EXPERIMENTAL EVALUATION OF PRESSURE DROP ELEMENTS AND FABRICATED NUCLEATION SITES FOR STABILIZING FLOW BOILING IN MINICHANNLES AND MICROCHANNELS

Satish G. Kandlikar¹, Daniel A. Willistein², John Borrelli³

Thermal Analysis and Microfluidics Laboratory
Mechanical Engineering Department
Rochester Institute of Technology, Rochester, New York, 14623, USA

¹sgkeme@rit.edu  ²daw7820@rit.edu  ³jxb9224@rit.edu

ABSTRACT

The flow boiling process suffers from severe instabilities induced due to nucleation of vapor bubbles in a minichannel or a microchannel in a superheated liquid environment. In an effort to improve the flow boiling stability, several modifications are introduced and experiments are performed on 1054 x 197 µm microchannels 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 phenomena. The results are compared with the unrestricted flow configurations in smooth channels.

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 MW/m² (100 W/cm²), 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 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 (2001) and also by Kandlikar and Balasubramanian (2004). Both employed a high-speed digital video camera to observe this behavior in minichannels and microchannels. Similar instabilities were observed by Hetsroni et al. (2003) and Peles (2003).

This paper addresses two methods to suppress the instabilities during flow boiling in a set of six 1054 x 197 µm 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 across the channels.

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 (2003):

- Conventional Channels - \( D > 3 \) mm
- Minichannels - \( 3 \) mm ≥ \( D > 200 \) µm
- Microchannels - \( 200 \) µm ≥ \( D > 10 \) µm
- Transitional Channels - \( 10 \) µm ≥ \( D > 0.1 \) µm
- Transitional Microchannels - \( 10 \) µm ≥ \( D > 1 \) µm
- Transitional Nanochannels - \( 1 \) µm ≥ \( D > 0.1 \) µm
- Molecular Channels - \( 0.1 \) µm ≥ \( D \)

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

NOMENCLATURE

\[ A_{HT} \quad \text{Heat transfer area, m}^2 \]
\[ \text{CHF} \quad \text{Critical heat flux, W/m}^2 \]
\[ D \quad \text{Minimum dimension of rectangular channel, µm} \]
Greek Letters
\[ \delta \quad \text{Thermal boundary layer thickness, } = k_L/h, \text{ m}\]
\[ \theta_r \quad \text{Receding contact angle, degrees} \]
\[ \rho_v \quad \text{Vapor density, kg/m}^3 \]
\[ \sigma \quad \text{Surface tension, N/m} \]

Subscripts
ONB Onset of nucleate boiling
Sat Saturation
Sub Subcooling

LITERATURE REVIEW

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 enhances heat transfer in the channel and reduces the local channel surface temperatures. Cho et al. (2003) 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.

The basic issues related to the instabilities associated with flow boiling in microchannels were presented by Kandlikar (2002). 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 (2005). The available experimental data on the CHF by Jiang et al. (1999), Bowers and Mudawar (1994), Qu and Mudawar (2004) indicate the severe reduction in CHF due to the associated instabilities. It may be noted that the CHF values reported in the microchannel geometries are 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 (2004). The instability resulting from the rapid expansion of a nucleating bubble was seen as one of the main reasons for instability.

A number of researchers proposed the nucleation criteria for the onset of nucleation during flow boiling. Hsu and Graham (1961), Hsu (1962), Bergles and Rohsenow (1964), Sato and Matsumura (1964), and Davis and Anderson (1966) provided the underlying theory relating the temperature distribution in the liquid prior to nucleation to the nucleation condition. Comparing the liquid temperature on the bubble interface at the farthest location from the wall with the saturation temperature inside a vapor bubble of a certain critical size resulted in their nucleation criteria. At the inception of nucleation, Hsu and Graham (1961) assumed a contact angle of 53.1 degrees, Bergles and Rohsenow (1964), and Sato and Matsumura (1964) used a hemispherical bubble shape (90 degree contact angle), while Davis and Anderson left the contact angle as a variable.

