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A comparative study of flow boiling heat transfer in three different configurations of microchannels

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ABSTRACT

In this work, an experimental investigation has been made to compare the flow boiling characteristics of deionized water in three different configurations of microchannels. The investigated channel configurations are uniform cross-section, diverging cross-section and segmented finned microchannels. In each configuration, an array consisting of twelve numbers of microchannels with rectangular cross-section has been fabricated on a copper block with footprint area of 25.7×12.02 mm^2. Experiments have been conducted with subcooled liquid state at the entry with coolant mass and heat fluxes vary in the range 100–350 kg/m^2 s and 10–350 kW/m^2, respectively. Depending upon the heat flux and coolant flow rate different regimes of two phase boiling have been observed. The comparison of three configurations has been made in terms of heat transfer coefficient, pressure drop characteristics and affinity towards backflow or flow reversal in the channels. Bubbles dynamics and their role in flow reversal and flow instability have been discussed for all three types of channels. For entire operating conditions, segmented finned channels demonstrate the highest heat transfer coefficient with negligible higher pressure drop compared to other two configurations of channels. The performance of diverging cross-section channels is better than the uniform cross-section channels. However, they underperform compared with segmented finned channels. At higher heat flux, bubble clogging and flow reversal problem is worst in uniform cross-section channels. The problem is partially solved in diverging cross-section channels. Segmented channels completely relieve the problem of bubble clogging allowing smooth and easy passage of growing bubbles. Moreover flow reversal is not observed in segmented channels for entire operating range of heat flux and coolant mass flux.

1. Introduction

In order to meet the requirement of enhanced functionalities, high speed operation and miniaturizing physical size, power density in electronic devices has been tremendously increased in recent years. This has resulted in high heat generation in the devices and conventional cooling systems such as fins and fans are not sufficient for thermal management of such devices. Microchannel based cooling techniques have immense prospect in dissipating high heat flux from such devices, due to high heat transfer coefficient and compactness of the system. From the perspective of cooling performance, two-phase evaporative flow or flow boiling in microchannels is more effective than the single phase flow due to involvement of latent heat in the process. High heat removal using low coolant flow rate and temperature uniformity in the channels are two favourable characteristics of two-phase cooling technique. However, backflow and instability occur during flow boiling in micro-channels resulting non-uniform flow and poor heat transfer in the system. All these phenomena create fluctuations in temperature and pressure of the coolant flow. The flow boiling in the microchannels is inhibited by flow instability caused by vigorous pressure and temperature fluctuations. Bogojevic et al. [1] experimentally investigated the instabilities during flow boiling in uniform cross-section microchannels. They observed that the instabilities depend on the ratio of heat flux and mass flux. It also depends on the sub-cooling condition of the working fluid.

Several attempts have been made in the past to overcome the shortcomings of flow boiling in microchannels. Few important research works undertaken in this direction have been highlighted in Table 1. Different techniques used to suppress the flow boiling instability have been also reported in Table 1. So far some prominent techniques used to suppress the instability of flow boiling in microchannels are: inlet constriction, diverging channel, artificial nucleation sites and seed bubble technique. In the inlet constriction technique, the inlet section of the microchannel is

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Nomenclature

a	length of side wall of segmented channel (mm)
A	area (mm^2)
D_h	hydraulic diameter of channel (mm)
G	mass flux (kg/m^2 s)
H	depth of microchannels (mm)
h	heat transfer coefficient (W/m^2 K)
I	applied current (A)
k	thermal conductivity (W/m K)
L	length of copper block (m)
m	fin parameter (–)
$\dot{m}$	mass flow rate (kg/s)
N	number of microchannels
P	pressure (Pa)
p	perimeter of fin (mm)
Q	power input (W)
q''	heat flux (kW/m^2)
T	temperature (°C)
t	time (s)
V	voltage (V)
W	total width of copper block (mm)
w	width of microchannels (mm)
y	distance (mm)

Greek symbols

Δ	gradient (–)
θ	angle (°)
η	fin efficiency (–)

