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Heat transfer performance of a fractal silicon microchannel heat sink subjected to pulsation flow

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ABSTRACT

Numerical simulation and experiment are conducted to study the heat transfer performance of a symmetrical fractal silicon microchannel network subjected to a pulsation flow. The distributions of pressure drop, temperature and the Nusselt number in the silicon microchannels are presented for different pulsation frequency. Compared to the steady flow case, the influences of pulsation frequency (0–40 Hz) and Reynolds number (1800–2800) on heat transfer enhancement are reported. For the low pulsation frequency (2–10 Hz) and high pulsation frequency (30–40 Hz), the heat transfer rate is higher than that for the moderate frequency (10–20 Hz) at the same Reynolds number. With the increase of the Reynolds number, enhancement factors decrease approximately from 40% to 5% for the investigated frequency range.

1. Introduction

Heat exchangers with microchannels are targeted for high heat flux applications such as electronics cooling [1]. Several techniques for heat transfer enhancement have been introduced to improve the overall thermal performance of heat exchangers resulting in the reduction of the heat exchanger size and the cost of operation [2–6]. The improvement of microchannel structure and fluid pulsation in microchannels are two main heat transfer enhancement techniques.

Fractal microchannel heat sinks are effective by increasing the convective heat transfer coefficient as well as the convective surface area per unit volume in the heat sink. Bejan [7] proposed a fractal-like bifurcating flow network and studied its flow performance. Chen and Cheng [8] first studied both heat transfer and pressure drop in the tree network. A comparison of it with the parallel channel structure shows that it has stronger heat transfer capacity and requires lower pumping power. Senn and Poulikakos [9] conducted a three-dimensional simulation for a tree-like net. Compared with a serpentine flow pattern, results showed that the tree net required only half the pressure drop and had a larger heat transfer capability for the same surface area and inlet Reynolds number. Although some researches were done on the fractal-like microchannel networks as presented by Refs. [10–14], the configuration designs were all different as a result of their specific applications. For example, in order to have a free circulation of the cooling fluid and an uniform heat transfer, the test section was designed to be composed of two microchannel networks resulting in more pressure loss.

The improvement mechanism of heat transfer performance in the fluid pulsation method promotes the turbulence near the channel wall surface to reduce the thermal boundary layer thickness and to produce a chaotic fluid mixing. Steinke and Kandlikar [15] proposed the pulsation flow in microchannel which could enhance single phase heat transfer aiding in electronics cooling. The flows were of special relevance to electronic systems which made it become a pulsation flow.

Persoons [16] investigated experimentally the potential for heat transfer enhancement using pulsating flow in a millimeter-scale heat sink in single-phase operation. Enhancement factors up to 40% are observed compared to the steady flow case. Kim [17] numerically investigated the pulsation flow and attendant heat transfer characteristics from two heated blocks in a channel.

Zohir [18] investigated the effect of pulsation frequency ranged from 0 to 40 Hz on heat transfer in a heat exchanger. Hot water (40–70 °C) was passed through the inner pipe with fixed mass flow rate while cold water was passed through the annulus with Reynolds number ranging from 2000 to 10,200 exposed to pulsation. The experimental results indicated the increase in heat transfer rate was about 14–90% for different pulsation frequency. Baird et al. [19] used a steam-water copper heat exchanger to test the

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heat transfer performance of a pulsation water flow for Reynolds number ranged from 4300 to 16,200. Frequency of pulsation ranged from 0.8 to 1.7 Hz while pulsation amplitude varied from 0.0274 to 0.335 m. The results showed a maximum enhancement of about 41% based on the overall heat transfer coefficient for Reynolds number of 8000. Shuai et al. [20] studied experimentally the effect of pulsed perturbation on convective heat transfer for laminar flow in a co-axial cylindrical tube heat exchanger of a viscous fluid. The flow pulsation was introduced by a reciprocating pump, located upstream of the heat exchanger. The pulses, obtained by strong-pulsed perturbations, significantly increased the heat transfer coefficient by more than 300%.

However, some numerical and experimental studies found enhancement factors of up to 11% for laminar [21] and 9% for turbulent pulsation flow [22] in smooth channels.

Although the fractal-like configuration and pulsation flow can enhance heat and mass transfer, few researches of heat transfer in a silicon fractal-like microchannel subjected to pulsation flow are reported to develop a new heat sink. To explore the performance of fractal silicon microchannel networks as heat sinks, an numerical and experimental investigation is performed to study heat transfer in fractal-like microchannel networks subjected to various pulsation frequencies. The surface temperature distribution, pressure drop and Nusselt number for different oscillatory frequencies and Reynolds number are analyzed and compared.

