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Review

Twenty first century cooling solution: Microchannel heat sinks

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ABSTRACT

Due to rapid evolution in a wide range of technologies in twentieth century, heat dissipation requirement has increased very rapidly especially from compact systems. There is an urgent need for high-performance heat sinks to ensure the integrity and long life of these petite systems. Use of forced convection cooling has been limited by the requirement of the excessively high flow velocity and associated noise and vibration problems. Microchannel heat sink seems to be most reliable cooling technology due to its superior command over heat carrying capability. Understanding the flow boiling phenomena in microchannel heat sink experimentally and analytically has been topic of intense research in twenty first century. In this review paper, the experimental studies on flow visualization, pressure drop and heat transfer characteristics of microchannels presented by different researchers are summarized. Some different flow patterns observed in microchannel geometry such as bubble nucleation in thin film, periodic variation of flow pattern, flow circulation, bubble suppression and cross-channel flow are explained briefly. The influence of vapour quality, heat flux, mass flux and channel geometry on pressure drop and heat transfer characteristics of microchannel are reported. Different correlations reported for single and two phase heat transfer characteristics are compared. The comparative analysis showed that available single phase and two phase correlations are inconsistence and large variation is observed among these correlations for same channel geometry, fluid and operating condition. Different instabilities associated with microchannels are also briefly presented.

1. Introduction

With advancement in almost all technology sectors, the world is moving towards miniaturization. Hence, it becomes necessary to remove high heat flux from highly compact systems such as high-performance computer chips, laser diodes and nuclear fusion and fission reactors for ensuring their consistent performance with long life. Heat generated per unit area has measured up to 10^4 W/cm^2 (nuclear reactor). Microchannels and minichannels are naturally well suited for this task, as they provide large heat transfer surface area per unit fluid flow volume. Hence, facilitating very high heat transfer rate. Use of microchannels can be explored in various applications i.e. turbine blades, rocket engine, hybrid vehicle, hydrogen storage, refrigeration cooling, thermal control in micro-gravity and capillary pump loops [1]. Heat flux removal requirement varies significantly based on the type of application. For densely packed integrated circuit (ICs) [2,3] and laser mirror [4] the maximum power flux reported is 10^2 W/cm^2, aviation and VLSI industry need up to 10^3 W/cm^2 [5] and fusion reactor and defence application contain components that require heat flux removal rate of the order of 10^4 W/cm^2 [6,7]. Kandlikar [8] reported that the use of enhanced microchannel geometry may provide heat dissipation rate up to 10^3 W/cm^2. Heat dissipation requirement will continue to rise with more advancement in technologies and further reduction in the size of these applications. Considering above facts, it can be concluded that microchannel heat sinks seem to be the plausible solution of twenty first century cooling problems.

In order to overcome the problem of high heat flux removal from small area, first time Tuckerman and Pease [9] had developed microchannel heat sink made up of silicon to remove heat flux of 790 W/cm^2 with water as working fluid. They found that the performance of VLSI circuit was accelerated with such type of microchannel heat sink. Keyes [10] carried out theoretical analysis of finned microchannel heat sink with conventional heat exchanger theory and concluded that the size of fin and channel dimensions could be optimized to provide maximum cooling under wide range of application. Thermal performance tests were conducted on silicon and indium phosphate microchannel heat sinks by Phillips [4]. He found that the thermal performance of microchannel heat sink was approximately two times better than conventional channel

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heat sink. Missaggia et al. [11] developed a microchannel heat sink (40 channels of dimension (W, H) (100, 400) μm made through etching on silicon wafer) for cooling of two dimensional high power density diode laser arrays, the use of microchannel heat sink provided significant increase in optical power output.

Classification of the microchannel is controversial issues. Some authors have classified based on channel dimension, whereas others believe that it should be based on flow stability. Following is the summery of criteria reported in literature to distinguish between microchannel and macrochannel. Kandlikar and Grande [12,13] had proposed the range as $10 \le D \le 200$ μm and Mehendale et al. [14] had suggested the range as $1 \le D \le 100$ μm for identifying microchannel, where D is the diameter of tube or smallest dimension for other cross-sections. Cornwell and Kew [15] and Kew and Cornwell [16] had defined the confinement number (Co) in order to distinguish between macro to microscale flow boiling as given by Equation (1);

$$Co = \left[\frac{\sigma}{g(\rho_l - \rho_v)D_h^2}\right]^{1/2} \tag{1}$$

As per their proposed criteria, channels with $Co \ge 0.5$ can be classified as microchannels, as influence of the gravity was surpassed by the surface tension above this level.

