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A REVIEW OF SINGLE-PHASE AND TWO-PHASE PRESSURE DROP CHARACTERISTICS AND FLOW BOILING INSTABILITIES IN MICROCHANNELS

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ABSTRACT

This study presents a comprehensive review on single and two-phase pressure drop characteristics and flow boiling instabilities in microchannels to outline the discrepancies in the literature. The effect of mass flux, heat flux, experimental conditions, channel geometrical parameters (hydraulic diameter, aspect ratio etc.) was surveyed critically over a broad range of literature studies including the past and recent researches. Additionally, conventional and micro-scale pressure drop correlations are discussed. This study showed that the continuum theory is applicable for single-phase pressure drop applications with some considerations. Also, the two-phase pressure drop in micro-scale was found to have similar characteristics with conventional-scale channels. On the other hand, flow boiling instability is one of the important issues in microchannel heat exchangers. Flow boiling instabilities affect the system performance and may cause system failures. Therefore, unstable flow boiling conditions were identified in this paper for a reliable design of micro heat exchangers.

Keywords: *Instability, Microchannels, Pressure Drop, Single-Phase Flow, Two-phase Flow*

INTRODUCTION

Over the past decade, microchannel heat exchangers have been finding applications in various fields such as air-conditioning systems, chemical reaction chambers or heat exchangers for electronic cooling purposes [1-3]. These extremely compact heat exchangers have become more advantageous compared to conventional-scale heat exchangers due to their low weight, low waste production, less coolant consumption and high thermal plant efficiency. Therefore, micro-scale heat exchangers provide an effective solution for the conservation of scarce resources and the environment in long-term policy decisions.

Consequently, many researchers have made efforts to identify the single-phase flow and flow boiling characteristics in micro-scale systems. These studies mainly focused on revealing the underlying physical phenomena in microchannels. Single-phase and flow boiling characteristics in conventional-scale systems are mostly understood with similar published results [4, 5]. However, the applicability of pressure drop and heat transfer results obtained from conventional-scale channels to micro-scale systems is still not clear with reported contradicting results. Most researchers found poor agreement between their micro-scale experimental data and conventional-scale correlations. In addition to this, micro-scale correlations and models did not give accurate predictions for some data sets in micro-scale. Because, a large number of studies in micro-scale have been published using different working fluids, various channel geometries and different channel material over a wide range of experimental conditions. Therefore, there is no general model or correlation to evaluate the reported data in micro-scale. Also, the large experimental uncertainty in the channel dimensions, roughness measurements, temperature and pressure values readings affect the accuracy of the experimental data.

This study systematically reviews single and two-phase pressure drop studies in micro-scale, aiming to provide collective comprehension about the topic. The effect of various experimental conditions and channel geometries on single and two-phase pressure drop characteristics was presented from the literature studies. Conventional and micro-scale pressure drop correlations were also investigated. Finally, flow boiling instabilities in microchannels were reviewed critically. Unstable flow boiling conditions in microchannels were pointed out in order to have a safe, reliable and effective process in micro-scale.

RESULTS AND DISCUSSION

SINGLE-PHASE PRESSURE DROP IN MICROCHANNELS

Effect of entrance and exit losses

Over the past decade, a number of studies have reported that the single-phase pressure drop in micro-scale obeys conventional-scale theory [6-12]. Pfund et al. [6] carried out experiments in rectangular horizontal

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microchannels (D_h = 0.25-0.99 mm) in laminar and turbulent flow regimes using water. They concluded that the conventional-scale theory can predict well the pressure drop data in micro-scale if the uncertainties and entrance/exit losses are carefully considered. In another study, Xu et al. [7] investigated aluminium and silicon microchannels (D_h = 0.03-0.39 mm) in laminar and turbulent flow regimes accounting for entrance and exit losses. The conventional fully developed flow theory could better predict the friction factor results of silicon microchannels. The authors attributed this to the high measurement errors in aluminium microchannels due to machining. On the other hand, silicon microchannels were bonded to the wafer. Henceforth, channel dimensions of silicon microchannels were measured accurately. Steinke and Kandlikar [9] tested silicon rectangular microchannels (D_h = 0.23 mm). They concluded that if the measured friction factor data were corrected for inlet and exit losses and developing flow, the experimental data shows better agreement with the conventional theory as shown in Fig. 1.

