Nucleation characteristics and stability considerations during flow boiling in microchannels

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Abstract

Flow boiling in microchannels and minichannels has received considerable attention in the past decade. The interest stems from the possibility of achieving the extremely high heat fluxes, over 1 kW/cm², needed for future generation electronics cooling application. The attention has been focused on obtaining experimental heat transfer and pressure drop data, but the fundamental aspects of nucleation have been largely overlooked. In the present paper, the local wall superheat and bulk liquid subcooling prevailing in the channel at the onset of nucleation are identified as critical in the flow boiling stability. To understand the role of local conditions on nucleation, the available literature on onset of nucleate boiling is critically reviewed and the relationships between the local bulk subcooling and local wall superheat as a function of nucleation cavity diameters are presented. The unique flow characteristics in microchannels and minichannels are further analyzed and their influence on flow boiling stability is investigated experimentally using visual images generated with a high-speed camera.

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1. Introduction

Microchannels and minichannels are fluid flow channels with small hydraulic diameters. Following the classification by Kandlikar and Grande [1], and later modifications suggested by Kandlikar et al. [2], channels with a minimum cross-sectional dimension between 200 μm and 3 mm are classified as minichannels and between 1 μm and 200 μm are classified as microchannels.

Employing smaller diameter channels is desirable because of two reasons: (i) higher heat transfer coefficient, and (ii) higher heat transfer surface area per unit flow volume. Combination of these two features makes single-phase heat transfer extremely efficient in minichannels and microchannels. Although the pressure gradient increases considerably, providing short flow lengths for fluid flow passages can effectively reduce the overall pressure drop in a microchannel heat exchanger [3].

Flow boiling heat transfer in conventional channels is associated with the latent heat transfer that can reduce the mass flow rate required for a given heat dissipation rate. Combination of microchannels with the flow boiling process is therefore expected to provide a significant improvement in the heat dissipation rates.

However, flow boiling in minichannels and microchannels poses a number of difficulties. These issues have been summarized by Kandlikar [4,5]. The major concerns relate to (i) increased effects of surface tension forces, (ii) reverse flow arising from nucleation followed by rapid bubble growth, and (iii) deterioration in heat transfer and critical heat flux due to flow instabilities.

This paper focuses on the nucleation characteristics in microchannels. These characteristics are intimately related to a number of issues associated with flow boiling in microchannels including stability, heat transfer rates and critical heat flux.
2. Nucleation criterion

Nucleation criteria for pool boiling and flow boiling in conventional sized channels were well established following the work of Hsu [6]. Bubbles are formed over the cavities that are present on a heater surface. As a bubble covers the mouth of a cavity, the local temperature field in the surrounding liquid dictates whether the bubble will grow further and nucleate. Since the equilibrium pressure inside a bubble increases as the bubble diameter reduces, a greater wall superheat is needed for nucleation over smaller cavities. The analyses presented by Hsu [6] and later researchers provide the necessary nucleation criteria for the onset of nucleate boiling. A brief summary of these nucleation criteria is presented here.

Hsu neglected the dynamic effects due to bubble growth and provided a model based on equilibrium considerations using the single-phase liquid flow conditions prior to nucleation for determining the temperature profile in the vicinity of the heater wall. As a bubble covers the mouth of a cavity, the local temperature field in the surrounding liquid dictates whether the bubble will grow further and nucleate. Since the equilibrium pressure inside a bubble increases as the bubble diameter reduces, a greater wall superheat is needed for nucleation over smaller cavities. The analyses presented by Hsu [6] and later researchers provide the necessary nucleation criteria for the onset of nucleate boiling. A brief summary of these nucleation criteria is presented here.

Hsu neglected the dynamic effects due to bubble growth and provided a model based on equilibrium considerations using the single-phase liquid flow conditions prior to nucleation for determining the temperature profile in the vicinity of the heater wall. As a bubble attains a certain radius \( r_b \) while covering the cavity mouth, the excess pressure inside the bubble is given by the following equation for static equilibrium of surface tension and pressure forces

\[
p_{V} - p_{L} = 2\sigma/r_b
\]

where \( p_{V} \) — pressure inside the bubble, \( p_{L} \) — pressure of the liquid surrounding the bubble, \( \sigma \) — surface tension, and \( r_b \) — bubble radius. Further growth of this bubble depends on whether the coldest liquid temperature encountered anywhere at the interface is above the saturation temperature corresponding to the vapor pressure inside the bubble. The liquid temperature adjacent to the heater surface is obtained by considering a linear temperature profile in the liquid layer. The thickness of the liquid layer \( \delta_t \) is obtained from the following equation:

\[
\delta_t = k_L/h_L
\]

where \( \delta_t \) — thickness of thermal boundary layer, \( k_L \) — liquid thermal conductivity, \( h_L \) — heat transfer coefficient with liquid flow prior to nucleation.

