ENTRAINMENT FREQUENCY MEASUREMENTS DURING MICRO-SCALE FLOW BOILING

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Abstract. *The present paper deals with the characterization of the frequency of intermittent entrainment during annular flow in micro-scale channels through analyses of high speed videos obtained in an experimental facility design to study flow boiling in small diameter channels. The intermittent passage of liquid droplet fronts within the vapor during annular flows is frequently reported in the literature and seems related to the presence of thermal instabilities. In the present study, the entrainment frequency was measured during flow boiling of R245fa in 1.1mm and 2.32 mm I.D tubes for mass velocities from 100 to 300 kg/m^{2}s and saturation temperature of 31 and 41^{o}C. A new image treatment method was developed in order to automatically identify the entrainment frequency. The entrainment frequencies were segregated according to two groups: low and high frequency. The first was characterized by frequencies lower than 20 Hz and the second by frequency ranges from 50-500 Hz.*

Keywords: *entrainment, microscale, flow boiling, instabilities*

1. NOMENCLATURE

D	tube diameter (m)	N_f	number of frames (frames)
f_e	entrainment frequency (1/s)	p	pressure (Pa)
FPS	recording frame rate (frames/s)	P	electrical power (W)
G	mass velocity (kg/m^{2}s)	T	temperature (°C)
h	enthalpy (kJ/kg)	x	vapor quality (dimensionless)
h_{LG}	latent heat of vaporization (kJ/kg)		

2. INTRODUCTION

Convective boiling heat transfer inside channels with hydraulic diameters less than 3 mm, identified in the present text as micro-scale channels, has been studied since the end of the 1950's (Lowdermilk and Lanzo (1958)). However, it became a relevant topic in the area of thermal sciences just recently. Significant parcel of this interest is due to the industrial demand for very compact devices able to dissipate very high heat flux rates. Despite of the great benefits that can be achieved by using accurate predictive methods, these designing tools are not available yet, and heat exchangers based on small diameter tubes have been developed based on empirical evaluation of prototypes. Thus, in the last decade a huge effort has been put into identifying the main parameters governing heat transfer during convective boiling in micro-scale channels in order to develop accurate predictive methods.

Ribatski et al. (2006) have pointed out huge discrepancies by comparing independent heat transfer databases and predictive methods. One of the reasons for such result is the presence of thermal instabilities characterized by intermittent passage of liquid droplet fronts within the vapor during annular flows, as shown in Fig. 1. The presence of intermittent entrainment is a phenomenon inherent to convective boiling and seems responsible for significant changes on the heat transfer, dryout, CHF and pressure drop behaviors. In this sense, in the present study results for the entrainment frequency during convective boiling in micro-scale channels are reported for different experimental conditions.

3. EXPERIMENTS

3.1 Test apparatus and experimental procedure

The experimental apparatus is composed by refrigerant and ethylene-glycol circuits. The refrigerant circuit is shown schematically in Fig. 2. It comprehends a micropump, to drive the working fluid through the circuit, two subcoolers, one before the micropump and the other after, a pre-heater, to establish the experimental conditions at the inlet of the test section, a test section, a visualization section, a condenser to condense the vapor created in the heated sections, and a reservoir.

The water-glycol circuit (not shown) is destined to condense and subcool the fluid in the refrigerant circuit. The cooling effect is obtained by a 60% solution of ethylene glycol/water, which operates as intermediate fluid in a system that comprises three water/glycol tanks, electrical heaters actuated by PID controllers, heat exchangers and a refrigeration circuit.

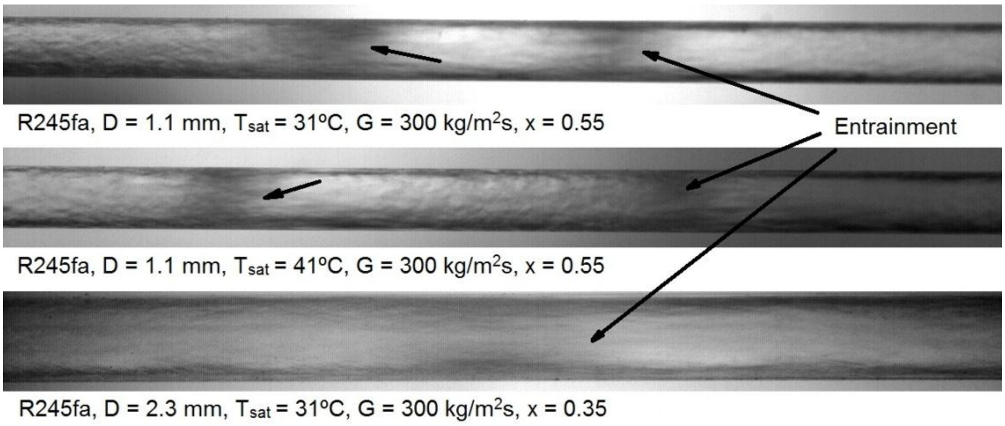

Figure 1. Liquid droplet fronts.

