CRITICAL HEAT FLUX MEASUREMENT AND MODEL FOR REFRIGERANT-123 UNDER STABILIZED FLOW CONDITIONS IN MICROCHANNELS

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ABSTRACT

The present work is aimed toward understanding the effect of flow boiling stability on critical heat flux (CHF) with Refrigerant-123 (R-123) in microchannel passages. Experimental data and theoretical model to predict the CHF are the focus of this work. The experimental test section has six parallel microchannels with each having a cross sectional area of $1054 \times 157 \mu m^2$. The effect of flow instabilities in microchannels is investigated using flow restrictors at the inlet of each microchannel to stabilize the flow boiling process and avoid the backflow phenomena. This technique resulted in successfully stabilizing the flow boiling process as seen through a high-speed camera. The present CHF result is found to correlate to mean absolute error (MAE) of 24.1% with a macro-scale empirical equation by Katto [13]. A theoretical analysis of flow boiling phenomena revealed that the ratio of evaporation momentum to surface tension forces is an important parameter. For the first time, a theoretical CHF model is proposed using these underlying forces to represent CHF mechanism in microchannels, and its correlation agrees with the experimental data with MAE of 2.5%.

INTRODUCTION

Advancements in microprocessors and other high power electronics have resulted in increased heat dissipation from those devices. In addition, to reduce cost, the functionality of microprocessor per unit area has been increasing. The increase in functionality accompanied by reduction in chip size has caused its thermal management to be challenging. In order to dissipate the increase in heat generation, the size of conventional fin-type heat sinks has to be increased. As a result, the performance of these high heat flux generating electronics is often limited by the available cooling technology and space to accommodate the larger conventional air-cooled heat sinks.

One way to enhance heat transfer from electronics without sacrificing its performance is the use of heat sink with many microchannels and liquid water passing through it. Because of the small size of microchannel heat sink, the performance of a computer system can also be increased by incorporating more microprocessors at a given space without the issue of overheated or burned-out chips. Flow boiling in microchannels is being studied worldwide because of its potential in high heat flux cooling. Comparing to single-phase flow, flow boiling is advantageous because it utilizes the heat of vaporization of a working fluid. Because of that, given a mass flow rate, the heat flux in flow boiling is much higher than that of single phase. In addition, flow boiling in microchannel heat sink can provide approximately uniform fluid and solid temperatures, and it can also be directly coupled with a refrigerant system to provide a lower coolant temperature.

In designing a two-phase microchannel heat sink, it is necessary to know its critical heat flux (CHF). This is because CHF determines the upper thermal limit on the microchannel operation, and the rapid rise in operating temperature after CHF is detrimental to electronics. That is why CHF data and a good understanding of CHF in microchannels are needed before the application of two-phase microchannel heat sink can be implemented. Furthermore, very few experimental CHF data have been reported in microchannels. Hence, the objective of the present work is to experimentally investigate the CHF of saturated flow boiling in microchannels using R-123 as the working fluid.
The present experiment involves the collecting of CHF data over the ranges of mass flux and heat flux supplied to the microchannels. For the first time, a theoretical CHF model is proposed using these underlying forces to represent CHF mechanism in microchannels. The predicted results from the model are then compared to the present experimental CHF data. Similarly, the CHF model is also used to predict Qu and Mudawar’s [1] water CHF data, and the predicted results are compared to their experimental CHF data. In their experiment, Qu and Mudawar obtained the CHF data using 21 parallel channels with each channel having a cross-sectional area of 215 × 821 µm². The operating conditions from Qu and Mudawar’s and present experiments can be found in Table 1.

