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Local measurement of flow boiling heat transfer in an array of non-uniformly heated microchannels

Susan N. Ritchey, Justin A. Weibel, Suresh V. Garimella *

Cooling Technologies Research Center, an NSF I/UCRC, School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907, USA

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ABSTRACT

As electronics packages become increasingly thinner and more compact due to size, weight, and performance demands, the use of large intermediate heat spreaders to mitigate heat generation non-uniformities are no longer a viable option. Instead, non-uniform heat flux profiles produced from chip-scale variations or from multiple discrete devices are experienced directly by the ultimate heat sink. In order to address these thermal packaging trends, a better understanding of the impacts of non-uniform heating on two-phase flow characteristics and thermal performance limits for microchannel heat sinks is needed. An experimental investigation is performed to explore flow boiling phenomena in a microchannel heat sink with hotspots, as well as non-uniform streamwise and transverse peak-heating conditions spanning across the entire heat sink area. The investigation is conducted using a silicon microchannel heat sink with a 5×5 array of individually controllable heaters attached to a 12.7 mm $\times$ 12.7 mm square base. The channels are 240 μm wide, 370 μm deep, and separated by 110 μm wide fins. The working fluid is the dielectric fluorinert liquid FC-77, flowing at a mass flux of approximately 890 kg/m^2 s. High-speed visualizations of the flow are recorded to observe the local flow regimes. Despite the substrate beneath the microchannels being very thin (200 μm), significant lateral conduction occurs and must be accounted for in the calculation of the local heat flux imposed. For non-uniform heat input profiles, with peak heat fluxes along the streamwise and transverse directions, it is found that the local flow regimes, heat transfer coefficients, and wall temperatures deviate significantly from a uniformly heated case. These trends are assessed as a function of an increase in the relative magnitude of the nonuniformity between the peak and background heat fluxes.

1. Introduction

Many studies in the literature have investigated uniform base heating profiles applied to microchannel heat sinks, as reviewed, for example, in [1–3]. These studies experimentally measured the onset of nucleate boiling [4], pressure drop [5,6], and heat transfer coefficient [5,7,8], and also developed models to predict the critical heat flux (CHF) [9,10]. In addition, flow regime maps have been developed under a variety of operating conditions [11,12]. While these studies have provided a thorough understanding of microchannel flow boiling under ideal heating conditions, realistic applications may impose highly non-uniform heat fluxes due to chip- and system-level variations [13]. In order to reliably predict the performance in actual applications, a better understanding of two-phase microchannel cooling under non-uniform heating conditions is needed, especially in terms of deviations in heat transfer performance and flow behavior compared to uniform heating conditions.

A discretized theoretical model for assessment of non-uniform heating in microchannels was developed by Koo et al. [14] using correlations for flow boiling heat transfer and pressure drop. The model was used to explore optimal geometric designs, but was limited in its ability to assess lateral flow instabilities across channels and for CHF prediction. A numerical model developed by Sarangi et al. [15] predicted the pressure drop and thermal resistance of a uniformly heated microchannel, and location of boiling incipience. The model was extended to include non-uniform heating, which showed a large impact on the overall fluid dynamics and heat transfer of the system. Revellin and Thome [9] developed a one-dimensional theoretical model to predict CHF in microchannels under uniform heating conditions, which was further modified by Revellin et al. [16] to incorporate non-uniform axial heat fluxes.

Past experimental efforts have studied the effects of non-uniform microchannel heating on flow boiling instabilities [17], pressure drop, and maximum wall temperatures [18–20]. It was found that hotspots near the inlet created a large transverse temperature variation across the heat sink due to non-uniform fluid distribution. Maldistribution was caused by a local increase in two-phase pressure drop due to boiling, which diverted single-phase liquid

* Corresponding author. Tel.: +1 765 494 5621.
E-mail address: sureshg@purdue.edu (S.V. Garimella).

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Nomenclature

A_b heat sink base area (m^2)
A_f wetted area of a fin (m^2)
A_w total wetted area of the microchannels (m^2)
c_p specific heat ($J\,m^{-2}K^{-1}$)
d microchannel depth (m)
G mass flux ($kg\,m^{-2}s^{-1}$)
h heat transfer coefficient ($W\,m^{-2}K^{-1}$)
k_{Si} thermal conductivity of silicon ($W\,m^{-1}K^{-1}$)
L heat sink width (m)
m variable in fin efficiency calculation (m^{-1})
N number of microchannels, heaters
Q power input (W)
q''_b base heat flux ($W\,m^{-2}$)
$\dot{q}_{cond}$ heat conduction (W)
$\dot{q}_{gen}$ heat generation (W)
$\dot{q}_{loss}$ heat loss (W)
$\dot{q}_{net}$ total heat transferred to the fluid (W)
q''_w wall heat flux ($W\,m^{-2}$)
T_d diode temperature (C)
T_f fluid temperature (C)
T_{in} inlet fluid temperature (C)
T_w wall temperature (C)
t heat sink thickness (m)
w microchannel width (m)
w_f fin width (m)

