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Analysis of two-phase pressure drop fluctuations during micro-channel flow boiling

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ABSTRACT

Two-phase pressure drop fluctuations during flow boiling in single micro-channel were experimentally investigated. Degassed FC-72 was tested in micro-channels with a hydraulic diameters of 571 μm, 762 μm and 1454 μm (the aspect ratio (W_{in}/d_{in}) is 20, 20 and 10) at liquid mass fluxes of 11.2 kg m^{-2} s^{-1}, 22.4 kg m^{-2} s^{-1} and 44.8 kg m^{-2} s^{-1} and heat fluxes of 0–18.31 kW m^{-2}. Flow instabilities were analysed based on the two-phase pressure drop, synchronous visualisation results and thermographic measurements of the channel surface temperature profiles. Low-frequency high-amplitude fluctuation and high-frequency low-amplitude fluctuation are identified, the main causes of which were found to be the periodic reverse and rewetting flow and the vapour slug cluster passage respectively. The analysis based on a non-dimensional parameter K_1 helps to better understand the dominant influence on the liquid–vapour interface movement during flow boiling. Effects of heat flux, mass flux and channel hydraulic diameter on the pressure drop fluctuation were discussed. Besides, the coefficient of variation of the pressure drop was calculated to further explore the impact of experimental conditions on the flow boiling instabilities in the high aspect ratio micro-channels.

1. Introduction

Flow instabilities encountered during two-phase flow boiling were found to cause severe non-uniformities of surface temperature [1] and to reduce the boiling heat transfer coefficients [2]. Flow instabilities would also result in pressure drop fluctuation and lead to high amplitude temperature oscillation [3,4]. In micro-channel flow boiling, two-phase flow instabilities are even more intense than in conventional channels owing to the confined space for vapour bubble growth. Bergles and Kandlikar [5] also reported reduced critical heat flux (CHF) accompanied with the flow instabilities. These instabilities might be catastrophic if followed by dry-out and could lead to heat exchanger burnout and system failure. Thus, before bringing the micro-channel flow boiling into wider applications, issues of flow instabilities must be addressed to better understand the occurrence of flow instabilities, the impact factors, and the possible options to control and reduce the instabilities.

Various types of instabilities and corresponding unstable flow behaviours in micro-scale flows have been reported in literature. The tendency that instabilities are more severe in micro-channels than macro-channels could be expected, as individual bubbles are more influential on the local pressures in smaller internal volume [6]. Flow instabilities were proved to cause pressure drop fluctuations and to deteriorate the heat transfer during flow boiling in uniformly heated micro-channels [7]. The pressure fluctuation consequently resulted in fluctuating channel wall temperatures.

So far, there is no theoretical criterion to identify stable and unstable boiling. Several stability criteria were proposed in the previous studies based on experimental data with the aid of visualisation as well as synchronous pressure and temperature measurements.

Brutin et al. [8] suggested a stability diagram in term of heat flux versus mass flow rate. The steady state referred to a low pressure drop fluctuation amplitude (<1 kPa) and no characteristic oscillation frequency; while the unsteady state was defined by a high fluctuation amplitude (>1 kPa) and a characteristic frequency of a peak amplitude-to-noise amplitude ratio higher than 20.

Chang and Pan [9] reported different flow patterns under unstable flows with visual confirmations of forward or reversed slug/annular flows in each channel of the heat sink. Pressure drop oscillation amplitude was suggested to be the index for the occurrence of reverse flow. However, the impact of the reverse flow on the instabilities was not provided in detail. Wang and Cheng [10] suggested the exit vapour quality to be the stable and unstable flow

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Nomenclature

d_h	hydraulic diameter (m)	ΔP_rms	root mean square of pressure drop
f	frequency (Hz)	q	heat flux (kW m^{-2})
G	mass flux (kg m^{-2} s^{-1})	T	temperature (°C)
P	pressure (Pa)	X_k	amplitude
ΔP_avg	arithmetic mean pressure drop		

regimes criterion. A critical vapour quality of 0.013 was proposed, above which the flow would turn into unstable.