Table 1 Operating conditions

<table>
<thead>
<tr>
<th>CHF Data by Fluid</th>
<th>Operating conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>G (kg/m²s)</td>
<td>86-368;</td>
</tr>
<tr>
<td>q” (kW/m²)</td>
<td>264.2-542.0;</td>
</tr>
<tr>
<td>x</td>
<td>0-0.56;</td>
</tr>
<tr>
<td>T_in (°C)</td>
<td>30;</td>
</tr>
<tr>
<td>P_in (kPa)</td>
<td>121.3-139.8;</td>
</tr>
<tr>
<td>R-123</td>
<td></td>
</tr>
<tr>
<td>G (kg/m²s)</td>
<td>410.5-533.8;</td>
</tr>
<tr>
<td>q” (kW/m²)</td>
<td>136.3-201.3;</td>
</tr>
<tr>
<td>x</td>
<td>0.79-0.93;</td>
</tr>
<tr>
<td>T_in (°C)</td>
<td>17.2;</td>
</tr>
<tr>
<td>P_in (kPa)</td>
<td>162.8-248.3;</td>
</tr>
</tbody>
</table>

LITERATURE REVIEW

Because of the limited number of investigations on CHF in microchannels, experimental studies related to both minichannels and microchannels will be reviewed. Minichannels cover the range from 200 µm to 3 mm channel diameter.

Bowers et al. [2] experimentally studied CHF in circular channels with diameters of 2.54 mm and 0.510 mm using R-113 as the working liquid. The heated length of the channels is 10 mm. In their experiment, CHF is found to be independent of the inlet subcooling at low flow rates due to fluid reaching the saturation temperature in a short distance into the heated channels.

Roach et al. [3] used uniformly heated channels to experimentally investigate CHF. The four different channels, all 160 mm in length, are: two circular with 1.17 mm and 1.45 mm diameter, and two other flow channels in microrod bundle with a triangular array and 1.131 mm hydraulic diameter. One of the microrod bundles is uniformly heated over its entire surface and the other is heated only over the surfaces of the surrounding rods. The authors found that the CHF occurs at high flow quality of 0.36 and higher, indicating dry-out as the CHF mechanism. In addition, the CHF increases with increasing mass flux and pressure, and depend on channel diameter.
Table 2  Summary of studies on CHF in small channels

<table>
<thead>
<tr>
<th>Author/ year</th>
<th>Fluid</th>
<th>Operating conditions</th>
<th>Channel geometry (mm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bowers and Mudawar</td>
<td>R-113</td>
<td>$G = 10-490; \quad q'' = 200-2000; \quad x = 0-1$</td>
<td>Circular, multi-channels, $d = 2.54$ and $0.51$, horizontal</td>
<td>Higher CHF can be obtained in microchannels, and presented correlation for CHF.</td>
</tr>
<tr>
<td>Roach et al.</td>
<td>Water</td>
<td>$G = 250-1000; \quad q'' = 860-3698; \quad x = 0.36-1.2; \quad T_{in} = 49 \text{ to } 72.5; \quad P_{in} = 407-1204$</td>
<td>Circular, $d = 1.17$ and $1.45$; microrod bundle with a triangular array, Hydraulic diameter = 1.131, vertical</td>
<td>CHF occurs at high flow quality between 0.36 and higher, indicates dry-out; CHF increase with increasing mass flux or pressure, and depends on channel diameter.</td>
</tr>
<tr>
<td>Jiang et al.</td>
<td>Water</td>
<td>$P = 50-320$</td>
<td>V-grooved, Hydraulic diameter = 0.04 and 0.08, horizontal</td>
<td>CHF condition depends on the flow rate and the channel size.</td>
</tr>
<tr>
<td>Yu et al.</td>
<td>Water</td>
<td>$G = 50-200; \quad q'' = 20-320; \quad x = 0.5-1.0; \quad T_{in} = \text{ambient to } 80; \quad P_{in} = 200$</td>
<td>Circular, $d = 2.98$, horizontal</td>
<td>CHF occurs at high quality between 0.5-1.0; CHF quality decrease with decreased mass flux.</td>
</tr>
<tr>
<td>Qu and Mudawar</td>
<td>Water</td>
<td>$G = 86-368; \quad q'' = 264.2-542.0; \quad x = 0-0.562; \quad T_{in} = 30 \text{ and } 60; \quad P_{in} = 121.3-139.8$</td>
<td>Rectangular, $0.215 \times 0.821$, 21 parallel channels, horizontal</td>
<td>Flow instability greatly amplified nearing CHF; CHF increases with mass flux; A new CHF correlation is proposed.</td>
</tr>
<tr>
<td>Koşar et al.</td>
<td>Water</td>
<td>$G = 41, 83, 166 \text{ and } 302; \quad q'' = 280-4450; \quad x = 0-0.9; \quad \Delta P = 0.4, 0.8, 1.7 \text{ and } 3.0.$</td>
<td>Rectangular, Hydraulic diameter = 0.223, 5 parallel channels, horizontal</td>
<td>CHF increases with mass flux and decreases with exit quality; CHF data correlated well with conventional correlation; A new CHF correlation is proposed.</td>
</tr>
</tbody>
</table>

