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Micro/Mini Channel flow Boiling Instabilities : A Review

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ABSTRACT: The future technological horizons for engineering applications (Automotive, Energy, Bio-Engineering) require the use of limited size heat exchangers with high efficiency. In the present work, the flow field in small scale channels of different geometries is investigated experimentally using μ PIV (micro Particle Image Velocimetry) and thermal measurements. The Reynolds number in the channels is changed as also the wall temperature, in order to investigate and improve the thermal efficiency at different flow rates, temperatures and geometrical configurations. The main result of this investigation is that a serpentine cell attains the highest efficiency regardless of flow regime, getting high Nusselt numbers combined with low pressure losses, as derived by the observation of quite high local velocities and few recirculation regions.

KEYWORDS: Flow Boiling, Two phase flow, Instabilities, Micro channel, Pressure drop.

I. INTRODUCTION

In the study of fluid flow in microchannels, characteristic flow lengths are sufficiently large for the applicability of 'fluid as continuum' approach. One of the merits of microchannels is considerably large ratio of surface area to volume resulting in higher heat transfer rate. On the other hand, small hydraulic diameter (D_h) causes a higher frictional pressure drop in the channels. Compared to large hydraulic diameter channels, effect of surface tension force and thermal boundary layer is different in microchannels. All these factors are applicable to both single phase and two-phase flows. Phase change from liquid to vapour may occur in microchannels due to application of heat or reduction in pressure or both. In two-phase flow, total pressure drop is increased multifold due to existence of acceleration pressure drop in addition to frictional pressure drop. Vapour bubble dynamics is greatly influenced by shape and size of the channel, which affects the performance of microchannels in cooling applications [1,2]. Two-phase flow in microchannels has enough scope in several applications such as micro thrusters, MEMS devices and most importantly in microchannel heat sinks. Microchannel heat sink composed of various parallel channels through which coolant passes. It is especially suited for high heat dissipation from a small area. Moreover, these heat sinks have less thermal resistance, mass and overall volume.

Development of compact electronic devices and high-speed processors has significantly increased power densities in electronic components. Consequently, heat generation per unit volume has increased drastically and it is expected that heat flux may reach up to 1000 W/cm² in near future [3]. This large heat flux needs to be dissipated for proper functioning of next generation electronic devices. In view of this, microchannel heat sink has received considerable attention of researchers in recent years. Numerous works have been reported in literature about cooling with single phase (liquid) and two-phase (liquidvapour) coolant flows through microchannels. Moreover, it has been established that two-phase flow (flow-boiling) cooling technique is more effective than single-phase flow due to involvement of latent heat. Therefore, major focus is needed on phase-change cooling that can facilitate higher heat transfer rate using small quantity of coolant [4]. Another advantage of flow boiling is that cooling can be achieved at uniform temperature that eliminates the possibility of hot-spot formation on the substrate of electronic devices.

Nomenclature

T	temperature, K	Greek symbols	
A	area, mm ²	ρ	density, kg/m
Bo	Bond number	Δ	gradient
Dh	hydraulic diameter, mm	Subscript	
F	force, N	f	liquid
G	mass flux, kg/m ² s	g	vapour
h	heat transfer coefficient, W/m ² K	fg	liquid-vapour
i	latent heat, (j/kg)	in	inlet
n	header geometric parameter	out	outlet
P	pressure, Pa	w	wall
q''	heat flux, W/m ²		
Q	total heat amount, Watt		
R	instability parameter		

II. BUBBLE DYNAMICS

It has been identified that severe flow boiling issues in microchannels start with bubbles clogging in the confined channels. Typically, nucleating bubbles and their growth rate significantly depends on flow conditions i.e. subcooled or saturated boiling and flow parameters such as mass flux, operation pressure, inlet condition of the coolant. Initially, tiny bubbles are nucleated at the various locations of the channels. Most of these bubbles are either condensed or detached from the channel wall before they grow to the channel size. These bubbles manage to smoothly pass from the channels without disturbing the coolant flow. However, with passes of time, few bubbles managed to grow to the channel size and start blocking the flow passages of the coolant. Further, they elongate and their dynamics becomes crucial for instabilities. Jacobi and Thome [5] and Thome et al. [6] have proposed a model of elongated bubble and liquid slug. They predicted the transient variation in local heat transfer coefficient (h) in each regime and concluded that thickness of evaporating thin liquid film plays a significant role in heat transfer.

