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Ultra-high pool boiling performance and effect of channel width with selectively coated open microchannels

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ABSTRACT

Recent developments in the microelectronics industry has placed increasing demand on developing high heat flux removal systems. Pool boiling offers a simple technique without introducing complicated header configurations and moving parts. Enhancement in pool boiling is achieved by delaying critical heat flux (CHF) and increasing heat transfer coefficient (HTC), which dictates the heat removal capability of a surface. This study focuses on the effect of channel width on the performance and heat transfer mechanisms on open microchannel surfaces with three coating configurations: (i) sintered-throughout, (ii) sintered-fin-tops, and (iii) sintered-channels. Pool boiling performance is obtained with water at atmospheric pressure for 300 μm, 500 μm and 762 μm channel widths. The separate liquid–vapor pathways in narrow channels, with sintered coatings only inside the channel, yielded an unprecedented performance with a CHF of 420 W/cm^2 based on the 1 cm^2 projected area at a wall superheat of 1.7 °C at the fin top surface, resulting in an HTC of 2.9 MW/m^2 °C. High speed videos were taken to understand the underlying mechanism. Furthermore, liquid–vapor pathways were identified to explain the parametric trends observed for each selectively enhanced configuration set.

1. Introduction

The increased number and closely packed heat emitting unit configurations of IC chips require efficient heat transfer systems to cool the devices effectively. Pool boiling offers a simple technique without moving parts and complex header arrangements. The evolution of passive enhanced pool boiling surfaces in recent years has been based on mechanistic considerations. Some of the augmentation features include providing additional surface area, additional nucleation sites and altering liquid wettability on the surface.

Placement of additional nucleation sites on the heater surface induces early nucleation and improved heat transfer [1–5]. The wicking mechanism in the porous structures further contributes to the liquid supply. Modulated porous coatings capable of generating separate liquid–vapor pathways were investigated by Liter and Kaviany [6]. Vapor venting pathways were created between two porous modulated structures through which bulk liquid was wicked in and fed to the nucleation sites. Min et al. [7] used compaction and sintering to achieve a 2D and 3D porous heat transfer surface. A CHF of 81.5 W/cm^2 was reported for a 2D structure with n-pentane as the working fluid. Li and Peterson [2] used sintered porous mesh of varying thickness to understand the effect of thickness. A CHF of 347 W/cm^2 was reported, however the wall superheat was in excess of 60 °C which is undesirable as the HTC is significantly lower. This study helped identify an optimal thickness to strike a balance between availability of additional nucleation sites and thermal resistance offered by the porous coatings. In another publication, Li et al. [8] used modulated porous coatings to reach a CHF of 450 W/cm^2 at a wall superheat of 25 °C. A maximum HTC of 200 kW/m^2 °C was obtained for this surface. The sintered porous coatings were placed on a circular area (8 mm diameter) and the importance of vertical and lateral liquid replenishing pathways through the porous structure were highlighted in their study.

A novel microstructure which exhibited separate liquid–vapor pathways was investigated by Kandlikar [9] to enhance both CHF and HTC. A contoured fin structure was fabricated in which the motion of the bubble on the surface was governed by evaporation momentum force. The surface was manufactured using an embossing technique in which the edge location between the land and fin served as a preferential nucleation site. It was found that the bubble deflected along the contour of the land with subsequent addition of liquid through the sidewall regions of the fin. A CHF of 300 W/cm^2 was reached with an HTC of 629 kW/m^2 °C. This

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structure formed the basis for developing the next generation of enhanced surfaces with separate liquid–vapor pathways.

Liquid wettability changes induced by hydrophobic and hydrophilic coatings is another type of enhancement technique. Betz et al. [10] conducted series of tests using hydrophilic and hydrophobic networked surfaces. They concluded that hydrophilicity improved the heat transfer performance whereas the hydrophobicity affected the nucleation characteristics. Graphene coatings are also employed to alter the liquid wettability. Recently, Jaikumar et al. [11] investigated the effect of graphene, graphene oxide and graphene quantum dot coatings. O'Hanley [12] studied the separate effects of wettability, porosity and roughness for a wide range of surfaces. They concluded that hydrophilic surface enhanced the CHF by 50%–60% while wettability and roughness had no effect on the CHF in the tested database. Rahman et al. [13] investigated the effect of bio-templated microstructures on a Si substrate based on liquid wettability changes. A CHF of 257 W/cm^2 was reported for these microstructures with a height of 32 μm.

Area augmented surfaces with liquid supply pathways have shown significant improvement in the heat transfer performance. Cooke and Kandlikar [14] developed open microchannels and reported heat fluxes in excess of 244 W/cm^2 at wall superheats of less than 10 °C. Liquid supply to the nucleation sites was identified to occur through the channels enhancing the HTC by improving microconvection in the region. The architecture of the surface ensured that the liquid was supplied continuously to the nucleation sites which increased CHF. Roughening the surface has shown to have a direct effect on the CHF. This understanding was highlighted by Chu et al. [15] in their work. The silicon heat transfer surfaces had microstructures with different roughness values and dissipated heat fluxes in excess of 200 W/cm^2 with increasing roughness values.