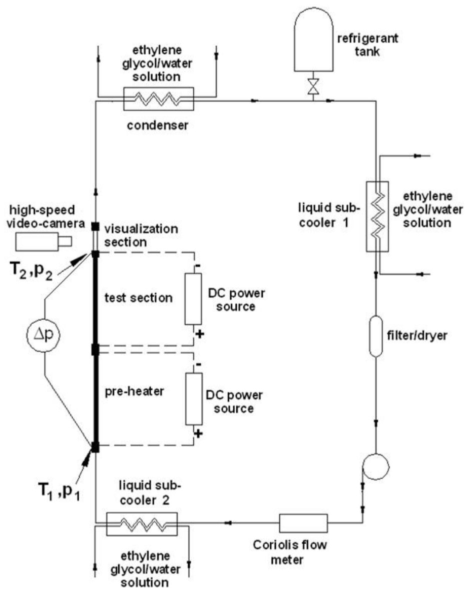

Figure 2. Schematic diagram of the refrigerant circuit.

In the refrigerant circuit, starting from subcooler 1, the test fluid flows through the filter to the micropump. The liquid flow rate is set by a frequency controller acting on the micropump. Then, there is a Coriolis mass flow meter to certify that the micropump provided the desired flow rate, and subcooler 2 to assure that the fluid entering the pre-heater will be subcooled. Upstream the pre-heater inlet, the enthalpy of the liquid is estimated from its temperature T_1 by a 0.25 mm thermocouple within the pipe and its pressure p_1 by an absolute pressure transducer. At the pre-heater, the fluid is heated up to the desired condition at the test section inlet. The pre-heater and the test section are horizontal stainless steel tubes. During the tests two different tube diameters were employed to investigate the diameter effect, so both pre-heater and test section were either 2.32 mm or 1.1 mm internal diameter tubes.

The pre-heater and test section are heated by Joule effect through a direct DC current applied to their surfaces and both heated sections are thermally insulated. The power is supplied to them by two independent DC power sources. A horizontal fused silica tube with length of 85 mm having the same internal diameter of the heated sections is used as visualization section. This transparent tube is located just downstream the test section. The flow images are acquired from the visualization section through an OPtronics high-speed camera, CamRecord600 model. For this, the illumination was set by high-brightness white LEDs. It was also used a tracing paper sheet to attenuate the intensity of the light and make its brightness diffuse.

Once the liquid leaves the visualization section, its temperature T_2 is determined from a 0.25 mm thermocouple within the pipe. The corresponding absolute pressure is estimated from a differential pressure transducer that gives the total pressure drop between the pre-heater inlet and the visualization section outlet, Δp. Then, the working fluid is directed to the tube-in-tube type heat exchanger where it is condensed and subcooled by exchanging heat with the anti-freezing ethylene glycol aqueous solution. The refrigerant tank operates as a reservoir of the working fluid and is used to control the saturation pressure in the refrigerant circuit in such a way that the refrigerant is transferred from the refrigerant circuit to the tank when aiming to reduce the operating pressure and refrigerant is transferred in the opposite way to increase the operating pressure.

The experiments were conducted first by setting the temperature in the refrigerant tank and maintaining it almost constant by a thermal-controller system in a way to establish the working saturation pressure. Then, the mass velocity was set through the frequency controller acting on the micropump. After that, the desired heat flux was imposed to the test section by varying the power applied to the pre-heater and test section. For further details of the experimental facility and procedure, the study of Tibiriçá and Ribatski (2010) is recommended.

3.2 Data reduction

3.2.1 Vapor quality at the inlet of the visualization section

In order to determine the vapor quality, an energy balance over the pre-heater and the test section was used, according to Eq. (1).

$$x = \frac{1}{h_{LG,out}}\left[\frac{4(P_1+P_2)}{G\pi D^2} + \left(h_{L,in} - h_{L,out}\right)\right] \quad (1)$$

The enthalpy of the liquid at the inlet of the pre-heater ($h_{L,in}$) was estimated based on the measured temperature T_1 and pressure p_1. The liquid enthalpy and the latent heat of vaporization at the visualization section ($h_{L,out}$ and $h_{LG,out}$, respectively) were estimated based on the fluid temperature T_2, measured just downstream the visualization section, and assuming a saturated state. In Eq. (1), the parameters P_1 and P_2 are the electrical power supplied by the DC power sources to the heated sections.