Fig. 1 shows a nucleating bubble over a cavity and the temperature profile in the liquid layer adjacent to the heater surface. Equating the temperature at the top of the bubble with the local liquid temperature at \( y = y_b \) provides the desired nucleation criterion. Different investigators used

\[
\Delta T_{Sat} \quad \text{wall superheat, } \Delta T_{Sat} = T_W - T_{Sat}, K
\]

\[
\Delta T_{Sub} \quad \text{liquid subcooling, } \Delta T_{Sub} = T_{Sat} - T_{bulk}, K
\]

\[
y \quad \text{coordinate axes}
\]

\[
y_b \quad \text{distance to the top of a bubble, m}
\]

\[
y_s \quad \text{streamline location, m}
\]

\[
\theta \quad \text{receding contact angle, degrees}
\]

\[
\rho \quad \text{density, kg/m}^3
\]

\[
\sigma \quad \text{surface tension, N/m}
\]

\[
D \quad \text{characteristic dimension (bubble departure diameter in critical heat flux modelling), m}
\]

\[
G \quad \text{mass flux, kg/m}^2\text{s}
\]

\[
h_L \quad \text{heat transfer coefficient for single-phase liquid, W/m}^2\text{K}
\]

\[
h_{LV} \quad \text{latent heat of vaporization, J/kg}
\]

\[
K_1 \quad \text{ratio of the evaporation momentum to inertial forces, non-dimensional, } K_1 = \left( \frac{\rho}{\rho_v} \right)^2 \frac{\rho}{\rho_v}
\]

\[
K_2 \quad \text{ratio of the evaporation momentum to surface tension forces, non-dimensional, } K_2 = \left( \frac{\rho}{\rho_v} \right)^2 \frac{\rho}{\rho_v}
\]

\[
l_L \quad \text{liquid thermal conductivity, W/m K}
\]

\[
p \quad \text{pressure, Pa}
\]

\[
q'' \quad \text{heat flux, W/m}^2
\]

\[
r_b \quad \text{bubble radius, m}
\]

\[
r_{c,crit} \quad \text{critical cavity radius at the onset of nucleate boiling, m}
\]

\[
r_{c,\text{min}} \quad \text{minimum cavity radius allowing for nucleation, m}
\]

\[
r_{c,\text{max}} \quad \text{maximum cavity radius allowing for nucleation, m}
\]

\[
T \quad \text{temperature, K}
\]

\[
\Delta T_{Sat} \quad \text{wall superheat, } \Delta T_{Sat} = T_W - T_{Sat}, K
\]

\[
\Delta T_{Sub} \quad \text{liquid subcooling, } \Delta T_{Sub} = T_{Sat} - T_{bulk}, K
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\]

\[
T \quad \text{temperature, K}
\]
different bubble shapes at this condition and obtained different expressions. Hsu [6] used a contact angle of \( \theta_r = 53.1^\circ \), while Bergles and Rohsenow [7] used 90\(^\circ\), and Davis and Anderson [8] retained it as a variable in their expression for the range of cavity radii that satisfy the nucleation criterion. Later, Kandlikar et al. [9] numerically simulated liquid flow around a nucleating bubble in a minichannel and found the location of the streamline, at \( y = y_s \) as shown in Fig. 1(b) that sweeps over the bubble. The location of this streamline was found to be at \( y_s = 1.1r_b \). Kandlikar et al. [9] then derived the nucleation criterion by comparing the liquid temperature at \( y \) with the equilibrium pressure corresponding to the radius of the bubble over the cavity mouth and maintaining the receding contact angle as a variable as shown in Eq. (3):

