Effect of Liquid-Vapor Phase Distribution on the Heat Transfer Mechanisms during Flow Boiling in Minichannels and Microchannels

SATISH G. KANDLIKAR
Thermal Analysis and Microfluidics Laboratory, Rochester Institute of Technology, Rochester, NY, USA

Heat transfer during flow boiling in minichannels and microchannels is intimately linked to the liquid-vapor phase distribution in the channels. The vapor phase exists as nucleating bubbles, dispersed bubbles, elongated bubbles, an annular core, or all vapor flow completely filling the channel. Similarly, the liquid can exist as bulk liquid, slugs, thin film on the heated wall, or dispersed droplets. A detailed analysis of various structures, supported by high-speed video images, is carried out, and the effects on the associated heat transfer rates are discussed. This information provides insight into the flow boiling mechanisms and guidance for future research in this area.

INTRODUCTION

Flow boiling in minichannels and microchannels has been a topic of recent research interest. Although small diameter channels of less than 1 mm are used extensively in single-phase and condensation applications, they are not typically employed in evaporators. For example, it is common to have condensers that employ the advanced extruded aluminum channels with passage hydraulic diameters on the order of 0.5 mm. There are several reasons why evaporators do not employ microchannels and minichannels in practical applications:

1. Stable operation needs to be demonstrated with flow boiling of water and refrigerants.
2. Heat transfer and pressure drop data collected over a wide range of operating conditions for different channel configurations and under stable operating conditions are needed.
3. Extending the critical heat flux limit and obtaining experimental CHF data need to be addressed.
4. In a vapor compression refrigeration application, the effect of refrigerant-rich oil in the evaporator needs to be investigated.
5. Above all, a fundamental understanding of the flow boiling mechanisms and accurate characterization of the heat transport processes are needed for developing the advanced heat transfer surfaces and systems employed in evaporator applications.

This paper deals with two major issues: (1) flow stabilization using artificial nucleation sites and entrance pressure drop elements, and (2) heat transfer mechanisms, as they are influenced by the liquid-vapor distribution during flow boiling.

The discussion presented here is applicable to microchannels and minichannels. We will use the channel classification scheme given in Table 1 as suggested by Kandlikar and Grande [1].

INSTABILITIES DURING FLOW BOILING

Instabilities during flow boiling have been studied extensively in large-diameter tubes. Comprehensive summaries of flow boiling issues are presented by Kandlikar [2, 3]. The excursive or Ledinegg and the parallel channel instabilities have been studied extensively in large-diameter channels, and these instabilities are also present in small-diameter channels, as discussed by Bergles and Kandlikar [4]. Nucleation followed by an increase
Table 1  Channel classification scheme [1]

<table>
<thead>
<tr>
<th>Channel Type</th>
<th>Diameter Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional channels</td>
<td>( D_h &gt; 3 , \text{mm} )</td>
</tr>
<tr>
<td>Minichannels</td>
<td>( 3 , \text{mm} \geq D_h &gt; 200 , \mu\text{m} )</td>
</tr>
<tr>
<td>Microchannels</td>
<td>( 200 , \mu\text{m} \geq D_h &gt; 10 , \mu\text{m} )</td>
</tr>
<tr>
<td>Transitional microchannels</td>
<td>( 10 , \mu\text{m} \geq D_h &gt; 1 , \mu\text{m} )</td>
</tr>
<tr>
<td>Transitional manochannels</td>
<td>( 1 , \mu\text{m} \geq D_h &gt; 0.1 , \mu\text{m} )</td>
</tr>
<tr>
<td>Nanochannels</td>
<td>( 0.1 , \mu\text{m} \geq D_h )</td>
</tr>
</tbody>
</table>

in the pressure drop due to two-phase flow in the channels leads to a minimum in the pressure drop demand curve, which leads to instabilities. Parallel channel instabilities also occur at the minimum in the pressure drop demand curve. In a microchannel, in addition to these two instabilities, there is an additional phenomenon associated with the rapid bubble growth rates that comes into play and causes significant flow reversal problems.

