Stabilization of Flow Boiling in Microchannels Using Pressure Drop Elements and Fabricated Nucleation Sites

The flow boiling process suffers from severe instabilities induced due to nucleation of vapor bubbles in a superheated liquid environment in a minichannel or a microchannel. In an effort to improve the flow boiling stability, several modifications are introduced and experiments are performed on $1054 \times 197 \mu m$ parallel rectangular microchannels (hydraulic diameter of $332 \mu m$) with water as the working fluid. The cavity sizes and local liquid and wall conditions required at the onset of nucleation are analyzed. The effects of an inlet pressure restrictor and fabricated nucleation sites are evaluated as a means of stabilizing the flow boiling process and avoiding the backflow phenomenon. The results are compared with the unrestricted flow configurations in smooth channels.

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Introduction

Presently, many advanced technologies, such as high speed processor chips and electronics components in high power lasers, have the requirement to dissipate increasingly high heat fluxes while maintaining specified surface temperatures. For heat fluxes above $1 \text{ MW/m}^2 (100 \text{ W/cm}^2)$, alternatives to the air cooling option are needed. Single-phase liquid cooling and flow boiling options are being considered in these high heat flux ranges. The flow boiling option has the advantage of a lower mass flow rate due to utilization of latent heat of vaporization. It can also be directly coupled with a refrigeration system to provide a lower coolant temperature.

There are, however, complexities associated with vaporization in multiple narrow channel arrays that are not completely understood. The phenomenon characterized by vapor expansion in both the upstream and downstream directions causing flow reversal was observed by Kandlikar et al. [1] and also by Kandlikar and Balasubramanian [2]. Both employed a high-speed digital video camera to observe this behavior in minichannels and microchannels. Similar instabilities were observed by Hetroni et al. [3] and Peles [4], among other investigators.

This paper addresses two methods to suppress the instabilities during flow boiling in a set of six $1054 \times 197 \mu m$ parallel channels. Inlet area restriction and artificial nucleation sites are studied alone and in conjunction with each other. Flow instabilities are characterized by visual observations and the pressure fluctuations measured between the inlet and outlet manifolds.

For the present study, channel size is classified by the smallest channel dimension $D$ according to the following modified list, originally proposed by Kandlikar and Grande [5]:

- Conventional channels: $D > 3 \text{ mm}$
- Minichannels: $3 \text{ mm} \geq D > 200 \mu m$
- Microchannels: $200 \mu m \geq D > 10 \mu m$
- Transitional channels: $10 \mu m \geq D > 0.1 \mu m$
- Transitional microchannels: $10 \mu m \geq D > 1 \mu m$
- Transitional nanochannels: $1 \mu m \geq D > 0.1 \mu m$
- Molecular channels: $0.1 \mu m \geq D$

where $D$ is the minimum channel dimension.

According to this convention, the channels used in this study with a gap size of $197 \mu m$ can be considered as microchannels, although they could be referred to as minichannels because of the closeness to the boundary of $200 \mu m$.

Because of the rapid bubble growth accompanied by the fluctuations in pressure drop, two phase flow boiling in minichannels and microchannels introduces instabilities. This condition has adverse effects on the heat transfer performance. Presently, the local reversed flow phenomenon is not well understood and not well studied, and few attempts have been reported to control it. The onset of boiling and the subsequent two-phase flow interactions are greatly dependent on the channel surface temperature, local liquid temperature, local heat transfer coefficient prior to nucleation, and availability of nucleation cavities. Uneven flow and pressure fluctuations lead to flow reversal, which may introduce vapor back into the inlet manifold and exacerbate the instability generated in the channels. When a large vapor bubble passes through a channel, the transient heat conduction and interface evaporation enhance heat transfer in the channel and reduce the local channel surface temperatures. Cho et al. [6] reported that modifying the channels with a cross-linked pattern improves the flow distribution and reduces the range of temperatures seen in microchannels with uneven heating. Very few researchers have tried to prevent the flow reversal phenomenon in microchannels.