\[
\left\{ r_{c,\text{min}}, r_{c,\text{max}} \right\} = \frac{\delta_i \sin \theta_i}{2.2} \left( \frac{\Delta T_{\text{Sat}}}{\Delta T_{\text{Sat}} + \Delta T_{\text{Sub}}} \right) \times \left[ 1 + \sqrt{1 - \frac{8.8 \rho_v \Delta T_{\text{Sat}} \left( \Delta T_{\text{Sat}} + \Delta T_{\text{Sub}} \right)}{\rho_v h_{LV} \theta_i \Delta T_{\text{Sat}}^2}} \right] \tag{3}
\]

where \( \rho_v \)—vapor density, \( \theta_i \)—receding contact angle, \( T \)—temperature, and \( h_{LV} \)—latent heat of vaporization. All cavities with radii between \( r_{c,\text{min}} \) and \( r_{c,\text{max}} \) will nucleate under the given wall superheat \( \Delta T_{\text{Sat}} \) and liquid subcooling \( \Delta T_{\text{Sub}} \). Assuming cavities of appropriate radii are present on the heater surface, the wall superheat corresponding to this condition is obtained by setting the term under the radical sign in Eq. (3) to zero. The critical cavity radius \( r_{c,\text{crit}} \) that will nucleate first under this condition is given by

\[
r_{c,\text{crit}} = \frac{\delta_i \sin \theta_i}{2.2} \left( \frac{\Delta T_{\text{Sat}}}{\Delta T_{\text{Sat}} + \Delta T_{\text{Sub}}} \right) \tag{4}
\]

where \( \Delta T_{\text{Sub}} = T_{\text{Sat}} - T_{\text{bulk}}, \Delta T_{\text{Sat}} = T_{W} - T_{\text{Sat}} \), and \( r_{c,\text{crit}} \) —critical cavity radius at the onset of nucleate boiling (ONB). The local wall superheat at this condition is given by

\[
\Delta T_{\text{Sat,ONB}} = \sqrt{8.8 \rho_v \Delta T_{\text{Sat}} g'' / (\rho_v h_{LV} k_l)} \tag{5}
\]

where \( g'' \) —heat flux. Note that there was a typographical error in the constant in Eqs. (3) and (5) as reported in the original publication by Kandlikar et al. [9]; it should be 8.8 as shown in these equations.

If the cavity of critical radius is not available, then the nucleation will occur on the appropriate cavity size that yields the minimum nucleation wall superheat under a given set of conditions. The wall superheat required to nucleate a given size cavity is obtained by Kandlikar et al. [9] as follows:

\[
\Delta T_{\text{Sat,ONB}} \text{ at } r_c = \frac{1.1r_c q''}{k_l \sin \theta_r} + \frac{2\sigma \sin \theta_i}{r_c} \frac{T_{\text{Sat}}}{\rho_v h_{LV}} \tag{6}
\]

The above criterion was used to compare the experimental data obtained by Kandlikar et al. [9] for water flowing over a spot heater in a 1 mm × 40 mm minichannel. The nucleating bubbles were observed using a high-speed camera and the underlying cavity radii were measured using a microscope. Fig. 2 shows the comparison of different nucleation criteria with the experimental data. It should be noted that the nucleation data points should fall above the line representing a criterion. The lines represent the minimum superheat needed to nucleate a cavity of a given radius. The cavity will continue to nucleate at higher wall superheats (as seen for most of the data points). A data point falling below a line indicates that the particular nucleation criterion is predicting a higher wall superheat than the experimental data. The nucleation criterion of Hsu [6] is seen to be most restrictive while the Bergles and Rohsenow [7] criterion is seen to predict the lowest wall superheat values. All data points fall above or very close to the line representing the truncated/stagnation model of Kandlikar et al. [9].

Such a study on bubble nucleation characteristics is not available for microchannels. However, the model described above should be applicable to microchannels as well. Experiments showing nucleation in microchannels are reported in this paper in a later section.

### 3. Bubble growth following nucleation in microchannels

Bubble growth following nucleation plays a critical role in the flow boiling stability in microchannels and minichannels. The resulting flow boiling instabilities were observed by a number of investigators:

Hetsroni et al. [10] observed periodic annular flow in microchannels of 103–129 \( \mu \)m hydraulic diameters with water flow; Kennedy et al. [11] studied the onset of instability as a function of flow rate and exit quality in circular minichannels of 1.17 and 1.45 mm diameter; Kandlikar et al. [12] observed flow instabilities leading to flow reversal with water in 1 mm square minichannels; Peles [13] studied local pressure fluctuations and flow reversals in 50–200 \( \mu \)m triangular microchannels; Balasubramanian and Kandlikar [14] obtained clear high-speed images of the flow phenomenon simultaneously in a set of six 1054 × 197 \( \mu \)m
rectangular channels. These studies indicated that the nucleation of a bubble followed by its rapid growth into a vapor slug resulted in reverse flow leading to flow instability.