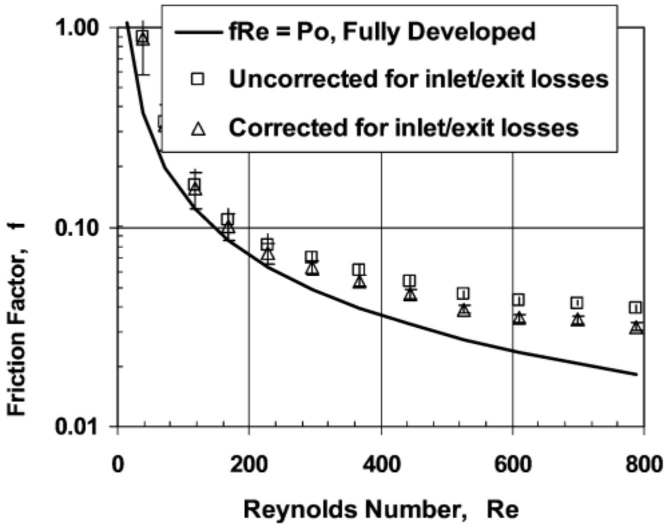


Figure 1. Friction factor vs Reynolds number considering entrance and exit losses [9]

Effect of channel hydraulic diameter and aspect ratio

Effect of microchannel hydraulic diameter and aspect ratio on single-phase friction factor was also investigated in the literature [10-13]. Sahar et al. [12] conducted a numerical study using a single microchannel. The microchannel hydraulic diameter range was 0.1-1 mm while the aspect ratio and length were fixed to 1 and 62 mm respectively. In the second part of the study, they varied the microchannel aspect ratio from 0.39 to 10 while the hydraulic diameter and length were kept constant at 0.56 mm and 62 mm respectively. They concluded that the single-phase friction factor increased with increasing channel hydraulic diameter. Moreover, the single-phase friction factor decreased slightly with the increase in aspect ratio until the aspect ratio value of 2. After that point, the single-phase friction factor increased continuously with increasing aspect ratio. Contrary to the study of Sahar et al. [12], Mirmanto [10] reported that the channel hydraulic diameter effect is insignificant on the single-phase friction factor. The former tested single copper microchannels (D_h = 0.44-0.64 mm) using de-ionised water as the working fluid under laminar and turbulent flow regimes. Moreover, their results were reasonably predicted by the developing flow theory. They concluded that when entrance effects, experimental uncertainties, inlet and exit pressure losses, departure from laminar flow were carefully evaluated, the results indicate that, equations developed for conventional scale flow are applicable for water flows in microchannels of that sizes. Contrary to the study of Sahar et al. [12], Özdemir [11] and Zhang et al. [13] stated that the channel aspect ratio has no effect on the single-phase friction factor, see Fig. 2. Özdemir [11] carried out an experimental study with rectangular copper microchannels (D_h = 0.56 mm, β = 0.5-4.94 and L = 62 mm) using de-ionised water. Özdemir [11] also reported that the conventional-scale fully developed and developing flow correlations reasonably predicted the experimental friction factor data in the laminar and turbulent flow regimes.

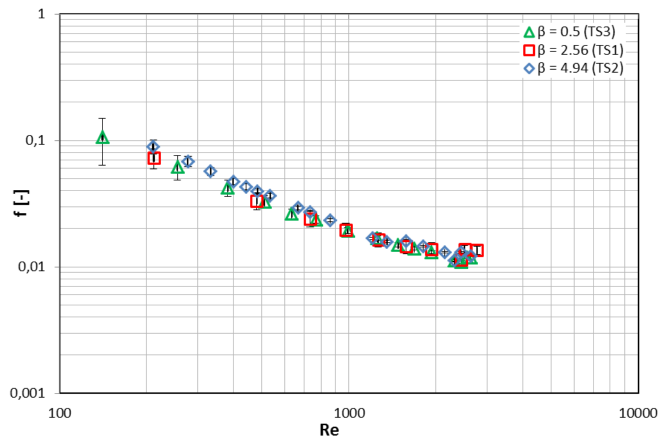


Figure 2. Effect of aspect ratio on friction factor [11]

Effect of surface roughness

Surface roughness effect was also studied in the literature [14, 15]. Shen et al. [14] investigated the single phase convective heat transfer in a brass microchannel heat sink (D_h = 0.44 mm). De-ionised water was used as the working fluid in a Re number range from 162 to 1257. The microchannels had a relative surface roughness 4-6 % of the channel hydraulic diameter. They concluded that surface roughness has a considerable influence on liquid laminar flow in microchannels due to increasing of Po that was higher than conventional theory, see Fig. 3. They also reported that at high Re numbers, the discrepancy between the measured and the predicted friction factor values was higher compared to those at low Re numbers. It is worth mentioning that Shen et al. [14] used the Po number 67 instead of 64. The authors calculated this value based on the aspect ratio of the channel instead of using conventional value (64) for the smooth tube.