The basic issues related to the instabilities associated with flow boiling in microchannels were presented by Kandlikar [7]. One of the major results of the instabilities is the severe reduction in the critical heat flux. A detailed survey of this effect was presented by Bergles and Kandlikar [8]. The available experimental data on the CHF by Jiang et al. [9], Bowers and Mudawar [10], Qu and Mudawar [11] indicate the severe reduction in CHF due to the associated instabilities. It may be noted that the CHF values re-
ported in the microchannel geometries are in some cases lower than even the pool boiling CHF values for water at the same pressure. Addressing flow reversal is expected to improve the heat transfer performance. Further research into the understanding and modeling of this behavior is needed. The objective of the present work is to address the basic causes of instabilities and to study the effects of pressure drop elements and fabricated nucleation sites on the flow reversal phenomenon and the corresponding heat transfer performance of the microchannels.

Nucleation in Microchannel and Minichannel Geometries

The heat transfer mechanisms during flow boiling in microchannels and minichannels were analyzed by Kandlikar [12]. The instability resulting from the rapid expansion of a nucleating bubble was seen as one of the main reasons for instability. Under unstable conditions, bubbles nucleate in the flow and cause severe flow fluctuations as they grow rapidly in both forward and backward directions to the main flow direction. On the other hand, under stable boiling conditions, inception of the first nucleating bubble on the wall followed by its steady growth in the flow direction is desired. Under such stable operation, the conditions at the onset of nucleation and bubble growth in the flow direction become relevant.

A number of researchers proposed the nucleation criteria for the onset of nucleation during flow boiling. Hsu and Graham [13], Hsu [14], Bergles and Rohsenow [15], Sato and Matsumura [16], and Davis and Anderson [17] provided the underlying theory relating the temperature distribution in the liquid prior to nucleation to the local nucleation condition. Comparing the liquid temperature on the vapor bubble interface at the farthest location from the wall with the saturation temperature inside the bubble of a certain critical size resulted in their nucleation criteria. At the inception of nucleation, Hsu and Graham [13] assumed a contact angle of 53.1 deg, Bergles and Rohsenow [15], and Sato and Matsumura [16] used a hemispherical bubble shape (90 deg contact angle), while Davis and Anderson [17] left the contact angle as a variable.

Kandlikar et al. [18] 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. 1. 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

\[ \{r_{c,min}, r_{c,max}\} = \frac{\delta_S \sin \theta_S}{2.2} \frac{\Delta T_{Sat}}{\Delta T_{Sat} + \Delta T_{Sub}} \times \left[ 1 \pm \sqrt{1 - \frac{8.8 \sigma T_{Sat} \Delta T_{Sat} + \Delta T_{Sub}}{\rho_v h_{LV} \delta_T \Delta T_{Sat}}} \right] \]  

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, \( \theta_S \) 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 \( \delta \) is the thickness of the thermal boundary layer, \( \approx k_l / h \), with \( k_l \) the liquid thermal conductivity and \( h \) 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. [18], 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 2 compares different nucleation criteria with the experimental results obtained for subcooled water at atmospheric pressure and 80°C by Kandlikar et al. [18] in a 3 mm × 40 mm rectangular channel. Note that the nucleation criteria represent the lowest temperature at which a cavity of a given size will nucleate. These cavities will continue to nucleate at higher superheats as seen in Fig. 2. It should be noted that if the cavities of this radius are not available, the onset of nucleation will be delayed into the downstream part of the channel until the wall superheat condition at nucleation corresponding to the available cavity sizes is met. The results from Hsu [14] and Kandlikar et al. [18] models yield very similar results for this case, while Davis and Anderson’s [17] criterion predicts somewhat higher wall superheat and Bergles and Rohsenow’s [15] model predicts somewhat lower wall superheat as seen from Fig. 2.

Instabilities Due To Nucleation and Rapid Bubble Growth.

