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Assessment of an active-cooling micro-channel heat sink device, using electro-osmotic flow

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ABSTRACT

Non-uniform heat flux generated by microchips causes “hot spots” in very small areas on the microchip surface. These hot spots are generated by the logic blocks in the microchip bay; however, memory blocks generate lower heat flux on contrast. The goal of this research is to design, fabricate, and test an active cooling micro-channel heat sink device that can operate under atmospheric pressure while achieving high-heat dissipation rate with a reduced chip-backside volume, particularly for spot cooling applications. An experimental setup was assembled and electro-osmotic flow (EOF) was used thus eliminating high pressure pumping system. A flow rate of 82 μL/min was achieved at 400 V of applied EOF voltage. An increase in the cooling fluid (buffer) temperature of 9.6 °C, 29.9 °C, 54.3 °C, and 80.1 °C was achieved for 0.4 W, 1.2 W, 2.1 W, and 4 W of heating powers, respectively. The substrate temperature at the middle of the microchannel was below 80.5 °C for all input power values. The maximum increase in the cooling fluid temperature due to the joule heating was 4.5 °C for 400 V of applied EOF voltage. Numerical calculations of temperatures and flow were conducted and the results were compared to experimental data. Nusselt number (Nu) for the 4 W case reached a maximum of 5.48 at the channel entrance and decreased to reach 4.56 for the rest of the channel. Nu number for EOF was about 10% higher when compared to the pressure driven flow. It was found that using a shorter channel length and an EOF voltage in the range of 400–600 V allows application of a heat flux in the order of 10^4 W/m^2, applicable to spot cooling. For elevated voltages, the velocity due to EOF increased, leading to an increase in total heat transfer for a fixed duration of time; however, the joule heating also got elevated with increase in voltage.

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1. Introduction

Intensive computing devices are projected to generate heat flux values that can exceed 2.5×10^6 W/m^2 [1]. With these high-heat generation rates the conventional cooling techniques have been found to be inadequate. Instead of forcing air to flow over fins, liquid can be forced to flow through channels that are in contact with the devices' surface. Various methods are being used to drive a liquid through micro-channels, which include pressure driven techniques that use mechanical pumps or pressurized gases. Another approach is to use electro-osmotic flow pumping technique; this technique has no moving parts and needs less maintenance compared to mechanical pumps.

1.1. Electro-osmotic flow (EOF)

Solid surfaces develop a charge when brought into contact with an aqueous solution [2]. Due to the formation of surface charge, counter ions in the solution will be attracted toward the surface. The concentration of counter ions in the vicinity of the surface will be higher than in the fluid bulk, whereas co-ions concentration in the fluid bulk is higher than its concentration in the vicinity of the surface. The charged surface and the thin layer of counter ions that balances its charge are defined as the electric double layer (EDL) [2].

Ions in the vicinity of the charged surface are attracted to it and this restricts their motion (immobile ions). Ions away from the charged surface are not strongly affected by the charged surface. This leads to a higher mobility (mobile ions). When an electric field is applied between two points of the aqueous solution, the mobile ions start to move under the influence of the electric field. The ions motion drags other fluid particles due to viscous forces. This leads to a bulk fluid motion known as electro-osmotic flow.

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Nomenclature

A_{cross}	cross sectional area of the channel, m^2
B	bias error
DAQ	data acquisition system
DI	de-ionized
E	electric field, V/m
EDL	electric double layer
EOF	electro-osmotic flow
h	heat transfer coefficient, W/m^2 K
h_i	Cooling fluid (buffer enthalpy) at the channel inlet, J/kg
h_o	cooling fluid (buffer enthalpy) at the channel outlet, J/kg
m	mass, kg
p	pressure, Pa
P	precision error
PDMS	polydimethyl siloxane
T	temperature

u	internal energy, J/kg
$\vec{u}$	velocity, m/s
U	total uncertainty

Greek symbols

α_f	cooling fluid (buffer) diffusivity
ε	permittivity, C/V m
Φ	applied voltage, V
ψ	wall surface charge, C/m^2
μ	water viscosity, Pa s
λ	bulk conductivity, S/m
q	energy loss from the reservoir, J
ρ	density, kg/m^3
ρ_e	bulk charge density, C/m^3
ζ	zeta potential, V