**Bubble Growth Rates during Flow Boiling**

As a bubble grows under pool boiling conditions, the bubble growth is controlled by the inertia forces and is proportional to the time \( t \). As the bubble grows further, the growth rate slows down and follows a \( t^{1/2} \) trend in the thermally controlled region (see Mikic et al. [5]). In a conventional evaporator employing large-diameter channels (greater than 3 mm), the bubble growth is similar to that in pool boiling, except that the flow causes the bubbles to deform in the flow direction and depart early. These departing bubbles contribute to the bubbly flow. As more bubbles are formed, they coalesce and develop into slug and annular flows.

Figure 1 schematically compares the two bubble growth processes. Schematic (1) shows the growth and departure of a bubble in a macro-channel. Here the bubble only interacts with the wall surface on which it nucleated. The schematics (2a–c) in Figure 1 show how a bubble grows and occupies an entire microchannel as it grow. The bulk liquid in the channel may also become superheated because of the efficient single-phase heat transfer from the heated walls to the liquid prior to nucleation. Furthermore, as the bubble grows and contacts the other heated channel walls, it continues to receive heat from both walls. The heat transfer rate is very high during this period due to the two modes of transfer: (1) the release of superheat in the bulk liquid at the liquid-vapor interface, and (2) the continuation of heat transfer from the wall to the bubble base, which has been extended to the other heated walls of the channel.

Figure 2 shows a high-speed image sequence obtained by Kandlikar et al. [6]. The images displayed are of the same channel at 1 ms time intervals. The nucleation and growth of the last two bubbles seen at the lower end of the channel is representative of the phenomenon illustrated in Figure 1. In the first three frames on the left of Fig. 2, the nucleating bubbles grow in the channel and eventually occupy the entire channel in the third frame from the left. At this point, the entire channel acts like the bubble base, and bubble growth rate is very high. This leads to the rapid expansion in both directions, as seen in the fourth frame from the left. The flow reversal observed in this image sequence has also been reported by other investigators, including Kandlikar et al. [7], Kandlikar [2, 3], Hetsroni et al. [8, 9], Peles [10], Brutin and Tadrist [11], Kandlikar and Balasubramanian [12, 13], Steinke and Kandlikar [14], and Balasubramanian and Kandlikar [15].

![Figure 1](image1.png)  
**Figure 1**  Schematic representation of bubble growth processes in (1) a large diameter channel, and (2a–c) microchannels and minichannels.

![Figure 2](image2.png)  
**Figure 2**  High-speed photographic image sequence at 1/1000 sec. intervals of flow boiling of water in a set of six parallel horizontal channels, each 1054 µm wide x 197 µm deep [6].
The bubble growth rates during flow boiling of water in a 1054 \( \times \) 197 \( \mu \text{m} \) channel have been measured by Balasubramanian and Kandlikar [16]. Figure 3 shows the bubble growth rate in m/s vs. the length of a vapor bubble growing inside the microchannel. The growth rate continues to increase and reaches a value of 3.5 m/s. The bubble was seen to rapidly expand in both directions in the channel.

**Instability Mechanisms**

In the following discussion, a subcooled liquid entry into the evaporator is considered. The large wall surface area to flow volume ratio in minichannels and microchannels causes the entering liquid to heat up rapidly as it flows in the channel. As will be discussed later, the high heat transfer coefficient in the single-phase liquid flow causes the nucleation to be delayed further downstream. The liquid adjacent to the heated wall thus attains a high degree of superheat prior to the onset of nucleation over suitable natural cavities. If the appropriate cavity sizes are not present on the wall at that location, nucleation is delayed further downstream and at higher wall superheats until the local nucleation conditions for available cavities are met. The bulk liquid temperature continues to rise and may even enter the superheated state. Under such conditions, when sufficient wall superheat is finally attained to activate the existing cavities, the nucleating bubble grows rapidly as it finds itself surrounded by superheated liquid. The bubble continues to grow and fill the entire channel and encounter other heated walls of the channel. The availability of heat—from (1) the superheated liquid layer near the other walls, and (2) the superheated liquid across the liquid vapor interfaces on the upstream as well as the downstream sides of the expanding bubble—leads to a very rapid expansion of the bubble. The bubble expansion in the reverse direction to the overall flow direction has been identified as the main source of instability during flow boiling.

