Applicability of Correlations for Boiling/Condensing in Macrochannels to Minichannels

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Abstract

Channels with small flow passages, commonly known as mini channels, are being widely used in heat exchangers for boiling and condensation. Correlations for heat transfer validated with macro channel data have been reported to sometimes fail for small diameter channels. Hence it is important to know the limits of applicability of such correlations. Many criteria have been proposed for boundary between macro and mini channels. The suitability of these criteria for determining the limits of applicability was evaluated by comparing wide ranging data for heat transfer during condensation, saturated boiling, sub cooled boiling, film boiling, and with data for CHF (critical heat flux), with well-validated correlations for macro channels. The criteria based exclusively on diameter or Bond number and its equivalents were found inadequate. Satisfactory criteria for mini-macro boundary were identified for condensation and saturated boiling heat transfer. Macro channel correlations for sub cooled and film boiling, and for CHF, were found to be satisfactory even for very small diameter channels.

Keywords: Channels; Mini/macro classification; boiling; condensation; heat transfer; correlations

Nomenclature

\[ Bd = \frac{g(\rho_L - \rho_G)D^2\sigma}{\rho_G} \]
\[ Bo = \frac{q}{G h h_{LG}} \]
\[ Co = \text{Confinement number} \]
\[ D = \text{Inside diameter of tube, or hydraulic equivalent diameter of non-circular channel (m)} \]
\[ Eo = \text{Eotvos number} \]
\[ F = \text{Factor in criterion for saturated boiling} \]
\[ FrL = \frac{G}{D \mu f} \]
\[ G = \text{Total mass flux (liquid + vapor) (kg m}^{-2}s^{-1}) \]
\[ g = \text{Acceleration due to gravity (m s}^{-2}) \]
\[ h = \text{Heat transfer coefficient (Wm}^{-2}\text{K}^{-1}) \]
\[ h_{LG} = \text{Latent heat of vaporization (J kg}^{-1}) \]
\[ L_{cap} = \text{Capillary length (m)} \]

\[ N = \text{Number of data points} \]
\[ p_r = \text{Reduced pressure} \]
\[ Re_L = \text{Reynolds number of liquid phase} = \frac{G D \mu f}{\mu f} \]
\[ We_{GT} = \text{Weber number for all mass flowing as vapor} \]
\[ x = \text{Vapor quality} \]

Greek

\[ \mu = \text{Dynamic viscosity (kg m s}^{-1}) \]
\[ \rho = \text{Density (kg m}^{-3}) \]
\[ \sigma = \text{Surface tension (N m}^{-1}) \]

Subscripts

\[ f = \text{Liquid} \]
\[ g = \text{Vapor} \]

1. Introduction

Channels with small flow passages, commonly known as mini channels, are being widely used in heat exchangers for boiling and condensation. There are several reasons for it. Use of mini
channels results in more compact and economical heat exchangers. For refrigeration systems, another advantage of mini channels is that they require smaller refrigerant charge which reduces the environmental impact and fire hazard in case of leakage. There are applications such as computer chip cooling in which mini channels are the only possible choice due to space limitations.

For designing the heat exchangers with mini channels, methods to predict heat transfer coefficients during condensation, various modes of boiling (saturated, sub cooled, film), and to predict CHF (critical heat flux) are needed. Well-verified methods for predicting these for macro/conventional channels are available. It is needed to know the limits of their applicability to smaller channels.

Many criteria for the boundary between mini and macro channels have been proposed. These have been reviewed among others by Cheng and Mewes [1], Ghiaasiaan [2], Ong [3] and Ong and Thome [4]. Some are based entirely on physical dimensions of channels. Others are based on flow pattern transitions, comparison of pertinent forces, theoretical analyses, and comparison of macro channel correlations with data for small channels. The present author recently proposed criteria based on comparison of extensive databases for saturated boiling and condensation with well-validated correlations for macro channels, Shah [5, 6].

In the following, the ability of these criteria to predict the limit of applicability of predictive techniques for macro channels is examined by comparison with results of extensive analyses of data for heat transfer during condensation, saturated and subcooled boiling prior to CHF, occurrence of CHF, and heat transfer during dispersed flow film boiling.

