COMPARISON OF FLOW PATTERNS DURING FLOW BOILING IN SINGLE \((D_h = 333 \ \mu m)\) AND PARALLEL RECTANGULAR CHANNELS \((D_h = 207 \ \mu m)\)

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ABSTRACT

The experimental observation of flow patterns during flow boiling in microchannels has been an interesting field of work intended to enhance our understanding of the heat transfer and two-phase flow mechanisms. A number of studies have been conducted recently to observe the flow patterns during boiling in small channels with hydraulic diameters ranging from 200 \(\mu m\) to 1 mm.

The present study is aimed at studying the flow patterns during flow boiling of water in two different channels of hydraulic diameter 207 \(\mu m\) and 333 \(\mu m\) respectively. High-speed photography is used to obtain video images of the flow field. The channels are machined on top of a copper block and are covered with Lexan to permit visual observation. The copper block along with the channel is heated by a cartridge heater. The effect of channel height on flow patterns in single and multiple channels is studied as a function of mass flux, heat flux and location along the flow length. The results provide important information regarding the boiling behavior in different aspect ratio channels with single and multiple parallel flow channels.

INTRODUCTION

Complex interactions are seen between the liquid and vapor phases and the channel walls during flow boiling in small diameter channels. These interactions have remarkable effects in altering the flow patterns. Kandlikar et al. [4]. The effect of surface tension forces is expected to be important. Triplet et al. [12].

The high pressure drops encountered in microchannels limit the flow rate, and the mass fluxes employed in these channels are generally smaller than the conventional diameter tubes. The low mass flux combined with the small channel diameter yield all liquid Reynolds numbers that are in the laminar region. In many cases, the Reynolds number is on the order of 100 or lower. The complex two-phase interactions are difficult to model, and currently we have to resort to experimental methods to obtain more information about the flows in these geometries.

In the present work, we will use the channel classification proposed by Kandlikar [7] as follows:

- **Conventional channels** - 
  - \(D_h > 3 mm\)
- **Minichannels** - 
  - \(3 mm \geq D_h \geq 200 \mu m\)
- **Microchannels** - 
  - \(200 \mu m \geq D_h \geq 10 \mu m\)
- **Transitional Channels** - 
  - \(10 \mu m \geq D_h > 0.1 \mu m\)
- **Transitional Microchannels** - 
  - \(10 \mu m \geq D_h > 1 \mu m\)
- **Transitional Nanochannels** - 
  - \(1 \mu m \geq D_h > 0.1 \mu m\)
- **Molecular Nanochannels** - 
  - \(0.1 \mu m \geq D_h\)

Under this definition, the 207 \(\mu m\) channel comes close to microchannel classification, and the 333 \(\mu m\) channel comes under minichannel classification.

NOMENCLATURE

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\begin{align*}
\text{d, w, l} & \quad \text{Channel depth, width and length (m)} \\
A & \quad \text{Area (m}^2) \\
G & \quad \text{Mass flux (kg/m}^2\text{s)} \\
h & \quad \text{Heat transfer coefficient (W/m}^2\text{K)} \\
\dot{m} & \quad \text{Mass flow rate (kg/s)} \\
P & \quad \text{Pressure (kPa)} \\
Q & \quad \text{Heat transfer (W)} \\
q & \quad \text{Heat flux (W/m}^2\text{)} \\
Re & \quad \text{Reynolds number (}= G*D_h/\mu\text{)} \\
T_s & \quad \text{Surface temperature (°C)} \\
\Delta T_s-amb & \quad \text{Difference in temperature between test section surface and ambient}
\end{align*}
\]
LITERATURE REVIEW

Experiments involving two-phase flow visualization in microchannels have been a subject of investigation of a few recent studies. Kandlikar et al. [4], Kandlikar [5, 6] and [9] report the flow patterns in a 1 mm square stainless steel channel heated with the flow of oil. They noted significant flow oscillations due to localized boiling with parallel channels. The expanding bubbles at any location experience very large growth rates and cause the liquid fronts outward on both sides of the bubble. The resulting flow reversal introduces significant pressure fluctuations in the channel. The reversed flow in the channels causes the vapor to flow back into the inlet manifold leading to flow maldistribution in the inlet header. This behavior leads to premature CHF condition.