In a more recent attempt to increase CHF and HTC simultaneously, Patil and Kandlikar [3,16,17] used a combination of enhancement techniques. Porous coatings were deposited on open microchannel fin tops using a two-step electrodeposition process. A CHF of 325 W/cm^2 at a wall superheat of 7.3 °C was reported with water. They identified separate liquid–vapor pathways as the enhancement mechanism. Nucleation was shown to occur on the fin tops with liquid supply through the channel regions similar to a jet impingement like mechanism.

This mechanism was further explored in the work conducted by Jaikumar and Kandlikar [4]. Three configurations identified as sintered throughout, sintered fin tops and sintered channels were developed using CNC machining, screen printing and sintering techniques. Heat transfer mechanisms were identified for each configuration as shown in Fig 1. In a sintered throughout surface, the 'area augmented nucleation activity' was shown to be the governing mechanism. The 'bubble induced liquid jet impingement' with disrupted and sustained flow was responsible for the enhancement in sintered fin tops and sintered channels, respectively. For the selected microchannel dimensions (channel width = 762 μm, channel depth = 400 μm, fin width = 200 μm) the sintered throughout configuration was identified as the best performing surface. However, changing the microchannel dimensions is expected to affect the relative merits in each configuration as the liquid and vapor pathways are influenced in fundamentally different ways.

The channel width is seen to be an important parameter in governing the heat transfer mechanism. To explore its effect further, a detailed experimental investigation is carried out in this work to study the effect of channel width for each configuration (sintered-throughout, sintered-fin-tops and sintered channels). Although the channel dimensions investigated here do not cover a wide range for optimization purposes, the range selected is derived from the performance trends noted in the earlier investigations.

The objective of the current work is to study the effect of channel width on pool boiling performance for the three selectively sintered open microchannel configurations (i) sintered-throughout, (ii) sintered-fin-tops, and (iii) sintered-channels. Literature has shown that channels widths over 1 mm significantly reduces the CHF [3,14]. Therefore in this study, three channel widths – 300 μm, 500 μm and 762 μm for each configuration were investigated with distilled water at atmospheric pressure. The heat transfer mechanisms proposed in [4] are explored further by using high speed imaging to identify the driving mechanisms in each configuration to explain the parametric trends observed.

2. Experimental test setup

A test setup similar to that described in [4] was used in this study and is shown in Fig. 2. It consisted of three main components namely, (i) a test chip (ii) a heater block, and (iii) a water reservoir. The test chip was housed in a ceramic chip holder on the bottom garolite plate. Ceramic was chosen to minimize radial heat losses to the atmosphere. A quartz glass water bath was installed over the test chip to hold the boiling fluid and to aid in visualization. A water reservoir was assembled over the glass water bath to replenish water in the bath as and when required. Two openings were provided in the top aluminum plate for the auxiliary cartridge heater and the saturation thermocouple probe, respectively.

The bottom section of the test setup consisted of a copper heater block with 4 × 200 W embedded cartridge heaters. The heater block was housed in a ceramic sleeve fitted in an aluminum base, which was supported on four compression springs to provide the required degree of movement to establish contact with the test chip and also to accommodate for any expansion during testing. The springs were supported on an x–y stage to establish good contact with the test chip. Grafoil paper was inserted as a thermal interface material between the heater block and test chip to minimize contact resistance. A solid stainless steel shaft connected the bottom garolite plate and the work table to ensure robustness of the setup.

A National Instruments cDaq-9172 data acquisition system with NI-9213 temperature module was used to record the temperature. A LabVIEWVR virtual instrument displayed and calculated the real-time surface temperature and heat flux.

3. Test section

The test section used in this study consisted of a 17 mm × 17 mm square copper chip with a central 10 mm × 10 mm boiling region as shown in Fig 3(a). The excess area outside the boiling surface was covered with Kaptons® tape (thickness = 75 μm) to prevent this area from participating in heat transfer. This tape has a thermal conductivity of 0.12 W/m-K at 23 °C and has been employed as a heat sealant for a wide range of applications [18]. Three thermocouples were inserted along the length of the test chip as shown in Fig. 3(b) to obtain accurate estimation of heat flux and surface temperature. It is noted that the area outside the boiling region on the chip is not exposed to the water. Although the Kaptons® tape is provided on this area, the lateral conduction in the copper induces heat loss to the surrounding air by natural convection only on the outside region of the chip exposed to air. To quantify this loss, a heat loss study is performed similar to Jaikumar and Kandlikar [19] which resulted in a loss of less than 3–4 W/cm^2 at higher heat fluxes. The heat flux was corrected and reported in Figs. 6, 8 and 10.

The manufacturing sequence for each test chip configuration was similar to that explained in [4]. A screen printing and sintering