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Experimental investigation of flow boiling heat transfer and instabilities in straight microchannels

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ABSTRACT

Flow boiling experiments were conducted in copper microchannels with two different footprints of 25 mm × 25 mm and 20 mm × 10 mm. The channels, having nominal dimensions of 300 μm width and 1200 μm depth with a surface roughness of 2 μm (Ra), were fabricated by wire-cut EDM. De-ionized water was used as the coolant fluid. Experimental data was plotted on Taitel–Dukler flow regime map to predict the flow boiling regimes existing within the channels under different operating conditions. An 'M' shaped variation of the local heat transfer coefficient was obtained with respect to the exit vapor quality and the heat transfer mechanism was explained based on the existent flow boiling regime. High speed visualizations were shown to validate the explanation. Assessment of the predictive accuracy of the classical two-phase heat transfer correlations from literature revealed that regime based correlations when applied to the respective regimes can better predict the heat transfer in microchannels. The occurrences of instabilities were observed and their effect on heat transfer was also studied.

1. Introduction

Experimental investigations of flow boiling in microchannels have received wide attention and are being rigorously pursued owing to the cooling demands from particularly the semi-conductor industry, not to exclude the defense, solar, medical and the energy sectors. Hence an intense need has arisen to understand the underlying mechanisms of heat transfer and pressure drop to effectively exploit this phenomenon for cooling applications.

As far as flow boiling in microchannels is concerned it is highly inaccurate to utilize the existing macrochannel flow boiling heat transfer coefficient models and the two-phase pressure drop models to predict their behavior. This is because the surface tension force becomes stronger and the gravitational force weaker with reducing channel dimensions. Hence the underlying physics changes substantially. In response to this issue, a number of works have been done to understand the heat transfer mechanism and pressure drop in microchannel flow boiling.

As early as 1982, Lazarek and Black [1] studied the evaporation of R113 in a SS tube of 3.1 mm diameter in a two part vertical test section with sub-cooled liquid at the inlet. They presented the variation of heat transfer coefficient with vapor quality. While in subcooled region the heat transfer coefficient increased with vapor quality, in the saturated region it became insensitive to vapor quality but showed a strong dependence on heat flux. Hence they concluded that nucleate boiling mechanism was dominating the heat transfer process.

Tran et al. [2] conducted experiments to study the flow boiling heat transfer coefficients in a small circular channel of $d = 2.46$ mm and a small rectangular channel of $d_h = 2.40$ mm both having a length of 0.9 m. They obtained local heat transfer results over a range of qualities up to 0.94, a mass flux range of 44–832 kg/m^2 s and a heat flux range of 3.6–129 kW/m^2. They observed that local heat transfer coefficient is independent of quality for qualities greater than 0.2. They also observed mass flux independence and strong heat flux dependence of local heat transfer coefficient in both the geometries. They concluded that for a broad range of heat fluxes, nucleate boiling is the dominant heat transfer mechanism in small passages considered in their study. They also noted that forced convection will dominate at very low heat fluxes, implying at very low wall superheat.

Bao et al. [3] experimentally investigated the flow boiling heat transfer coefficients for Freon R11 and HCFC123 in a smooth copper tube with an inner diameter of 1.95 mm. They examined under heat fluxes ranging from 5 to 200 kW/m^2, mass fluxes from 50 to 1800 kg/m^2 s, vapor quality from 0 to 0.9, system pressures from 200 to 500 kPa and experimental heat transfer coefficients from 1 to 18 kW/m^2 K. They found that the heat transfer coefficients were a strong function of the heat flux and the system pressure, while the effects of mass flux and vapor quality were very small in the range examined. Thus they suggested that the heat transfer is mainly via nucleate boiling.