Kandlikar et al. (1997) 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:

\[
y_S = 1.10r_b \tag{1}
\]

where \( y_S \) – distance of the stagnation location from the heated wall, and \( r_b \) – 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:

\[
\left\{ r_{c,max}, r_{c,min} \right\} = \frac{\delta \sin \theta}{2.2} \left( \frac{\Delta T_{sat}}{\Delta T_{sat} + \Delta T_{sub}} \right) \left[ 1 + \frac{1}{1 - \frac{8.86\sigma T_{sat} (\Delta T_{sat} + \Delta T_{sub})}{\rho_v h_L \delta \Delta T_{sat}}} \right] \tag{2}
\]
where \( r_{c,\text{min}} \) and \( r_{c,\text{max}} \) – minimum and maximum radii of the nucleating cavities, \( \Delta T_{\text{Sat}} \) and \( \Delta T_{\text{Sub}} \) – wall superheat and liquid subcooling, \( \theta_r \) - receding contact angle, \( \sigma \) - surface tension, \( h_{LV} \) – latent heat of vaporization, \( \rho_V \) - vapor density, and \( \delta_t \) - thickness of the thermal boundary layer, \( = k_L/h \), with \( k_L \) – liquid thermal conductivity and \( h \) – heat transfer coefficient in the liquid prior to nucleation. Note that there is a typographical error in the original publication by Kandlikar et al. (1997), 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).

\[
\Delta T_{\text{Sat,ONB}} = \sqrt{8.8\sigma T_{\text{Sat}} q''/(\rho_V h_{LV} k_L)}
\]

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 5 \( \mu \text{m} \), and the minimum wall superheat required to initiate nucleation in the channel under the given conditions is 8 \(^\circ\text{C} \). If cavities of 5 \( \mu \text{m} \) radius are not available, the wall superheat will be higher as given by the plot.

Figure 2 compares different nucleation criteria with the experimental results obtained for subcooled water at atmospheric pressure and 80 \(^\circ\text{C} \) by Kandlikar et al. (1997) in a 3 mm \( \times \) 40 mm rectangular channel. Note that the nucleation criteria represent the lowest temperature at which a cavity of a given size will nucleate. 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 (1962) and Kandlikar et al. (1997) models yield very similar results for this case, while Davis and Anderson’s (1966) criterion predicts somewhat higher wall superheat and Bergles and Rohsenow’s (1964) 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.
METHODS TO REDUCE INSTABILITIES

In order to suppress or completely eliminate the instabilities, it is desirable to have the liquid and wall superheat at the nucleation location as low as possible. This can be achieved by the introduction of nucleation cavities of the 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 effect of area reduction at the entrance was studied through a numerical simulation of an expanding bubble by Mukherjee and Kandlikar (2004). 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 \( \mu \text{m} \). To ascertain a wider range of operation, cavities of diameters 5 to 30 \( \mu \text{m} \) are drilled using a laser beam.

The pressure drop effects will be studied by introducing area reductions of 51 percent and 4 percent 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 (2004). It is comprised of three different layers. The top layer (a) 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 the 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 (b) is the copper microchannel block. The copper is an Electrolytic Tough Pitch alloy number C11000 which is 99.9 percent copper and 0.04 percent oxygen (by weight). It has a thermal conductivity of 388 W/m-K at 20 °C. The third layer (c) 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 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 333 \( \mu \)m. The measured width and depth values all fall within ±10 \( \mu \)m of the average values.

The test section is held together with ten mounting screws that provide the force necessary to seal the copper block to the Lexan without the use of 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 diameter hole.

The diagram in Fig. 9 shows how each inlet connects to the inlet manifold to the microchannel. Water enters through the inlet manifold and is diverted through each restriction hole and into the corresponding microchannel. This small diameter hole has 51 percent of the area of a single microchannel and is 1.6 mm long. It acts as the physical pressure drop element that is being studied. A more restrictive inlet header is also machined with 102 \( \mu \)m diameter holes, giving a flow area of 4 percent of the channel cross-sectional area.

**EXPERIMENTAL PROCEDURE**

The experimental procedure for obtaining degassed water is the same degassing procedure as described by Kandlikar et al. (2001), and Steinke and Kandlikar (2004). A heat exchanger in conjunction with a coolant bath (see Fig. 7) maintains the degassed water delivered to the test section at a
set temperature. 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, \(q_{elec}\). 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 to 4 watts for \((T_s - T_{Amb})\) of 40 °C to 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 fifteen minute time interval. The flow meter is calibrated and is used to set the flow for the test section. LabView software is used as 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 per second to capture the details of 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 of the experimental data is calculated. The accuracy of the digital signals are reported as: Volts = ±0.05 V, \(I = ±0.005\) Amp, \(T = ±0.1°\) C, \(\Delta P = ±0.1\) kPa.