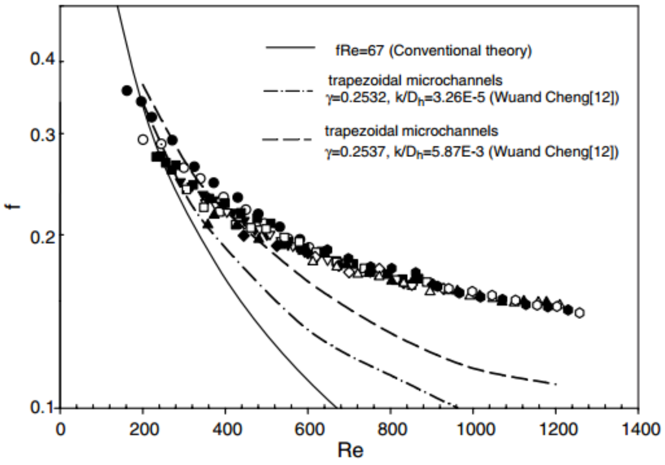


Figure 3. Effect of surface roughness on friction factor [14]

From the above review, we can infer that the single-phase friction factor in microchannels can be predicted using conventional scale theory and correlations. However, measurement uncertainties, inlet and exit pressure losses, developing effects in entrance region, channel surface roughness and laminar to turbulent transition should be carefully considered.

FLOW BOILING PRESSURE DROP IN MICROCHANNELS

Effect of heat flux and mass flux

Thus far, several studies have examined the flow boiling pressure drop in micro-scale [16-24]. Warrier et al. [16] carried out flow boiling experiments in rectangular aluminium microchannels with 0.75 mm hydraulic diameter using FC-84 as the working fluid. They found that the flow boiling pressure drop increased linearly with increasing heat flux. In another study, flow boiling pressure drop in a copper rectangular microchannel heat sink

(D_h = 0.35 mm) with R-134a as the working fluid was examined [17]. The authours found that the flow boiling pressure drop increased with increasing heat and mass flux as shown in Fig. 4. Similar to abovementioned studies, other past experimental studies in the literature agreed that the flow boiling pressure drop increased with increasing heat and mass flux in microchannels [18-24].

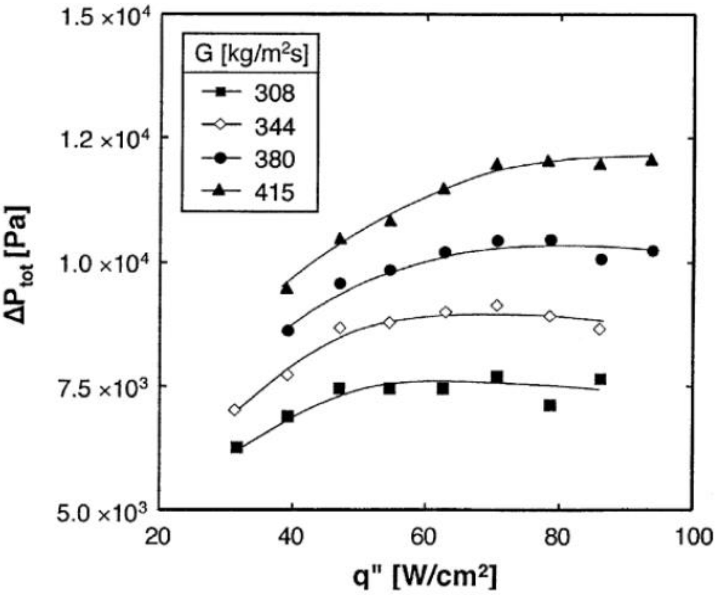


Figure 4. Flow boiling pressure drop vs heat flux [17]

Effect of system pressure

Some other researchers investigated the system pressure effect on the flow boiling pressure drop in the literature. Karayiannis et al. [22] tested five circular channels using R-134a as the working fluid to examine flow boiling pressure drop (D = 0.52-4.26 mm). They reported that the flow boiling pressure drop increased with decreasing system pressure. They stated that the increase in the flow boiling pressure drop occurred due to the reduction in the liquid to vapour density ratio as the pressure increases. Similarly, Tran et al. [20] investigated the flow boiling pressure drop in two circular channels (D = 2.46 and 2.92 mm) and one rectangular microchannel (D_h = 2.4 mm). The working fluids were R-134a, R-113, and R-12. They concluded that the flow boiling pressure drop increased with decreasing system pressure during the tests. The above brief literature review showed that the flow boiling pressure drop increases with decreasing system pressure in micro-scale.