Jiang et al. [4] investigated the CHF condition in diamond-shaped channels with hydraulic diameter ranging from 0.04 mm to 0.08 mm using water as the working fluid. The authors suggest that the evolution of the phase change from liquid to vapor in microchannels is different from conventional channels. They found that the CHF condition depends on the flow rate and the channel size. The authors speculated that in such small channels, bubble formation may be suppressed and recommended flow visualization studies to determine the governing heat transfer mechanism.

Yu et al. [5] found that CHF occurs at high flow quality between 0.5 and 1.0 for water, and such qualities are higher than those found in larger diameter tubes at higher pressures and mass fluxes. The CHF quality was found to decrease with decreasing mass flux, and this trend is opposite to the one found in larger tubes. Their experiments were performed using a horizontal tube with 2.98 mm inside diameter and 910 mm heated length.

Qu and Mudawar [1] measured CHF for a water-cooled heat sink containing 21 parallel 0.215 mm x 0.821 mm channels. The authors found that flow reversal caused by flow instabilities have resulted in a CHF independent of inlet temperature but which increases with increasing mass velocity. Koşar et al. [6] found that CHF increases with mass flux and decreases with vapor mass fraction at the exit.

The summary of the above literature review can be found in Table 2.

**EXPERIMENTAL FACILITY**

The experimental setup developed by Kuan and Kandlikar [7] is used in the present work. The experimental setup is designed to provide R-123 at a constant flow rate and temperature to the test section.

The inputs to the test section are the working fluid (R-123) and the converted heat energy from the supplied electric current. The outputs from the test section are the heated working fluid and the heat loss from the test section.
Test Section Design

Microchannels are fabricated on a copper 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/mK at 20°C. An optically clear glass (fused silica) is then placed on top of the copper block to serve as a transparent cover through which flow patterns can be observed. The glass cover has a thermal conductivity of 1.3 W/m·K. Figure 1 shows a schematic of the copper block with the glass cover. The resistive cartridge heater provides a uniform heat flux to the copper block. The length and width of the copper block are 88.9 mm × 29.6 mm. The thickness of the copper block and the glass cover are 19.1 mm and 12.3 mm respectively. The cross section of each of the microchannels measures 1.054 mm × 0.157 mm, and their edge to edge spacing is 0.589 mm. The length of each microchannel is 63.5 mm. There are a total of six microchannels on the copper block. The glass cover is being held onto the copper block by ten mounting screws, and the force provided by the screws and a thin layer of vacuum grease are enough to seal the microchannels from the ambient environment. The assembled test section is shown in Fig. 2. The mounting screws are secured onto the phenolic plate that is placed on the bottom of the copper block. The phenolic plate also acts as an insulating layer on the bottom surface of the copper block. It has the same length and width as the copper block, but its thickness is 12.7 mm. It is a laminate of paper and has a thermal conductivity of 0.2 W/m·K. The copper block is cleaned in an ultrasonic bath using water before it is assembled with the glass cover and the phenolic plate.

