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Flow boiling instabilities in microchannels and their promising solutions – A review

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ABSTRACT

The present work has been undertaken with an aim to address major challenges during two-phase flow boiling in microchannels. A comprehensive review of literatures has been presented that highlights the problems of two-phase flow boiling and its suppression techniques. Emphasis has been given to the recent literatures addressing the issues of flow boiling instabilities in microchannels. The broad aspects that have been covered are overview of instabilities, their causes, consequences and suppression techniques. Major attention has been paid to highlight the promising solutions that have been investigated to mitigate the instabilities. Study revealed that inception of instabilities is inherent during flow boiling. Nevertheless, it is more sensitive to trigger-out in microchannels compare to macro or conventional channels. Researchers have common agreement over the causes of instabilities and their consequences such as pressure and temperature fluctuations, severe unstable flow boiling, flow reversal, early CHF (critical heat flux) and dry out. It has been identified that instabilities during flow boiling depends on mass flow rate, flow regimes, bubble dynamics, inlet subcooling, inlet compressibility and coolant properties. Study also revealed that in the recent year's more attention has been paid to overcome the instability and issue has been addressed simultaneously with heat transfer enhancement studies. In order to suppress the instability various techniques have been investigated however, geometrical modification has been prominently considered to overcome the instability phenomenon.

1. Introduction

In the study of fluid flow in microchannels, characteristics 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 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/cm^2 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 (liquid-vapour) 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. Nevertheless, large amount

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Nomenclature

T	temperature, K
A	area, mm^2
Bo	Bond number
D_h	hydraulic diameter, mm
F	force, N
G	mass flux, kg/m^2 s
h	heat transfer coefficient, W/m^2 K
i	latent heat, (j/kg)
n	header geometric parameter
P	pressure, Pa
q''	heat flux, W/m^2
Q	total heat amount, Watt
R	instability parameter
x_e	thermodynamic equilibrium quality

Greek symbols

ρ	density, kg/m^3
Δ	gradient

Subscript

f	liquid
g	vapour
fg	liquid-vapour
in	inlet
out	outlet
w	wall

of vapour generation at high heat flux causes vapour bubble clogging and rapid bubble growth in downstream as well as upstream sections leading to flow instabilities [5]. Broadly, two-phase flow instabilities have been classified as static and dynamics based on existing mechanism [6,7]. Instabilities can be further characterized by uneven distribution of coolant between channels, pressure and temperature fluctuations, and intermittent flow reversal leading to local dry-out. Two-phase flow instabilities modify the hydrodynamics inside the channels that create mechanical vibrations and may cause premature critical heat flux (CHF) finally lead to damage of the device [8]. Microchannel heat sinks with two-phase flow are still in research stage and the cooling technology has not been yet commercialized. Kandlikar [9] outlined the fundamental issues encountered during two-phase flow in microchannels. Several issues related to flow-boiling in microchannels such as stability, effect of multichannel, flow pattern, bubble growth, temperature and pressure characteristic were comprehensively discussed. Flow reversal, bubble clogging and flow instabilities are some of the major challenges in the implementation of two-phase flow microchannel cooling in electronic chips [10–12]. According to Kandlikar et al. [13] flow instability may be defined as an unstable flow condition induced by the dynamic interaction between the internal and external systems and shows various modes with different mechanisms. Qu and Mudawar [14] identified two kinds of flow boiling instabilities namely upstream compressible volume instability and parallel channel interaction instability. Wang et al. [15] quantified stable and unstable flow-boiling modes occurred in microchannels, depending on four factors, that is, heat/mass flux ratio, channel geometry, inlet water subcooling, and physical properties of the working fluid.

In conventional or macro scale passages such as nuclear reactors, heat exchangers, boilers, instabilities during flow boiling have been extensively studies [6,7,16–21]. Instabilities have been classified as static and dynamic type. Causes of static instabilities are associated with steady state laws. In static instabilities, fluid flow may oscillate between two steady state conditions. Ledinegg instability has been considered as static instability. The occurrence of ledinegg is susceptible when pressure slope with respect to mass flux of internal flow system is less than the pressure supply system. Zhang et al. [22] studied the ledinegg static instability experimentally and numerically in horizontal microchannels. Effects of several flow variables have been examined on ledinegg instability. System pressure has found to be significant influence on static instability since, higher pressure is capable of improving stability in microchannel. It has been pointed out that reducing the number of parallel channels and lesser length to diameter ratio enhances that static stability. Prime causes of instabilities in conventional devices have been identified as interaction of boiling pressure drop with upstream compressibility, appearing due to external circuit or pump behaviour. Instabilities in such channels are characterised by pressure drop oscillation, temperature oscillation and density wave oscillation. Major factors affect such oscillations are mass flux (G), coolant subcooling (T_{in}) and heat flux (q''). Most of the studies were focused on determining the amplitude, frequency and periods of the oscillations. A layout of two-phase flow instabilities has been presented in Fig. 1.

Compared to macro channels, flow boiling instabilities are more sensitive in micro/confined flow passages. Due to confined space, an elemental disorder during flow boiling triggers the unstable conditions that ultimately lead to instability. The elementary phenomenon behind the dynamic instability is peculiar bubble dynamics that originated during flow boiling [5]. It incepts from bubble clogging followed by rapid bubble growth/elongation that finally results in flow reversal as shown in Figs. 2 and 3. This peculiar bubble dynamics is caused by inherent confined geometry of the microchannels, operating and flow conditions, properties and quality (in terms of dissolved gasses) of working fluid along with design of flow loop. Large inlet subcooling condition further accelerates the two-phase instabilities in microchannels [23–25]. Parallel channel interactions and inlet compressibility are well identified factors to elevate and accelerate the adverse bubble dynamics. A simple sketch has been shown in Fig. 3 that represents the stages of bubble growth that originates the instabilities in microchannles. Severe instabilities start with bubble clogging followed by rapid bubble growth and reverse flow of the vapour in the inlet section. In addition to these, parallel channel interactions, upstream compressibility trigger the process. All these three factors independently or cumulatively cause instabilities in the microchannels.

Review articles [21,26–34] suggest that flow boiling instability is a very notable problem hence needs to be addressed property. The phenomenon is not understood as well as streamlined very well. Thome [26] pointed out that small number of papers address the issue of steady state and instability of the flow. Kakac and Bon [21] present a comprehensive review on instabilities mainly focused on boiling phenomenon in tubular systems. Authors have covered the important models that predict the two-phase flow instabilities. According to Tibirica and

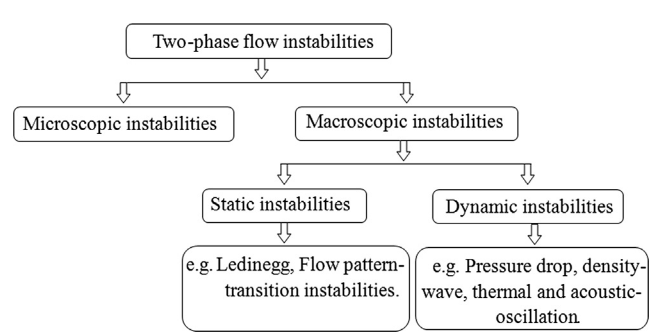

Fig. 1. Flow diagram of two-phase flow instabilities.