The early studies in literature focused on gas-water flows; Fukano et al. [2] used a horizontal capillary tube with inner diameter of 1.0 mm to 4.9 mm and Wambsganss et al. [13] used a horizontal round tube of inside diameter 2.90 mm. Kasza et al. [10] studied rectangular channel of size 2.5mm by 6.0mm and compared the flow pattern transitions with the available flow pattern maps. They confirmed the presence of bubbly, plug, slug, and annular flow patterns, with stratified region limited to very small flow rates. Triplet et al. [12] used a circular microchannels with inner diameter of 1.1mm and 1.45mm. They suggested that due to the dominance of surface tension, stratified flow is essentially absent, slug (plug) and churn flow patterns occur over extensive ranges of parameters, and the slip velocity under these flow patterns is small. The flow pattern observation was done in a systematic fashion by Cornwell and Kew [1] with R-113 in 0.9 mm x 1.2 mm rectangular minichannels. They identified a flow pattern referred to as the confined bubble region. Here the bubbles nucleate and grow to occupy the entire channel. Large vapor bubbles fill the channel with liquid slugs between the consecutive elongated bubbles. A good summary of flow pattern visualization in minichannels is given by Kandlikar (2001a).

Hetsroni et al. [3] conducted a study on microchannels of 103-129 µm hydraulic diameter with all water Reynolds number in the range 20-70. They visualized the flow to be annular, with intermittent dryout and rewetting of the channels. Nucleation was not observed during the annular flow. Vapor was observed in the inlet plenum; similar observations were made by Kandlikar et al. [4] for 1 mm parallel channels. The instability resulting from the boiling in parallel channels was confirmed in microchannels as well.

OBJECTIVES OF THE PRESENT WORK

The present work is aimed at visualizing the two-phase flow behavior of water boiling in single and multiple parallel small diameter channels. The effect of varying the channel height will be investigated. The interaction of nucleating bubbles and the liquid flow, and other flow characteristics, will be investigated as a function of flow rate and heat flux. In addition, the two-phase flow near the exit manifold will also be studied.

EXPERIMENTAL SETUP

The experimental setup for the horizontal channel flow loop is designed to deliver a constant mass flow rate to the test heat exchanger. Figure 1 shows the schematic of the water delivery system with its associated components.

The test section details are shown in Fig. 2. It is a combination of three layers. The top layer is made of Lexan, an optically clear polycarbonate material with thermal conductivity of 0.19 W/mK. The water inlet and outlet plenums are machined into the polycarbonate layer. This is done to eliminate the heat transfer in the inlet and outlet manifolds. The second layer is a copper block that contains the microchannels. The copper is an Electrolytic Tough Pitch alloy number C11000. It is comprised of 99.9% copper and 0.04% oxygen (by weight) with a thermal conductivity of 388 W/mK at 20°C. The third piece is a Phenolic. It is a laminate of epoxy and paper with a thermal conductivity of 0.2 W/mK and acts an insulator on the lower surface of the copper plate. It is used to secure the test section with the help of ten mounting screws. A cartridge heater supplied with a constant DC input power is used for heating the test section.

Figure 1: Fluid delivery system, Pressure chamber, Flat plate HX, Throttling needle valve, Flow meter, Test section, and Condensate collection.

There are six parallel microchannels machined into the copper substrate. Using a microscopic vision system, the channel depth and width are measured at six locations along the channel length. The average channel dimensions are 1054 µm wide by 197 µm deep and 63.5 mm long with a calculated hydraulic diameter of 333 µm. All of the measured values fall within ± 5% of the average values.
The remaining dissolved air present in the water will not precipitate as long as the temperature stays below this saturation temperature. Thus by using the pressure cooker the water is degassed and supplied to the test section while maintaining a constant pressure.

Once the test section is assembled and well insulated, heat loss experiments are conducted. The heat loss calibration chart is plotted between the supplied power to the test section in Watts and the difference in temperature between the test section surface and the ambient. For example, $\Delta T_{s-amb}$ of 50°C and 90°C had corresponding heat losses of about 3.26 W and 5.86 W respectively. The heat loss data is used in calculating the actual heat carried away by water flowing in the test section.

The experiments were performed with degassed water. The water is drawn from the bottom of the pressure vessel and is passed through a flat plate heat exchanger to provide the desired water inlet temperature to the test section. A flow meter is used to measure the flow rate. The accuracy of the flow meter is 3% of the full scale, or 0.25 cc/min. LabVIEW is used to monitor the thermocouples measuring temperature. Flow is started in the channel and the cartridge heater is powered. The mass flux is held constant while the input power is varied through the desired range. The resulting thermal performance was recorded in terms of water flow rate, inlet and outlet water temperatures, six temperatures inside the copper block along the flow length, and the inlet and exit pressures.