Two layers of six thermocouples each are placed into the sides of the copper block along the length of the microchannels. The thermocouple layers are 3.18 mm apart from each other, and the top layer is placed at 3.18 mm below the top surface of the microchannels. The thermocouples are inserted into the copper block until it reaches half the width of the copper block. The thermocouple layers are inserted into the copper block from the opposite directions. The thermocouples from both layers are placed at the same locations along the length of the microchannels. The locations, as measured from the inlet of the microchannels and along the its length are 6.35 mm, 19.05 mm, 25.40 mm, 38.10 mm, 44.45 mm, and 57.15 mm [8].

To reduce heat transfer in the manifold, the inlet manifold is machined into the glass cover and the working fluid is delivered at the very beginning of the microchannels as shown in Fig. 3. Only the pressure drop across the inlet and outlet manifolds is measured because the actual pressure drop in the microchannels could not be easily measured.
A new flow boiling CHF model will be developed based on the forces shown in Fig. 4.

Based on the earlier CHF model on pool boiling by Kandlikar [9, 10], the surface tension force per unit length is given by

\[ F_s' = \sigma \cos \theta \]  

(1)

In a nucleating bubble, the difference in the density of the two phases causes the vapor phase to leave the liquid-vapor interface at a much higher velocity than the corresponding liquid velocity toward the receding interface. The change in momentum as result of evaporation introduces a force at the interface [9, 10]. The magnitude of this force is the highest near the heater surface because of the higher evaporation rate in the contact line region near the heater surface. The equation for force per unit length due to momentum change is given by

\[ F_m' = \frac{q^* D q^*}{h_{h_f} h_{l_f} \rho_g} = \left( \frac{q^*}{h_{h_f}} \right)^2 \frac{D}{\rho_g} \]  

(2)

where \( D \) is the characteristic dimension.

The stress resulting from inertia force is given by \( \rho V^2 \).

The force per unit length due to inertia is given by

\[ F_i' = \frac{1}{2} \rho \frac{Q^2}{D} = \frac{G^2 D}{2 \rho} \]  

(3)

The forces shown in Fig. 4 are used in the development of a new flow boiling CHF model. In the new CHF model, the forces are considered in per unit channel width as shown in Eqs. (4) to (6).

\[ F_s = 1 \cdot \sigma \cos \theta \]  

(4)

\[ F_m = \frac{q^* b q^*}{h_{h_f} h_{l_f} \rho_g} = \left( \frac{q^*}{h_{h_f}} \right)^2 \frac{b}{\rho_g} \]  

(5)

\[ F_i = \frac{1}{2} \rho \frac{Q^2}{b} = \frac{G^2 b}{2 \bar{\rho}} \]  

(6)

where \( b \) is the channel height, and \( \bar{\rho} \) is the average density given by Eq. (7). Note that the channel height is used instead of \( D \) in Eq. (5) since the CHF occurs on the lower wall and the channel height \( b \) is the relevant dimension at a particular section. The heat flux \( q^* \) is based on the liquid vapor interfacial area.

\[ \frac{1}{\bar{\rho}} = \frac{x}{\rho_s} + \frac{1-x}{\rho_f} \]  

(7)

The \( x \) in Eq. (7) is the thermodynamic quality at the microchannel exit because CHF has been observed to occur at the exit end of the microchannels. The range of \( x \) in the present CHF model is from 0 to 1.

