Experimental Study and Model on Critical Heat Flux of Refrigerant-123 and Water in Microchannels

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The present work is aimed toward understanding the effect of flow boiling stability on critical heat flux (CHF) with Refrigerant 123 (R-123) and water in microchannel passages. Experimental data and theoretical model to predict the CHF are the focus of this work. The experimental text section has six parallel microchannels, with each having a cross-sectional area of 1054 × 157 μm². 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. The present experimental CHF results are found to correlate best with existing correlations to overall mean absolute errors (MAEs) of 33.9% and 14.3% with R-123 and water, respectively, when using a macroscale rectangular equation by Katto (1981, “General Features of CHF of Forced Convection Boiling in Uniformly Heated Rectangular Channels,” Int. J. Heat Mass Transfer, 24, pp. 1413–1419). A theoretical analysis of flow boiling phenomena revealed that the ratio of evaporation momentum to surface tension forces is an important parameter. 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%.

Keywords: critical heat flux, modeling critical heat flux, boiling, channel flow, heat transfer, microscale, two phase

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 increased 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 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. Compared to a 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 a 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 and water as the working fluids. The present experiment involves the collection of CHF data over the ranges of mass flux and heat flux supplied to the microchannels.

A theoretical analysis of flow boiling phenomena revealed that the ratio of evaporation momentum to surface tension forces is an important parameter. 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 experiments and the present experiments can be found in Table 1.

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 and Mudawar [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 dryout as the CHF mechanism. In addition, the CHF increases with increasing mass flux and pressure, and depends on channel diameter.
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 suggested 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 they 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 × 0.821 mm² channels. The authors found that flow reversal caused by flow instabilities has resulted in a CHF independent of inlet temperature but which increases with increasing mass velocity. Kosar et al. [6] and Wojtan et al. [7] found that CHF increases with mass flux and decreases with vapor mass fraction at the exit.

### Experimental Facility and Experimental Procedure

The experimental setup and experimental procedure developed by Kuan and Kandlikar [8,9] are 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 experimental facility for water can be found in an earlier paper by Kuan and Kandlikar [10]. A common test section is used for both the R-123 and water experiments.

### Modeling Critical Heat Flux

A new flow boiling CHF model is developed based on the forces shown in Fig. 1. The earlier CHF model by Kandlikar [11,12] for pool boiling CHF considered the forces per unit width of the contact line. The same concept is extended here to flow boiling by including additional forces due to fluid flow. The surface tension force per unit length is given by

\[ F_s = 

\]

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 [11,12]. 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

\[ F_M = \frac{q'' D^2}{h_f \rho g} \left( \frac{q'' b}{h_f} \right)^2 \frac{D}{\rho g} \]

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

\[ F_I = \frac{1}{2} \rho V^2 b = \frac{1}{2} \frac{G^2 b}{\bar{\rho}} \]

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,

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

The \( x \) in Eq. (7) is the thermodynamic quality at the microchannel exit because CHF has been observed to occur first 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. 1.

\[ F_s = 2F_s + F_I \]

Substituting Eqs. (4)–(6) into Eq. (8), we get

\[ q'' = \frac{h_f \rho_g}{2 \pi \cos \theta} \left( \frac{2x \cos \theta}{b} + \frac{G^2}{2 \bar{\rho}} \right) \]

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 CHF model is shown in Eq. (10) with the constant \( C \) introduced into Eq. (9).

### Table 1 Operating conditions

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>Fluid</th>
<th>Operating conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHF data by Qu and Mudawar [1]</td>
<td>Water</td>
<td>( G = 86 - 368 ) kg/m² s; ( q'' = 264.2 - 542.0 ) (kW/m²); ( x = 0 - 0.56 )</td>
</tr>
<tr>
<td>Present work</td>
<td>R-123</td>
<td>( G = 410.5 - 533.8 ) kg/m² s; ( q'' = 136.3 - 201.3 ) (kW/m²); ( x = 0.79 - 0.93 )</td>
</tr>
<tr>
<td>Present work</td>
<td>Water</td>
<td>( G = 50.4 - 231.7 ) kg/m² s; ( q'' = 205.8 - 544.6 ) (kW/m²); ( x = 0.39 - 0.81 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( T_a = 17.2 ) °C; ( T_m = 25.4 ) °C; ( P_m = 162.8 - 248.3 ) kPa; ( P_a = 10.6 - 110.9 ) kPa</td>
</tr>
</tbody>
</table>

### Fig. 1 Forces acting on a liquid-vapor interface

The forces shown in Fig. 1 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)–(6),

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

\[ F_M = \frac{q'' b}{h_f} \rho_g \left( \frac{q'' b}{h_f} \right)^2 \frac{D}{\rho g} \]

\[ F_I = \frac{1}{2} \rho V^2 b = \frac{1}{2} \frac{G^2 b}{\bar{\rho}} \]