2. Classification of Channels

2.1 Based on Physical Dimensions

According to Shah [7], the heat exchangers with area to volume ratio more than 700 $m^2/m^3$ are compact. This results in 6 mm diameter being the boundary between mini and macro channels. Mehendale et al. [8] proposed:

- $D > 6 \text{ mm}$, macro channels
- $D = 1$ to 6 mm, compact channel
- $D = 100 \mu\text{m}$ to 1 mm, meso channel
- $D = 1 \mu\text{m}$ to 100 $\mu\text{m}$, micro channel

A widely used one is by Kandlikar [9] according to which:

- Conventional Channels: $D > 3\text{ mm}$
- Minichannels: $3 \text{ mm} \geq D > 0.2 \text{ mm}$
- Microchannels: $0.2 \text{ mm} \geq D > 0.01\text{ mm}$

This classification was based mainly on single phase flow of gases but for uniformity, he also recommended it for boiling and condensing flows. This is the most widely used classification.

2.2 Based on Condensation Studies

Li and Wang [10] studied condensation in mini channels. They observed the transition of flow patterns from symmetrical to asymmetrical and noted that these depend on the capillary length $L_{cap}$ (also known as Laplace constant) defined as:

$$L_{cap} = \left[\frac{\sigma}{g(\rho_f - \rho_g)}\right]^{0.5}$$

Their conclusions were:

- $D < 0.224L_{cap}$: Gravity forces are negligible compared to surface tension forces. Flow
regimes are symmetrical.

- $0.224L_{cap} < D < 1.75L_{cap}$: Gravity and surface tension forces are comparable. Flow distribution is slightly stratified.
- $1.75L_{cap} < D$: Gravity forces dominate surface tension forces and the flow regimes are similar to macro channels.

Cheng and Wu [11] re-arranged the above results of Li and Wang in terms of Bond number as below:

- Microchannel, if $Bd < 0.5$ (negligible effect of gravity)
- Minichannel, if $0.5 < Bd < 3.0$ (both gravity and surface tension have significant effect)
- Macrochannel, if $Bd > 3.0$ (surface tension has negligible effect)

Bond number is the ratio of surface tension and gravitational forces and is defined as:

$$Bd = \frac{gd^2 (\rho_f - \rho_g)}{\sigma} \quad (2)$$

It is also the ratio of channel diameter to capillary length.

Based on the comparison of his general correlation for condensation in tubes [12, 13] with a wide ranging database, Shah [5] gave the following criterion. It is mini channel if:

$$We_{GT} < 100 \quad (3)$$

where

$$We_{GT} = \frac{g^2D}{\rho_g \sigma} \quad (4)$$

2.3 Based on Boiling Flow Studies

The growth of bubbles during boiling in small channels may be restricted due to the limitation of tube diameter. This has led several authors to use the confinement number $Co$ defined as:

$$Co = \frac{1}{D} \left[ \frac{\sigma}{g(\rho_f - \rho_g)} \right]^{0.5} \quad (5)$$

Kew and Cornwell [14] compared the data from their tests on heat transfer during boiling in tubes of diameter 1.39, 2.87, and 3.69 mm, and a square channel 2 x 2 mm, to several correlations based on macro channel data. They found that these failed when the confinement number $Co$ is less than 0.5. Accordingly, they gave the following classification.

- Micro/mini channel: $Co > 0.5$
- Macro channel: $Co < 0.5$

According to Ong and Thome [5], the lower threshold of macroscale flow is $Co = 0.3\text{--}0.4$ while the upper threshold of symmetric microscale flow is $Co = 1$ with a transition (or mesoscale) region in-between. This was based on the experimental two-phase flow pattern transition data together with a top/bottom liquid film thickness comparison for refrigerants R134a, R236fa and R245fa during flow boiling in channels of 1.03, 2.20, and 3.04 mm diameter.

Li and Wu [15] have given a transition criterion based on their analysis of data for boiling heat transfer in a variety of channels. According to it, it is mini channel if:

$$Bd \cdot Re_{LO}^{0.5} \leq 200 \quad (6)$$

Shah [6] compared a very wide ranging database for saturated boiling prior to CHF with several correlations for macro channels including Shah [17]. He concluded that it is minichannel if:

$$F = (2.1 - 0.008 We_{GT} - 110 \text{Bo}) > 1 \quad (7)$$
For horizontal channels, \( F = 1 \) if \( Fr_L < 0.01 \). If \( F \leq 1 \), it is macro channel. This is discussed in detail in Section 3.2.

