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A comparative study of experimental flow boiling heat transfer and pressure characteristics in straight- and oblique-finned microchannels

Matthew Law, Poh-Seng Lee *

Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore

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ABSTRACT

Flow boiling experiments are conducted in straight-finned and oblique-finned microchannels with similar channel dimensions and operating conditions using the FC-72 dielectric fluid. Both heat sink geometries consist of 40 parallel microchannels, and are fabricated on a copper block with a footprint area of 25 mm × 25 mm. The oblique fins are produced by introducing diagonal cuts with angle of 27° and width which is half of that of the parallel microchannels. The comparative study with straight fins shows significant augmentation in heat transfer and the delay in the onset of critical heat flux for the oblique-finned microchannels. This is due to enhancement in the flow boiling stability offered by the oblique fins in terms of reduced wall temperature gradients and pressure fluctuations. Flow visualisations performed on both microchannel geometries show increased bubbles generation in the nucleate boiling region and a continuously developing thin liquid-film in the convective boiling region for the oblique fins, which is believed to be the primary factor in heat transfer enhancement. However, the improved heat transfer performance incurs a higher pressure drop penalty compared to its straight-finned counterpart. This drawback could possibly be overcome by careful modifications in the oblique-finned geometry, so as to control the amount of secondary flow.

1. Introduction

Flow boiling heat transfer in microchannels has been a subject of wide interest due to its ability to dissipate high heat fluxes from a relatively small footprint. Pioneering study in this area was first demonstrated by Tuckerman and Pease [1] by achieving high heat flux removal capacity of up to 800 W/cm^2 with microchannels in two-phase flows. In view of this huge advantage and the ever-increasing need for ultra-high heat flux removal, various microhannel design schemes have been put in place to further improve heat transfer performance and reduce pressure drop penalty. Nevertheless, the main purpose of these design improvements is to stabilise the flow boiling process by reducing pressure drop fluctuations caused by unsteady boiling within the microchannels.

1.1. Instabilities in straight-finned microchannels

Kuo and Peles [2] conducted experimental investigations to examine the effects of pressure on flow boiling instabilities in straight-finned microchannels with re-entrant cavities. Pressures ranging from 0 to 205 kPa are tested in the investigations, and instability parameters which are considered include the commencement of flow oscillation and CHF conditions, as well as local temperature measurements. The authors observed that flow boiling instabilities are significantly influenced by system pressure. High system pressure at a given mass flux delayed the commencement of flow oscillation, which causes the extension in CHF to high vapour qualities. Local temperature measurements, on the other hand, show lower amplitudes of oscillation amid at higher frequencies at high system pressure.

Qu and Mudawar [3] explored several aspects of fluid flow and heat transfer in two-phase microchannel heat sinks. They identified two types of two-phase dynamic instability, which are pressure drop oscillation and parallel channel instability. Pressure drop oscillation is associated with fairly periodic, large amplitude fluctuations in inlet and outlet pressure as well as heat sink temperature. This type of instability can be suppressed by throttling a control valve situated upstream of the heat sink. Parallel channel instability, on the other hand, produces only mild fluctuations in the net pressure and temperature, and therefore, does not play a very significant role in overall flow boiling instabilities. However,

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* Corresponding author. Tel.: +65 6516 4187; fax: +65 6779 1459.

E-mail addresses: matthew.law@nus.edu.sg (M. Law), mpelps@nus.edu.sg (P.-S. Lee).