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.
The availability of heat from the downstream sides of the expanding bubble leads to a very high superheat at the bubble interface. The superheated liquid environment, the evaporation rate is very high due to release of the liquid superheat at the bubble interface. The bubble continues to grow and encounters other heated walls and heated liquid layer near the other walls leading to a very high superheat condition as low as possible. This can be achieved by introducing nucleation cavities of desirable radii as shown in Fig. 3. It is also observed that the wall superheats at the onset of nucleate boiling (ONB) condition are in general quite high in microchannels, even in the presence of the right sized cavities. Introduction of artificial nucleation cavities alone therefore may not be enough to suppress the instabilities arising due to rapid bubble expansion. In such cases, introduction of pressure drop elements at the entrance to each channel is expected to reduce the reverse flow condition. The PDEs introduce a significant increase in the flow resistance in the reversed flow direction. The effect of area reduction at the entrance was studied through a numerical simulation of an expanding bubble by Mukherjee and Kandlikar [19]. Their results clearly demonstrated the efficacy of the PDEs in reducing the reversed flow. In the present paper, the effects of artificial nucleation cavities and the pressure drop elements of different area reduction ratios on flow boiling stability are studied experimentally. For the conditions of the experiments that will be studied, the desired cavity radius for a minimum wall superheat condition is around 5 μm. To ascertain a wider range of operation, cavities of diameters 5–30 μm are drilled using a laser beam.

The pressure drop effects will be studied by introducing area

\[ \Delta T_{\text{Sat,ONB}} = \sqrt{\frac{8.8 \sigma T_\text{Sat} q^*}{(\rho_L h_L V_h)}} \]  

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

\[ \Delta T_{\text{Sub,ONB}} = \frac{q^*}{h} - \Delta T_{\text{Sat,ONB}} \]  

Figure 3 shows the range of active cavity radii that will nucleate, if present, for a given wall superheat as calculated from Eq. (2). The onset of nucleation occurs over cavities of radius 3 μm, and the minimum wall superheat required to initiate nucleation in the channel under the given conditions is 15°C. If cavities of 3 μm radius are not available, the wall superheat will be higher as given by the plot.

Considering subcooled liquid inlet into a 1054×197 μm channel, Fig. 4 is plotted to show the local wall and bulk liquid temperatures at the nucleation condition. Figure 5 shows the actual wall and liquid temperatures as a function of the nucleation cavity radius.

The effect of reducing the channel size is seen in Fig. 6, which shows a plot of local wall and bulk liquid temperatures similar to Fig. 5 at the nucleation location. For this case, since the heat transfer coefficient is very high, the bulk liquid is superheated over the entire nucleation cavity size range. As a bubble nucleates in the superheated liquid environment, the evaporation rate is very high due to release of the liquid superheat at the bubble interface. The bubble continues to grow and encounters other heated walls as it fills the channel. The availability of heat from (a) the superheated liquid layer near the other walls and (b) 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, and introduction of vapor into the inlet manifold have been identified as the main sources of instability during flow boiling.

**Methods to Reduce Instabilities.** In order to suppress or completely eliminate the instabilities, it is desirable to have the wall superheat at the nucleation location as low as possible. This can be achieved by introducing nucleation cavities of desirable radii as shown in Fig. 3. It is also observed that the wall superheats at the onset of nucleate boiling (ONB) condition are in general quite high in microchannels, even in the presence of the right sized cavities. Introduction of artificial nucleation cavities alone therefore may not be enough to suppress the instabilities arising due to rapid bubble expansion. In such cases, introduction of pressure drop elements at the entrance to each channel is expected to reduce the reverse flow condition. The PDEs introduce a significant increase in the flow resistance in the reversed flow direction. The effect of area reduction at the entrance was studied through a numerical simulation of an expanding bubble by Mukherjee and Kandlikar [19]. Their results clearly demonstrated the efficacy of the PDEs in reducing the reversed flow. In the present paper, the effects of artificial nucleation cavities and the pressure drop elements of different area reduction ratios on flow boiling stability are studied experimentally. For the conditions of the experiments that will be studied, the desired cavity radius for a minimum wall superheat condition is around 5 μm. To ascertain a wider range of operation, cavities of diameters 5–30 μm are drilled using a laser beam.

