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The effects of inlet restriction and tube size on boiling instabilities and detection of resulting premature critical heat flux in microtubes using data analysis

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HIGHLIGHTS

- The effects of inlet restriction, mass flux, and tube size on premature CHF were investigated.
- Inlet restrictions have a significant effect on expanding the surface temperature curve.
- Microtube size has a significant effect on the boiling instabilities leading to premature CHF.
- Fast Fourier Transform could be used as a detection tool for premature critical heat flux.
- The side-lobe energy becomes significantly higher at the inception of premature critical heat flux.

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ABSTRACT

In order to achieve high heat removal rates for micro scale cooling, it may be necessary to exploit boiling heat transfer. The size of corresponding heat sinks is continuously decreasing from mini size to micro size, and one of the most practical and extensive cooling methods is boiling heat transfer in plain microchannels and microtubes, which might be limited by inherent boiling instabilities. This study provides useful information about boiling instability phenomena in microtubes and offers a parametric comparative investigation. Experimental data are obtained from microtubes having 254 μm and 685 μm inner diameters, which were tested at low mass fluxes (78.9–276.3 kg/m^2 s) to reveal potential boiling instability mechanisms. De-ionized water was used as working fluid, while microtubes were heated by Joule heating. Configurations prone to boiling instabilities (low system pressures, low mass fluxes) were imposed to observe boiling instabilities in microtubes. Fine restriction valves were introduced to the system for providing flow restriction at the inlet. Alongside the experiments without any inlet restriction, experiments were conducted with configurations having inlet restrictions, where pressure drops over inlet restriction elements were 4 and 8 times as much as pressure drop over the microtube to suppress boiling instabilities. Temperature and pressure drop fluctuation signals were recorded and processed before premature CHF (Critical Heat Flux) conditions and at impending premature CHF conditions. Furthermore, Fast Fourier Transform (FFT) of the recorded data is performed for revealing the frequency correlations of the obtained fluctuations for observing the change in the FFT behavior. A significant rise in energy of the side lobes, which are basically the high frequency spectral regions, was observed from FFT profiles for impending premature CHF conditions implying that FFT could be used as a detection tool for premature CHF.

1. Introduction

Over the last decade, an astonishing progress in MEMS (Microelectromechanical systems) technology has been witnessed with paramount significance of micro structured devices. From the aspect of micro scale heat exchangers, there are many studies in the literature about flow boiling in small channels. As a result of this interest, the demand for micro scale cooling devices has proportionally increased, and two-phase flow boiling systems are becoming more important because of their highly effective heat transfer capabilities. They are also practical in numerous micro scale applications in addition to electronics cooling such as microchips in microreactors [1], fuel cells [2], drug delivery [3],

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automotive industry [3], micropropulsion [4], wireless power transmission [5], thermal actuation [6], medical surgery [7], evaporator applications for air-conditioning [8], micropumps [9], and various MEMS devices [10]. On the other hand, a large palette of applications is increasingly motivating researchers towards understanding physics behind micro scale flow boiling. However, working in such small scales comes with potential flow boiling instability problems particularly observed at low flow rates and pressures [11]. Flow boiling instabilities significantly affect the performance of microfluidic systems and might lead to premature critical heat flux (CHF) [12,13]. Comprehensive knowledge about premature critical heat flux and its causes is imperative for the extensive use of microchannels in futuristic applications.

Premature critical heat flux in microtubes is regarded as a consequence of upstream compressible volume instability or excursive instability [14]. In the studies reporting two-phase flow instabilities in single channels [15–17], wall temperature and pressure fluctuations were carefully recorded. Kennedy et al. [18] determined the onset of the instability by using pressure drop signals. Several authors also reported instabilities in single and parallel micro-channels [18–22]. Kandlikar [20] observed fluctuations with large amplitudes in multi-channel evaporators. Flow pattern observations revealed a flow reversal in some channels with expanding bubbles pushing the liquid–vapor interface in both upstream and downstream directions [19]. Qu and Mudawar [22] found two types of hydrodynamic instability, which were identified on a set of parallel channels: 1) severe pressure drop oscillations, which can trigger the premature critical heat flux (CHF), 2) mild parallel channel instability. Consolini and Thome [23] observed cyclical boiling behavior including liquid filling, bubble nucleation, growth and coalescence of bubbles, vapor expansion of vapor and evaporation of liquid film on walls.

Zhang et al. [24] presented a systematic framework for the transient analysis and active control of microchannel flow oscillations from a system-level perspective. They developed a lumped oscillator model, which was derived from momentum equations. Their models for predictions of flow oscillations agreed well with the experimental pressure-drop observations in a microchannel heat sink.