This rapid expansion of the bubble is able to overcome the inertia of the liquid in both directions, and the liquid-vapor interface pushes into both the downstream and upstream directions.

The availability of parallel channels connected through an inlet manifold reduces the flow resistance in the upstream direction.

Figure 4 shows the interaction among six parallel channels undergoing reverse flow in some of the channels. The overall flow is from left to right, but three of the channels are experiencing a reversed flow toward the inlet manifold.

The flow of liquid upstream of an expanding bubble and the vapor evaporating from the liquid-vapor interface are shown in Figure 5. Rapid evaporation is caused by the release of the liquid superheat and the efficient heat transfer near the wall surface. The resulting vapor velocity is considerably higher than the evaporating liquid at the interface. This results in a net momentum force on the interface that forces the liquid to move backward, in a direction opposite to the general flow direction. The forces due to the momentum change during evaporation are discussed later.

**NUCLEATION DURING FLOW BOILING IN MICROCHANNELS AND MINICHANNELS**

The onset of nucleation plays an important role in the stability of the flow boiling process. Further details of the nucleation condition and the local liquid state at the onset location are discussed here.

Nucleation criteria were established by researchers for flow in conventional-sized channels during the early 1960s. Hsu and Graham [17], Hsu [18], Bergles and Rohsenow [19], Sato and Matsumura [20], and Davis and Anderson [21] provided the underlying theory relating the temperature distribution in the liquid prior to the nucleation condition. Comparing the liquid temperature on a bubble interface at the farthest location from the wall with the saturation temperature inside the vapor bubble of a certain critical size resulted in their nucleation criteria. At the inception of nucleation, Hsu and Graham [17] assumed a

Figure 3 Bubble growth rate during flow boiling in a set of six parallel horizontal channels, each 1054 \( \mu \text{m} \) wide \( \times \) 197 \( \mu \text{m} \) deep [16], \( G = 112 \text{ kg/m}^2 \text{ s}, T_s = 109.5^\circ \text{C} \).

Figure 4 Simultaneous forward and reverse flow in a set of six parallel horizontal channels, each 1054 \( \mu \text{m} \) wide \( \times \) 197 \( \mu \text{m} \) deep, bulk flow from left to right [16], \( G = 112 \text{ kg/m}^2 \text{ s}, T_s = 109.5^\circ \text{C} \).

Figure 5 Schematic representation of the liquid-vapor interface and liquid motion in a microchannel during reverse flow; bulk flow is from left to right.
contact angle of 53.1° Bergles and Rohsenow [19] and Sato and Matsumura [20] used a hemispherical bubble shape, and Davis and Anderson left it as a variable.

Kandlikar et al. [22] numerically modeled the flow over a bubble attached to a channel wall at a given contact angle and noted that a streamline corresponding to a stagnation point on the upstream interface of the bubble swept over the top of the bubble, as shown in Fig. 6. The location of this stagnation point was found to be given by the following equation for a wide range of contact angles and flow Reynolds numbers:

$$y_S = 1.10 r_b$$

where $y_S$ is the distance of the stagnation location from the heated wall, and $r_b$ is the radius of the bubble at nucleation. Using the liquid temperature at this location in deriving the nucleation criterion, they obtained the following equation for the range of active nucleation cavities:

$$\{r_{c,\min}, r_{c,\max}\} = \frac{\delta_r \sin \theta_r}{2.2} \left(\frac{\Delta T_{Sat}}{\Delta T_{Sat} + \Delta T_{Sub}}\right)$$

$$\times \left[1 \mp \sqrt{1 - \frac{8.8 \sigma T_{Sat} (\Delta T_{Sat} + \Delta T_{Sub})}{\rho_v h_{LV} \delta_r \Delta T_{Sat}^2}}\right]$$

(2)

where $r_{c,\min}$ and $r_{c,\max}$ are the minimum and maximum radii of the nucleating cavities, $\Delta T_{Sat}$ and $\Delta T_{Sub}$ are the wall superheat and liquid subcooling, $\theta_r$ is the receding contact angle, $\sigma$ is the surface tension, $h_{LV}$ is the latent heat of vaporization, $\rho_v$ is the vapor density, and $\delta_r$ is the thickness of the thermal boundary layer, $=k_L/h$, with $k_L$ being the liquid thermal conductivity and $h$ being the heat transfer coefficient in the liquid prior to nucleation. Note that there is a typographical error in the original publication by Kandlikar et al. [22]: the correct constant is 8.8, as given in Eq. (2), whereas the constant was incorrectly typed as 9.2 in the original publication (although their results were plotted using the correct value).