Effect of channel hydraulic diameter and aspect ratio

The effect of channel geometry on flow boiling pressure drop was investigated by many researchers in the literature [10, 19, 23-28]. Tong et al. [19] performed experiments using stainless steel tubes (D = 1.05-2.44 mm). They reported that the flow boiling pressure drop increases with the decrease in the tube diameter. In another study, Shuai et al. [25] examined the flow boiling pressure drop of water in rectangular microchannels (D_h = 0.8-2.67 mm). They stated that the flow boiling pressure drop increases with decreasing channel hydraulic diameter. Mahmoud [26] compared the flow boiling pressure drop of two stainless steel tubes (D = 0.52 mm and 1.1 mm) using R-134a as shown in Fig. 5. They reported that when the diameter decreased from 1.1 mm to 0.52 mm the pressure drop per unit length increased around 300 %. The authour attributed this to the high-velocity gradient in the boundary layer next to the wall arising from the thinning of the liquid film when the diameter decreased. Consequently, the frictional pressure drop increased due to the large velocity gradient.

Mirmanto [10] also investigated the hydraulic diameter effect on the flow boiling pressure drop in copper rectangular single microchannels (D_h = 0.44 mm, 0.56 mm and 0.64 mm). Similarly, he reported that the flow boiling pressure drop increases with decreasing channel hydraulic diameter. The effect of channel aspect ratio on the flow boiling pressure drop was reported by some researchers in the literature [23-24, 28]. Singh et al. [23] carried out experiments with silicon rectangular microchannels with varying aspect ratios (1.23-3.75) but constant hydraulic diameters and lengths (D_h = 0.14 mm and L = 20 mm). They concluded that the flow boiling pressure drop first decreases with an increase in aspect ratio from *1.23* to *1.56*, and then increases with a further increase in aspect ratio at particular heat and mass flux input. Contrary to Singh et al. [23], Markal et al. [24] stated that the relationship between the flow boiling pressure drop and channel aspect ratio is irregular, see Fig. 6. They conducted sets of experiments with de-ionised water in six rectangular multimicrochannels. The hydraulic diameters and the lengths of the channels were the same (D_h = 0.1 mm and L = 48 mm) but the channel aspect ratios were different (0.37-5). They attributed the irregular relationship to the complex nature of flow physics. However, they did not present any explanation based on these results.

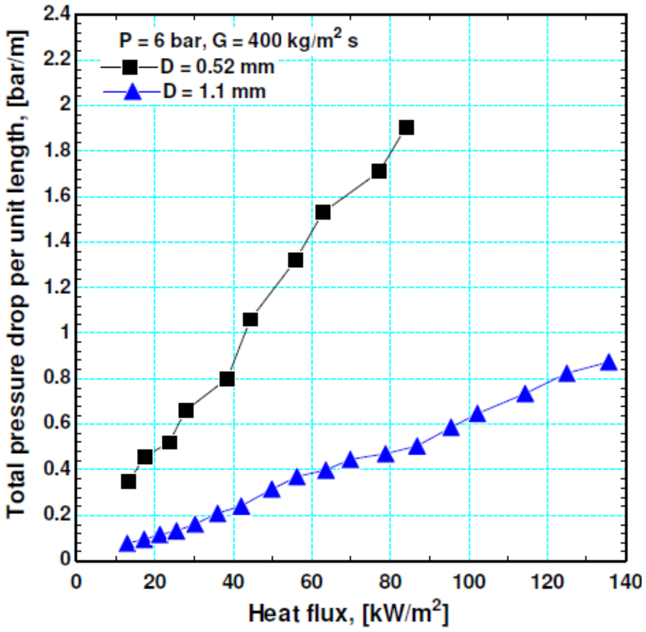


Figure 5. The effect of tube diameter on the flow boiling pressure drop [26]