Subscripts

b	base
c	channel
cu	copper
eff	effective
f	fluid
in	input
out	output
s	segmented
t	total
w	wall

contracted to form a small nozzle or orifice. The flow velocity at the inlet increases, which help in clearing the blockage due to bubble growth. Mukherjee and Kandlikar [2] presented a numerical analysis of microchannels with an inlet constriction to suppress flow boiling instability. They observed that the bubble formed due to vapour generation had a tendency to move towards the unrestricted end. Later on Mukherjee and Kandlikar [3] numerically simulated a growing bubble placed near the inlet constriction of the channel. They concluded that due to inlet constriction, velocity was significantly increased in the upstream of the channel which helped in flushing out the clogged bubble towards downstream direction of the channel. They have also recommended diverging cross-section channels to suppress the instability in flow boiling.

In the artificial nucleation sites (ANS) technique, artificial nucleation sites are created by making micro-indents on the channel surfaces, which increases the bubble density to enhance heat transfer. The ANS technique works well with inlet constriction method as bubbles formed are cleared by high velocity jet. Kandlikar et al. [4] performed experimental investigation by introducing PDEs (pressure drop elements) in the form of inlet constriction with two types of inlet opening. They implemented 51% and 4% opening of the channel cross-sectional area. Further they observed that 51% opening with ANS was partially successful in reducing instability, whereas 4% opening could significantly mitigate the instability.

Another method which has been proved in reducing instability in flow boiling is use of diverging cross-section of microchannels. The bubbles in a diverging channel move easily with the flow due to the additional driving force caused by the difference in surface tension force. The surface tension force is inversely proportional to bubble radius. Due to divergence in the channel, the slug formed in the channel has smaller radius at the upstream side compared with that on downstream side. Consequently, the higher surface tension force at the upstream pushes the slug out of the channel. The divergence angle needs to be chosen carefully as higher angle of divergence may create adverse pressure gradient in the channel resulting ultimately in reverse flow. Lee and Pan [5] investigated the flow boiling in a single uniform and diverging cross-section channel. The divergence angle of the channel wall was set at 0.183 degree. They observed higher heat transfer rate in diverging channel compared with uniform cross-section channel. Lee et al. [6] conducted experiments with both diverging channels and inlet constriction techniques to reduce instability. Pan et al. [7–10] investigated the heat transfer characteristics during flow boiling in diverging cross-section microchannels and channels with artificial nucleation sites (ANS) for different coolants, e.g. water, methanol and other binary mixtures. They also investigated the effect of aspect ratio of the channels on heat transfer characteristics. Their results confirmed the earlier findings of better performance in diverging channels. Balasubramanian et al. [11] presented the comparative experimental study of diverging cross-section and uniform cross-section microchannels. At higher heat flux, lower pressure drop and stabilized flow in diverging microchannels were observed. The effect of cross-section shape on the flow boiling in diverging minichannel was investigated by Wang et al. [12]. They performed experiments on diverging minichannels with rectangular and U-shaped cross-section and made a comparison of results uniform cross-section channels. The flow reversal was observed at the inlet plenum of the uniform cross-section channels. Rectangular minichannels were found to perform better than the U-shaped cross-section minichannels. Liu et al. [13] introduced upstream compressibility by varying gas volume located in the upstream of the test section. Due to the upstream compressibility, they observed the steady oscillation in flow parameters and wall temperature during flow boiling in a single tube.

Recently another geometrical variant of microchannels i.e. segmented or oblique finned channels appears to be promising for reducing instabilities in flow boiling. In segmented micro-channel, the flow passage is interconnected. The side fins of each microchannel are segmented in place of continuous fins which create the interconnected passage for coolant flow. The interconnected passage may help in relieving the growing bubbles during boiling. This may avoid the undesirable clogging of bubbles in the confined channels. So far only a few research works have been reported on segmented microchannels. Lee et al. [14] investigated the single phase flow through oblique finned microchannels. They observed better heat transfer performance, relative to the uniform cross-section microchannels. Mihailovic et al. [16] compared four configurations of microchannels developed using MEMS technology. They investigated the performance of flow boiling in microchannel at low coolant flow rates (1–5 ml/h). They found that diamond