Jiang et al. [3] designed a closed-loop two-phase micro-channel cooling system with an external EOF pump and a heat rejecter, a maximum of 7 ml/min coolant flow rate was achieved, with a chip temperature maintained less than 120 °C. Laser et al. [4] used the EOF through narrow deep micro-channels to reduce the temperature of the high-power density spots of microchips, 170 μL/min of coolant flow was achieved at 400 V of applied EOF voltage. Zhang et al. [5] tested a single micro-channel for the pressure distribution along the heating length and measured the temperature variations during the phase change, the flow was pressure driven using a syringe pump. Jung et al. [6] used a single micro-channel to study the heat transfer to nanofluids, and investigated the differences between nanofluids and pure water for convection heat transfer coefficient and friction factor. Eng et al. [7] designed an electro-osmotic flow silicon-based heat spreader that generated a coolant flow rate of 0.2 μL/min at 2 V/mm electric field; a 4 °C reduction in device temperature was achieved.

Tiselj et al. [8] studied the effect of axial conduction on heat transfer in micro-channels, where experimental and numerical approaches were adopted. It was shown that the bulk fluid and the channel walls' temperatures do not vary lineally along the channel. The most significant changes in the temperature gradient were reported in the axial flow direction. In the flow direction the effect of axial heat flux was maximum at the channel inlet and minimum at outlet. Yin and Bau [9] studied the performance of micro-heat exchangers theoretically. The micro-heat exchanger was optimized to achieve a minimum heat resistance. Gillot et al. [10] designed a micro-heat sink to handle the heat generated by a module of insulated gate bipolar transistor (IGBT); a thermal resistance of 0.08–0.12 K/W was achieved for the module of IGBT chips.

Sze et al. [11] measured the zeta-potential for an electro-osmotic flow in a parallel plate micro-channel. Using Smoluchowski equation and current time relationship, zeta potentials for glass and PDMS were evaluated. Husain and Kim [12] numerically studied the performance of an EOF driven flow and a pressure driven flow in a microchannel heat sink with wavy channels. The study showed an increase in heat transfer to the cooling fluid for the pressure driven flow due to recirculation. They found that applying EOF flow increased the flow rate but eliminated the effect of channel waviness due to its uniform flow profile. Dasgupta et al. [13] of our group studied the effects of the applied-electric field and micro-channel wetted-perimeter on electro-osmotic velocity. These numerical and experimental studies found that, as the wetted perimeter increases, the electro-osmotic velocity decreases, and the electro-osmotic velocity increases as the applied electric field increases.

Studies of heat removal techniques using fluid flow through micro-channels, reported in recent literature, can be classified into three main pumping categories, which are pressure driven pump, external EOF pump, and integrated EOF pump. These are identified by the type of technique used to drive the fluid flow through the micro-channels. In the case of pressure driven flow, fluid is forced through the channels by an external mechanical pump or compressed gas. An external EOF pump can also be used to drive the fluid flow through electrically charged micro-channels. The micro-channels of the heat removal device can itself be used as an integrated EOF pump. For devices that fall in the first two categories, there is the need for an external pump that occupies larger volume and needs higher power for its operation. For devices that fall in the third category, the electrically charged microchannels serve both as a heat exchanger and an integrated pump. Hence the volume and power requirement are reduced. The maximum heat flux removal capacity and the cooling fluid flow rate for the three categories vary. A brief comparison between the cooling capacities of the three categories is presented in the following paragraphs.

1.2. Pressure driven flow

A recent study by Chiu et al. [14] used a pressure driven flow which removed a maximum heat flux of 1.57×10^5 W/m^2. The maximum flow rate of the cooling fluid was 300 ml/min. In another study by Ornatskii and Viyarskii [15] the maximum heat flux removed using micro-channel fluid flow was 4×10^7 W/m^2. Due to the higher flow rates of the cooling fluid, pressure driven flows are typically capable of removing higher heat flux values. The convective heat transfer due to pressure driven flow is typically limited by the parabolic nature of the velocity profile in the developed region. Due to the size and power limitations of modern electronic devices, such pressure driven pump has major challenges because of the high operating pressure needing better sealing mechanism, larger pump size, and higher pumping power. The reliability of such a system with moving parts is a major operational issue.

1.3. External EOF pump

Using an external EOF pump Jiang et al. [3] removed a 3.8×10^5 W/m^2 of heat flux and achieved a maximum cooling fluid flow rate of 4 ml/min. This system eliminated the need of high pressure mechanical pump and replaced it with an EOF pump. While such external EOF pumping system can be more reliable

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