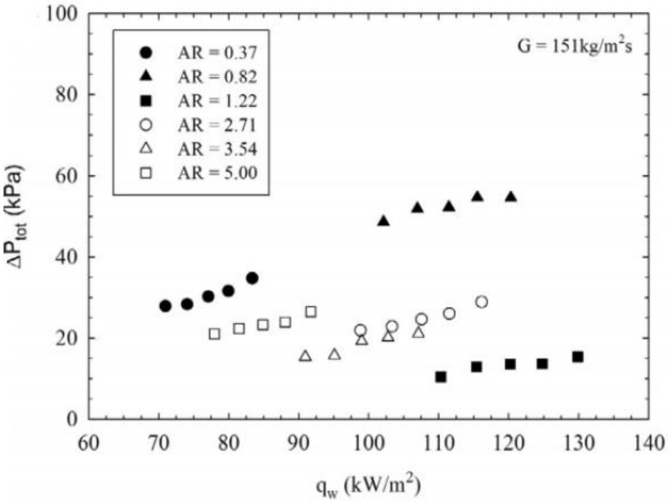


Figure 6. The effect of aspect ratio on the flow boiling pressure drop [24]

The above literature review shows that the flow boiling pressure drop in microchannels increases with increasing heat flux, increasing mass flux, decreasing system pressure and decreasing channel diameter. On the other hand, the effect of the channel aspect ratio on the flow boiling pressure drop is inconclusive.

FLOW BOILING PRESSURE DROP CORRELATIONS

Two-phase pressure drop correlations are important in order to design reliable and high-performance microchannel heat sinks. In horizontal channels, the total two-phase pressure drop is the sum of frictional and accelerational pressure drop components. Several correlations were proposed to predict the total two-phase pressure drop in the literature. In this section, principles of correlations were presented. The homogeneous flow model (HFM) and separated flow model (SFM) are the two fundamental approaches that were proposed to model the two-phase pressure drop. The details of these approaches can be found in Collier and Thome [29]. The HFM was proposed for horizontal flow in channels based on the steam-water mixture for various system pressures. The two-phase fluid was assumed to be a single-phase fluid with its mixture properties weighted by vapour quality. On the other hand, the fluid was separated into liquid and vapour phases in the SFM. The equations of frictional and accelerational two-phase pressure drop components are presented in Eqns. (1-4) for both models.

$$\Delta P_f = \frac{2 f_L L G^2 v_L}{D_h}\left[1+\frac{x_e}{2}\left(\frac{v_{LG}}{v_L}\right)\right] \text{ (HFM)} \qquad (1)$$

$$\Delta P_f = \frac{L_{tp}}{x_e}\int_0^{x_e}\frac{2 f_L G^2 (1-x_e)^2 v_L}{D_h}\phi_L^2 dx \text{ (SFM)} \qquad (2)$$

$$\Delta P_a = G^2 v_{LG} x_e \text{ (HFM)} \qquad (3)$$

$$\Delta P_a = G^2 v_L\left[\frac{x_e^2}{\alpha_e}\left(\frac{v_G}{v_L}\right)+\frac{(1-x_e)^2}{1-\alpha_e}-1\right] \text{ (SFM)} \qquad (4)$$

From Eqs. (1) and (3), it can be seen that the total two-phase pressure drop can be calculated straightforwardly using the HFM. On the other hand, void fraction (α) and two-phase multiplier (ϕ_L^2) are needed to be calculated in the SFM. Consequently, several correlations were proposed to predict the void fraction and the two-phase multiplier in the literature. The principle of the two-phase multiplier was first proposed by Lockhart and Martinelli [30]. They defined the two-phase multiplier as a function of the Martinelli parameter (*X*) for different flow phases (laminar/turbulent) as given in Eq. (5).

$$\phi_L^2 = 1+\frac{C}{X}+\frac{1}{X^2} \qquad (5)$$

The constant (*C*) is called as Chisholm constant and takes a value ranging from 5 to 20 dependent on the phase of the flow, see Chisholm [31]. In this way, many researchers attempted to use the HFM and SFM approaches to predict the total two-phase pressure drop in microchannels. Some researchers found that these models predicted their data poorly, see [20, 22, 32-35]. Ribatski [36] stated that the reason for the poor prediction of the conventional models might be: i) the liquid part of the flow is laminar in two-phase microchannel flows, which is different than conventional scale channels and ii) the surface tension effect is more significant in microchannels than conventional-scale channels. Also, Ribatski et al. [37] also reported that the bubbly flow was rarely encountered in microchannels due to the confinement of the channel where the bubbles coalesce or grow and occupy the entire channel size. Contrary to the above-stated studies, some other researchers reported that the HFM predicted their experimental data well, see [17, 26, 38-39]. Mahmoud [26] stated that the HFM showed success in some studies and failure in some others might be attributed to different fluids tested in these studies. Mahmoud [26] added that fluid properties have an influence on the boundaries of the isolated bubbly and slug flow regimes where the HFM works better. Consequently, many researchers developed new two-phase pressure drop correlations for micro-scale [16, 34, 40-42].