**RESULTS**

The evaluation of pressure drop elements 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 fluctuation across the channels.

In the video images shown in the paper, the large nucleation cavities seen in the center of the channel are 100 \(\mu\)m diameter 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 \(\mu\)m in diameter. The observed wall superheat was between 12 and 14 °C, as confirmed by the earlier experiments conducted by Balasubramanian and Kandlikar (2005).

**EFFECT OF PRESSURE DROP ELEMENTS ONLY**

Pressure drop elements offering 51 percent area were added in the passage leading from the inlet manifold to the individual microchannels. This pressure restrictor is expected to force an expanding vapor bubble after nucleation to flow downstream and not enter the inlet manifold. Flow reversal was observed and is shown in Fig. 10.

![Flow reversal in 51 percent area pressure drop manifold with no nucleation sites. Successive frames from (a) to (f) taken at 1.67 ms time interval illustrating partially stabilized flow in a single channel from a set of six parallel microchannels. Bulk flow direction is from top to bottom with the inlet near the top of the frames. G=120 kg/m²s, q"=308 kW/m², T_s=113 °C.](image)

The sequence of frames in Fig. 10 shows an expanding vapor bubble nucleating and moving toward and eventually reaching the inlet manifold. Frame (a) shows a vapor bubble nucleating from the left wall of the channel. Frame (c) shows the bubble developing into a plug as it begins to push water upstream and downstream. The smaller bubbles present in the flow upstream from the main vapor slug also move upstream indicating the flow is actually reversing rather than slipping around the vapor slug. Finally, Frame (f) shows the vapor reaching the inlet manifold and the channel drying out.

This reverse flow shows that the 51 percent area pressure drop elements do not completely eliminate the reverse flow trend. Comparing these results with those presented by Kandlikar and Balasubramanian (2004), the 51 percent 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 later in this section.

**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 given operating conditions. For this reason, a range of 5 to 30 µm diameter cavities was created. The cavities were spaced at a regular interval of 762 µm in the center of each of the six microchannels for their entire length. Figure 11 shows images of two typical laser drilled holes created. Imaging software was used to capture images of the holes and to measure the sizes of their features.

Fig. 11 Laser drilled holes on microchannel surface. Cavity in image (a) has an average diameter of 8 µm and cavity in image (b) has an average diameter of 22 µm.

In a few events, nucleation was observed at naturally occurring 1 to 2 µm nucleation sites along the walls of the microchannel. When the nucleation occurred without a pressure drop element to force the expanding bubble downstream, flow reversal was still common for the majority of observations.

Fabricated nucleation sites were intended to stimulate boiling earlier in the microchannels. It is proposed that without these nucleation sites, the water attains a higher superheat before nucleation eventually occurs in the corners or edges of the microchannel. Once the bubbles appear in the flow, the high superheat causes an explosive growth that leads to the backflow phenomenon. The reason for the flow reversal with fabricated nucleation sites is believed to be the proximity of the nucleation sites to the inlet manifold.

EFFECT OF COMBINED PRESSURE DROP ELEMENTS AND FABRICATED NUCLEATION SITES

The test section with the fabricated nucleation sites was tested with three different headers. The first case employed no pressure drop elements in the manifold. The second case was observed at the same flow rate and heat flux, but with the 51 percent area pressure drop elements added. Finally, the third case was observed at the same flow and heat flux, but with the 4 percent area pressure drop elements instead. For all three cases the manufactured nucleation sites were incorporated.

The sequence of frames shown in Fig. 12 shows classic flow reversal occurring in the microchannel with no pressure drop element. The bubble nucleates at the corner of the microchannel and grows in both the upstream and downstream directions until it eventually dries out the channel.

All of the conditions were held constant as the effect of the 51 percent area pressure drop element manifolds was tested instead of the open inlet manifold. While flow reversal was still present, its occurrence was reduced and pressure fluctuations were also reduced as a result.

