspot thermal management using a microchannel-pinfin hybrid heat sink

Danish Ansari, Kwang-Yong Kim*

Department of Mechanical Engineering, Inha University, 100 Inha-Ro, Nam-Gu, Incheon, 22212, Republic of Korea

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ABSTRACT

An energy-efficient micro heat sink is presented for the thermal management of microprocessors with heterogeneous power distributions. The performance of the proposed microchannel-pinfin hybrid heat sink was evaluated numerically and compared with that of a simple microchannel heat sink. The hybrid heat sink was designed with two separate zones: rectangular microchannels were used over the low-heat-flux zone (background area), and an array of cylindrical pinfins were incorporated over the high-heat-flux zone (hotspot area) of the heat sink. Conjugate heat transfer analysis was performed by solving the three-dimensional Navier-Stokes and energy equations with the temperature-dependent thermophysical properties of the fluid. The thermal resistance, pumping power, temperature non-uniformity, and maximum temperature rise at the hotspot were selected as the performance parameters. The hybrid heat sink exhibited remarkable improvement in the thermal performance compared to the non-hybrid heat sink with a reasonable increase in the pumping power.

1. Introduction

The first microprocessor developed by the Intel Corporation in 1971 had only 2300 transistors [1]. Following the roadmap predicted by the Gordon Moore [2], this number has risen to 5.4 billion [3]. The increase in the design complexity and dynamic power dissipation in a single-core processor has pushed microprocessor design architectures toward multicore technology [4,5]. The heat flux generated at the cores is significantly higher than that in the remaining area (the background area) of the microprocessor. These high-heat-flux regions are known as hotspots. The large temperature gradient caused by the difference in the heat flux among the cores and the background area (which includes caches, a memory controller, input/output, and SMP bandwidths) [6] can reduce the efficient functional life of a microprocessor [7]. About 55% of the damage in electronic devices is caused by inadequate thermal management [8].

Air-cooling technology has reached its limits [9] and is not sufficient for present electronic devices with high heat dissipation requirements in a slim-form-factor design. Tuckerman and Pease [10] demonstrated the high heat transfer capability of a microchannel heat sink with a single-phase fluid flow in their pioneering work. Single-phase liquid cooling using microchannels [11–13] has become one of the widely explored cooling solutions for the next generation electronics, including micro-jet cooling [14], multiphase cooling [15], thermoelectric cooling [16], phase change material (PCM) [17], electroosmotic flow [18], and nanofluid [19–21].

Numerous studies have been performed to understand the flow phenomena inside microchannels using the conventional theory of fluid mechanics. Although some contradictions were reported for the transition from laminar to turbulent flow in microchannels [22,23], the conventional theory reasonably predicts the laminar and turbulent flows [24]. Liu and Garimella [25] experimentally analyzed the fluid flow in microchannels over a wide range of Reynolds numbers and compared the results with numerical results obtained using conventional theory. They concluded that the flow phenomena in microchannels could be reproduced well by the numerical simulation. To closely relate to the real phenomena, it is generally recommended to use temperature-dependent variable fluid properties in numerical studies [26,27].

For efficient performance of a silicon microprocessor, the junction temperature must be maintained below 100 °C [8,9]. If it exceeds the recommended temperature, the processor starts throttling to reduce the amount of heat generated, which limits its performance temporarily [28]. Generally, a heat sink is designed while assuming that a uniform heat flux is produced at the top surface of a microprocessor, and the performance of the heat sink is evaluated in terms of the thermal resistance or maximum temperature rise only. However, the temperature uniformity at the chip surface is equally important [7,29].

In actual conditions, the location and intensity of the hotspot vary with the processor usage [30], and the heat flux at the hotspots could be up to eight times higher than the average background heat flux [29,31]. Due to the large difference in the heat flux between the hotspots and

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* Corresponding author.

E-mail addresses: danishansari@live.in (D. Ansari), kykim@inha.ac.kr (K.-Y. Kim).

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background, it is not possible to maintain isothermal temperature conditions at the chip's surface with conventional uniform cooling techniques. If only the high heat flux at the hotspot is considered to design a heat sink, the background area of the chip would be unnecessarily overcooled, creating large temperature gradients. Moreover, it will reduce the heat sink's economic viability due to an increase in the pumping power. For an efficient thermal management of microchips with a non-uniform heat flux distribution (which includes all present high-performance processors), one of the best solutions is to design a heat sink with multiple zones using low cooling capacity for the background area and high cooling capacity for the hotspots.

Several studies have been presented in the area of microchannel cooling since its advent [10,11,13,15,19,21,22,24,25,27,32–35]. However, thermal solutions incorporating dedicated techniques to minimize large temperature variations due to the hotspots are relatively scarce. Attention is needed in this area to explore different approaches of non-uniform cooling, which is also known as the hotspot-targeted cooling, to maintain the junction temperature of a microprocessor near isothermal conditions. Most of the earliest studies for hotspot alleviation focus on the use of the Peltier effect to develop a hotspot-targeted solid-state thermoelectric cooling system [36–40]. However, thermoelectric cooling suffers from complex design, the limitations of contact parasitic resistance [37], and low coefficient of performance (COP) [39].