In these correlations, the two-phase multiplier ( ) in Eq. (5) were modified in order to take account the microscale effects. For example, Mishima and Hibiki [40] defined the Chisholm's constant (C) as a function of hydraulic diameter as given in Eq. (6). On the other hand, Yu et al. [41] used the two-phase multiplier ( ) as the only function of the Martinelli parameter, see Eq. (7).

$$C = 21\left(1 - e^{0.319 D_h}\right) \tag{6}$$

$$\phi_L^2 = \frac{1}{X^{1.9}} \tag{7}$$

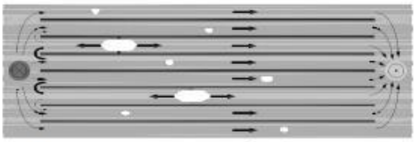
FLOW BOILING INSTABILITIES

Flow boiling instabilities are very important in microchannels due to their effect on the system performance and failures. They can cause premature dry-out with reducing critical heat flux (CHF). Thus, stable flow boiling conditions should be identified in order to have a safe and reliable operation. Two-phase flow instabilities can be categorised into static and dynamic instabilities. Static instabilities are flow pattern transition instability and Ledinegg instability (flow excursion). On the other hand, dynamic instabilities are pressure and thermal oscillations, and parallel channel instability [43, 44].

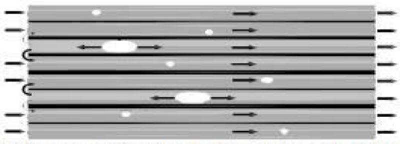
Flow boiling instabilities in micro-scale have a greater effect on the overall system performance than conventional scale ones owing to their low flow velocity operation and occurrence in confined space. The most encountered instabilities in micro-scale are Ledinegg instability, flow pattern transition instability, non-uniform flow distribution among the channels and pressure, mass flux and thermal oscillations. Moreover, the rapid bubble growth instability is unique in micro-scale where the bubbles grow explosively in the channel and travel both to upstream and downstream of the test section. Consequently, many researchers examined the flow boiling instabilities in microchannels.

Wu and Cheng [45] performed sets of experiments in parallel silicon microchannels with trapezoidal cross section (D_h = 0.083 mm and 0.159 mm) using water as the working fluid. They reported that when the heat flux was increased gradually at constant mass flux, large fluid inlet and outlet pressure, temperature, wall temperature oscillations with large amplitudes were observed. Also, the mass flux decreased rapidly at the boiling incipience. Their visualisation study showed that at the middle of the channel, single phase, bubbly, slug, elongated slug, churn flows appeared periodically at the boiling incipience. However, they reported neither measurement nor visualisation results after boiling incipience. The authours concluded that fluctuation periods at boiling incipience depend on channel dimensions, heat and mass flux. Steinke and Kandlikar [46] performed an experimental study on flow boiling of water in copper multi-microchannels of (D_h = 0.207 mm). Under some conditions, they observed parallel channel instability where bubbles moved towards the inlet of the channel due to rapid bubble growth in some channels whilst the flow was stable in other channels at the same time. Hetsroni et al. [47] investigated the heat transfer coefficient and visualised flow patterns during explosive boiling of water in a silicon microchannel with triangular cross section (Dh = 0.129 mm). It is worth mentioning that they did not perform any degassing process during the experiments so that gas vapour mixture occurred below the saturation temperature. Their results showed that long vapour slugs occurred in a microchannel at low mass flux values with periodic wetting dry-out. They described this behaviour as an explosive boiling phenomenon. Upstream compressibility and the Ledinegg instability were shown to be the reasons of the vapour slug back-flow phenomenon in microchannels by Bergles and Kandlikar [48] Also, Gedupudi et al. [49-51] performed a numerical study and concluded that upstream compressibility in the system is responsible for the back-flow due to improper degassing or boiling in preheaters that cause non-dissolved air in the system. Kandlikar [52] discussed nucleation and flow instability in microchannels. He reported that the location of boiling incipience affects flow reversal. When nucleation occurs near the channel exit, the flow resistance in the back-flow direction is higher and consequently, no flow reversal occurs. On the contrary, when nucleation occurs near the channel inlet, the flow resistance in the back-flow direction is lower and thus flow reversal occurs. In another study, Balasubramanian et al. [53] conducted flow boiling experiments in parallel copper microchannels having two different planform areas of 25 mm x 25 mm and 20 mm x 10 mm. The channels had 0.3 mm width and 0.12 mm height and the working fluid was de-ionised water. They observed pressure drop fluctuations and wall temperature oscillations when instabilities occurred. They also reported the reversal vapour slug flow instability when the heat flux was increased at low mass flux values. However, instabilities decreased at higher mass flux values.