The images are acquired after the system has reached steady state. To detect nucleation in the flow channel, a microscopic lens is used. Once the entire channel is imaged, the lens is used to gather detailed images of specific features and events.

The uncertainty of the experimental data was determined. The accuracy of the instruments is reported as: $T = \pm 0.1 \degree C$, $DP = \pm 0.01$ psi, Volts = $\pm 0.05$ V, $I = 0.005$ Amp. The bias and precision errors were estimated, and the resulting uncertainty in the heat transfer coefficient is 8.6% and the friction factor is 7.2%.

**RESULTS**

1. **333 MICRON SINGLE CHANNEL FLOW VISUALIZATION**

   In literature, there is no flow visualization information available on flow boiling in a single minichannel. With this in mind, first single channel tests are performed using the high speed camera and the microscopic lens. The channel is 1054 $\mu$m wide and 197 $\mu$m deep. The calculated hydraulic diameter of the channel is 333 $\mu$m. The inlet and outlet headers were designed to provide flow through the single channel. In the following figures, image sequences from high speed camera are shown. The visible light and dark regions surround the flow channel. Changes in image capture rate, ambient light, and exposure time may have some affect on the appearance of the channel and its surroundings. Figure 3 shows a local nucleation site, where a bubble starts to grow and subsequently develops into a slug. Note in Fig. 3(a), a bubble is nucleating in the middle of the channel. Figure 3(b), 12ms later, the bubble has grown in size.
Figure 3: Local Nucleation, bubble growth and slug formation. Successive frames (a) through (j) at 12ms interval of a single channel showing local nucleation, bubble growth and slug formation near the channel inlet. G=62 kg/m²s, q=47.25 kW/m², Tₛ=102°C

Figures 3(c) to 3(g) show the gradual increase in the size of the bubble until it blocks the entire width of the channel. Figures 3(h) to 3(k) show the bubble further expanding on both sides and developing to a slug. Figure 3(k), 12ms after Fig. 3(j) shows the movement of the slug in the direction of bulk flow, with change in contact angles with the channel walls. This process of bubble growth, slug formation and slug movement is seen to occur periodically.

Figure 4 illustrates a rapid sequence of bubble nucleation, growth, slug formation and departure. This pattern was observed in the middle along the length of the channel. Figure 4(a), at 0ms shows a nucleation site along one of the side walls, where a bubble nucleates and starts growing. Figures 4(b) and 4(c), which are at 2ms and 4ms later respectively, show the increase in size of the bubble. Figures 4(d) to 4(h) show the bubble expanding to its right but still sticking to the walls of the channel. Figures 4(i) and 4(j), which are at 16ms and 18ms later, show the bubble’s liquid vapor interface getting collapsed and the subsequent departure of the bubble.

Figure 4(k), 20 ms later, shows three more nucleation sites on both side walls of the channel. Further, downstream, there is another bubble growth seen in the upper right side wall of the channel. This bubble follows the same pattern of growth and departure as explained before. The difference between this when compared to Fig. 3 is that the nucleation site is seen along the channel side wall and the slug formation is partial and it does not block the entire channel.

Dryout is represented in Fig. 5. For the flow pattern shown, the liquid film is reduced until the channel wall is dry and only vapor flows in the channel. Figures 5(a) to 5(n) are at equal time intervals of 5ms. This flow pattern was not seen as a stable one and occurs only intermittently. Figures 5(a) to 5(c) show the channel filled with liquid. The vapor flow is seen in Fig 5(d) and it’s more enhanced as seen from the subsequent frames. A close look into the figures from 5(d) to 5(m) show that the vapor flow does not fill up the entire width of the channel and there is a thin film of liquid trapped at the edges of the channel. This vapor flow is seen continues until the channel again gets rewetted by a liquid front entering the channel as seen in Fig. 5(m).

In Fig. 5(n) the channel is filled up with all liquid flow. An important thing to note is that the flow patterns in minichannel are not stable, they fluctuate periodically from all liquid flow to slug flow, annular flow and dryout region. It is not possible to assign a single flow pattern for a given set of flow and heat flux conditions.