In their review study of two-phase flow instabilities, Boure et al. [25] proposed a classification of the boiling instability phenomena. They made a distinction between “static” and “dynamic” instabilities, and between “primary” and “secondary” phenomena. According to those distinctions, they came up with a full classification of flow instabilities and their corresponding instability characteristics. Within this frame, they reviewed various analytical techniques for predicting the instability threshold, in terms of applicability and accuracy.

The review study performed by Kakaç and Bon [26] states that in the two-phase flow dynamic instabilities there are three major modes of oscillations, namely density-wave (high frequency), pressure drop (low frequency) and thermal oscillations, in single and multichannel, electrically heated, up flow and horizontal systems.

Yüncü et al. [27] investigated the instability phenomenon in an electrically heated single channel having a horizontal heating system and used Freon-11 as the working fluid. They determined the operating characteristics of stable and unstable regions as a function of heat flux, exit orifice diameter and mass flow rate. Consequently, they developed a mathematical model to predict the transient behavior of two-phase systems.

Balasubramanian et al. [28] investigated flow boiling instabilities inside parallel and oblique finned microchannels. They found out that the oblique finned inner channel geometry helped the thermal boundary layers to be re-initialized at the leading edge of each oblique fin and reduced the boundary-layer thickness. Thus, the flow always remained under developing conditions. They proved that oblique channels caused a fraction of the flow to branch into adjacent main channels. This geometric modification was reported to mitigate flow boiling instabilities.

Silvérlo and Moreira [29] used a borosilicate glass channel to investigate flow boiling characteristics in microchannels by using methanol and ethanol as the working fluid. They also visually observed flow boiling. At high heat flux conditions, the two-phase flow acquired an unstable state, and this process occurred in a semi-periodic form of change of bubbly to slug to annual flow, dryout, rewet and refilling of the channel. They noticed that at high heat fluxes the temperature oscillation frequency increased.

Bogojevic et al. [30] conducted an experimental investigation of bubble dynamics in a multiple-microchannel heat sink. The results demonstrated that the bubble growth rate in microchannels was different from that in macro scale channels. Confinement of microchannel and interactions between the channel and bubble result in unique bubble dynamics in microchannels. They revealed that the frequency of temperature and pressure oscillations was determined by bubble dynamics. They observed that flow instabilities and flow reversals were the cause of axial bubble growth in multiple microchannels.

Wu et al. [31] investigated pressure drop and flow boiling instabilities in silicon microchannel heat sinks. They found that the difference in mass fluxes corresponding to the onset of nucleate boiling (ONB) and the onset of flow instability (OFI) decreased as the heat flux was increased. According to their visualization study, the appearance of flow reversals of the vapor core in parallel microchannels was not in phase, and liquid/two-phase alternating flows and liquid/two-phase/vapor alternating flows were present as flow patterns under unstable boiling conditions.

Chen et al. [32] investigated flow boiling of perfluorinated dielectric fluid FC-77 in a microchannel heat sink. The heat sink had 60 parallel microchannels each having 100 μm width and 389 μm depth. Their results showed that in the upstream region the flow transitioned from single phase liquid flow at low fluxes to pulsating two-phase flow at high heat fluxes for the duration of flow instability, which started at a threshold heat flux in the range of 30.5–62.3 W/cm^2 depending on the flow. On the other hand, in the downstream region, they investigated different flow patterns such as bubbly flow, slug flow, elongated bubbles or annular flow, alternating wispy-annular and churn flow, and eventually wall dryout at higher heat flux values. They observed that instability occurred under the condition of co-existence of binary states of liquid and two-phase flows in parallel channels, when there was adequate channel flow instability and surface heat flux was less than the heat flux at boiling inception. Moreover, bulk fluid temperatures did not reach the saturation temperature at the channel outlet.

Bogojevic et al. [33] presented an experimental study on boiling in a multi-channel silicon heat sink with non-uniform heating using water as the cooling liquid. They integrated thin Ni film sensors on the backside of the heat sinks in order to have insight into temperature fluctuations caused by two-phase flow instabilities under non-uniform heating. They observed that boiling inside microchannels with axially non-uniform heating leads to high temperature non-uniformities in the transverse direction.

Koşar et al. [34] conducted an experimental study about the suppression of boiling flow oscillations in parallel microchannels by inlet restrictors, where water was used as the working fluid. They deduced a direct relationship between the pressure drop increase imposed by the inlet restrictors and the onset of unstable boiling. They managed to eradicate parallel channel and upstream compressible volume instabilities with inlet restrictions.

For delaying CHF and parallel channel instability conditions, Kuo and Peles [35] introduced reentrant cavities in microchannels. They