3.2.2 Entrainment frequency

The entrainment frequency (f_e) was determined at first by observing the high-speed videos in slow motion mode and counting the number of frames (N_f) between the beginning of an entrainment sequence and the beginning of the next one, just after the non-entrainment period. So, as the recording frame rate (frames/s) FPS is known, the entrainment period could be determined and consequently the entrainment frequency, as follows in Eq. (2).

$$f_e = \frac{FPS}{N_f} \quad (2)$$

In order to obtain automatically these frequencies, without the need of observing the videos and counting the number of frames between consecutives liquid droplets fronts, software based on LabVIEW was developed. This program is able of recognizing the entrainment within the flow by analysing the color variance of a fixed pixel of the video. This procedure is based on the fact that the flow image regions containing the entrainment are darker. The software analyses the variance of the color of the pixel and through a Fourier Transform of this signal determine the entrainment main frequencies.

4. EXPERIMENTAL RESULTS

The analyses of the videos reveal that the liquid droplet fronts (entrainment) during annular flow present two distinct behaviors. The first is the presence of consecutive liquid droplets fronts separated by short periods of time presenting a high frequency (50 – 500 Hz). The second behavior is related to the fact of this group of liquid droplets fronts occurs periodically according to a frequency less than 20 Hz according to the present study. In this study, the behavior of this low frequency phenomenon with varying experimental parameters is investigated for flow boiling of R245fa, in 1.1 and 2.32 mm internal diameter tubes.

Figure 3a shows the entrainment frequency behavior with varying the vapor quality and mass velocity. According to this figure, the frequency of the liquid droplets fronts increases with increasing mass velocity while the vapor quality effect on the entrainment frequency seems marginal until high vapor qualities. Figure 3b displays the variation of the entrainment frequency with vapor quality for different tube diameter and saturation temperature. According to Fig. 3b, the frequency of the liquid droplets fronts decreases with increasing tube diameter and saturation temperature. In Fig. 3b, the effect of the vapor quality on the frequency is again only marginal until high vapor qualities. However, at high vapor quality ranges, the entrainment frequency decreases drastically with increasing vapor quality according to Figs. 3a and 3b.

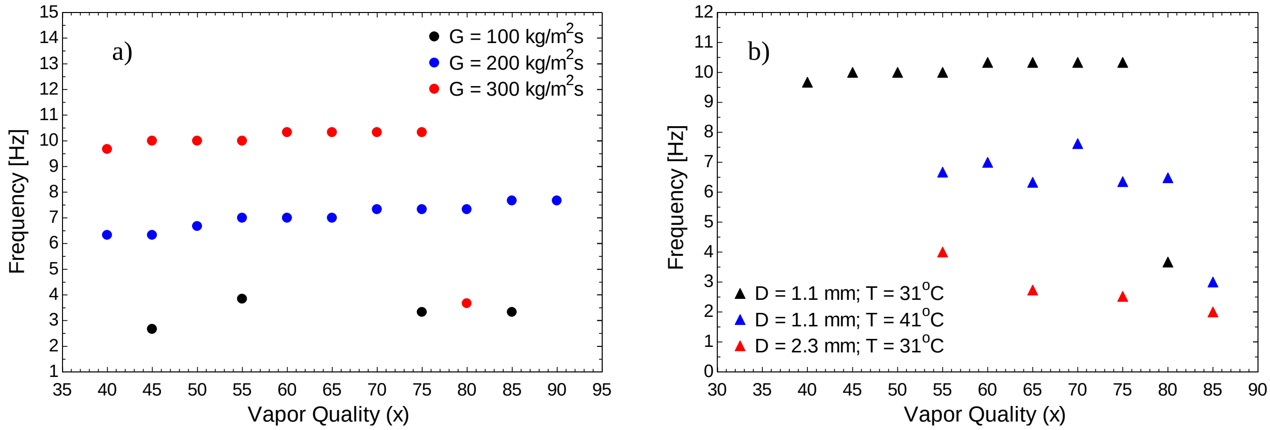

Figure 3. (a) Entrainment frequency for R245fa flow in 1.1 mm diameter tube and saturation temperature of 31°C; (b) Entrainment frequency for R245fa and mass velocity of 300 kg/m^{2}s

In general, the frequency values were in the range of 2 to 10 Hz and are similar to the values observed by Tibiriçá et al. (2012) when investigating flow boiling instabilities in micro-scale channels.

5. CONCLUSIONS

In the present study, the effects of experimental parameter on the entrainment frequency during flow boiling in small diameter tubes were characterized and from this analysis the following conclusions can be drawn:

- A technique based on the treatment of flow images was developed and allows determining automatically the entrainment frequency from two-phase flow high-speed videos;
- Two main range of entrainment frequencies were recognized, one characterized by frequencies lower than 20 Hz and the second by frequencies within the range from 50 to 500Hz.
- The low entrainment frequencies have their value increased with decreasing saturation temperature and tube diameter and increasing mass velocity. The effect of vapor quality on the entrainment frequency is almost negligible until high vapor qualities.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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