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Flow patterns and bubble departure fundamental characteristics during flow boiling in microscale channels

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ABSTRACT

This paper presents an experimental investigation into the fundamental characteristics of flow boiling in microscale channels based on diabatic high-speed flow visualizations. Experiments were conducted with R134a and R245fa refrigerants flowing in a 0.40 mm circular horizontal channel for mass velocities ranging from 100 to 900 kg/m^2 s and heat fluxes of up to 226 kW/m^2. Flow images were captured at recording speeds of up to 100,000 frames/s. Results for bubble departure diameter and frequency, bubble growth ratio, slug frequency and velocity, flow pattern transitions, characteristics of the liquid film and liquid–vapor interface are provided. The experimental data obtained are carefully analyzed, discussed and compared against previous results for tubes of 1.00 and 2.00 mm internal diameter. Predictive methods available in the literature for bubble departure diameter and frequency are evaluated by comparing their predictions against the data obtained in the present study. New bubble departure diameter and frequency correlations are proposed for small channels. The following conclusions can be drawn from the present study: (i) bubbles can detach from the wall with diameters much smaller than the tube diameter; (ii) the bubble growth process has a square root time-dependence; (iii) two different methods for estimating the average surface heat flux based on flow boiling videos have been developed; (iv) bubble active nucleation sites are observed for all flow patterns; (v) buoyancy effects are still present for a 0.40 mm tube, and (vi) six different sources of vapor–liquid interface oscillations have been identified.

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1. Introduction

Flow boiling and two-phase flow systems are composed of many complex thermo-hydraulic phenomena that are still not completely understood. As a result of these complexities, several authors have adopted simplifications and assumptions in their models without an established experimental evidence of the phenomenon. Such simplifications are more frequent in microscale systems because of the experimental difficulties inherent to small dimensions. Regarding flow boilng in microscale systems, even fundamental questions, as the existence and the effect of bubble nucleation sites on heat transfer during annular flow have not been appropriately addressed. Several other fundamental questions should also be properly investigated.

Chen's [1] theory has been well established for conventional channels ($d_h > 3$ mm). According to this theory, the flow boiling heat transfer rate is given as a result of the superposition of convective and nucleate boiling effects. However, different theories can be found in the literature for microscale conditions. Some authors [2–4] have concluded that under microscale conditions the heat transfer is dominated by nucleated boiling effects. Such a conclusion is usually based on heat transfer coefficient trends similar to those identified in pool boiling experiments, although distinct experimental heat transfer coefficient behaviors can be frequently found in the literature [5]. Therefore, the predominance of a certain heat transfer mechanism cannot be concluded only on the hermeneutics of the trends of experimental results, but fundamental observations and characterizations of the real flow boiling process are necessary.

Likewise, laminar flow regime is usually assumed for small-diameter tubes because of the low liquid Reynolds numbers involved. Some models and correlations for pressure drop and heat transfer coefficient under two-phase flow conditions have been developed assuming the occurrence of fully developed laminar flows [6–9]. However, under flow boiling conditions, the laminar flow development can be continuously disrupted by transient phenomena, such as bubbles nucleation, interfacial waves, flow pattern transitions, detachment followed by deposition of liquid droplets and disruption of the liquid film by local surface dryout, indicating that the fundamental concepts and simplifications used

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Nomenclature

A_i	tube internal area (m^2)
D	tube diameter (m)
D_b	bubble departure diameter (m)
d_{bubble}	bubble diameter along growth (m)
f_b	bubble departure frequency (Hz)
g	gravitational acceleration (m/s^2)
G	mass velocity (kg/m^2 s)
i	enthalpy (J/kg)
Ja	Jacob number (–)
k	constant (–)
L_{tr}	length, from the inlet position to the flow pattern transition position (m)
Pr	Prandl number (–)
P_{ss}	heat power in the stainless steel section (W)
q	heat flux (W/m^2)
Re	Reynolds number (–)
t	time (s)
T	temperature (°C)
T_{sat}	saturation temperature (°C)
u	speed (m/s)
u_v	vapor speed in slug flow (m/s)
u_w	wave speed (m/s)
x	vapor quality (–)
z	axial position along the tube (m)

Greek symbols

σ	surface tension (N/m)
α	void fraction (–), thermal diffusivity (m^2/s)
ρ	density (kg/m^3)

Subscripts

0	initial
annular	during annular flow
b	bubble departure diameter
est,fpt	estimated based on flow pattern transition
est,ssv	estimated based on slug speed variation
in	inlet
in,transp	inlet of transparent section
l	liquid
lv	liquid–vapor
ss	stainless steel section
tr	flow pattern transition
unif	uniform film thickness
v	vapor

in some models for laminar flow under flow boiling may not be so realistic.