Kew and Cornwell [7] pointed out that inception of instabilities appears when growing bubble diameter approaches to the channel diameter. Bubble clogging is the initial cause for the inception of the various flows boiling issues encounters in microchannels. Steinke and Kandlikar [8] observed that in confined channels, pressure drop is highly sensitive to the bubble dynamics. Lee et al. [9] studied bubble dynamics in a single trapezoidal microchannel of very small hydraulic diameter. They observed that surface tension and inertia force due to bulk flow significantly affected the phenomenon. Further, it was found that initial bubble growth rate was moderate and later it increased with bubble size. Lee and Mudawar [10] pointed out that inlet subcooling of the coolant play significant role in all the aspects of bubble dynamics (nucleation, growth and coalescence) in microchannels. Tibirić and Ribatski [11] have done comprehensive experimental study on bubble dynamics in a circular channel of 0.4 mm using refrigerants R134a and R245fa. Authors found that detachment diameter of the bubbles could be significantly lesser than tube diameter and bubble growth rate was square root time-dependence. Furthermore, several annular liquid-vapour interfacial wave fronts have been discussed. It has been mentioned that out of various wave fronts, waves caused by flow instabilities never damp out and originates temperature and pressure fluctuations. Gedupudi et al. [12] studies the bubble confinement experimentally and numerically. Numerical model predicts the two stages of bubble growth namely, partially and fully confined bubble growth. Two experimental conditions with and without upstream compressibility were examined, possible consequence of upstream compressibility on instability and flow reversal have been discussed.

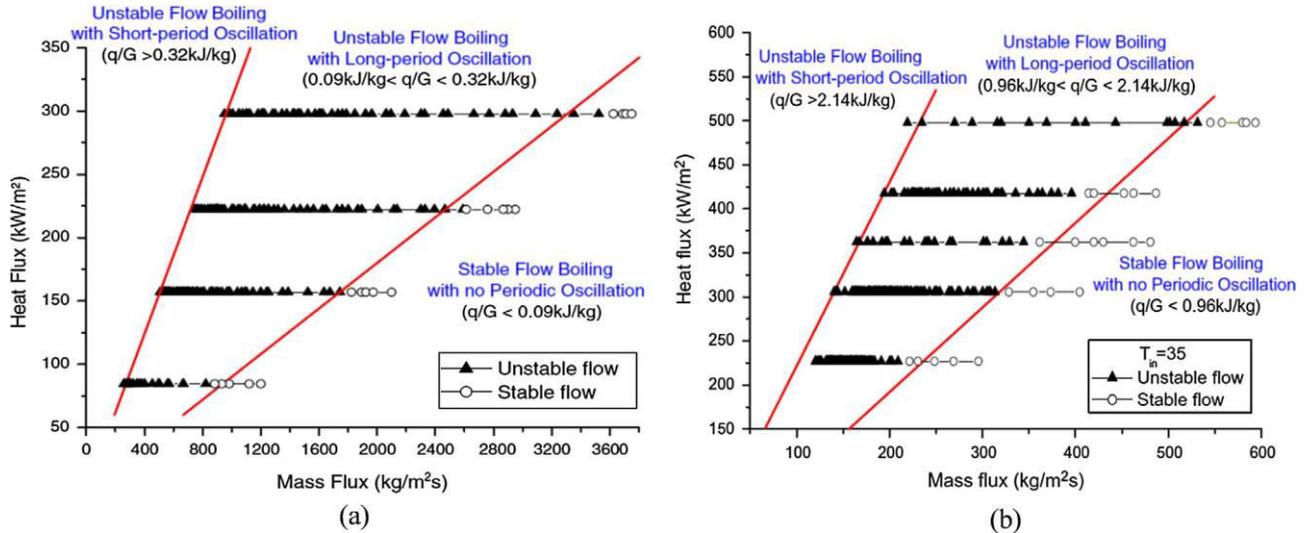


Fig. 1 Stable and unstable flow regime in (a) single and (b) parallel microchannel