The pressure drop effects will be studied by introducing area

**Fig. 3** Range of active cavities given by Eq. (2) for a given wall superheat, saturated water in 1054×197 μm channel, \( G = 120 \text{ kg/m}^2 \text{s} \); \( q^* = 300 \text{ kW/m}^2 \)

**Fig. 4** Local wall superheat and liquid subcooling corresponding to onset of nucleation over a given cavity radius, Eqs. (3) and (4), water in 1054×197 μm channel, \( G = 120 \text{ kg/m}^2 \text{s} \); \( q^* = 300 \text{ kW/m}^2 \)

**Fig. 5** Local wall and liquid temperatures corresponding to onset of nucleation over a given cavity radius, replotted data from Fig. 4, water in 1054×197 μm channel, \( G = 120 \text{ kg/m}^2 \text{s} \); \( q^* = 300 \text{ kW/m}^2 \)

**Fig. 6** Local wall and liquid temperatures corresponding to onset of nucleation over a given cavity radius, water in 1054×50 μm channel, \( G = 120 \text{ kg/m}^2 \text{s} \); \( q^* = 300 \text{ kW/m}^2 \)
 reductions of 51% and 4% at the inlet of each channel. The details of the experimental setup and the results are presented in the next sections.

**Experimental Setup**

The experimental setup is shown in Fig. 7 and consists of a water supply loop, the test section, data acquisition system, and the high-speed digital video system. The experimental setup is designed to provide degassed water at a constant flow rate and temperature to the test section. For simplicity, Fig. 7 shows only the water supply loop and the test section.

The details of the test section are shown in Fig. 8. It is very similar to the test section used by Kandlikar and Balasubramanian. It is comprised of three different layers. The top layer is made of an optically clear polycarbonate known as Lexan, which has a thermal conductivity of 0.19 W/m K. This layer provides a direct view of vapor activity in the microchannels below it. It however limits the operating temperature to about 115°C, which is the temperature at which the polycarbonate will begin softening. The second layer is the copper microchannel block. The copper is an Electrolytic Tough Pitch alloy number C11000 which is 99.9% copper and 0.04% oxygen by weight. It has a thermal conductivity of 388 W/m K at 20°C. The third layer is a phenolic plate which acts as an insulating layer on the bottom surface of the copper block as well as a means of securing the test section together with 10 mounting screws. The top surface of the copper block was lap-finished to provide a leakproof assembly with the Lexan top cover. The phenolic is a laminate of paper and epoxy and has a thermal conductivity of 0.2 W/m K. Also shown is the resistive cartridge heater that supplies heat to the test section when a dc voltage is applied.

Six parallel microchannels 63.5 mm long are machined into the copper block as shown in Fig. 8. The channel depth, \( D \), and width, \( W \), are measured at six locations along the channel length using a microscopic measuring system. The average channel dimensions are 1054 \( \mu \)m wide by 197 \( \mu \)m deep with a hydraulic diameter of 332 \( \mu \)m. The width and the height of the channels were measured at several locations and were noted to fall within ±10 \( \mu \)m and ±3 \( \mu \)m of the average values, respectively. This represents an uncertainty of ±1% in the width measurement and ±1.5% in the height measurement. The resulting uncertainty in the hydraulic diameter is estimated to be ±1.4%.

The test section is held together with ten mounting screws that provide the force necessary to seal the copper block to the Lexan without using a gasket. At the pressures experienced within the microchannels this contact force is enough to prevent water from escaping the test section.

To reduce heat transfer in the manifold, the inlet manifold is machined into the Lexan and the water is delivered at the very beginning of the microchannels. Each microchannel has a dedicated inlet machined into the Lexan consisting of a 0.368-mm-diam hole.

The diagram in Fig. 9 shows how each inlet connects to the inlet manifold on the Lexan cover. Water enters through the inlet manifold and is diverted through each restriction hole and into the corresponding microchannel. This small diameter hole has 51% of the cross-sectional area of a single microchannel and is 1.6 mm long. It acts as the physical pressure drop element (PDE) that is being studied. A more restrictive inlet header is also machined.
with 102-μm-diam holes, giving a flow area of 4% of the channel cross-sectional area. The pressure drop is measured across the inlet and outlet manifolds. Temperatures are measured at six locations along the length.

Experimental Procedure

The experimental procedure for obtaining degassed water is the same degassing procedure as described by Kandlikar et al. [1], and Steinke and Kandlikar [20]. A heat exchanger in conjunction with a coolant bath (see Fig. 7) maintains the temperature of the degassed water delivered to the test section at a set value. The water then passes through a flow meter before entering the test section via the inlet manifold.