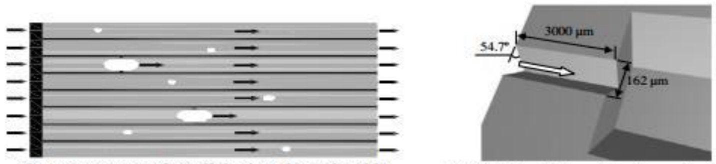
Following the above literature review on flow boiling instabilities in microchannels, it is worth mentioning the studies that tried to suppress instabilities in micro-scale. Qu and Mudawar [54] investigated flow boiling of de-ionised water in 21 parallel rectangular copper microchannels (D_h = 0.35 mm). After boiling was initiated, the flow pattern in the microchannels became rapidly intermittent flow with increasing heat flux. Flow reversal between the inlet and outlet of the channel with significant pressure and temperature fluctuations were observed by the authors. However, they managed to mitigate the pressure drop oscillation instability by installing a control valve at the upstream of the test section. Kandlikar et al. [55] proposed that the wall superheat at the nucleation location should be as low as possible in order to stabilise the two-phase flow instabilities. This is probably because that the wall superheat at the boiling incipience is higher in microchannels compared to conventional-scale channels. Therefore, Kandlikar et al. [55] introduced artificial nucleation cavities and inlet control valves at the upstream of the parallel microchannel test section. They reported that the two-phase flow instabilities and flow reversal were prevented in their experiments. Kosar et al. [56] performed an experiment with parallel rectangular silicon microchannels of (D_h = 0.23 mm) with inlet restrictors. They stated that small orifices at the inlet of the channel can prevent pressure and parallel channel instabilities in microchannels. Kuan and Kandlilar [57] installed flow restrictors at the inlet of each channel that (D_h = 0.33 mm) consist of parallel copper rectangular microchannels. They compared the results with and without the flow restrictor and reported that microchannels having flow restrictors at the inlet yielded 6.1 % better heat transfer performance than the normal ones due to avoiding reverse flow. Similarly, Kuo and Peles [58] reported that the presence of re-entrant cavities into the microchannel heat sink helped in reducing the pressure drop oscillations, parallel channel instability, and flow reversal problem by creating nucleation sites and also extended CHF. Wang et al. [59] performed experiments with three different inlet and outlet configurations. The first configuration had both inlet and outlet restrictors at the test section, the second configuration did not have any restrictions and the third configurations had only restrictions at the inlet of each microchannel as shown in Fig. 7. They observed that the flow became stable and flow reversal was reduced in the third configuration whilst temperature and pressure fluctuations with reverse flow existed in the first and second configurations. The possible explanation of this might be that the inlet and outlet restrictors at the first test section are due to the inlet and outlet flow manifold. These restrictors are quite different than the restrictors at the third test section. Therefore, the stable flow conditions were not encountered in the first test section.



(a) Type-A connections: flow entering and exiting from parall microchannels with restrictions because inlet/outlet conduits perpendicular to microchannels



(b) Type-B connection: flow entering to and exiting from microchannels freely without restriction



(i) Arrangement of parallel microchannels with restrictive inlet

(ii) Sketch of the microchannel with a restrictive inlet

(c) Type-C connection: flow entering with restriction and exiting without restriction in microchannels

Figure 7. Parallel microchannels with three different inlet/outlet connections [59]

In another study, Kuo and Peles [60] experimentally studied the effects of pressure on flow boiling instabilities using water in silicon microchannels (D_h = 0.22 mm). They found that high system pressure reduced pressure fluctuations. In addition, it reduced the bubble departure diameter and also extended CHF. Zhang et al. [61] studied the Ledinegg instability in microchannels. They proposed that fewer channels, high system pressure, low heat flux, low sub-cooling and short channels should be preferred in order to avoid instability problems to obtain better heat transfer performance in microchannels. In a recent study, Tuo and Hrnjak [62] recommended a new vapour venting method to suppress flow reversal problem. They installed two venting valves at the inlet plenum to vent the back vapour slug flow. They reported that the cooling capacity was increased 5 % with this new method.