Greek symbols
η_f fin efficiency
η_o overall heat sink efficiency
Φ degree of nonuniformity

Subscripts
high peak-heater element region
i heater element in the flow direction
j heater element in the transverse direction
low background heater element region

to other locations; this effect was most pronounced for a hot spot at the inlet. Transient non-uniform heating situations have also been investigated [19,21].

Prior experimental studies with non-uniform heating conditions have typically focused on single point hotspots. The effect of location and configuration of the hotspot as well as that of multiple hotspots on thermal performance has not been fully explored. In addition, a rigorous study of other heating profiles, especially superposed on a uniform background heat flux as would be realized in application, has not been reported. The present work studies both local hotspots and increasingly non-uniform peak-heating profiles across the heat sink, both in the flow direction and perpendicular to it, with respect to thermal performance and flow boiling phenomena. This work considers the effects of non-uniform heating on the local heat transfer coefficients, wall temperatures, heat fluxes, and boiling characteristics of a microchannel heat sink. Concentration of the heat input typically results in higher local heat transfer coefficients due to transition into the more efficient boiling regime at the expense of increased local wall temperatures. This work enables better assessment of existing heat transfer models for prediction of non-uniform heating profiles.

2. Experimental methods

2.1. Test section

The microchannel test section used in the current study was described in detail by Harirchian and Garimella [12]; it was modified for the purposes of the current study and is shown in Fig. 1a. A transparent, polycarbonate manifold cover plate seals and routes the working fluid through a silicon microchannel heat sink with a base area of 12.7 mm × 12.7 mm. The total silicon thickness is approximately 650 μm. The heat sink is mounted on a printed circuit board that is offset from an electrical quick-connect board with an insulating G10 glass–epoxy composite layer. An insulating 0.4 mm thick borosilicate glass sheet is sandwiched between the microchannel heat sink and cover plate to protect the polycarbonate (rated to a temperature of 115–130 °C), and forms the rigid top wall of the microchannels. The fluid enters the channels through an inlet header section with a flow length of 10 mm, width of 12.7 mm, and a height equal to that of the heat sink plus borosilicate glass thickness.

Parallel microchannels are cut into the top surface of the silicon chip using a dicing saw, and are shown in Fig. 1b. A single heat sink with 35 microchannels was used for the current study (240 μm channel width, 370 μm channel depth, and 110 μm fin width). Each channel was cut with a number of passes, which created some waviness on the bottom surface. The average channel bottom roughness in the region of a single cut is 0.2 μm, and the overall average surface roughness of the bottom and sides of the channels are 0.82 μm and 0.1 μm, respectively.

A 5 × 5 array of resistance heaters and temperature-sensing diodes is fabricated on the bottom side of the heat sink, as shown in Fig. 1b. Since the individual heater resistances are nearly identical, a single voltage can be applied across multiple heaters in parallel to provide a uniform flux over a desired area. Up to two DC voltage power supplies are connected to provide the customized, non-uniform heat flux profiles applied to the underside of the microchannels investigated in the current study. The heat generated and local temperature at each element are calculated based on the calibrated heater/sensor resistance and the applied voltage. The relationship between the voltage and temperature of each sensor is calibrated in a convection oven. More details about the calibration procedure for each element can be found in [6].

2.2. Flow loop

The experimental flow loop used is the same as that described by Harirchian and Garimella [12], and a schematic diagram is shown in Fig. 2. The dielectric fluid FC-77 is circulated through the flow loop using a Micropump 415A magnetically coupled gear pump. A preheater sets the fluid to the desired inlet temperature upstream of the test section. Downstream of the test section, a liquid-to-air heat exchanger cools the fluid back to room temperature before it enters the reservoir. A McMillan Flo-114 liquid flow meter, with a range of 20–200 mL/min, measures the liquid flow rate through the loop. T-type thermocouples are located upstream of the preheater, upstream and downstream of the test section, and downstream of the heat exchanger. A 2200 series Omega differential pressure transducer measures the pressure drop across the test section.

High-speed visualization is performed with a Photron Fastcam Ultima APX high-speed digital video camera and a Nikon ED 200 mm lens. A Sunoptics Titan 300 xenon arc lamp is used for in-line illumination of the test chip for the visualizations. Images are extracted from high-speed videos captured at 6,000 frames per second with a shutter speed of 6 kHz.