2.4 Based on Two-Component Flow

Triplett et al. [16] studied gas-liquid flow in small diameter channels. They proposed that mini/micro channels are those with diameter less than capillary length \( L_{\text{cap}} \). This is equivalent to \( Bd < 1 \).

Brauner and Ullman [18] studied flow pattern transitions in gas-liquid flow in channels and proposed that the transition between mini and macro channels depends on the Eotvos number \( Eo \) which is the ratio of buoyancy force to surface tension force. It is written as:

\[
Eo = \frac{g(\rho_f - \rho_g)D^2}{8\sigma}
\]

They proposed that mini channels are those with \( Eo < 0.2 \).

2.5 Summary

A number of criteria have been proposed for the boundary between mini and macro channels. These are summarized in Table 1.

<table>
<thead>
<tr>
<th>Author</th>
<th>Criterion for Minichannel</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shah [7]</td>
<td>( D &lt; 6 \text{ mm} )</td>
<td>Surface area to volume ratio &gt; 700 m²/m³</td>
</tr>
<tr>
<td>Mehendale et al. [8]</td>
<td>( D &lt; 6 \text{ mm} )</td>
<td>Same as above</td>
</tr>
<tr>
<td>Kandlikar [9]</td>
<td>( D \leq 3 \text{ mm} )</td>
<td>Based on mean free path of common gases</td>
</tr>
<tr>
<td>Kew &amp; Cornwell [14]</td>
<td>( Bd &lt; 4 )</td>
<td>Bubble growth confinement during boiling in channels</td>
</tr>
<tr>
<td>Triplett et al. [16]</td>
<td>( Bd &lt; 1 )</td>
<td>Flow pattern transitions in gas-liquid flows</td>
</tr>
<tr>
<td>Brauner &amp; Ullman [18]</td>
<td>( Bd &lt; 1.6 )</td>
<td>Flow pattern transitions in adiabatic gas-liquid flows</td>
</tr>
<tr>
<td>Ong and Thome [4]</td>
<td>( Bd &lt; 1 )</td>
<td>Flow pattern transitions and top-bottom liquid film thickness during boiling in channels</td>
</tr>
<tr>
<td>Li and Wu [15]</td>
<td>( Bd \text{ Re}_{L_0}^{0.5} \leq 200 )</td>
<td>Correlation of heat transfer coefficients during saturated boiling in channels.</td>
</tr>
<tr>
<td>Shah [5]</td>
<td>( We_{GT} &lt; 100 )</td>
<td>Comparison of test data with correlation for condensation heat transfer in macro channels</td>
</tr>
<tr>
<td>Shah [6]</td>
<td>( F = (2.1-0.008We_{GT}-110Bo) &gt; 1 )</td>
<td>Comparison of test data with correlation for saturated boiling heat transfer in macro channels</td>
</tr>
</tbody>
</table>

To make comparison easy, the criteria using \( Eo \) and \( Co \) have been given in terms of Bond number as they are related by the following equation:

\[
Eo = \frac{Bd}{8} = \frac{1}{8Co^2}
\]

It is seen that the value of the transition Bond number in various criteria varies from 1 to 4.
3. Data Analyses by the Author

The present author analyzed wide ranging databases for developing correlations for the following:
1. Heat transfer during condensation.
2. Heat transfer during saturated boiling prior to CHF.
3. Heat transfer during subcooled boiling prior to CHF
5. Critical heat flux in channels.

in Section 2. The other three studies resulted in correlations which agreed with a very wide range of data that included diameters from very small to very large and a very wide range of parameters. These correlations did not include any factor for the effect of surface tension. Hence The first two also resulted in correlations for boundary between mini and macro channels given the threshold of mini channel was not reached in these studies. These therefore provide the range of parameters in which macro channel predictive techniques remain applicable. This is useful information for designers of heat exchangers.