CONCLUDING REMARKS

A detailed literature review on single-phase flow and flow boiling pressure drop characteristics and flow boiling instabilities in micro-scale is presented above. Main conclusions are given below.

Single-Phase Pressure Drop

In the literature, many studies were conducted to investigate single-phase pressure drop characteristics in micro-scale. A lot of work was carried out to reveal the sources of the discrepancies between the conventional theory and the single-phase parameters. Although recent studies showed that conventional theory is valid in single-phase pressure drop in microchannels, some points are needed to be considered while evaluating single-phase pressure drop in micro-scale.

- Inlet and exit pressure losses need to be considered.
- Developing effects need to be evaluated in the entrance region.
- The single-phase friction factor strongly depends on channel surface characteristics.
- Laminar to turbulent transition in microchannels may occur earlier than conventional channels due to the size effect.
- Measurement uncertainties need to be evaluated properly in order to have accurate results.

Flow Boiling Pressure Drop

In microchannels, it was found that the flow boiling pressure drop has similar characteristics as in conventional-scale channels. The following conclusions are summarised from the above literature review:

- All experimental studies concluded that the flow boiling pressure drop increases with increasing mass flux, increasing heat flux, decreasing system pressure and decreasing channel diameter.
- The effect of the channel aspect ratio on the flow boiling pressure drop was examined in only three studies and is not conclusive. In one study, it was found that the flow boiling pressure drop increases as the channel aspect ratio increases. In another study, the researchers stated that the flow boiling pressure drop is higher in the channel with the lower aspect ratio. In a recent study, it was found that there is not any regular relationship between the effect of the channel aspect ratio and the flow boiling pressure drop.

Flow Boiling Instabilities

- Inlet and outlet temperature and pressure signal fluctuations, wall temperature signal fluctuations and mass flux oscillations having high amplitudes were recorded during flow boiling in microchannels.
- It was found that the temperature, pressure, and mass flux signal fluctuations and period of these fluctuations increase as the heat flux to mass flux ratio increases (q”/G).
- Most of the researchers attributed the flow boiling instability to the rapid bubble growth phenomenon which is unique in microchannels due to their confined space. Bubbles nucleate, grow and travel to the upstream and downstream of the microchannels leading to flow reversal in rapid bubble growth phenomenon.
- Upstream compressibility was found to be responsible for the flow reversal in microchannels. It was reported that the occurrence of the upstream compressibility is due to the improper degassing of the system that causes non-dissolved air in the system.
- Flow boiling instabilities have an effect on the local flow boiling heat transfer behaviour. The local heat transfer coefficient was found to be higher by some investigators in stable flow boiling compared to

unstable flow boiling conditions. Moreover, the CHF value was found to be extended under stable flow boiling conditions.

- Flow boiling instabilities can be suppressed with several methods. Some researchers mitigated the flow boiling instabilities by designing microchannels with inlet restrictions or using microchannels having artificial cavities. On the other hand, a group of researchers proposed seed bubble generation on microheaters at the upstream of the microchannel. They reported that these seed bubbles prevent flow boiling instabilities by soaking up energy from superheated liquids.

NOMENCLATURE

C	Chisholm constant	[-]
D	Diameter	[m]
f	Friction factor	[-]
G	Mass flux	[kg m^{-2} s^{-1}]
HFM	Homogeneous flow model	[-]
L	Length	[m]
P	Pressure	[kPa]
Po	Poiseuille’s number	[-]
q"	Heat flux	[W m^{-2}]
Re	Reynolds number	[-]
SFM	Separated flow model	[-]
X	Martinelli parameter, vapour quality	[-]
β	Aspect ratio	[-]
α	Void fraction	[-]
ϕ	Two-phase multiplier	[-]
ΔP	Pressure drop	[kPa]
ν	Specific volume	[m^3 kg^{-1}]
a	Accelerational	
e	Exit	
f	Frictional	
h	Hydraulic diameter	
L	Liquid	
LG	Liquid-vaporization	
tot	Total	
tp	Two-phase	

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