Figure 7 compares different nucleation criteria with the experimental results obtained for water at 80°C by Kandlikar et al. [22] in a 3 mm-high rectangular channel. Note that the nucleation criteria represent the lowest temperature at which a cavity of a given size will nucleate. Using this nucleation criteria, Kandlikar et al. [6] calculated the required cavity sizes for initiating nucleation for stabilizing the flow boiling process. Further discussion on the work by Kandlikar et al. [6] is included in a later section on flow stabilization.

The local liquid conditions play an important role in the stability of the flow boiling phenomenon at the onset of nucleation. Assuming nucleation cavities of appropriate sizes are available, the local wall superheat at the inception location is obtained by setting the term under the radical sign in Eq. (2) to zero:

$$\Delta T_{Sat,ONB} = \sqrt{\frac{8.8 \sigma T_{Sat} q''}{(\rho_v h_{LV} k_L)}}$$

(3)

and the local liquid subcooling is obtained by using the single-phase heat transfer equation prior to nucleation:

$$\Delta T_{Sub,ONB} = \frac{q''}{h} - \Delta T_{Sat,ONB}$$

(4)

As the channel diameter becomes smaller, the single-phase liquid heat transfer coefficient $h$ increases prior to nucleation. Thus, for small channel diameters, the temperature difference between the wall and the liquid could be quite small, and at the ONB condition, the liquid subcooling may also become quite small. Under certain conditions, the local subcooling may even become negative, indicating that the bulk liquid is in the superheated state. As described earlier in this section, the highly superheated liquid surrounding a nucleating bubble causes rapid bubble growth in both upstream and downstream directions and may lead to flow instabilities in a parallel channel. The nucleation characteristics and onset of nucleation for microchannels have not been investigated in the literature, and there is a need to conduct a similar systematic study for small-diameter channels with different channel geometries. The basic equations are expected to be still applicable, as the fundamental processes in liquid flow nucleation, temperature and velocity fields in the liquid remain unaltered at these scales.

**SCALING OF FORCES DURING FLOW BOILING**

The forces acting on an evaporating interface under pool boiling conditions were analyzed by Kandlikar [23], as shown in
Figure 8. The force $F'_M$ represents the net force due to the momentum change caused by evaporation. This force is balanced by surface tension and inertia forces.

Figure 9 shows the forces due to evaporation momentum and surface tension acting on a vapor bubble that fills the entire channel cross-section. The net force due to the evaporation momentum change acts in the direction opposite to the flow. At lower heat fluxes, the surface tension and inertia forces are large enough to prevent a reverse flow. However, at higher heat fluxes, the evaporation momentum forces overcome the two opposing forces and cause the reverse flow.

The surface tension and evaporation momentum forces are dominant in small-diameter channels operating under high heat flux conditions. Kandlikar [23] proposed two non-dimensional numbers to account for these forces. The ratio of evaporation momentum to inertia forces is represented by $K_1$:

$$K_1 = \left( \frac{q'' h_{LV}}{G \rho_L} \right) \frac{D}{\rho_G} = \left( \frac{q'' h_{LV}}{G \rho_L} \right) \frac{\rho_L}{\rho_G}$$

where $q''$ is the heat flux, $h_{LV}$ is the latent heat of vaporization, $G$ is the mass flux, $D$ is the channel diameter, and $\rho_L$ and $\rho_G$ are the liquid and gas phase densities, respectively. Note that $K_1$ represents the Boiling number $(q''/Gh_{LV})$ modified by the density ratio of the two phases. The second non-dimensional number, $K_2$, represents the ratio of the evaporation momentum force to the surface tension force.