Reverse flow or flow reversal is seen in Fig. 6. The bulk flow in the channel is from left to right. Figure 6(a) at 0ms, shows the channel filled with liquid. Figure 6(b), 2ms late shows the appearance of an annular slug to the right of the channel. Figures 6(c), (d) and (e), which are at 4ms, 6ms and 8ms respectively, show the movement of the slug form right to left, which is opposite to the direction of bulk flow in the channel.
Figure 5: Successive frames (a) through (n) at 5ms interval of single channel showing dryout and rewetting. 

G=81 Kg/m²s, q=54.69 KW/m², Tₛ=101°C

In Fig. 6(f), 10ms later the slug stops moving backward and 12ms later, as seen in Fig. 6(g), the slug now changes its direction and starts moving from left to right, which is along the direction of bulk fluid flow. Figures 6(h) to (k) show the slug moving in the same direction and in Fig. 6(l) the slug passes away and the channel is again filled with liquid.

By this observation, the occurrence of the reverse flow in a single channel is also seen to occur, although it does not extend all the way to the inlet manifold under the range of conditions investigated here.

Figure 7 illustrates the two-phase flow near the exit manifold. The top view of the exit manifold is seen on the right end of each frame. Figures 7(a) to (j) are at equal time intervals of 2ms. Figure 7(a) shows the vapor filling up the entire length of the channel leading to the exit manifold. Figure 7(b), 2ms later, shows a shift in the liquid vapor interface, which straightens out later in Fig. 7(c) again filling the entire channel.

This change in the interface is observed to occur periodically as seen from Figs. 7(d) to (j). In Figs. 7(g) and 7(h), this shift in interface is more pronounced and the slug, which fills the entire channel to the left, thins out in to a thin film as it approaches the exit manifold. The flow rate and heat flux for this figure are higher than those for the earlier observations. This leads to a somewhat uniform flow pattern near the exit manifold. For the lower mass flux and heat flux cases, the flow pattern changed periodically at the exit manifold, cyclically changing from very short all liquid flow to almost all vapor flow.

Figure 6: Flow reversal, Successive frames (a) through (l) at 2ms interval of single channel showing flow reversal. G=106 Kg/m²s, q= 85.40 KW/m², Tₛ=101.43°C

Figure 7: Annular two-phase flow near the exit manifold, Successive frames (a) through (j) at 2ms time interval of single channel showing two phase flow at the exit manifold. G=106 Kg/m²s, q= 85.40 KW/m², Tₛ=101.43°C.
Steinke and Kandlikar [11] presented flow visualization in a set of six parallel microchannels of 214 µm x 200 µm square cross section. The calculated hydraulic diameter is 207 µm. In their work, they observed bubbly flow, slug flow, churn flow, annular flow and dryout. Figures 8 to 11 show the bubbly flow, churn flow, reversed flow, and dryout in a 207 µm hydraulic diameter square parallel microchannels. In all these figures, the bulk flow is from left to right. The small bubbles seen in Fig. 8 appear to be attached to the wall as well as free floating in some frames. The bubble sizes are seen to be from 15 µm to the entire channel width. These bubbles move at different velocities, which depend upon their sizes. The smaller bubbles stay close to the wall and the wall influences their behavior. The larger bubbles have diameters comparable to the width of the channel and their behavior is also largely influenced by the friction and the drag of the wall. This flow pattern was not seen in the wide rectangular channel shown in Figs. 4 to 7. The reason for this is perhaps the bubbles are entrapped at the corners of the long aspect ratio microchannel, and tend to coalesce there into a larger bubble that fills the side of the channel as seen in Fig. 4.

Figure 9 shows the occurrence of Churn flow. Figure 9(a) shows an annular flow. Figure 9(b) shows a wavy interface of vapor and liquid. The liquid is on the top side of the channel and the vapor occupies the bottom side of the channel. The wavy interface is seen through the entire length of the channel. Figure 9(d) shows the channel getting rewetted again with liquid. For the conditions studied for the single channel earlier, no churn flow was observed. The rapid movement of the interface in the square confined channel during bubble growth is not present in the large aspect ratio minichannel. The effect of aspect ratio is thus clearly seen in some of the flow patterns.

