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Effects of varying secondary channel widths on flow boiling heat transfer and pressure characteristics in oblique-finned microchannels

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ABSTRACT

The oblique-finned structure has been proven to exhibit significant enhancements in heat transfer in both single-phase and two-phase modes of operation coupled with slight increment in pressure drop. These enhancements come with the mitigation of two-phase flow instability compared to the conventional straight-finned microchannels, which encourages further parametric studies on the fin geometry. In the present work, flow boiling experiments are conducted in oblique-finned microchannels using the FC-72 dielectric fluid with varying secondary channel widths to investigate its effects on two-phase heat transfer, pressure drop and flow boiling instabilities. Three different secondary channel widths of 0.15 mm, 0.30 mm and 0.45 mm are tested with mass fluxes ranging from 197 kg/m^2 s to 394 kg/m^2 s, and effective heat fluxes from 14.9 W/cm^2 to 70.2 W/cm^2 with the aid of high-speed visualisations. From the experiments and flow visualisations, it is found that increasing the width of the secondary channels has adverse effect on heat transfer performance and critical heat flux limit due to the inability of the microchannels to suppress flow boiling instabilities. Pressure drop penalty of the larger secondary channel configurations are higher as a result of greater amount of flow diversion, which amplifies flow migration from the draining edge to the filling edge of the oblique-finned array.

1. Introduction

Interests in two-phase heat management in microscale have been steadily on the rise since the turn of the last decade or so. This is chiefly due to the clear advantages of two-phase cooling over its single-phase counterpart – uniform temperature distributions and high heat transfer coefficients which translates to low pumping power requirements. These are made possible because the coolant consumes its latent heat of vaporisation during the cooling process at its saturation temperature.

In view of the benefits of two-phase cooling, numerous research works are focussed on this area to further improve the heat transfer performance in microchannels. Some of the recent efforts are highlighted and discussed in the following paragraphs.

1.1. Recent work in microchannel enhancements

Markal et al. [1] investigated the effect of aspect ratio (width to depth) on saturated flow boiling in microchannels. The microchannels have different widths and heights but the same hydraulic diameter of 100 μm for fair comparisons. Experiments are conducted for various values of the aspect ratio including 0.37, 0.82, 1.22, 2.71, 3.54 and 5.00. Results show that the heat transfer coefficients increase with an increase in the aspect ratio up to 3.54, after which is followed by a decrease for much higher values of aspect ratio. Pressure drop, on the other hand, does not exhibit any significant relationship with aspect ratio due to the complex flow boiling phenomena in the microchannels.

Wang and Peles [2] presented an experimental study of subcooled flow boiling in a microchannel with a pin fin and an induced secondary liquid jet in crossflow. The secondary jet is introduced into the flow to examine its effect to subcooled boiling heat transfer enhancement. In contrast to the authors' previous work on the effect of a secondary jet on single-phase flow [3], the introduction of the jet during flow boiling does not seem to have any heat transfer improvements, regardless of the momentum coefficients of the secondary jet. This, as explained by the authors, is because of the nucleate boiling dominated regime of the flow, where the heat transfer process and liquid convection effects are negligible.

Kalani and Kandlikar [4] studied the flow patterns and heat transfer mechanisms during flow boiling in microchannels with tapered manifold. It is found that the bubbles nucleate from the base of the microchannel, grow over the channel fin and expand into the manifold region. The departed bubbles then occupy the

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Nomenclature

A	area [mm^2]
c_p	specific heat capacity [J/kg °C]
d	distance from temperature probe to channel surface [mm]
D_h	hydraulic diameter [mm]
G	mass flux [kg/m^2 s]
h	heat transfer coefficient [W/m^2 °C]
H	height [mm]
I	current [A]
k	thermal conductivity [W/cm °C]
l	length [mm]
L	length of heat sink [mm]
m	fin parameter [−]
$\dot{m}$	mass flow rate [kg/s]
N	number of [−]
p	perimeter [mm]
P	pressure [Pa]
ΔP	pressure drop [Pa]
q	heat transfer rate [W]
q''	heat flux [W/cm^2]
t	time of flow visualisation frame [s]
t_{fin}	fin thickness [mm]
T	temperature [°C]
V	voltage [V]
w	width [mm]
W	width of heat sink [mm]
z	distance from microchannels inlet [mm]