Guo et al. [13] numerically captured the interfacial instabilities during slug flow in microchannel. Authors pointed out that even in fully developed, laminar annular flow instabilities may appear due to relative velocity that exist at the interface between two fluid streams. Liu and Palm [14] numerically predicted the growing and merging behaviour of bubbles in microchannel of 0.64 mm diameter. Reynolds number (Re) of 549 for fluid R134a has been considered and applied heat flux range was 14–28 kW/m². During three stages of transition i.e. sliding, merging and post-merging, bubble dynamics and heat transfer characteristics was different. Heat transfer has been found maximum during growing and sliding stage since thermal boundary layer was highly disturbed and thinner. However, at post-merging stage bubble growth as well as heat transfer decreases since boundary layer becomes thicker and continuous. Parajapati et al. [15] studies the clogging behavior of bubble slug in two different configurations of microchannels namely uniform and diverging for various mass fluxes and wettabilities. Numerically it has been predicted that during adiabatic flow condition in diverging channel bubble detachment occurs at small contact angles (0° and 30°) for the range of Re=80–319. Yin and Jia [16] studies the bubble confinement phenomenon in a microchannel of dimension 0.5 mm× 1mm. Bubble dynamics have been studied at atmospheric pressure and without liquid flow as shown in Fig. 5. Root contact angle and increased bubble growth force due to confined space have been identified as dominant mechanisms for bubble confinement in microchannels.

III. PRESSURE DROP OSCILLATIONS

Temperature and pressure oscillation inherently appears with the inception of flow boiling in microchannels. For a certain conditions, this periodic behaviour may become self-sustained, such condition may be characterise as temperature and pressure oscillation. Two-phase flow instability caused by adverse bubble dynamics, cyclic dry out and wetting of the channel further prompt the temperature and pressure fluctuations. It should be noted that temperature and pressure oscillations are most covered and reported phenomenon in instabilities studies. Hetsroni et al. [17] reported the hydraulic instabilities during flow boiling in microchannels that causes irregularities in temperature distribution. Moreover, with application of non-uniform heat flux, condition becomes worse. Periodic annular flow as well as dry zone was also observed. Subsequently, in the next publication Hetsroni et al. [18] observed temperature and pressure fluctuations during uniform heating that result in decreasing heat transfer. Temporal nature of temperature oscillations was in accordance to pressure fluctuations as shown in Fig. 2.

Figure shows the oscillations for very short duration of time i.e. 15 s also, the amplitude of temperature oscillation is very marginal. Qu and Mudawar [14] reported severe and mild pressure drop fluctuations in parallel rectangular microchannels using water as coolant. It has been pointed out that severe pressure oscillation is jointly caused by higher vapour generation in channel and upstream compressible volume. They suggested that it could be eliminated by throttling the flow immediately upstream of the test module. Lee and Mudawar [19] also gave a similar recommendation in their subsequent study. Wu and Cheng [20,21] reported the three unstable modes during flow

boiling of water in silicon parallel microchannels with hydraulic diameter 186 μm . These modes were observed for varying ranges of heat and mass fluxes. At low heat and high mass flux, liquid/two-phase alternating flow was observed. For moderate values of heat and mass fluxes, continuous two-phase flow mode whereas liquid/two-phase/vapor alternating flow mode exists corresponding to high heat flux and low mass flux. Moreover, the amplitude and periods of oscillations were different for different modes.