A new flow boiling CHF model is developed based on a force balance as shown in Eq. (8), which uses the forces as shown in Fig. 4.

\[ F_M = F_s + F_i \]  

(8)

Substituting Eqs. (4), (5) and (6) into (8), we get Eq. (9).

\[ q^* = h_{h_f} \sqrt{\rho_s} \left( \frac{2 \sigma \cos \theta}{b} + \frac{G^2}{2 \bar{\rho}} \right) \]  

(9)

The interfacial-area-based \( q^* \) in the above equation is related to the CHF based on the channel wall. Since this relation is not explicitly known, a constant \( C \) is introduced to express the CHF based on the channel-wall surface area. The new flow boiling critical heat flux model is shown in Eq. (10) with the constant \( C \) introduced into Eq. (9).

\[ q^*_{\text{CHF}} = C h_{h_f} \sqrt{\rho_s} \left( \frac{2 \sigma \cos \theta + G^2}{b} \right) \]  

(10)

This new CHF model will be used to predict flow boiling CHF. The single constant \( C \) will be determined from the experimental
data. Because of the complex liquid-vapor behavior at the interface, especially near the CHF condition, it is not possible at this stage to develop models to predict the constant $C$. It is expected that with the availability of large number of data sets for different fluids, and with advanced numerical simulation of the interface, further insight will be obtained on the nature of the constant $C$ in the future. The predicted CHF results will be compared to experimental CHF results. The receding contact angles, $\theta$, for water/copper and R-123/copper systems are 45° and 5°, respectively [10].

**EXPERIMENTAL PROCEDURE**

The Micropump drives the flow of the R-123 through a 5 $\mu$m filter before it goes through the Coriolis flowmeter. A heat exchanger in conjunction with a coolant bath [7] maintains the temperature of the R-123 delivered to the test section at a set value. The R-123 then enters the test section via the inlet manifold.

Heat loss calibration is performed on the test section after it is well insulated. The calibration is performed without working fluid in the test section. Using the resistive cartridge heater, electric power is supplied to the test section. The test section is then allowed eight hours to reach steady state. 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 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.

R-123 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 Coriolis flowmeter is calibrated and is used to set the flow for the test section. The calibration is performed by recording the output signals in volt from the Coriolis flowmeter at specific mass flow rates. The mass flow rates are then plotted against the flowmeter output signals. Based on the plot, a linearly fitted equation is then obtained. LabView software is used as the data acquisition system and is used to monitor temperatures of all of the thermocouples, pressure transducers and the Coriolis flowmeter. The software is also used to control the flowrate of the working fluid by controlling the speed of the Micropump. The heated R-123 coming out from the test section is cooled by a heat exchanger that acts as a condenser when used in conjunction with a coolant bath [7].

**UNCERTAINTY**

The uncertainty in the hydraulic diameter is estimated to be ± 1.4%. The accuracies of the digital signals are reported as: Voltage = ± 0.005 V, $T$ = ± 0.1 °C, Pressure transducer accuracy = ± 1.724 kPa. The flow meter has a volumetric flow accuracy of ± 0.1% of flowrate. 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 experimental heat loss plot. 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 [11]. The critical heat flux uncertainty is estimated to be less than 9.69%.

**RESULTS**

CHF experiments are conducted using the test section as shown in Fig. 2. The test section has six parallel microchannels and each microchannel has a cross sectional area of 1054 × 157 $\mu$m², and the operating conditions are stated in Table 1.

The effect of pressure drop elements (PDEs) on CHF is presented in this section. All tests in this section are conducted with microchannels in the horizontal orientation with R-123 as the working liquid.

The results from the case without PDEs are compared to those with 7.7% PDEs at the inlet of each channel. The latter case uses a manifold which incorporates inlet openings of 127 $\mu$m diameter at the inlet to each channel, giving an open area that is 7.7% of the cross sectional area of a 1054 × 157 $\mu$m² microchannel. These pressure restrictors are expected to reduce the backflow by forcing an expanding vapor bubble in the downstream direction and not allowing the liquid-vapor mixture to enter the inlet manifold.

CHF has been observed to occur at the exit end of the microchannels for all runs conducted using R-123 as the working liquid. The heater power is increased in steps of 1 to 2 W increments and the temperatures in the copper blocks are monitored. As the CHF is reached, the temperature of the last thermocouple near the exit end experiences a gradual temperature rise of around 0.5 °C per minute due to the thermal mass of the assembly. To prevent damage to the test section assembly, the heaters are shut off when the highest temperature in the block (near the exit end) reached 100 °C. The temperature then overshoots by a few degrees before cooling down after shutting off the power. Again, thermocouple 6 (TC 6) is leading the temperature rise during CHF condition, thus indicating that the microchannel exit is where CHF first began.