Once the test loop is built and well insulated, heat loss experiments are performed at steady state. The cartridge heater provides a constant heat input to the test section. A heat loss calibration chart is constructed by plotting the temperature difference between the microchannel surface and the ambient air \( T_s - T_{Amb} \) versus the corresponding steady state electrical power input, \( q_{in} \). Heat losses, \( q_{loss} \), were found to be a linear function of the temperature difference between the microchannel surface and the ambient air and generally ranged between 3 and 4 W for \( (T_s - T_{Amb}) \) of 40–50°C, respectively. During the actual experiments, this chart is used to calculate the actual heat carried away by the microchannel array.

Water flow rate and inlet temperature are set and the electrical power is applied to the microchannels. Steady state is achieved when the surface temperature of the microchannels remains constant over a 15 min time interval. The flow meter is calibrated and used to set the flow for the test section. LabView software is used in the data acquisition system and is used to monitor temperatures of all of the thermocouples and pressure transducers.

All of the image sequences are recorded with a high-speed digital camera system once the test section has reached steady state. The camera frame rate is set to 6000 frames/s to capture the rapid two-phase flow interactions and events occurring within each microchannel. Sequences of individual frames are selected to illustrate the boiling characteristics and behavior at the set flow rate and heat flux conditions.

Uncertainty

The uncertainty in the experimental data is calculated. The uncertainty in the hydraulic diameter is estimated to be ±1.4%. The accuracies of the digital signals are reported as: Voltage \( ±0.05 \) V, \( I = ±0.005 \) A, \( T_s = ±0.1 \) °C, \( ΔP = ±0.1 \) kPa. The flow meter has a volumetric flow accuracy of ±0.0588 cc/min. Heat loss measurements were conducted and a plot of heat loss versus copper block temperature was plotted. The actual heat supplied to the fluid was then calculated by subtracting the heat loss obtained from the plot from the electric power supplied to the cartridge heater. The uncertainty in the heat supplied is estimated to be less than 1%. The thermal uniformity of the test section temperature distribution was verified using temperature measurements and numerical simulation as described in detail in a previous publication by Steinke and Kandlikar [21]. The pressure drop was measured with a pressure transducer with a 1 kHz frequency. Further details on the pressure fluctuations and pressure measurements were given in an earlier publication by Balasubramanian and Kandlikar [22].

Results

The evaluation of pressure drop elements (PDE) and manufactured nucleation sites for stabilizing the flow boiling process is presented in this section. Flow stability is determined through high-speed visual observations and measurement of pressure drop fluctuations across the channels. All tests are conducted with microchannels in the horizontal orientation.

In the video images shown in the paper, the large nucleation cavities seen in the center of the channel are 100-μm-diam punch marks. These “cavities” were too large for nucleation and did not initiate nucleation. This is in accordance with the active cavity size plot shown in Fig. 3. Also, the largest natural cavity sizes observed on the machined channel surfaces were noted to be relatively few and were 1 to 2 μm in diameter. The observed wall superheat was between 12 and 14°C, as confirmed by the earlier experiments conducted by Balasubramanian and Kandlikar [22].

The results are reported for the following five cases:

- **Case (a) Base case, no PDE (pressure drop element), no ANS (artificial nucleation sites)**
- **Case (b) 51% PDE only**
- **Case (c) ANS only**
- **Case (d) 51% PDE with ANS**
- **Case (e) 4% PDE with ANS**

The test section with the fabricated nucleation sites was tested with three different headers. The first header with no pressure drop elements was employed in cases (a) and (c). The second header with 51% area PDEs at the inlet of each flow channel was used in cases (b) and (d). Finally, the third header with 4% area PDEs at the entrance to each flow channel was used in case (e). For cases (c), (d), and (e), the manufactured artificial nucleation sites were incorporated. The results show the visual observations of these two headers in combination with the artificial nucleation sites.

- **Case (a) Base Case.** The results for the base case were presented in earlier publications [21,22]. Severe pressure drop fluctuations and flow reversal were observed indicating unstable operation.

- **Case (b) Effect of Pressure Drop Elements Only.** Pressure drop elements offering 51% area were added in the passage leading from the inlet manifold to the individual microchannels. The manifold incorporates inlet openings of 368 μm diameter at the inlet to each channel, giving an open area that is 51% of the area of a 1054×197 μm microchannel. These pressure restrictors are expected to prevent the backflow by forcing an expanding vapor bubble in the downstream direction and not allowing the liquid-vapor mixture to enter the inlet manifold. Flow reversal was still present and is depicted in Fig. 10.