Similarly, under low vapor quality conditions bubble departure diameter and frequency are expected to play a key role in the heat transfer mechanism [10]. However, few studies have reported experimental results for bubble detachment diameter and frequency during microscale flows [11] and predictive methods for these parameters developed for conventional channels and nucleated boiling conditions should be used with caution for flow boiling in microchannels.

Other fundamental flow boiling phehomena that can drastically affect the heat transfer coefficient and pressure drop and have been often neglected by authors in model development are interfacial wave effects, as addressed by Tibiriçá and Ribatski [12]. Several characteristics of interfacial waves can be studied by the analyses of high speed flow images.

In this context, this paper investigates fundamental microscale flow boiling characteristics based on diabatic flow images obtained through high-speed filming. Care was taken in the analyses of the complete development of the flow boiling process from the onset of nucleate boiling, corresponding to the first nucleation site, to the region of intermittent surface dryout. Experimental results were obtained for bubble departure diameter and frequency, bubble growth ratio, elongated bubble frequency and speed, flow pattern transitions, characteristics of the liquid–vapor interface and behavior of the liquid film during annular and slug flows.

2. Experiment

2.1. Experimental facility

The experimental setup diagram is shown in Fig. 1. In this experimental facility a micropump drives the working fluid (R134a or R245fa) through the circuit. A horizontal stainless steel tube is used for the establishment of the experimental conditions at the inlet of the 0.40 mm I.D. (internal diameter) horizontal transparent section, where diabatic flow visualization is performed using external controlled hot air flow. Following the visualization section there is a condenser to condense the vapor generated in the heated sections and a refrigerant tank. The refrigerant tank, which contains a serpentine coil, operates as a reservoir of the working fluid and control the saturation pressure in the refrigerant circuit. A frequency controller that actuates on the micropump sets the desired liquid flow rate and a Coriolis mass flow meter determines the mass flow. Just upstream the stainless steel tube the enthalpy of the liquid is estimated from its temperature T_1, by a 0.125 mm thermocouple in an adiabatic position on the outside wall of the pipe and, its pressure p_1, by an absolute pressure transducer.

The stainless steel tube has internal diameter of 0.38 mm and length of 200 mm, is thermally insulated from surroundings and heated by application of a direct DC current to its surface. Electrical power is supplied by two independent DC power sources controlled by a data acquisition system. The visualization section is a horizontal fused quartz tube of 0.40 mm inner diameter, 0.55 mm outer diameter and 85 mm length. Both stainless steel and flow visualization sections are connected through junctions specially designed and machined to match up their ends and keep a smooth and continuous internal surface.

The experiments were conducted first by setting the saturation temperature and pressure in the refrigerant tank. The temperature was kept constant by a thermal-controller system. Once the desired saturation pressure had been established in the refrigerant circuit, the mass velocity was set through a frequency controller acting on the micropump. Subcooled liquid entered the stainless steel section and electrical DC power was applied along the tube for the control of the inlet fluid state in the visualization section. The inlet condition could be either a subcooled single-phase flow or a two-phase flow whose desired vapor quality depends on the power applied to the stainless steel tube. A 1 °C inlet subcooling was used in most results in this experimental campaign, and this value should be considered in the foregoing results unless other value is clearly mentioned.

An external controlled hot air flowing transversal to the tube was used for the observation of a diabatic two-phase flow process in the visualization section. The hot air flow came from a hot air electrical gun, supplying air temperatures of up to 500 °C and a volumetric flow of up 6.5 liters per second. The air stream jet was

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