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Nomenclature

A	area [cm^2]
c_p	specific heat capacity [J/kg °C]
d	distance from temperature probe to channel surface [cm]
G	mass flux [kg/m^2 s]
h	heat transfer coefficient [W/m^2 °C]
h_{fg}	latent heat of vaporisation [J/kg]
H	height [cm]
I	current [A]
k	thermal conductivity [W/cm °C]
l	length [cm]
L	length of heat sink [cm]
m	fin parameter [–]
$\dot{m}$	mass flow rate [kg/s]
n	number of data points [–]
N	number of [–]
p	perimeter [cm]
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 [cm]
T	temperature [°C]
ΔT_{sat}	degree of wall superheat [°C]
V	voltage [V]
w	width [cm]
W	width of heat sink [cm]
x	vapour quality [–]
z	distance from microchannels inlet [cm]

Greek symbols

Δ	gradient [–]
η	fin efficiency [–]
θ	oblique angle [°]
ρ	density [kg/m^3]

Subscripts

ch	channel
CHF	critical heat flux
cs	cross section
Cu	copper
eff	effective
exp	experimental
f	fluid
fin	fin
in	inlet
l	liquid
*loc*3	location of the third (most downstream) temperature sensor
loss	loss
ob	oblique cut
out	outlet
pred	predicted
sat	saturated
sub	subcooled
supplied	supplied
total	total
unfin	unfinned
v	vapour
wall	wall
*wall*3	third (most downstream) wall
$x = 0$	location of zero thermodynamic equilibrium quality

this type of instability causes the flow in an individual channel to oscillate between different flow regimes even at constant operating conditions.

Wang et al. [4] carried out simultaneous visualisation and measurement studies to investigate effects of inlet/outlet configurations on flow boiling instabilities in parallel microchannels. Three types of inlet/outlet connections (Type-A, Type-B and Type-C connections) have been tested experimentally. For flow boiling in microchannels without inlet restrictions (Type-A and Type-B connections), temperature and pressure oscillations occur when a bubble grows to channel size and expands upstream. This causes severe flow reversal as captured by the high-speed camera. In microchannels with the Type-A connection where the outlet conduit is perpendicular to the microchannels, the amplitudes of pressure and temperature fluctuations and the strength of the reversed vapour flow are the highest among the three types of connections because the outlet configuration is most restrictive. For microchannels with the Type-C connection where flow entering to the microchannels is restricted, steady flow boiling with no oscillations of temperature and pressure can be achieved. No reverse flow of vapour bubbles was observed under the experimental conditions. This configuration is recommended for high-heat-flux microchannel applications to avoid large temperature fluctuations and early burnout.

Wu and Cheng [5] performed a series of experiments to study different boiling instability modes of water flowing in microchannels at various heat flux and mass flux. The test piece consists of eight parallel silicon microchannels, with an identical trapezoidal cross-section. The authors observed three different unstable boiling modes: liquid/two-phase alternating flow (LTAF), continuous two-phase flow (CTF), and liquid/two-phase/vapour alternating flow (LTVAF). Generally, oscillation amplitudes in LTVAF are largest while oscillation amplitudes in CTF are smallest. Oscillation amplitudes in LTAF are between the LTVAF and CTF modes. LTAF occurs at lower heat flux with higher average mass flux, when the fluid at the outlet reaches a saturated temperature while inlet water is at a large subcooled temperature. CTF occurred at medium heat flux and medium mass flux, when the fluid at the outlet reaches a saturated temperature while inlet water is slightly subcooled. LTVAF occurs at higher heat flux and lower mass flux, when the water at the outlet is superheated while the inlet water temperature is slightly superheated with occasional dips of subcooling.

1.2. Benchmarking of straight-finned with enhanced microchannels

Krishnamurthy and Peles [6] conducted flow boiling experiments on in-line micro pin fins with a single microchannel using HFE 7000 dielectric coolant. The thermal performance evaluation with a plain microchannel shows that heat transfer coefficient during subcooled boiling for the pin fins microchannel is higher than that for plain microchannel. However, the enhancement is smaller in comparison to that observed during single-phase flow, which is attributed to the reduction in fin efficiency.

Bai et al. [7] performed experimental investigations on parallel microchannels with metallic porous coating. The authors analysed and benchmarked the flow boiling and pressure drop performances, as well as instability characteristics of the porous-coated microchannels with conventional microchannels. They found that