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Nomenclature

A	footprint area, m^2
A_c	convection area per channel, m^2
A_{cs}	cross sectional area of the fin, m^2
Bo	boiling number
Co	confinement number
F	convective boiling enhancement factor
f	friction factor
Fr	Froude number
F_s	shape factor
F_{sh}	constant defined in Shah correlation
H	fin height, m
L	substrate length, m
N	number of channels
N_s	parameter defined in Shah correlation
P_f	fin perimeter, m
P	pressure, bar
ΔP	overall pressure drop, bar
ΔP_{ch}	pressure drop across the microchannels, bar
Pr	Prandtl number
Re	Reynolds number
S	suppression factor
T	temperature, °C
c_p	specific heat capacity, kJ/kg K
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/mK
G	mass flux, kg/m^2 s
$\dot{m}$	mass flow rate, kg/s
m	fin parameter
h_{fg}	heat of vaporization, J/kg
q	heat transfer rate, W
q''	heat flux, W/m^2
d	distance from thermocouple to channel surface, m
D_h	hydraulic diameter, m
U	superficial velocity, m/s
w	width, m
W	width of the substrate, m
x	vapor quality
X	Martinelli parameter
z	distance from channel inlet, m

Greek symbols

η	fin efficiency
μ	dynamic viscosity, Ns/m^2
ρ	density, kg/m^3
α_o	void fraction
Ψ	heat transfer enhancement factor (Shah correlation)

Subscripts

c	channel
f	fluid or liquid
fd	fully developed
dev	developing
g	vapor or gas
i	inlet
s	substrate
sat	saturation
o	outlet
$tc3$	3rd thermocouple (most downstream location)
w	wall
eff	effective
$exit$	exit of the microchannel
sp	single phase
tp	two-phase

Lin et al. [4] conducted an experimental study of two-phase flow and heat transfer of refrigerant R141b, in small tubes. Four circular tubes with diameters of 1.1, 1.8, 2.8, 3.6 mm and one square tube of 2×2 mm^2 were used in their test. The parameter ranges were mass flux 50–3500 kg/m^2 s, heat flux 1–300 kW/m^2, and inlet pressure 1–3 bar resulting in mean boiling heat transfer coefficients of 0.1–10 kW/m^2 °C. They found that local heat transfer coefficients are not only a strong function of heat flux but also a function of vapor quality and a weaker function of mass flux for the all the small tubes tested. So they deduced that both nucleate boiling and convective evaporation occur in small tubes. The mean heat transfer coefficient was found to be primarily a function of the heat flux, rather than the mass flux. They also concluded based on comparison with data in the literature that a general flow map developed from adiabatic two-phase flow tests can provide guidance for prediction of flow regimes in heated tubes. They observed that the flow regime transitions are also influenced by mass flux. At a high mass flux, the transitions from confined bubble to slug, from slug to churn and from churn to annular flow were seen to occur at lower vapor qualities.

Kandlikar and Balasubramanian [5] undertook an experimental study to determine the effect of gravitational orientation on flow boiling characteristics of water in a set of six parallel minichannels, each 1054 μm wide by 197 μm deep and 63.5 mm long with a hydraulic diameter of 333 μm. Three orientations—horizontal, vertical downflow, and vertical upflow—were investigated under identical operating conditions of heat and mass fluxes. High-speed images were obtained to reveal the detailed two-phase flow structure and liquid–vapor interactions. They observed that the nucleating bubbles were found on the wall during passage of the bulk liquid as well in the thin liquid film surrounding the vapor plug and in the annular film. They explained that these visual observations supported the conclusions indicating dominance of nucleate boiling as seen from the decreasing trend in h versus x reported in their as well as other earlier investigations [6].

Agostini et al.[7] conducted a three part study on flow boiling of refrigerants R236fa and R245fa in a silicon multi-microchannel heat sink composed of 67 parallel channels, which are 223 μm wide, 680 μm high and 20 mm long with 80 μm thick fins separating the channels. The base heat flux was varied from 3.6 to 221 W/cm^2, the mass velocity from 281 to 1501 kg/m^2 s and the exit vapor quality from 2% to 75%. The working pressure and saturation temperature were set nominally at 273 kPa and 25 °C, respectively. Three main heat transfer trends were outlined in their first part of the study on R236fa. At low heat flux, vapor quality and mass velocity, the heat transfer coefficient increased with vapor quality and was independent of heat flux and mass velocity. At medium heat fluxes the heat transfer coefficient was almost independent of the vapor quality and increased with heat flux. Besides, the heat transfer coefficient was weakly dependant on the mass velocity. At very high heat fluxes the heat transfer coefficient increased weakly with mass velocity and decreased with increasing heat flux. They suggested that this later trend is probably due to intermittent dry-out before reaching CHF.

In part II of their study, Agostini et al. [8],utilizing the same test setup, measured local heat transfer coefficients for R245fa flow