After the CHF has been reached, the temperatures at all locations in the copper block start to go up, indicating that the CHF location was gradually moving upstream. Since the heater
power was fixed, the local heat flux increased in the microchannels upstream, following the CHF condition toward the exit.

Figure 5 shows the present critical heat flux data with and without the 7.7% PDEs in manifold plotted against Weber number. As shown in the figure, CHF increases with Weber number. This indicates that as the mass flux increased, the CHF increased as one might expect.

Table 3 CHF correlation results for R-123

<table>
<thead>
<tr>
<th>Reference</th>
<th>Recommended channel geometry and size</th>
<th>MAE</th>
<th></th>
<th>with 7.7% PDEs</th>
<th>without 7.7% PDEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bowring [12]</td>
<td>Circular, conventional channels</td>
<td>i)</td>
<td>66.2%</td>
<td>ii) 68.8%</td>
<td></td>
</tr>
<tr>
<td>Katto [13]</td>
<td>Rectangular, conventional channels</td>
<td>i)</td>
<td>29.4%</td>
<td>ii) 38.5%</td>
<td></td>
</tr>
<tr>
<td>Qu and Mudawar [1]</td>
<td>Rectangular, (d_h = 0.38-2.54) mm</td>
<td>i)</td>
<td>519.4%</td>
<td>ii) 450.7%</td>
<td></td>
</tr>
</tbody>
</table>

Present CHF data are compared to the correlations reported by previous researchers [12, 13, 1], and the results can be found in Table 3. The predicted CHF values are plotted against the experimental values in Figs. 6 to 8. The experimental results with and without the 7.7% PDEs in manifold are compared to the CHF correlations by Bowring [12], Katto [13], and Qu and Mudawar [1] as shown in Figs. 6, 7, and 8, respectively. The Experimental results with and without the 7.7% PDEs in manifold are compared to predicted results from various correlations using the Mean Absolute Error method as shown in Eq. (11).

\[
MAE = \frac{1}{M} \sum \left| \frac{q_{\text{CHF,exp}} - q_{\text{CHF,pred}}}{q_{\text{CHF,exp}}} \right| \times 100\%
\] (11)

The macro-scale equation by Katto [13] for rectangular channels has an overall MAE of 33.9%. For a rectangular channel, this equation has the lowest MAE.

Figure 5 CHF data from present experiment with and without the 7.7% PDEs in manifold plotted against Weber number, R-123.

Figure 6 Present CHF data with and without the 7.7% PDEs in manifold compared to the correlation by Bowring [12], R-123.
The present water CHF data and those reported by Qu and Mudawar [1] are compared to the predicted results using the new CHF model, Eq. (10), from the Modeling CHF section.

\[
q_{\text{CHF}}^* = \frac{Ch_{fr} \sqrt{\rho_c}}{b} \left( \frac{2 \sigma \cos \theta + G^2}{2 \rho_c} \right)
\]

The present R-123 CHF data are also compared to the predicted results using Eq. (10). A common value of \( C \) is used to predict CHF for both R-123 and water, and their respective MAEs are reported. In addition to that, a different \( C \) value for each R-123 and water will be used, which allow the model to correlate better to each R-123 and water data. Table 4 shows the summary of comparing the experimental CHF data to the predicted CHF results using the CHF model by Kandlikar and Kuan, Eq. (10).

