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Bubble dynamics and flow boiling characteristics in three different microchannel configurations

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ABSTRACT

Flow boiling experiments have been performed to compare bubble growth and flow instabilities in uniform, diverging and segmented finned microchannels. Experiments have been conducted in an array of 12 microchannels with 522 μm hydraulic diameter in each configuration. Deionized water has been used as coolant and investigation has been made for coolant mass flux range of 100–350 kg/m^{2}s and heat flux range of 10–350 kW/m^2. Flow visualization has been performed to analyze bubbles growth, their coalescence and motion in each microchannel configuration. A comparative study of bubble growth phenomena in all three channel configurations has been presented. The role of bubble dynamics on flow instability has been discussed. Bubble growth pattern in segmented channel is completely different than that in uniform and diverging cross-section channels. Bubbles are characterized with multiple growing interfaces and suppressed growth along the upstream direction of coolant flow. The suppressed growth of bubble slug in segmented finned reduces flow reversal and subsequent instabilities in flow boiling.

1. Introduction

Microchannels have the advantage of large surface to volume ratio for which they can dissipate heat at higher rate. They can also be fabricated at chip scale of an electronic device. As such, microchannels with liquid coolant have the potential to replace conventional heat sinks in modern electronic devices. Further heat transfer rate in microchannels can be enhanced by implementing flow boiling of coolant. However, coolant flow reversal and instabilities arise during flow boiling in microchannels which affect the heat transfer performance. The coolant flow reversal occurs due to rapid growth of vapour bubbles towards inlet section of the channel and blocking the channel passage. Flow reversal of coolant results in fluctuations in temperature, pressure and flow rate which finally leads to poor heat transfer. For low applied heat flux, single -phase flow of coolant is observed at the upstream part whereas flow boiling starts at the downstream part of the microchannels. Thus nucleation of vapour bubbles, their growth and coalescence are confined to downstream part of the microchannels. With increase in applied heat flux, bubble growth phenomena spreads towards microchannels inlet and flow boiling occupies almost entire channel length. Therefore, bubble dynamics play a very important role in overall performance of microchannel heat sinks.

Many research works on bubble dynamics in microchannel heat sinks has been reported in the literature. Edel and Mukherjee [1] investigated the bubble growth and instability in a single rectangular microchannel. They observed the suppressed growth rate of bubbles for higher coolant flux. Lee and Mudawar [2] presented comprehensive flow visualization and heat transfer study mostly for subcooled flow boiling of HFE 7100 in various configurations of parallel microchannels. With high degree of subcooling they were able to achieve the high cooling rate up to a value of 700 W/cm^2. Recently, Yin et al. [3] experimentally investigated the bubble confinement and its elongation in a rectangular microchannel of 667 μm hydraulic diameter. Using deionized (DI) water as coolant, they observed that growth rate of confined bubble was much higher than the unconfined bubble. They also observed that coolant mass flux significantly affected bubble dynamics. Huh and Kim [4] studied nucleation, growth and elongation of bubbles during flow boiling in a single microchannel of rectangular cross-section. They observed that bubble elongated due to evaporation of thin liquid film, trapped between bubble and the wall of the channels. Thome et al. [5] proposed three zone flow boiling model to comprehend the regime based heat transfer and role of liquid film in

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microchannels. Furthermore, based on bubble flow behavior and liquid film thickness Ong and Thome [6,7] pointed out that surface tension force dominates over gravity force in microchannels. Harirchian and Garimella [8] investigated the effect of channel width on flow pattern during flow boiling in microchannels. They observed a demarcation of channel width of 400 μm above and below which the flow patterns exhibited striking difference. Bogojevic et al. [9,10] investigated role of bubble dynamics in flow instability for subcooled and saturated flow boiling in an array of rectangular microchannels. They classified bubble growth phenomena in three phases i.e. rapid bubble growth, stagnation state and accelerated bubble growth. It was difficult to capture unstable growth of bubble along axial direction during saturated flow boiling.

Several review articles [11–15] on flow boiling in microchannels have highlighted the issues of boiling instabilities due to explosive bubble growth rate in confined flow passage of microchannels. These articles have also discussed various techniques such as increased nucleation activity, enhanced surface area, wettability, nanofluid, vapour venting etc for enhancing heat transfer coefficient and critical heat flux (CHF) limit during flow boiling in microchannles. One of the important techniques suggested for heat transfer enhancement is modification of the channel surface area. Diverging cross-section and segmented finned (oblique finned) microchannels are such two modifications recently reported in the literature.