Recently, solutions for hotspot alleviation were proposed using microgaps [41–43], heterogeneous pinfin clustering [44,45], and manifold microchannel heat sinks [46,47]. The concept of local pinfin clustering suffers from the flow bypass effect, however, it can be minimized by using spanwise clustering at the expense of increased pressure drop [45]. Hybrid solutions combining different cooling techniques such as microchannel-thermoelectric [48], minichannel-thermoelectric [49], and microchannel-microjet [50] were reported with dedicated cooling techniques to manage the background and hotspot heat flux separately. Some of the previously presented hotspot investigations and management techniques are summarized in Table 1 [36–55].

Microchannel heat sinks and pinfin heat sinks are some of the widely explored liquid solutions due to their excellent cooling performance and relatively simple manufacturing. In the present study, a novel hotspot-targeted cooling technique combining microchannels and pinfins is presented for an efficient thermal management of microprocessors with heterogeneous power distributions. The proposed heat sink was designed with two separate zones (the background area and the hotspot area) with each zone having a different cooling capability. The design uses rectangular microchannels over the background area and an array of cylindrical pinfins over the hotspot area of the microprocessor. The performance was evaluated and compared with that of a simple rectangular microchannel heat sink. The hybrid heat sink concept was analyzed by considering only one hotspot at the center of a microprocessor due to computational limitations. However, application of the presented concept is not limited to single-core processors only and can be very easily adapted for multicore power maps.

2. Heat sink models

Fig. 1 shows diagrams of the non-hybrid rectangular microchannel (NH-RM) and proposed microchannel-pinfin hybrid (H-MPF) heat sink designs. Each heat sink design is composed of 20 microchannels. In the case of NH-RM design, the complete heat sink is composed of only rectangular microchannels for the cooling of the hotspot and the background area, as shown in Fig. 1(a). The geometric parameters of the hotspot (shown in red at the center of the heat sink) and microchannels are indicated in Fig. 1(a)-(c).

The proposed H-MPF heat sink (Fig. 1(c)) has two zones and uses microchannels for the background cooling and micro-pinfins with a circular cross section for the hotspot cooling. In the H-MPF heat sink, a 10 × 10 array of inline cylindrical micro-pinfins with a uniform height (Fig. 1(d)) was used over the hotspot area, and 20 microchannels were used for the background cooling. The pinfin's geometric parameters are shown in Fig. 1(d) and (e). The values of all geometric parameters of the microchannels, pinfins, and hotspot are listed in Table 2.

3. Numerical analysis

3.1. Numerical scheme and boundary conditions

Three-dimensional conjugate heat transfer analysis was performed using a robust general-purpose CFD code ANSYS CFX 15.0® [56]. Its solver engine uses an implicitly coupled multigrid technique [57] to solve the governing equations. Initial iterations are performed on a fine mesh and then on a virtually created coarser mesh. Finally, the fine mesh is used again to obtain accurate results. The coupled solver solves the entire set of hydrodynamic equations simultaneously, which reduces the convergence time. The calculations were considered to have converged when the normalized root-mean-square residual for each equation was less than 10^{-6}. The calculations were performed using fourth-generation Intel Core i7 processors (3.4 GHz) with 32 gigabytes of RAM.

Assumptions were made to simplify the calculations. The flow was considered to be steady, laminar (Reynolds number: 200 to 1000), and incompressible. The gravitational effect and heat transfer due to radiation were neglected. The steady-state governing equations for the conservation of mass, momentum, and energy in the fluid domain are expressed as:

3.2. Continuity equation

$$\nabla.\,(\rho_f \overline{V}) = 0 \tag{1}$$

Momentum equations:

$$\overline{V}.\,\nabla(\rho_f \overline{V}) = -\nabla p + \nabla.\,(\mu_f \nabla \overline{V}) \tag{2}$$

Energy equation:

$$\overline{V}.\,\nabla(\rho_f C_p T_f) = \nabla.\,(k_f \nabla T_f) \tag{3}$$

The energy equation in the solid domain is expressed as:

$$\nabla.\,(k_s \nabla T_s) = 0 \tag{4}$$

The performance of the heat sinks was evaluated in terms of the total thermal resistance, total pumping power, temperature non-uniformity, and maximum temperature rise at the hotspot. The total thermal resistance is defined as [10,34,58]:

$$R_{th,tot} = \frac{T_{s,\,max} - T_{f,\,in}}{Q_{tot}} \tag{5}$$

where $T_{s,\,max}$ and $T_{f,\,in}$ are the maximum temperatures at the base of the heat sink (solid) and fluid temperature at the inlet (300 K), respectively. Q_{tot} is the total heat applied at the base of the heat sink (solid), which is expressed as [34]:

$$Q_{tot} = q_{bg}A_{bg} + q_{hs}A_{hs} \tag{6}$$

where q_{bg} and q_{hs} are the heat fluxes applied at the background area and hotspot area of the heat sink, respectively. A_{bg} and A_{hs} are the background area (area of the base excluding the hotspot area) and hotspot area of the heat sink, respectively.

The total pumping power is expressed as:

$$P_{tot} = n_{ch}u_{avg}A_c\Delta p_{avg,ch} \tag{7}$$

where n_{ch} is the total number of channels, u_{avg} is the average inlet velocity of fluid, A_c is the cross-sectional area of a channel, and $\Delta p_{avg,ch}$ is the average pressure drop across a single channel. The pressure drops