$$K_2 = \left( \frac{q'' h_{LV}}{\sigma} \right) \frac{D}{\rho_G} = \left( \frac{q'' h_{LV}}{\sigma} \right) \frac{\rho_L}{\rho_G}$$

where $\sigma$ is the surface tension at the liquid-vapor interface. In microchannels and minichannels, the surface tension forces become relatively more important compared to gravitational forces. The parameter $K_1$ is expected to replace the boiling number in modeling the heat transfer performance. The parameter $K_2$ has already been shown to be useful in representing the CHF in pool boiling [24]. The CHF under flow conditions could be modeled by incorporating the flow effects in the basic pool boiling model. The new non-dimensional numbers utilizing the surface tension forces are therefore expected to help in modeling the flow patterns and critical heat flux in minichannels and microchannels.

**EFFECT OF GRAVITY ON FLOW BOILING IN MICROCHANNELS AND MINICHANNELS**

The influence of gravitational forces on flow boiling in minichannels was studied by Kandlikar and Balasubramanian [13]. Figure 10 shows a comparison among the horizontal, vertical upflow, and vertical downflow configurations under the same conditions. The vertical downflow case exhibited a higher degree of instability, which resulted in a slightly lower heat transfer coefficient. In the horizontal and vertical flows, the flow was similar, and the heat transfer coefficients were identical. This illustrates the insensitivity of the boiling process to the gravitational orientation in narrow channels. This feature makes the minichannels and microchannels very attractive for microgravity applications.

Figure 10. Effect of gravitational orientation on flow boiling in minichannels; vertical downflow exhibiting increased instability, leading to lower heat transfer performance [13].
The reversed flow leading to unstable operation poses a major concern in implementing flow boiling in practical applications. The rapid growth of a vapor bubble in a superheated liquid environment leads to flow reversal, which is identified as a major cause of instability. Mukherjee and Kandlikar [25, 26] conducted an extensive numerical analysis of bubble growth in a microchannel. They utilized the level set method to define the interface and tracked its movement by applying conservation equations. Figure 11 shows the numerical simulation of a bubble growing in a microchannel. The flow resistance in both the upstream and downstream directions was assumed to be the same. The bubble growth is seen to be slow at the beginning but becomes more rapid after the bubble touches the other heated channel walls. This leads to an extension of the inertia-controlled region, where the heat transfer is more efficient because it does not depend on the diffusion of heat across a thin layer surrounding the liquid-vapor interface.

One of the ways to reduce the reverse flow is to introduce an upstream flow resistance at the entrance to the microchannel from the header. Mukherjee and Kandlikar [26] introduced a new parameter $R$ to represent the upstream-to-downstream flow resistance. In their simulation, they showed that increasing the upstream resistance reduced the intensity of the backflow. As expected, the backflow characteristics were also dependent on the heat flux and liquid superheat.

The velocity field in the liquid surrounding an expanding bubble gives valuable insight into the nature of the two-phase flow. Mukherjee and Kandlikar [26] plotted the velocity vectors in the flow domain, as shown in Fig. 12. The case shown in Fig. 12a corresponds to an equal resistance on both sides of a growing vapor bubble. The velocity vectors are drawn after the bubble
has completely filled the channel cross-section. Figure 12b corresponds to the case when the outlet resistance is considerably lower than the resistance to backflow.

Note the large velocity vectors in front of the expanding bubble in Fig. 12(b), which is from left to right. Another point to note is that the liquid film surrounding the vapor core is essentially stagnant from the detailed velocity vectors obtained in the numerical simulation.

FLOW STABILIZATION WITH NUCLEATION CAVITIES AND PRESSURE DROP ELEMENTS AT THE INLET

Introducing artificial nucleation sites in the flow is another method of reducing instability. Introducing nucleation cavities of the right size would initiate nucleation before the liquid attains a high degree of superheat. Kandlikar et al. [6] experimentally observed the nucleation behavior with the introduction of such cavities along with the pressure drop elements placed at the inlet to each channel. The cavity diameters were derived using the nucleation criterion presented earlier. Figure 13 shows nucleation on these artificial cavities much earlier in the microchannel, where the local wall superheat is lower at ONB as compared to the case without artificial cavities. A significant reduction in the reverse flow and flow instabilities was observed. The introduction of pressure drop elements in conjunction with the artificial cavities lowered the pressure fluctuations even further.