Unstable flow boiling was also classified into two sub-types according to the oscillation period length. Wang et al. [11] identified two unstable flow regimes with long-period oscillation (more than 1 s) and short-period oscillation (less than 0.1 s). Based on the visualisation results, it was found that the long-period oscillation unstable flow boiling was induced by the transition from annular flow to mist flow. On the other hand, the short-period oscillation unstable flow boiling was a result of vapour expansion. Efforts have been made to find the influence factors on two-phase flow stability. Effects of inlet conditions on two-phase flow pressure fluctuation amplitude and frequency were discussed by [12], revealing a much smaller fluctuation amplitude at a constant inlet liquid velocity than a constant outlet velocity. In addition, the differences between single channel and parallel channels were evidenced. Ding et al. [13] believed that less upstream compressible volume was required in single channel to initiate pressure-drop instability than in parallel channels. Therefore it was easier to detect the flow instability in single micro-channel. Wang et al. [11] emphasised the much longer temperature fluctuation in single channel than in parallel channels which they believed was a result of the significant flow interaction from neighbouring parallel channels. Singh et al. [14] pointed out that for both single channel and multi-channel conditions, averaged pressure drop increased with increasing heat flux for a constant mass flux. It was noticed that the fluctuations in parallel channels were not as periodic as in single channel. Nevertheless, higher pressure drop was found in parallel channels, reinforcing the explanation that fluctuation was caused by periodic bubble formation and departure.

Recently published investigations revealed some new flow instability characteristics. A fluctuation minimum with increasing heat flux was firstly reported by Singh et al. [14]. Additionally, the transitions between flow patterns showed different stabilities depending on the heat flux and mass flux [15]. Stable alternation was observed at high or very high heat flux and mass flux conditions while oscillating flow with instabilities were captured at low heat flux and mass flux.

Accordingly, two-phase pressure drop fluctuation can be significantly affected by the employed experimental conditions, the tendency of which needs to be explored by further experimental investigations. In the present study, flow instabilities are analysed based on the two-phase pressure drop and channel surface temperature fluctuations as well as the synchronous visualisation results. Effects of heat flux, mass flux and the microchannel geometry on flow boiling pressure drop oscillation are discussed.

2. Experimental setups

The experimental setups used in the present investigation of two-phase flow instabilities can be found in [16]. All the experiments were conducted at atmospheric pressure. Degassed FC-72 was used as the working liquid. Ambient temperature was maintained at 25 °C. The inlet and outlet pressures of the micro-channel test section were acquired via a National Instruments® Data Acquisition card at a predetermined acquisition frequency of 200 Hz. The offset pressures resulted from the background noises were recorded prior to each test when the channel was filled with stagnant working fluid. Then the offset pressures were subtracted from the acquired raw data. Meanwhile, the boiling process was synchronously visualised by the high speed camera and analysed with the Image Pro.® software. Pressure drop fluctuation was associated with the synchronous visualisation results to show liquid–vapour behaviours in time domain. Subsequently, Fast Fourier Transformation (FFT) was performed on the pressure drop results in Origin® software to assess the pressure drop fluctuation in frequency domain. In addition, an Infrared camera Thermovision® 900 (maximum speed: 7 fps; accuracy: ±1%) was utilised to obtain the temperature profile along the channel outer surface. Table 1 lists the test conditions of the present study.

3. Data reduction

Efforts have been made to reasonably obtain reliable averaged pressure data from the temporal inlet and outlet pressure measurements. In order to assess the sensitivity of the averaged pressure results to the averaging method used, we averaged the temporal pressure data using three methods. Firstly, arithmetic mean $\left(\overline{P} = \frac{1}{n}\sum_{i=1}^{n} P_i\right)$ was applied on the entire pressure data group. The average pressure could also be computed as $\overline{P} = \frac{1}{\tau}\int_0^t P(t)dt$, where τ is the time during which the data group is obtained (usually lasts 240–400 s). In the present study, the pressure fluctuation period is found to be less than 20 s. Since τ is much higher than the fluctuation period, the influence of τ on the mean pressure can be neglected. In order to evaluate the integration, two numerical methods, *Simpson's Rule* and *Newton–Cotes Formula* were used to solve the integration. The averaged pressure data with Simpson's Rule and Newton–Cotes Rule were compared with that of the arithmetic mean results. As can be seen in Table 2, the differences among these three methods are insignificant. Besides, arithmetic mean is the simplest and least time-consuming among the three. Thus, arithmetic mean method is chosen as the pressure averaging method in the present study.

4. Results and discussion

4.1. Two-phase pressure and synchronous visualisation results

After boiling incipient, the two-phase pressures were found to be fluctuating with high amplitude. The fluctuations were believed to be triggered by the liquid–vapour two-phase flow according to the comparison with single phase pressure measurements. Transient pressure measurements accompanied with the visualisa-

Table 1
Experimental conditions in the present study.

Channel d_h [μm]	Heat flux q [kW m^{-2}]	Mass flux G [kg m^{-2} s^{-1}]
571, 762, 1454	0–18.31	11.2, 22.4 and 44.8