With partial stabilization seen by the 51 percent 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. This second manifold incorporates holes with a diameter of 102 µm, which gives an area that is 4 percent of the area of the 1054 x 197 µm microchannels. All of the conditions were held constant as the effect of the 4 percent area pressure drop element manifolds in conjunction with the fabricated nucleation sites were tested. The sequence of frames shown in Fig. 13 shows extremely stabilized flow boiling in the same channels. Unlike previous cases, flow reversal was not seen at any time and a pattern recognized as truly stabilized was seen. Figure 13 shows longer durations between the frames (11.7 ms) to illustrate that the pattern was stable indefinitely. 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.

Figure 14 shows the improved surface temperature of the channel under the three conditions tested. The temperatures with the 4 percent pressure drop element case are generally lower than that of the case without pressure drop elements.
This is an indication of the improved performance associated with the more stable boiling pattern. It may be noted that the system pressure in the channels remained the same irrespective of the presence of the 51 percent pressure drop elements.

Figure 15 shows the transient pressure drop behavior for the three cases. The open header shows significant pressure fluctuations indicating instability. The 51 percent area pressure drop element header shows less fluctuations, while the 4 percent area pressure drop elements produce much more stable results with respect to pressure drop across the elements and the microchannels. This increase in stability comes at the cost of higher pressure drop as seen in Fig. 15. Further experiments with different inlet restrictors are needed before accurately characterizing the relationship between restrictor size and pressure drop behavior.

Table 1 shows a summary of the test conditions and results corresponding to each case. For each case, there are corresponding average microchannel surface temperatures and pressure drops across the microchannels. Also characterized are the pressure drop fluctuations for each case and the observed stability from the visual images.

The presence of 51 percent pressure drop elements helped in improving the stability, but did not completely stop the reversed flow. The nucleation sites alone did not prevent the reverse flow, as the early nucleation in the channel closer to the inlet manifold provided a lower resistance in the backflow direction. The nucleation sites with the 51 percent area reduction reduced the instability, but did not completely prevent it. The severe restriction from the 4 percent area ratio header provided a stable flow, but a very high pressure drop value.

Interestingly, the 51 percent area header did not cause an increase in the total pressure drop in the channel as seen from
Fig. 15, although the pressure fluctuations were reduced to a large extent, while the 4 percent area header increased the pressure drop significantly. Providing headers with intermediate area ratios (between 4 percent and 51 percent) may provide stable flow boiling with little or no extra pressure drop penalty. A complete mapping over a wide range of operating conditions is recommended.

### Table 1 Summary of Test Results

<table>
<thead>
<tr>
<th>Case</th>
<th>Average surface temp. (°C)</th>
<th>Pressure drop kPa</th>
<th>Pressure fluctuation ± kPa</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open header, 5-30 μm nucleation sites</td>
<td>113.4</td>
<td>12.8</td>
<td>2.3</td>
<td>unstable</td>
</tr>
<tr>
<td>51% area PDEs, 5-30 μm nucleation sites</td>
<td>113.0</td>
<td>13.0</td>
<td>1.0</td>
<td>partially stable</td>
</tr>
<tr>
<td>4% area PDEs, 5-30 μm nucleation sites</td>
<td>111.5</td>
<td>39.5</td>
<td>0.3</td>
<td>completely stable</td>
</tr>
</tbody>
</table>

### CONCLUSIONS

1. The flow reversal phenomenon was observed in a 1054 x 197 μm microchannel. This was evidenced visually by noting the movement of smaller bubbles upstream from the main reversing bubble. During flow reversal, the expanding bubble as well as the much smaller bubbles present in the flow move toward and often reach the inlet section.

2. Introduction of nucleation sites in conjunction with the 51 percent area pressure drop elements was seen to partially reduce the reverse flow phenomenon. Partially stabilized flow was observed for the first time.

3. Fabricated nucleation sites derived from the nucleation criterion (5 to 30 μm diameter) in conjunction with the 4 percent 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.

4. 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.

### ACKNOWLEDGEMENTS

All of the experimental work was performed in the Thermal Analysis and Microfluidics Laboratory at RIT. Part of the work was conducted under a grant from the National Science Foundation, CTS #0245642.

### REFERENCES