The sequence of frames in Fig. 10 shows an expanding vapor bubble nucleating and moving backward as well and eventually reaching the inlet manifold. Frame (a) shows a vapor bubble nucleating from a nucleation site near the corner of the channel. Frame (c) shows the bubble developing into a plug as it begins to push water upstream and downstream. The smaller bubbles seen in the flow upstream also move in the reverse direction rather than slipping around the vapor slug. Finally, Frame (f) shows the vapor reaching the inlet manifold and the channel drying out.

As seen from the above discussion, the 51% area pressure drop elements do not eliminate the reverse flow. Comparing these results with those presented by Kandlikar and Balasubramanian [2], the 51% area pressure drop elements in the inlet manifold seem to reduce the severity of backflow but they do not completely eliminate it. Apparently, the area reduction is not sufficient to prevent the reverse flow in the channels. Another indicator of stability is the magnitude of pressure fluctuations across the microchannels. A pressure drop fluctuation comparison is presented in a later section.

- **Case (c) Effect of Nucleation Sites Only.** Nucleation sites were created at regular intervals on the bottom surface of the microchannels. The sites consisted of cavities created by a laser engraving process to achieve their very small sizes. According to the nucleation theory presented earlier, there is a range of nucleation site sizes that are active for a given set of operating conditions. For this reason, a range of 5- to 30-μm-diam cavities was created. The cavities were spaced at a regular interval of 762 μm.
slightly offset from the center of each of the six microchannels for their entire length. Figure 11 shows images of two typical laser drilled holes created. The cavities were slightly deeper than their width at the mouth. Imaging software was used to capture images of the holes and to measure the sizes of their features.

In a few events, nucleation was observed at naturally occurring, 1- to 2-μm-diam nucleation cavities close to the walls of the microchannel. These sites were generated as a result of the machining process and were limited to diameters smaller than 1 to 2 μm as noted above.

The addition of only nucleation sites however caused a significant increase in the flow instability. The backflow was seen to be more pronounced. The pressure drop fluctuations were also higher. The availability of nucleation sites closer to the inlet manifold facilitated their backflow into the manifold.

Case (d) Effect of Combined 51% PDE and ANS. The visual images for this case are shown in Fig. 12. A bubble is seen to nucleate near the corner of the microchannel and grow in both the upstream and downstream directions until the channel is eventually dried out. The flow is observed to be unstable, but the severity of the flow reversal is seen to be somewhat reduced as compared to the base case (a).

With partial stabilization seen by the 51% area pressure drop elements and fabricated nucleation sites, and occasional stable boiling patterns seen with natural and fabricated nucleation sites alone, a manifold with an even greater area reduction was tested next.

Case (e) Effect of Combined 4% PDE and ANS. The third manifold incorporates inlet openings of 102 μm diameter at the inlet to each channel, giving an open area that is 4% of the area of a 1054 × 197 μm microchannel. All of the conditions were held constant as the effect of the 4% area pressure drop element manifolds in conjunction with the fabricated nucleation sites was tested. The sequence of frames in Fig. 13 shows extremely stable flow boiling in the channels. Unlike previous cases, flow reversal was not seen at any time and a pattern recognized as truly stabi-
lized was seen. Figure 13 shows longer durations between the frames (11.7 ms) to illustrate that the pattern was stable over long period of operation. This was the case in all six channels. Bubbles often formed at the fabricated nucleation sites as well in the corners of the microchannels and expanded in the downstream direction.

**Comparison of Pressure Drop, Pressure Fluctuations, and Heat Transfer.** Figure 14 shows a comparison of the transient pressure drop behavior for the five cases studied. The base case, case (a), shows significant pressure fluctuations indicating instability. Case (b) with 51% PDEs shows partially stable flow with lower pressure drop fluctuations.

The presence of 51% PDEs in case (b) helped in improving the stability, but did not completely stop the reversed flow. Interestingly, the total pressure drop remained almost identical with case (a). Case (c) with the nucleation sites alone actually increased the pressure fluctuations and reduced the total pressure drop. The early nucleation in the channel closer to the inlet manifold provided a lower resistance in the backflow direction leading to unstable operation.

