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Dryout characteristics during flow boiling of R134a in vertical circular minichannels

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ABSTRACT

In this paper, the experimental results of dryout during flow boiling in minichannels are reported and analysed. Experiments were carried out in vertical circular minichannels with internal diameters of 1.22 mm and 1.70 mm and a fixed heated length of 220 mm. R134a was used as working fluid. Mass flux was varied from 50 kg/m^2 s to 600 kg/m^2 s and experiments were performed at two different system pressures corresponding to saturation temperatures of 27 °C and 32 °C. Experimental results show that the dryout heat flux increases with mass flux and decreases with tube diameter while system pressure has no clear effect for the range of experimental conditions covered. Finally, the prediction capabilities of the well known critical heat flux (CHF) correlations are also tested.

1. Introduction

Due to the fact that reduced channel diameter offers numerous advantages [1,2], a great deal of effort is being made by the scientific and the industrial community to introduce microchannel and minichannel heat exchangers in practical applications. Reduced fluid inventory, light weight, less material consumption and low cost of the heat exchange device are the factors which attract the industrial and scientific community's attention to develop micro-heat exchange devices. Microchannels appear to be a potential and viable option for cooling of electronics, as air-cooling is reaching its limits. Other potential application areas for microchannels may be the automotive industry, the refrigeration and air conditioning industry, the aerospace industry and the fuel cells. Tremendous efforts are underway to understand the basic physics involved in single and two phase flow and heat transfer in microchannels.

Flow boiling of fluids in a microchannel is associated with high heat transfer rates but at the same time it is a complex phenomenon and models developed for macroscale flow boiling do not work for microscale [3]. It is of prime importance to be able to know heat transfer rates, pressure drop and dryout condition for the safe, effective and economic operation of the microchannel heat exchangers. As observed by Refs. [4,5], heat transfer performance of a microchannel is reduced when partial dryout condition is reached. Therefore, it is very important to be able to accurately predict the dryout conditions for the safe and effective operation of the system [2,6]. Critical heat flux (CHF) studies carried out to date mostly employ water as working fluid and larger diameter channels and due to limited data available for other fluids, the well known CHF prediction methods available are based on water. Moreover, the dryout and CHF data for microchannels is very limited [7]. Hence, more accurate data is needed for developing models and correlations to design the microevaporators. The purpose of this study is, therefore, twofold, firstly to provide more insight and understanding of CHF mechanism and secondly to enhance the CHF data bank available for microchannels and fluids other than water for developing models and prediction methods for CHF in microchannels.

Critical heat flux (CHF) may occur by different mechanisms depending upon whether the fluid at the inlet is highly sub-cooled or saturated. In highly sub-cooled flow boiling the CHF usually occurs at very high heat flux due to departure from nucleate boiling (DNB) while in saturated conditions or low sub cooling conditions at the inlet, the CHF may also occur at lower heat flux due to complete dryout of the liquid film. Moreover, in the literature some researchers usually define the CHF with regard to physical burnout of the test section while the others state that CHF may not necessarily be accompanied with the physical burnout of the heater surface [8]. It is therefore, necessary to first define the term CHF which will be used throughout this paper. CHF is characterised by low heat transfer coefficient and abruptly increasing heater surface temperature (for a heat flux controlled system). Therefore, it is undesirable to operate a system near the CHF condition. In microchannels, heat transfer deteriorates even before CHF, when intermittent dryout is encountered [4,5]. In this paper, the condition where the heat transfer coefficient is reduced considerably

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Nomenclature

A	heat transfer area (m^2)
Bo	bond number, $g(\rho_l - \rho_g)D^2/\sigma$ (–)
CHF	critical heat flux (W/m^2)
C_p	specific heat (J/kg K)
D	diameter (m)
DI	dryout incipience
DC	dryout completion
G	mass flux (kg/m^2 s)
I	current (A)
i_{lg}	latent heat of vaporisation (J/kg)
Δi_{in}	liquid inlet sub cooling enthalpy (J/kg)
k	Thermal conductivity (W/m K)
L	length (m)
MAD	mean absolute deviation, $1/N\sum(\lvert X_{pred} - X_{exp}\rvert/X_{exp})$
m	mass flow of refrigerant (kg/s)
P	pressure (bar)
q''	heat flux (W/m^2)
T	temperature (°C)
V	voltage (V)
x_{th}	thermodynamic vapour quality (–)
z	length, axial position (m)
z^*	normalised length, z/L_h