Fig. 3 shows a high-speed video image sequence obtained by Kandlikar and Balasubramanian [15]. The rapid bubble growth filling the entire channel causes backflow in the channel. This backflow coupled with the inlet manifold interactions between the parallel channels causes the unstable operation. The instabilities occurring in conventional evaporators due to a negative slope in the pressure drop demand curve are also present in microchannels [16].

The bubble growth rate following nucleation depends on the wall superheat and the local liquid conditions surrounding a bubble. The local liquid subcooling at the onset of nucleate boiling (ONB) can be obtained from the following single-phase heat transfer equation:

$$
\Delta T_{\text{Sub, ONB}} = \frac{q''}{h_L} - \Delta T_{\text{Sat, ONB}} \quad (7)
$$

where $\Delta T_{\text{Sub}} = T_{\text{Sat}} - T_{\text{bulk}}$. The wall superheat at the ONB condition can be calculated from Eqs. (5) or (6) depending on the available cavity sizes.

Analyzing Eq. (7) further, it is observed that the high heat transfer coefficient in the microchannels may lead to a low subcooling at the nucleation site. In some cases, the liquid may become superheated (negative subcooling). Under these conditions, the nucleating bubble experiences a superheated environment as it grows from the nucleation site on the wall into the bulk liquid. This causes an extremely rapid bubble growth, which pushes the liquid in both the upstream and downstream directions as seen in Fig. 3.

Fig. 4 shows a plot of local wall superheat and liquid subcooling as a function of cavity radius, water in a 1054 × 197 μm microchannel at 340 kW/m².

The plot shows that the local wall superheat and liquid subcooling at the ONB location as a function of cavity radius, water in a 1054 × 197 μm microchannel at 340 kW/m².

Fig. 4 is generated with a wall heat flux of 340 kW/m². Similar plots can be generated for any other operating conditions. It is also noted that the liquid subcooling condition represented in Fig. 4 corresponds to the bulk liquid condition, and the liquid closer to the wall may be superheated even further.
As the heat flux increases, the local subcooling and wall superheat at the nucleation location, and the nucleation characteristics also change. Fig. 5 shows the local wall superheat and liquid subcooling plot for a heat flux of 1 MW/m² for the same channel depicted in Fig. 4. The wall superheat and the local subcooling are affected and both increase as seen from Eq. (7). The bulk liquid subcooling increases with heat flux and the region between the cavity radii 1.5–7 μm becomes subcooled. The increased wall superheat will lead to a very rapid bubble growth, while the increased liquid subcooling will present a colder liquid at the interface. However, the rapid expansion from the increased wall superheat is expected to dominate with a resultant increase in the backflow intensity.

### 4. Stabilization of flow boiling following nucleation

The high heat transfer coefficient in microchannels causes the liquid surrounding a nucleating bubble to be close to its saturation state, or even in the superheated state as shown in Fig. 4. The flow boiling characteristics in microchannels therefore differs from that in the conventional sized channels because of this additional factor affecting the flow boiling stability.

Consider a microchannel under flow boiling conditions. Assuming equilibrium and stable operating conditions, the pressure varies qualitatively as shown in Fig. 6. The single-phase pressure gradient is relatively small. The gradient increases in the two-phase region following the onset of nucleation.

As a bubble grows over a cavity, the maximum pressure that can be sustained inside the bubble is dictated by the saturation pressure corresponding to the heater surface temperature. This condition assumes that the entire bubble interface is in contact with superheated liquid at the same temperature as the heater surface, and neglects the excess pressure required to sustain the dynamic growth of the bubble, Mikic et al. [17].

The onset of nucleate boiling thus introduces a pressure spike at the nucleation location as shown in Fig. 6. The maximum pressure that can be theoretically attained, as a limiting case, inside the nucleating bubble is governed by the saturation pressure corresponding to the wall temperature at the nucleation location as discussed above

\[ p_{V,\text{max}} = p_{\text{Sat} \mid T_{W,\text{ONB}}} \]  

where \( p_{V,\text{max}} \) — maximum pressure inside a nucleating bubble, and \( p_{\text{Sat} \mid T_{W,\text{ONB}}} \) — saturation pressure corresponding to the wall temperature at ONB.