Diverging microchannel configuration has a proven record of reducing instability and bubble clogging. Mukherjee and Kandlikar [16] originally proposed the idea of widening cross-section area of microchannels along the flow direction for improving heat transfer performance. Bubbles in a diverging channel move easily with flow stream due to divergence in the channel and additional driving force caused by the difference in surface tension force pushes bubble slug out of the channel. Lee and Pan [17] investigated flow boiling in single uniform and diverging channel having 0.183° divergence angle. They observed higher heat transfer rate in diverging channel compared to uniform cross-section channel. Pan and his co-workers [18,19] extensively investigated heat transfer performance in diverging microchannels with different coolants, e.g. water, methanol, ethanol and other binary mixtures. Effects of channel aspect ratio and divergence angle on heat transfer characteristics were also investigated. Their findings confirmed that diverging channel favoured smooth evacuation of bubble slug with reduced instabilities. Overall pressure drop was less compared to uniform cross-section channels. Balasubramanian et al. [20] conducted a comparative experimental study of diverging and uniform cross-section microchannels. Diverging channel was more effective at higher heat flux with low pressure drop and reduced instability.

Kalani and Kandlikar [21] used tapered microchannel for heat transfer enhancement with the help of inertia force of liquid coolant. Inlet constriction or pressure drop element also helps in overcoming bubble clogging problem during flow boiling in microchannels. Mukherjee and Kandlikar [22,23] and Mukherjee et al. [24] pointed out that inlet constrictions provide enough drag force by incoming coolant to flush out bubbles from the channel. Kosar et al. [25] have also introduced inlet restrictor to suppress flow boiling in parallel microchannels. Recently, Parajapati et al. [26] numerically compared clogging behavior of bubble slug in adiabatic uniform and diverging microchannels for different wettabilities and mass flow rates. It has been observed that bubble detachment takes place in diverging channel at small contact angles (0° and 30°) for entire range of Reynolds number (80–319). However, for 60° contact angle, bubble detachment takes place only for higher Reynolds number ($Re = 319$).

In recent years, heat transfer studies on oblique finned or segmented finned microchannels have been reported. In segmented finned channels, secondary channels are cut across the main channels. Due to interconnections between the main and secondary channels, enhanced mixing, regeneration of thermal and hydraulic boundary layer of coolant flow are possible in segmented channels. Lee et al. [27,28] performed both experimental and numerical investigations of segmented finned channels and observed the enhanced heat transfer rate during single-phase flow with small penalty of pressure drop. Mihailovic et al. [29] performed the flow boiling experiments in segmented and three other configurations of microchannels. For low coolant flow rate (1–5 ml/h), they observed that segmented channels were able to suppress the reverse flow along with significant reduction in temperature and pressure oscillations. Law et al. [30] investigated heat transfer characteristics of flow boiling in segmented channel. They observed the dominance of nucleate boiling heat transfer at low and medium heat flux range. Fan et al. [31] investigated flow boiling of FC-72 dielectric fluid in oblique finned microchannel with secondary channel aligned at an angle of 27° having width as half of the main channel. Recently, our group (Prajapati et al. [32,33]) has compared heat transfer characteristics in segmented microchannels with those in uniform and diverging cross-section microchannels. The work was mainly focused on the comparison of heat transfer characteristics in three different types of channels. Heat transfer performance of segmented finned microchannels was better among all three configurations. Moreover, better transient performance of segmented channel has also been reported.

The objective of present work is to investigate the role of bubble nucleation, growth and coalescence on temperature, pressure and flow instabilities in all three configurations of microchannels, i.e. uniform, diverging and segmented finned.

2. Experimental setup and procedure

Present experimental setup consists of microchannel test module, mini gear pump, flow meter, coolant reservoir, collecting tank, high-speed digital camera and data acquisition system as shown in Fig. 1. The liquid coolant is circulated through the test module by a mini gear pump. A by-pass valve is used to reduce the flow rate to test module by re-circulating excess amount of liquid to reservoir. During experiments, microchannel test module is kept horizontal. The coolant flow rate is measured with the help of rotameter with working range of 2.4–120 ml/min and accuracy of ±3% reading. Two pressure transducers having a range of -1 bar to $+1$ bar are connected to inlet and outlet plenums to measure the coolant pressure at inlet and outlet of microchannels respectively. Pressure transducers are based on piezoresistive sensors with response time of 1.5 ms. Maximum uncertainty associated with pressure transducer is ±50 Pa. A total of five T-type thermocouples (TCin, TC1, TC2, TC3 and TCout) have been used to measure temperature at different locations of the test module as shown in Fig. 1. Three thermocouples (TC1, TC2, TC3) at distance of 6.425 mm, 12.850 mm and 19.275 mm respectively from the channel inlet are used to measure the wall temperature of channels. These thermocouples are fixed at 2 mm beneath channel's bottom wall. Remaining two thermocouples (TC_{in} and TC_{out}) are flush inserted into inlet and outlet plenum to measure the inlet and outlet temperature of the coolant. The accuracy of each thermocouple is found to be within ±0.3 °C. A high speed camera has been used to capture images of flow boiling regimes. High speed data acquisition system has been used to acquire and record temperature and pressure data. All the sensors have been calibrated prior to performing experiments.

All three microchannel geometries namely uniform, diverging and segmented finned, shown in Fig. 2 have been fabricated on a