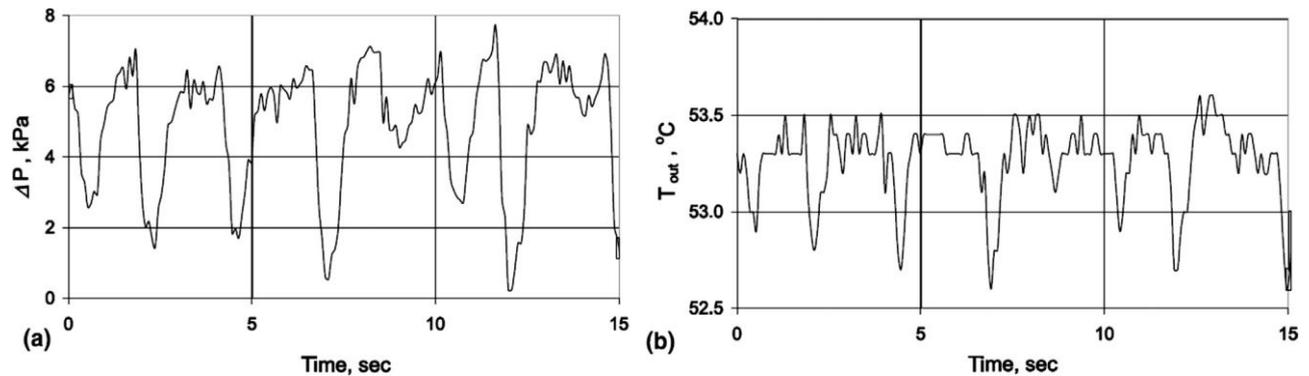


Fig. 2 (a) Pressure and (b) temperature fluctuation at $G= 148 \text{ kg/m}^2 \text{ s}$, $q'' = 36 \text{ kW/m}^2$

Brutin et al. [22] captured the oscillation phenomenon during flow boiling in rectangular channels of hydraulic diameter 889 μm . Based on flow visualization and fluctuating nature of flow, authors tried to quantify the steady and unsteady flow. Low amplitude pressure oscillation (0.5–5 kPa/m) and no characteristic frequency have been identified as steady state whereas high amplitude pressure fluctuation (20–100 kPa/m) with varying frequency range 3.6–6.6 Hz was unsteady flow. It has been emphasized that heat flux and mass flux are two governing factors of flow behavior. In the subsequent work, Brutin and Tadrist [23] proposed the stability map based on exit vapour quality and Reynolds number. They claimed that slight increase in exit quality at Re lower than 1000 could be presumed as unstable regime. Bergles and Kandlikar [8] pointed out that critical heat flux in parallel microchannels is prominently caused by an upstream compressibility or an excursive instability rather than the conventional dry out mechanism.

Therefore, it was concluded that most of the available CHF data have been taken under unstable flow boiling conditions. Hetsroni et al. [24] conducted the periodic boiling experiments in parallel triangular microchannels of hydraulic diameter ranging between 100 and 220 μm . Authors reported fluctuations in temperature, pressure drop and mass flux in phase. With the increase in heat flux, oscillation amplitudes of all factors intensified. Further, they pointed out that unlike single conventional channel, in microchannel heat sink, parallel channel instabilities amplified before the occurrence of CHF. Qi et al. [25] conducted flow boiling experiments on two tubes of diameters 1.931 and 1.042 mm using nitrogen as working fluid. Oscillations of wall temperature, mass flux and pressure drop were observed at regular intervals in both tubes. Such oscillations were considered as stable oscillations, since it remains stable if operating conditions are unchanged. Xu et al. [26] also reported the different types of oscillation patterns of temperature and pressure in parallel rectangular microchannels of hydraulic diameter approximately 450 μm . Onset of boiling instabilities have been considered very early when just nucleation incepts. During large amplitude/long period oscillation, negative pulse shows that cold liquid occupies the channel, causing higher heat transfer rate whereas the positive pulse represents the occupancy of vapour leading to less heat transfer rate.

IV. CONCLUSION

A comprehensive review of literatures focusing flow boiling instabilities in microchannels has been presented. Possible causes of instabilities, its consequences and most importantly its suppression techniques have been covered thoroughly. Both experimental and numerical studies have been simultaneously discussed. Following conclusions could be drawn from the above literature survey.

- Stability is an essential criterion for fruitful and efficient functioning of microchannel heat sink during flow boiling. It has been commonly accepted that suppressing the flow boiling instability could increase the heat transfer coefficient and CHF

- Source of instability in microchannel may be understood as the consequence of inherent characteristic of two-phase flow boiling and confined space of channel geometry. Therefore, rather than focusing on complete mitigation, efforts should be made to suppress it so that more function able, stable, smooth and efficient system could be possible.
- Compared to earlier studies, in the recent literatures, more attention has been paid to overcome the instability and this issue has been addresses simultaneously with heat transfer enhancement studies. Nevertheless, numerical/analytical works are very less explored compared to experimental studies.
- Bubble clogging, rapid bubble growth, flow reversal, large inlet subcooling, parallel channel interaction, upstream compressibility, oscillating flow have been identified as major causes to trigger instabilities.
- Studies on flow boiling instabilities mostly illustrate oscillation of temperature, pressure and mass flux however; influence of instability on CHF has not been emphasized.
- So far, there is no robust scheme developed that identify the stable and unstable flow. However, few works have been reported distinguishing these two flow characteristics.

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