2. Design of the microchannel heat sink

Based on Murray's study on blood vessels [23], it has been found that there is an optimal size step (change in hydraulic diameter) at each paring node of the fractal-like networks such that the global flow resistance is minimized. It is given by [24]

$$D_{i+1}/D_l = n^{-1/3} \tag{1}$$

where D is the hydraulic diameter, and n is the number of branches into which each channel splits. For the present analysis, $n = 2, 3$. Subscript m denotes a low-order branching level and $i + 1$ denotes a higher-order branching level at a bifurcation. The first channel emanating from the center of the disk is the zeroth-order branch, $i = 0$. A typical schematic physical model is shown in Fig. 1.

As was done in Pence [24], the fractal-like microchannel nets in this study (Fig. 1(b)) can be characterized by the hydraulic diameter of each branch, d_k and length of each branch, L_k. k indicates the level of each branch is indexed from 0 to 3.

$$\beta = \frac{d_{k+1}}{d_k} = n^{-1/3} \tag{2}$$

$$\gamma = \frac{L_{k+1}}{L_k} = n^{-1/2} \tag{3}$$

For the bifurcating channel configuration $n = 2$ and according to Eqs. (2) and (3), the diameter ratio β and the length ratio γ are 0.7937 and 0.7071 respectively. For the ease of fabrication in the experimental validation, the channel network has a constant channel depth H. The equation of the hydraulic diameter is as follows:

$$d_k = \frac{4A_k}{P_k} = \frac{2Hw_k}{H + w_k} \tag{4}$$

where A_k is the wet area of the k_{th}-level segment, P_k is the wet perimeter of the k_{th}-level segment, w_k is the k_{th}-level segment width. According to Darcy's law, the equation of w_k is:

$$w_k = \frac{w_{k+1}H}{\beta(w_{k+1} + H) - w_{k+1}} \tag{5}$$

According to Eq. (3), the equation of the total length of the whole flow channel is as follows:

$$L_{k_t} = \frac{L_{tot}}{\sum_{i=0}^{k_t}(1/\gamma^i)} \tag{6}$$

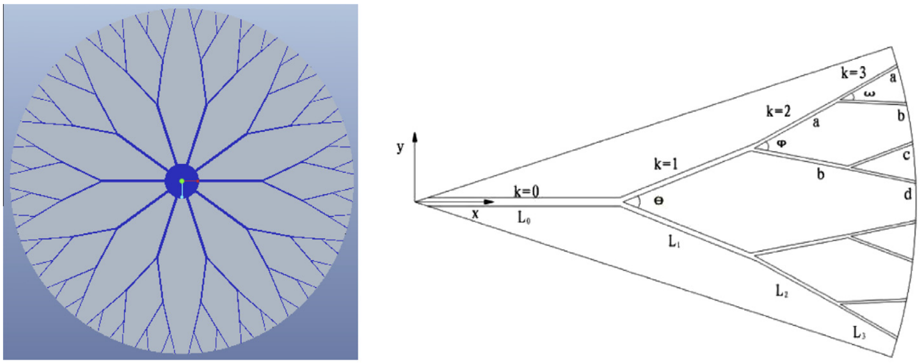
where L_{k_t} is the length of the end of the pipe, k_t is the level of the end of the pipe, L_{tot} is the total length of the flow channel.

Based on the conditions given above, the channel dimensions for the fractal-like network are shown in Table 1.

3. Experimental setup

The fractal-like microchannel is fabricated in a silicon wafer using standard micro-electro-mechanical technologies. The processes include a SiO_2 deposition, photoresist coating and developing, oxide and microchannel etching, photo resist and oxide removing, glass-silicon bonding, etc. The primary steps in the process flow are shown in Fig. 2. More details about the processes can be obtained from Ref. [25]. The Pyrex glass cover is bonded on the top of the silicon microchannels. The microchannel heat sink device is equipped with fluidic ports at the inlet and the exit to connect the pumping system. The inlet/outlet ports are created in the cover plate by laser processing before anodic bonding process.

A fixture is designed and fabricated to fix the specimen. Fig. 3(a) shows the assembling of silicon microchannel heat sink, and Fig. 3(b) shows the fixture made from steel (approximately 20 W/m K) and the test specimen with fluidic connections. The material of waterproof layer is waterproof silicone grease DX-9030 and the material of thermally conductive filling layer is



(a) (b)

Fig. 1. (a) Physical model of fractal-like branching channels embedded in a heat sink (b) parameters of the computational domain.