The flow pattern developed after nucleation is initiated is an important feature of flow boiling in microchannels and minichannels. The bubbles expand to occupy the entire cross-section, with intermittent liquid slugs between two successive expanding bubbles. Additional nucleation in the slugs further divides them. Figures 2, 4, 13, and 14 show the two-phase structure with the vapor core surrounded by a film of liquid. This flow pattern is similar to the annular flow pattern, but with an important distinction. In an annular flow pattern, liquid flows in the thin film surrounding the vapor core. The velocity profile and flow rate of the film in the classical annular flow are determined from the well-known triangular relationship between the wall shear stress, pressure drop, and liquid film flow rate. Further work is needed to include the local nucleation phenomenon in these models while assessing the instability characteristics.

EXPANDING-BUBBLE FLOW PATTERN

The two-phase flow pattern observed in microchannels after a vapor core fills the cross-section can be termed the “expanding-bubble” flow pattern. In this case, the liquid surrounding the vapor core is essentially stagnant, similar to the liquid film on a heater surface at the base of a growing bubble under pool boiling conditions. A comparison of the two flow patterns is shown in Figure 15.

The liquid flow in an expanding-bubble flow pattern occurs as intermittent slugs. The time-averaged liquid flow rate in the slugs and vapor flow in the core together yield the local quality at a given section. As the liquid slugs flow downstream, additional bubbles are nucleated within the slugs, and new expanding bubbles are formed. These new bubbles interact with the other expanding bubbles, sometimes merging with them and forming a larger vapor core, or creating new expanding-bubbles with smaller liquid slugs appearing between the two successive liquid vapor interfaces. This behavior is illustrated in Figure 14.
Figure 14 shows the flow boiling in a minichannel. The successive frames are taken at time intervals of 0.16 ms. In frame (a), a new vapor bubble is seen to grow between the two vapor bubbles on either of its sides. This middle bubble effectively reduces the size of the liquid slug. In successive frames (b–f), this bubble is seen to expand rapidly, pushing the upstream bubble on the right side. The bubble on the left side also continues to grow. All three bubbles are seen to occupy the entire channel cross-section, with a thin liquid film trapped between the vapor core and the channel side walls.

Figure 13 also shows the presence of bubbles in the liquid slugs. These bubbles are seen to disappear as the liquid slug is pushed forward by an expanding bubble appearing upstream. Some of the smaller bubbles may eventually grow as expanding bubbles, causing the liquid slug to break up further.

Figure 16 shows another video sequence obtained at the same location as Figure 14. In frame (a), the liquid slug near the center has opened up and joined the two bubbles. In frame (b), another small liquid slug is seen to enter the channel on the left side. The vapor breaks through this slug as well in frame (c). A liquid film is formed with waves appearing over a short distance downstream. The waves are broken up in frames (d–g) resulting in a condition similar to churn flow. The flow pattern in frame (g) is similar to the conventional annular flow pattern, with waves appearing on the liquid film attached to the channel walls.

Heat transfer during flow boiling in microchannels is thus dictated by the intermittent passage of liquid slugs and expanding bubbles. Under high heat flux conditions, the evaporation of the thin film leads to periodic dryout patches on the channel walls. The heat transfer mechanism due to periodic movement of the liquid-vapor interface over the heated surface is similar to the transient conduction mechanism around a nucleating bubble in pool boiling, as was pointed out by Kandlikar [23]. In the case of the microchannels, the entire microchannel wall acts as the bubble base during the periodic movement of the liquid-vapor interface.

A number of researchers have confirmed that nucleate boiling is the dominant mode of heat transfer in microchannels. Some of the pool boiling type correlations have been shown to predict heat transfer reasonably well. Therefore, under high heat flux conditions, heat transfer is expected to exhibit the same characteristics as in pool boiling.

It should be recognized that flow boiling in microchannels needs to be stabilized before obtaining valid experimental data. Inlet restriction and artificial nucleation cavities are some of the methods that will provide stable boiling conditions. Kandlikar et al. [6] have shown the efficacy of these methods in their experimental investigation.