Greek symbols

η	fin efficiency [−]
θ	oblique angle [°]
ρ	density [kg/m^3]
σ	standard deviation [Pa]

Subscripts

amb	ambient
avg	average
ch	channel
cs	cross section
Cu	copper
DO	dryout
eff	effective
f	fluid
fin	fin
in	inlet
l	liquid
loc3	location of the third (most downstream) temperature sensor
loss	loss
max	maximum
ob	oblique cut
out	outlet
sat	saturated
sub	subcooled
supplied	supplied
total	total
unfin	unfinned
wall	wall
wall3	third (most downstream) wall
$x = 0$	location of zero thermodynamic equilibrium quality

space in the manifold region above the microchannels and expand in the flow direction. This causes the channels to remain filled with liquid while the large bubbles flow over the microchannels. As observed by Kalani and Kandlikar in an earlier study [5], the taper helps in reducing pressure drop due to increasing flow area in the flow direction. Unlike closed microchannels which suffer from flow reversal, pressure drop fluctuations and low heat transfer performance, the microchannels with tapered manifold is able to constantly provide liquid supply to the channels, thus maintaining stable flow boiling and reach a very high heat flux.

Woodcock et al. [6] developed a novel structured microchannel called the Piranha Pin Fin and studied its single-phase and two-phase heat transfer performances and pressure drop characteristics. The novel heat sink consists of an array of 150 μm diameter microstructures machined on an overall device footprint of 12 mm by 28 mm. Two flow configurations – open flow and extraction flow – are experimentally investigated. It is reported that the extraction flow configuration performed better in heat transfer compared to the open flow configuration, with higher heat transfer coefficients and lower recorded surface temperatures. However, the heat transfer enhancement is accompanied by an increase in pressure drop penalty, which is, according to the authors, attributed to the mouth configuration of the Piranha Pin Fins.

Yang et al. [7] experimentally investigated the flow boiling heat transfer performance of microchannels coated with Si nanowires. The authors reported that the nanowire-coated microchannels exhibit more superior heat transfer coefficients compared to the plain-wall microchannels. The improvements in heat transfer are due to the high density of active nucleation sites and the enhanced thin-film evaporation by properly using nanowires. This heat transfer improvement is accompanied by a reduction in pumping power of up to 40% under relatively low mass flux conditions. However, at high mass flux, the extra flow resistance presented by the high surface roughness and porosity of the nanostructured walls causes the pumping power of the nanowire-coated microchannels to be greater than its plain-wall counterpart.

Flow boiling in microchannels remains an interesting heat transfer technology due to its effectiveness in heat dissipation at a small surface-to-volume ratio. However, the issues associated with the straight fins hinder its implementation in real-world applications and therefore, efforts are ongoing to develop novel microchannel fin structures to overcome these issues.

1.2. Motivation and objectives

The oblique-finned geometry has been proven to operate well in single-phase flow by Lee et al. [8] and in two-phase flow by Law and Lee [9]. Both exhibited better heat transfer performance compared to the conventional straight fins with a slightly higher pressure drop penalty. Besides that, the oblique-finned microchannels in two-phase mode offer mitigated flow instabilities of up to 4 times as well as extended the occurrence of critical heat flux by as much as 2.8 times. All these advantages of the oblique fins serve as a motivation for further parametric studies to determine the best configuration with highest heat transfer capability and low pressure drop penalty.

The mentioned works on the oblique fins [8,9] only involve the primary-to-secondary channel width ratio of 2:1, i.e. the main channel is twice the width of the secondary oblique channels. Larger secondary channels were not considered, and although Prajapati et al. [10] performed experiments using 1:1 primary-to-secondary channel width ratio, a comparison of the