Dimensionless numbers

Pr	Prandtl number, $\mu C_p/k$
Re	Reynolds number, GD/μ
We	Weber number, $G^2L/(\rho_l\sigma)$ (–)
We_D	Weber number, $G^2D/(\rho_l\sigma)$ (–)

Greek letters

μ	dynamic viscosity (N s/m^2)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ΔT_{sub}	sub cooling degree, $T_{sat} - T_{in}$ (°C)
ΔT_w	wall superheat, $T_w - T_{sat}$ (°C)

Subscripts

c	cross sectional
e	exit
exp	experimental
g	gas
h	heated section
i	inner
in	inlet
l	liquid
o	outer
$pred$	predicted
sat	saturation
w	wall

and the surface temperature of the heater rises abruptly, will be termed dryout completion (DC) heat flux instead of CHF to avoid confusion as the complete burn out of the heater surface is not reached in these tests.

Celata et al. [9,10] analysed the effects of different parameters on CHF, based on the data available in the literature, and provided an overview of the sub-cooled flow boiling CHF. The authors also discussed the correlations and models available for the prediction of CHF and identified sub cooling, pressure, tube diameter, heated length, and fluid velocity as the main parameters having influence on CHF. Celata et al. [11] also experimentally investigated the influence of tube diameter, heated length and wall thickness on sub-cooled CHF. Based on their own experimental results [11], the authors found that CHF increased with decreasing diameter until a defined value, after which CHF remained constant and independent of channel diameter. They found almost no effect of wall thickness on CHF. These experiments by Celata et al. [11] were conducted at highly sub-cooled conditions which are expected to be different from the current experiments at very low inlet sub cooling conditions which may expectedly influence the mechanism of CHF, i.e. dryout type or DNB type CHF.

Teyssedou et al. [12] carried out an experimental investigation of CHF in vertical tubes of 8 mm internal diameter and different heated lengths ranging from 0.75 m to 1.8 m. Exit pressure ranged from 5 bar to 30 bar, inlet sub cooling from 0 °C to 100 °C and exit quality ranged from 5% to 70%. The experiments were thus performed for both dryout type CHF and DNB type CHF. From their experimental data, the authors observed that CHF decreased with increase in exit quality in general, except for some cases in which they observed a limiting vapour quality condition for CHF. For constant exit vapour quality, they observed a decrease in CHF with increasing heated length but this effect was seen to disappear at medium exit pressures. Different correlations available in the literature and Groeneveld's CHF look-up table [13] were compared with experimental results. They found that the look-up table performed well for low pressures as compared to correlations; while for medium pressures and high mass fluxes the Katto and Ohno [14] correlation predicted the results well.

Cavallini et al. [15] performed experiments to study the dryout and critical quality conditions during flow boiling in a circular microchannel. They suggested using the standard deviation in wall temperature as a criterion to identify the periodic dryout and critical quality conditions. Condensation tests for the same set up and test conditions were also performed and in this case temperature fluctuations were not found. Fluctuations were also absent during low quality flow boiling. Based on these observations the authors related the wall temperature fluctuations to the oscillating dryout of the film adjacent to the heated wall. The vapour quality at the channel axial length where the abrupt increase of the wall temperature standard deviation occurred was termed as the dryout quality. The authors found little dependence of dryout vapour quality on mass flux and heat flux.

Qi et al. [16] experimentally investigated flow boiling heat transfer coefficients and CHF in microchannels with four different diameters of 0.531 mm, 0.834 mm, 1.042 mm and 1.931 mm. They identified two different heat transfer regions for low and high vapour qualities; for low qualities, nucleate boiling dominated while for high vapour qualities, convective boiling dominated. They observed higher CHF and critical vapour quality values as compared to macrochannels. CHF was observed to increase and critical vapour quality to decrease with mass flux in their experiments. Based on their experimental observations, they identified CHF to be reached by dryout of the liquid film.

Wojtan et al. [17] performed experiments to investigate the CHF during saturated flow boiling of R134a and R245fa in 0.5 mm and 0.8 mm internal diameter microchannel tubes. The heated length in their experiments was varied between 20 mm and 70 mm. Other experimental parameters included; inlet sub cooling from 2 °C to 15 °C, saturation temperatures 30 °C and 35 °C, mass flux from 400 kg/m^2 s to 1600 kg/m^2 s and heat flux from 3.2 kW/m^2 to