Figure 10 illustrates the occurrence of reversed flow. This is very similar to what is seen in Fig. 6 for a single channel. Figure 10(a) shows a bubble, which nucleates in the center of the channel. Figure 10(b) shows the bubble expanding to its right into a slug. Figure 10(C) shows the slug moving opposite to the direction of bulk flow. Figure 10(g) shows again a shift in the direction of slug and as seen in Fig. 10(h) it is again moving in the direction of bulk flow. A notable difference is that in a single channel, the reversed flow is rather mild, with the liquid-vapor interface retracting only a short distance, while in the case of parallel channels, the reversed flow is rather dramatic and in some cases, the flow of vapor is reversed into the inlet manifold.
Figure 11: Annular to CHF, Successive frames (a) to (o) at a time interval of 4ms showing Annular to CHF in a single channel from a set of six parallel microchannels. G = 375 kg/m²s, q = 632 kW/m²

Figure 11(a) shows the channel in dryout condition. Figure 11(b) shows an annular slug moving in the direction of bulk flow. The annular slug has a head of liquid as a front cap. An advancing contact angle is seen from Fig. 11 (b) to Fig. 11 (d). In Fig 11(e) the contact angle changes from advancing to receding contact angle. In case of a single channel, the dryout observed was extremely rapid, as seen in Fig. 5. The liquid vapor interface and the contact angles could not be established. However, the phenomenon of dryout is seen to occur in both cases. In the case of a single channel, the rewetting occurs more rapidly as the liquid is forced to flow in the channel, whereas in the case of the parallel channels, the liquid finds a lower resistance path through other parallel channels that are not experiencing the dryout condition.

COMPARISON BETWEEN SINGLE CHANNEL AND MULTIPLE PARALLEL CHANNEL FLOW PATTERNS

The following flow patterns were observed in a single 333 µm rectangular minichannel: Nucleate boiling, slug formation, Dryout, Reverse flow and Two phase flow at the exit manifold. The visual observation for the single channel can be summarized as follows:

- The process of bubble nucleation and its subsequent expansion into a slug is observed with changes in the contact angle.
- The rapid process of bubble nucleation, departure and partial slug formation is also observed with disturbance in the liquid vapor interface.
- The occurrence of channel dryout and rewetting is observed. This pattern was not seen as a stable one; it is seen to occur intermittently with almost a fixed periodicity to it.
- The occurrence of the reversed flow in a single channel is also seen, although it does not extend all the way to the inlet manifold.
- Two-phase flow at the exit manifold is observed with continuous change in the liquid film thickness in response to the upflow changes occurring in the channel.

The following flow patterns were observed in a set of six parallel 207 µm rectangular microchannels: Bubbly flow, Churn flow, Counter flow and Annular to CHF. The visual observation for the multiple channel can be summarized as follows:

- Bubbly flow is observed with different sizes of bubbles, ranging from 10 – 200 µm in size with varying velocities.
- As some of the attached bubbles grew, they transformed into a large bubble (slug) that pushes the liquid-vapor interface in both upstream and downstream directions.
- Churn flow is observed with a rapid change in the liquid vapor interface. During churn flow, the vapor occupies the upper side of the channel and the liquid occupies the lower side of channel.
- Flow reversal in multi-channels is also observed similar to its occurrence in single channel.
- Dryout is observed during change of annular flow to dryout. The advancing and receding contact angles are clearly seen.

Comparing the flow patterns in a single minichannel with the array of six parallel square microchannels, the following observations are made:

- Bubbly flow appears in a square channel, while in the large aspect ratio channel, it leads to a bubble that is attached at the corners of the channel allowing liquid to flow around it.
- The reversed flow in a set of parallel microchannels was seen to be more pronounced, while in a single channel, the inlet liquid did not allow the reversed flow to continue into the inlet header.
- Churn flow was not observed in the large aspect ratio channel. This is believed to be a combination of channel size and aspect ratio effects.
Dryout and rewetting phenomena occur vary rapidly in a single channel, whereas in the parallel channels, other channels not experiencing the dryout condition, allow for more liquid to flow through them. It is therefore expected that the CHF value in a single channel would be higher than that in the parallel channels under the same conditions of mass flux and geometry.

CONCLUSION

Experimental investigation is conducted to study the flow patterns observed in a single minichannel of hydraulic diameter 333 μm and the results are compared with the flow patterns observed in a set of six parallel microchannels of hydraulic diameter 207 μm. The effect of varying the channel height has been studied as a function of heat flux, mass flux and location along the channel flow length. Specific features of single channel flow and multichannel flow, and the differences between the two flow characteristics have been identified. Future work will involve a detailed study of channel interaction by comparing the flow patterns between single and parallel channels of same hydraulic diameter.

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REFERENCES