CONCLUSIONS

Flow boiling in microchannels and minichannels is an important process that is directly applicable to high heat flux evaporators. One of the main issues currently preventing the implementation of channels smaller than about 1 mm in such applications is identified as the instability resulting from rapidly expanding vapor bubbles. Experimental evidence gathered through high-speed imaging and numerical simulation of a growing vapor bubble in the superheated liquid confirm the high growth rates at the liquid-vapor interfaces, forcing the liquid to flow in the reverse direction toward the inlet manifold. Introducing nucleation sites and restricting inlet flow are seen as effective methods to reduce the instabilities.

The heat transfer mechanisms during flow boiling in minichannels and microchannels are seen to be strongly influenced by the flow patterns. The expanding-bubble flow pattern is identified
as one of the most important flow patterns. A nucleating bubble grows rapidly and occupies the entire channel as an expanding bubble, trapping a liquid film between the expanding vapor core and the channel walls. The liquid film evaporates into the core and dries out until a liquid slug arrives and rewets the surface. A basic understanding of the flow patterns and heat transfer mechanisms was made possible by identifying the flow patterns with high-speed imaging techniques, obtaining accurate local heat transfer information, and using advanced numerical simulation techniques.

**NOMENCLATURE**

- $D$: diameter, m
- $F_M'$: force due to evaporation momentum, N
- $F_S'$: force due to surface tension, N
- $G$: mass flux, kg/m² s
- $h$: heat transfer coefficient, W/m² K
- $h_{LV}$: latent heat of vaporization, J/kg
- $k_1$: liquid thermal conductivity, W/m K
- $K_1$: new dimensionless number, $= \left( \frac{q''}{G h_{LV}} \right)^2 \frac{\rho_l}{\rho_v}$
- $K_2$: new dimensionless number, $= \left( \frac{q''}{G h_{LV}} \right)^2 \frac{D}{\rho_g \sigma}$
- $q''$: heat flux, W/m²
- $R$: ratio of upstream-to-downstream flow resistance
- $r_b$: bubble radius at nucleation, m
- $r_{c,max}$: maximum radius of nucleating cavities, m
- $r_{c,min}$: minimum radius of nucleating cavities, m
- $T_{Sat}$: saturation temperature, K
- $y_S$: distance of the stagnation location from the heated wall, m

**Greek Symbols**

- $\Delta T_{Sat}$: wall superheat, K
- $\Delta T_{Sat,ONB}$: wall superheat at the onset of nucleate boiling, K
- $\Delta T_{Sub}$: liquid subcooling, K
- $\Delta T_{Sub,ONB}$: liquid subcooling at the onset of nucleate boiling, K
- $\delta_t$: thermal boundary layer thickness, m
- $\theta_r$: receding contact angle, deg
- $\mu$: dynamic viscosity, Ns/m²
- $\rho$: density, kg/m³
- $\sigma$: surface tension, N/m

**Subscripts**

- L: liquid
- V: gas or vapor

**REFERENCES**


Satish Kandlikar is the Gleason Professor of Mechanical Engineering at RIT. He received his Ph.D. from the Indian Institute of Technology in Bombay in 1975, and has been a faculty member there before coming to RIT in 1980. His research is mainly focused in the area of flow boiling. After investigating the flow boiling phenomena from an empirical standpoint, which resulted in widely accepted correlations for different geometries, he started to look at the problem from a fundamental perspective. Using high-speed photography techniques, he demonstrated that small bubbles are released at a high frequency under flow conditions. His current work involves stabilizing flow boiling in microchannels, interface mechanics during rapid evaporation, and advanced chip cooling with single-phase liquid flow. He has published more than 100 journal and conference papers. He is a fellow member of ASME and has been the organizer of the two international conferences on microchannels and minichannels sponsored by ASME. He is also the Heat in History Editor for Heat Transfer Engineering. He is the founder of the ASME Heat Transfer chapter in Rochester and founder and first Chairman of the E-cubed fair—a science and engineering fair for middle school students in celebration of Engineers Week.