Manufacturing of the microchannel of required shape and size on required material is another major issue. Researchers have used different manufacturing techniques for the fabrication of microchannel. Table 1 summarizes few of the typical manufacturing techniques and the type of microchannel produced. Kandlikar and Grande [12,13] had reported that the technology to fabricate microchannels had quickly evolved from the miniaturization of traditional machining techniques (milling and sawing) to the adoption of modern techniques (anisotropic wet chemical etching, dry plasma etching and surface micromachining, LASER cutting) used in the semiconductor manufacturing industry. These techniques have changed the scenario of microchannel heat sink field, lot of companies i.e. IBM Zurich Research laboratory, AAVID THERMALLOY, Furukawa electric Co., Ltd. and Siliton R&D Corporation have come in business related with microchannels.

Table 2, presents the summary of geometric parameter of microchannels, working fluid and operating conditions used by different researchers, Fig. 1 shows typical parallel microchannel heat sink and different cross sections of microchannel used. It can be concluded from Table 2 that majority of studies have been carried out on copper and silicon substrate based test sections. Copper is very popular material in thermal process equipments due its high thermal conductivity and silicon is good semiconductor extensively used in VLSI and electronics industries. From Table 2, it can also be concluded that most of studies have been carried out by using water or refrigerant as working fluid. Water is not an appropriate coolant for electronic devices due to its current carrying capability and corrosive nature, which may be responsible for complete burnout of electronic devices or scale formation hampering heat transfer characteristics. However, common refrigerants used in field of microchannel heat sink are R410A, R134a, FC-72, FC-77, HFE-7000 and HFE-7100. Table 3 compares thermo-physical properties, ODP and GDP values of different refrigerant. Thermo-physical properties play an important role in boiling process like high viscosity of liquid phase, stabilizes thin liquid layer in slug flow and annular flow. Hence, ensure smooth boiling process (by slowing down flow instabilities). Similarly, large density of vapour will facilitate boiling process by ensuring more energetic vapour bubbles (vapour bubble will travel along heated wall after departure, discussed in the flow visualization section) are generated in boiling process. High liquid density is not desirable as it tries to suppress growth of bubble. Whereas, low enthalpy of vaporization, activates large number of nucleation site at early stage. Hence, facilitating boiling process and reduces the thermal non equilibrium of liquid and vapour phase. Thus, low enthalpy of vaporization also helps reducing the boiling instabilities associated with microchannel.

Table 1
Different microchannel fabrication techniques.

Author	Process	Material	Dimensions (W, H) μm
Papautsky et al. [17]	Electroplating	Silicon and glass	Rectangular, $W = 300–1500$, $H = 50–100$
Lee et al. [18]	Micro-milling	Copper	Rectangular, $W = 194–534$, $H = 5^*W$
Wu and Cheng [19]	Photolithography method	Silicon	Trapezoidal, $W_1 = 251$, $W_2 = 155.7$, $H = 56.5$
Mei et al. [20]	Micro-moulding	Copper and aluminium	Rectangular, $W = 137–174$, $H = 400$
Wu et al. [21]	Deep reactive chemical etching	Silicon	Rectangular, $W = 483.4$, $H = 50$
Chen and Garimella [22]	Saw- Cutting	Silicon	Rectangular, $W = 100$, $H = 389$
Lee et al. [23]	Dry Etching	Silicon	Rectangular, $W = 100$, $H = 100$
Hwang et al. [24]	Laser	Mythacrylate	Circular, $D_h = 8–20$

In this paper effort has been put to study different flow patterns observed, pressure drop characteristics, heat transfer characteristics and flow instability in microchannels. Dependency of pressure drop and heat transfer characteristics of microchannels on various parameters is described in pressure drop and heat transfer section. Eventually, instabilities associated with microchannels such as flow reversal, pressure fluctuation, wall temperature fluctuation and Ledinegg instability are addressed.

2. Flow visualization

The study of different flow regimes that exist in microchannels is important because the pressure drop and heat transfer characteristics can not be predicted accurately in absence of comprehensive information about different types flow regime. It is very difficult to predict the sequence of flow patterns in microchannels unlike conventional channels without high speed photography. In conventional channels as explained by Thome [52], the sequence of flow pattern is bubbly, slug, churn, wispy-annular and annular flow in vertical flow, whereas for the horizontal flow bubbly, slug, plug, annular, stratified, annular with mist and wave flow exists, as shown Fig. 2(a) and (b), respectively. In case of microchannels flow patterns are quite different than conventional channels. Hence, two phase flow pattern maps and flow boiling heat transfer methods developed for macrochannels fail to predict behaviour of microchannels through simple extrapolation. Pfahler et al. [53] carried out experiments on three different microchannels (W, H) (100, 8) (100, 17) and (53, 135). They found that the largest cross section channel roughly followed Navier–Stokes equation. However, as the channel size reduced, they observed significant deviation from Navier–Stokes prediction.

In the last two decades various researchers have carried out flow visualization study on a single microchannel, multiple microchannels and microtubes.

Sobierska et al. [37] performed experiments using water in a single rectangular microchannel (W, H) (2000, 860) and observed bubbly, slug and annular flow. Lee and Mudawar [5] visualized the