The stresses resulting from inertia force is given by \( \rho V^2 \). The force per unit length due to inertia is given by

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The forces shown in Fig. 1 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)–(6),

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\[ F_I = \frac{1}{2} \rho V^2 b = \frac{1}{2} \frac{G^2 b}{\bar{\rho}} \]

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\[ F_M = \frac{q'' b}{h_f} \rho_g \left( \frac{q'' b}{h_f} \right)^2 \frac{D}{\rho g} \]

\[ F_I = \frac{1}{2} \rho V^2 b = \frac{1}{2} \frac{G^2 b}{\bar{\rho}} \]
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 a 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 deg and 5 deg, respectively.

Results

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. 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 that 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 $1054 \times 157 \mu$m$^2$ 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. The heater power is increased in steps of 1 W 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/min 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 and 160°C for R-123 and water, respectively. The temperature then overshoots by a few degrees before cooling down after shutting off the power. Again, the last thermocouple near the exit end leads the temperature rise during the 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.

Figures 2 and 3 show the present experimental R-123 and water CHF data with and without the 7.7% PDEs in manifold plotted against the Weber number. As shown in the figures, CHF increases with the Weber number. This indicates that as the mass flux increased, the CHF increased, as one might expect.

Present experimental R-123 and water CHF data are compared to the correlations reported by previous researchers [1,13,14], and the results can be found in Tables 2 and 3. The experimental results with and without the 7.7% PDEs in manifold are compared to the predicted results using the CHF correlations by Bowring, Katto, and Qu and Mudawar [1]. The CHF correlations by Bowring, Katto, and Qu and Mudawar have better performance when predicting CHF using water as the working liquid rather than R-123. 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 (MAE) method, as shown in Eq. (11).

$$\text{MAE} = \frac{1}{M} \sum \frac{|q_{\text{CHF, exp}} - q_{\text{CHF, pred}}|}{q_{\text{CHF, exp}}} \times 100\%$$

The macroscale equation by Katto [14] for rectangular channels has overall MAEs of 33.9% and 14.3% for R-123 and water, respectively. For a rectangular channel, this equation has the lowest MAEs for both the working fluids.

The present R-123 and water CHF data, and those reported by Qu and Mudawar [1], are compared to the predicted results using the new Kandlikar and Kuan CHF model (Eq. (10)) from the section on modeling CHF:

$$q_{\text{CHF}} = \frac{Ch_{fg} \sqrt{ \frac{2 \pi \cos \theta}{b} + \frac{G^2}{2b} } }{\rho}$$

A common value of $C$ is used to predict CHF for both R-123 and water, and their respective MAEs are reported. In addition, individually optimized $C$ values for 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 2 CHF correlation results for R-123

<table>
<thead>
<tr>
<th>Reference</th>
<th>Recommended channel geometry and size</th>
<th>MAE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>With 7.7% PDEs</td>
</tr>
<tr>
<td>Bowring [13]</td>
<td>Circular conventional channels</td>
<td>(i) 66.2%</td>
</tr>
<tr>
<td>Katto [14]</td>
<td>Rectangular conventional channels</td>
<td>(i) 29.4%</td>
</tr>
<tr>
<td>Qu and Mudawar [1]</td>
<td>Rectangular, $d_c=0.38\sim2.54$ mm</td>
<td>(i) 519.4%</td>
</tr>
</tbody>
</table>
Table 3 CHF correlation results for water

<table>
<thead>
<tr>
<th>Reference</th>
<th>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>Bowring [13]</td>
<td>Circular</td>
<td>0.002679</td>
<td>215 ( \times 821 ) ( \mu m^2 ); 21 parallel</td>
<td>13.0</td>
</tr>
<tr>
<td>Ku and Mudawar [1]</td>
<td>Rectangular</td>
<td>0.003139</td>
<td>1054 ( \times 157 ) ( \mu m^2 ); 6 parallel</td>
<td>16.4</td>
</tr>
</tbody>
</table>

Critical Heat Flux Correlation (Common \( C = 0.002679 \) for Both Water and R-123). Qu and Mudawar’s [1] water CHF data and the present R-123 and water CHF data are compared to the predicted values from the Kandlikar and Kuan CHF model. Using the \( C \) value of 0.002679, the correlation agrees with Qu and Mudawar’s experimental data with a MAE of 13.0%. In addition, the correlation agrees with the present R-123 and water experimental data with MAEs of 16.3% and 8.2%, respectively.

Critical Heat Flux Correlation (\( C = 0.002492 \) for Water Only). Using the individually optimized \( C \) value of 0.002492, the correlation agrees with Qu and Mudawar’s experimental data with a better agreement between the correlation and the experimental data.