The pressure spike in the flow at the nucleation site introduces a disruption in the flow. Depending on the local conditions, the excess pressure inside the bubble may overcome the inertia of the incoming liquid and the pressure in the inlet manifold, and cause a reverse flow of varying intensity depending on the local conditions.

There are two ways to reduce the flow instabilities:

(i) reduce the local liquid superheating at the ONB, and
(ii) introduce a pressure drop element at the entrance of each channel.

The local liquid superheat at ONB can be reduced by making cavities of the right radii (minimum wall superheat as seen in Fig. 4) available on the heated surface. The reversed flow can be reduced by introducing pressure drop elements at the entrance of each channel and operating the system with an inlet manifold pressure higher than the maximum pressure given by Eq. (8).

\[ p_{\text{Inlet manifold}} > p_{\text{Sat} \mid T_{W,\text{ONB}}} \]  

Flow stabilization was experimentally investigated by Kandlikar et al. [2]. They introduced pressure drop elements of various area constriction ratios at the inlet of 1054 × 197 μm rectangular channels and incorporated artificial nucleation sites of 5–30 μm radii in the heated wall.
The flow was completely stabilized with inlet pressure drop elements providing only a 4% free flow area. The average heater surface temperature was 111.5 °C for a heat flux of 340 kW/m², which corresponds to a cavity radius range of 2–11 μm as seen from Fig. 4. Artificial nucleation sites (radius range 5–30 μm) cover part of this active range. The inlet pressure in the manifold was 139.5 kPa, which is slightly less than the saturation pressure of 150 kPa corresponding to the average heater surface temperature of 111.5 °C. Fig. 7 shows a high-speed image sequence under stabilized conditions in one of the channels. Slight movement of the bubble interface in the reverse flow direction is due to liquid film flow between the wall and the bubble. The location of the ONB point plays an important role in the stability of the flow boiling process. When the nucleation occurs toward the exit end, see Fig. 8, the flow resistance in the backflow direction is higher than that in the flow direction due to a longer distance from the inlet manifold. On the other hand, if the nucleation occurs near the inlet end, the flow resistance to backflow is lower, and vapor may flow back into the inlet manifold. Mukherjee and Kandlikar [18] studied the problem numerically and confirm that introducing the pressure drop elements and operating the inlet manifold at a higher pressure leads to a reduction in the backflow intensity.

Flow boiling characteristics are intimately linked to the local nucleation characteristics in the microchannels. In addition, the increasing importance of the surface tension force and the diminishing effect of the gravitational force have been recognized by many investigators. Scaling these forces, two new non-dimensional groups were proposed by Kandlikar [19]. The group $K_1$ represents the ratio of the evaporation momentum to inertia forces, and $K_2$ represents the ratio of the evaporation momentum to surface tension forces

\begin{align}
K_1 &= \left( \frac{\rho_v}{\rho_l} \right) \frac{q''}{G h_{LV}} \quad (10) \\
K_2 &= \frac{D^2}{\rho_v \sigma} \left( \frac{\rho_v}{\rho_l} \right) \frac{q''}{h_{LV}} \quad (11)
\end{align}

where $G$—mass flux, $D$—characteristic dimension (bubble departure diameter in critical heat flux modelling), and $\sigma$—surface tension. The group $K_1$ replaces the boiling number $q''/(G h_{LV})$ by incorporating the density ratio effect, and the group $K_2$ was seen to be useful in modelling the critical heat flux in pool boiling conditions, Kandlikar [20].

5. Conclusions

Nucleation during flow boiling in microchannels is studied and expressions for local wall superheat and liquid subcooling at the nucleation location are obtained. The high heat transfer coefficient in microchannels leads to a superheated liquid environment surrounding a nucleating bubble. The rapid increase in the pressure inside a bubble introduces a pressure spike, which is governed by the saturation pressure corresponding to the local temperature of the heater wall. Introducing a pressure drop element, in addition to the artificial nucleation sites, and operating the system with an inlet pressure above the pressure spike stabilizes the flow. The results have been confirmed by conducting experiments with flow boiling of water.

References