<table>
<thead>
<tr>
<th>CHF data by Working Fluid</th>
<th>C in the new CHF model</th>
<th>Microchannel geometry, ( w \times b ); number of channels</th>
<th>MAE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using single value for ( C )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qu and Mudawar [1] Water 0.002679 215 × 821 ( \mu m^2 ); 21 parallel 13.0</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>present work R-123 0.002679 1054 × 157 ( \mu m^2 ); 6 parallel 16.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Using individually optimized values of ( C )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qu and Mudawar [1] Water 0.002492 215 × 821 ( \mu m^2 ); 21 parallel 6.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>present work R-123 0.003139 1054 × 157 ( \mu m^2 ); 6 parallel 2.5</td>
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</tbody>
</table>

CHF correlation (common \( C = 0.002679 \) for both water and R-123)

Qu and Mudawar’s [1] CHF data are compared to the present Kandlikar and Kuan CHF model. Figure 9 shows the experimental and predicted CHF plotted against Weber number. Using the \( C \) value of 0.002679, the correlation agrees with the experimental data with the MAE of 13.0%.
Figure 9 Qu and Mudawar [1] CHF data compared to the present Kandlikar and Kuan CHF model, Eq. (10), plotted against Weber number, $C = 0.002679$, water.

Figure 10 shows the experimental and predicted CHF plotted against Weber number. Using the $C$ value of 0.002679, the correlation agrees with the experimental data with the MAE of 16.3%.

Figure 11 shows the experimental and predicted CHF plotted against Weber number. Using the individually optimized $C$ value of 0.002492, the correlation agrees with the experimental with the MAE of 6.8%.

Comparing the experimental CHF data to the model prediction, the ability of the model to predict the CHF for R-123 and water with a remarkable accuracy is extremely encouraging. It indicates that the underlying mechanisms are well represented through the forces employed in the model development. A larger data set with different channel sizes, fluids and wider ranges of operating condition will be helpful in refining this model further in the future work.
CONCLUSIONS

Experiments are conducted to obtain the CHF data for R-123 in microchannels. The present CHF result is found to correlate to overall MAE of 33.9% with R-123 when using a macro-scale rectangular equation by Katto [13]. The results of the present work are summarized in the following. A theoretical analysis of flow boiling phenomena revealed that the ratio of evaporation momentum to surface tension forces is an important parameter. A new model is proposed using this parameter and the inertia force to represent the CHF mechanism in microchannels. The theoretical model agrees with the experimental data with MAEs of 16.4% and 13.0% for R-123 (from present CHF experiment) and water (from Qu and Mudawar’s [1] data), respectively, when using a single value of 0.002679 for $C$. Using individually optimized $C$ values for each fluid, the MAEs are 2.5% and 6.8% for R-123 and water, respectively. The new theoretical model is able to predict correct parametric trends. CHF is found to increase with increasing mass flux.

- CHF data is slightly lower when using the 7.7% PDEs.
- PDEs help in flow stabilization, but the CHF is somewhat reduced. The ability of the restrictors to reduce localized dryout is however more important and therefore PDEs are still recommended for use in the operating range as shown in Table 1.
- CHF is found to increase with increasing Weber number, which indicates that as the mass flux increased, the CHF increased.
- The trends in CHF with mass flux and quality are similar to those obtained by earlier investigators.
- The present experimental CHF results are found to correlate with an overall MAE of 33.9% with the macro-scale equation by Katto [13] for rectangular channels.
- A new theoretical model is developed to predict flow boiling CHF in microchannels. The Kandlikar and Kuan CHF model is developed based on the surface tension, evaporation momentum and inertia forces.
- The theoretical model is found to represent the trend accurately for the flow boiling CHF in microchannels. The correlation based on this model is compared against present experimental R-123 CHF data, and the water CHF data reported by an earlier investigator shown in Table 4.
- The new model is able to correlate with present experimental R-123 CHF data to MAEs of 16.4%, when using a single constant $C$ value of 0.002679. The best correlation seen is with the individually optimized $C$ value of 0.003139 for R-123, which has an MAE of 2.5%. Comparing the experimental CHF data and the model prediction, this CHF model is able to predict CHF to an impressive accuracy.
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