Critical Heat Flux Correlation (\( C = 0.003139 \) for R-123 Only). The correlation agrees with the present R-123 experimental CHF and the predicted CHF plotted against the Weber number.

Table 4 CHF data compared to the predicted results using the CHF model

<table>
<thead>
<tr>
<th>CHF data by</th>
<th>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>Water</td>
<td>0.002679</td>
<td>215 ( \times 821 ) ( \mu m^2 ); 21 parallel</td>
<td>13.0</td>
</tr>
<tr>
<td>Present work</td>
<td>R-123</td>
<td>0.002679</td>
<td>1054 ( \times 157 ) ( \mu m^2 ); 6 parallel</td>
<td>16.4</td>
</tr>
<tr>
<td>Present work</td>
<td>Water</td>
<td>0.002679</td>
<td>1054 ( \times 157 ) ( \mu m^2 ); 6 parallel</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Using individually optimized values of \( C \)

<table>
<thead>
<tr>
<th>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>Water</td>
<td>0.002492</td>
<td>215 ( \times 821 ) ( \mu m^2 ); 21 parallel</td>
<td>6.8</td>
</tr>
<tr>
<td>Present work</td>
<td>R-123</td>
<td>0.003139</td>
<td>2.5</td>
</tr>
<tr>
<td>Present work</td>
<td>Water</td>
<td>0.002492</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Conclusions

Experiments are conducted to obtain the CHF data using R-123 and water in microchannels. The present experimental CHF results are found to correlate best with existing correlations to overall MAEs of 33.9% and 14.3% with R-123 and water, respectively, when using a macroscale rectangular equation by Katto [14]. 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 new theoretical model is able to predict correct parametric trends. CHF is found to increase with increasing mass flux. The results of the present work are summarized in the following.

- CHF is found to increase with increasing Weber number, which indicates that as the mass flux increased, the CHF increased.

Fig. 4 Qu and Mudawar [1] CHF data compared to the present Kandlikar and Kuan CHF model (Eq. (10)), plotted against the Weber number, \( C = 0.002492 \), water.
The trend in CHF with mass flux is similar to those obtained by earlier investigators.
CHF data are slightly lower when using the 7.7% PDEs with R-123. PDEs have negligible effect on CHF in the present water experiment.
PDEs help in flow stabilization, but the CHF is somewhat reduced when using R-123. The ability of the restrictors to reduce localized dryout is, however, more important, and therefore PDEs are still recommended for use in the operating ranges, as shown in Table 1.
The present R-123 and water experimental CHF results are found to correlate with overall MAEs of 33.9% and 14.3%, respectively, with the macroscale equation by Katto [14] for rectangular channels.
A new theoretical model is developed to predict flow boiling CHF in microchannels. It is developed based on the surface tension, evaporation momentum, and inertia forces.
The new model is able to correlate with present experimental R-123 and water CHF data to MAEs of 16.4% and 8.2%, respectively, 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%.

Acknowledgment
The authors would like to thank the National Science Foundation for providing financial support (CTS Grant No. 0245642) for this research.

Nomenclature

- $b$ = height of microchannel, m
- $C$ = constant in the present CHF model
- $D$ = characteristic dimension, m
- $d$ = diameter of circular channel, m
- $F_I$ = force due to inertia, N
- $F_M$ = force due to momentum change, N
- $F_S$ = surface tension force, N
- $F^*$ = force per unit length, N/m
- $G$ = mass flux, kg/m$^2$ s
- $I$ = electrical current, A
- $P$ = pressure, kPa
- $\Delta P$ = pressure drop, kPa
- $q^*$ = heat flux, kW/m$^2$
- $q_{cW}$ = critical heat flux, kW/m$^2$
- $q_{f}$ = heat input to the test section, W
- $q_{loss}$ = heat loss from the test section, W
- $T$ = temperature, °C
- $\Delta T_{amb}$ = differential temperature for use in performing test section heat loss calibration, °C
- $T_s$ = surface temperature, °C
- $V$ = average velocity based on average density $\rho$, m/s
- $We$ = Weber number, $(G^2 D)/(\rho \sigma)$
- $x$ = thermodynamic quality

Greek Symbols

- $\rho$ = density, kg/m$^3$
- $\bar{\rho}$ = average density, kg/m$^3$
- $\theta$ = dynamic receding contact angle, deg.
- $\sigma$ = surface tension, N/m

Subscripts

- $\text{amb}$ = ambient
- $\text{CHF}$ = critical heat flux, kW/m$^2$
- $\text{expt}$ = experimental
- $G, g$ = gas or vapor
- $l$ = inlet
- $f$ = liquid
- $\text{loss}$ = unrecoverable loss
- $M$ = due to momentum change
- $\text{pred}$ = predicted
- $s$ = microchannel surface
- $S$ = surface tension

References