Case (d) with 51% PDEs and ANS reduced the instability, and made the flow boiling partially stable. It also resulted in a reduction in the pressure drop as well compared to cases (a)–(c). Finally, case (e) with 4% PDEs and ANS provided a stable flow, but a very high pressure drop value.

Table 1 summarizes the pressure drop, pressure fluctuations, and heat transfer results for the five cases studied. The results for case (c) show an increased pressure fluctuation with the presence of ANS as compared to the base case (a). The presence of nucleation sites alone increased the instabilities. Case (d) provides partially stabilized flow with a decrease in the pressure drop. The improvement in flow stability contributes to a lower pressure drop as well. Case (e) provides the most stable flow, but the pressure drop is significantly higher due to the inlet restrictors. In this study, the actual channel pressure drop could not be measured and only the pressure drops between the two headers are reported.

The heat transfer performance is presented in Table 1 through the wall temperatures for the five cases. The presence of ANS clearly shows an improvement in the heat transfer performance as seen in cases (c), (d), and (e). Introducing only ANS in case (c) increased the instability, but lowered the wall temperatures. Case (e) offers the best heat transfer performance, although the pressure drop is very high. Case (d) offers an intermediate result, indicating a need for further experimental study to cover a wider range of PDEs.

**Conclusions**

1. The present study focused on evaluating the effect of pressure drop elements and artificial nucleation sites on the instability observed during flow boiling in microchannels. Their individual as well as combined effects were studied experimentally using high speed video imaging and pressure drop measurements. The artificial nucleation sites of diameters 5–30 μm, derived from the nucleation criterion, and inlet area restrictors providing 51% and 4% open channel area were studied. All cases were studied under the same mass flow and heat flux conditions.

2. Introduction of pressure drop elements alone partially reduced the instabilities. Introduction of nucleation sites alone increased the instabilities.

3. Introduction of nucleation sites in conjunction with the 51% area pressure drop elements was seen to partially reduce the reverse flow phenomenon. Partially stabilized flow was observed for the first time. The reverse flow did not extend into the inlet manifold and the pressure drop fluctuations were reduced considerably.

4. Fabricated nucleation sites in conjunction with the 4% area pressure drop elements completely eliminated the instabilities associated with the reverse flow. Early indications of increased thermal performance were also seen. Use of pressure drop elements in conjunction with fabricated nucleation sites is recommended based on this study.

5. Stable flow provided an improvement in heat transfer as seen by a reduction in the channel wall temperatures.

6. Further research is warranted to study the effect of different pressure drop elements, and different size and distribution of the nucleating cavities on stability of the flow boiling phenomena.

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**Nomenclature**

- $A_{HT}$ = heat transfer area, $m^2$
- $CHF$ = critical heat flux, $W/m^2$
- $D$ = minimum dimension of rectangular channel, $μm$
- $G$ = mass flux, $kg/m^2 s$
- $h$ = heat transfer coefficient, $W/m^2 K$
- $h_{LV}$ = latent heat of vaporization, $J/kg$
- $I$ = electrical current, $A$
Greek Letters

\( k_L \) = thermal conductivity of liquid, W/m K

\( \Delta P \) = pressure drop, Pa

\( PDE \) = pressure drop element

\( q_{in} \) = heat input to the test section, W

\( q_{loss} \) = heat loss from the test section, W

\( q'' \) = heat flux, W/m²

\( r_b \) = radius of the bubble at nucleation, m

\( r_{c,max} \) = maximum radius of nucleating cavity, m

\( r_{c,min} \) = minimum radius of nucleating cavity, m

\( T_s \) = surface temperature, °C

\( T_{Amb} \) = ambient air temperature, °C

\( T_{Sat} \) = bulk temperature, °C

\( T_{Sat} \) = saturation temperature, °C

\( \Delta T_{Sat} \) = wall superheat, \( = T_{Wall} - T_{Sat} \), °C

\( \Delta T_{Sub} \) = liquid subcooling, \( = T_{Sat} - T_{Bulk} \), °C

\( T_{Wall} \) = wall temperature, °C

\( W \) = width of microchannel, m

\( y_S \) = stagnation location from wall, m

Subscripts

ONB = onset of nucleate boiling

Sat = saturation

Sub = subcooling

References