Table 2 provides the range of parameters in these studies. Detail of these studies are discussed in the following. Mean absolute deviation (MAD) and average deviation mentioned in these discussions are defined as

\[
\text{MAD} = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{h_{\text{predicted}} - h_{\text{measured}}}{h_{\text{measured}}} \right|
\]

\[
\text{Average Deviation} = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{h_{\text{predicted}} - h_{\text{measured}}}{h_{\text{measured}}} \right)
\]

Table 2. Range of parameters for mini and macro channels in various studies by the present author.

<table>
<thead>
<tr>
<th>Heat Transfer Mode, Study</th>
<th>Geometry</th>
<th>Fluids</th>
<th>Channel Macro or Mini</th>
<th>Range of Parameter Minimum/Maximum</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturated boiling, Shah [6]</td>
<td>Tubes, single &amp; multi-channels (round, rectangular, triangular), full or partly heated, H, V.</td>
<td>30 (water, refrigerants, organics, cryogens, N H3, CO2)</td>
<td>Mini (F &gt; 1)</td>
<td>p_r (kg m^-2s^-1) 0.0046 0.6103</td>
<td>23 300 0.51 6.4 0.31 13.7 22 124 Includes D and Bd&gt;all criteria for minichannels</td>
</tr>
<tr>
<td>Condensation, Shah [5]</td>
<td>Tubes, single &amp; multi-channels (round, rectangular, triangular), full or partly heated, H, V.</td>
<td>33 (water, refrigerants, organics, CO2)</td>
<td>Mini (WeGT &lt; 100)</td>
<td>p_r (kg m^-2s^-1) 0.0008 0.6542</td>
<td>3 300 0.494 47.5 0.43 417 2 97 Includes D and Bd&lt; all criteria for macro chan.</td>
</tr>
<tr>
<td>Subcooled boiling, Shah [24]</td>
<td>Tubes, annuli, single/multi channels, H, V</td>
<td>13 (water, refrigerants, organics, NH3)</td>
<td>Macro (as data analysis shows no effect of surface)</td>
<td>p_r (kg m^-2s^-1) 0.005 0.922</td>
<td>59 31500 0.176 22.8 0.025 7100 158 11.6E7 Satisfactorily predicted by correlations which do not include surface tension</td>
</tr>
<tr>
<td>Film boiling, Shah [25]</td>
<td>Tubes, H, V</td>
<td>10 (water, refrigerants, organics,</td>
<td></td>
<td>p_r (kg m^-2s^-1) 0.005 0.990</td>
<td>4 5176 0.98 25.4 2 6824 32 8.7E5</td>
</tr>
</tbody>
</table>
3.1 Condensation Heat Transfer

Shah [5] compared a wide range of data with his general correlation for condensation in tubes, Shah [12, 13]. The database included 4063 data points from 136 data sets from 77 studies. It was found that most of the data including those for small diameter channels were satisfactorily predicted but some data at low mass flow rates were under-predicted. It was felt that it may be due to effect of surface tension. At low mass flow rates, inertia force may be weak compared to surface tension force. Weber number is the ratio of inertia and surface tension forces. It was found that the Shah correlation [12, 13] is satisfactory at We\textsubscript{GT}>100 but underpredicts at lower values. Thus for condensation, the boundary between mini and macro channels was found to be We\textsubscript{GT}=100.

Table 3 shows the mean absolute deviations (MAD) of Shah correlation and two other correlations below and above We\textsubscript{GT}=100. The correlation of Ananiev et al. [19] is among the most verified for macro channels. The correlation of Kim and Mudawar [20] was verified with data for channels of diameter 6.2 mm and smaller. It is seen that for all three, deviations at We\textsubscript{GT}<100 are much larger than at We\textsubscript{GT}>100, for diameters smaller as well as larger than 3 mm. The Kim & Mudawar correlation was specifically developed for mini channels and its database included channels down to 0.42 mm diameter. Yet its MAD for D < 3 mm is 16.9 % for We\textsubscript{GT}>100 and rises to 25.1 % for We\textsubscript{GT}<100. Thus all the three correlations indicate transition at We\textsubscript{GT} = 100. This is the boundary for applicability of macro channel correlations for condensation heat transfer.

Table 3: Deviations of some correlations for condensation in the mini and macro regimes proposed by Shah [5].

<table>
<thead>
<tr>
<th>D (mm)</th>
<th>Channel Mini or Macro</th>
<th>N</th>
<th>Mean Absolute Deviation (MAD), %</th>
<th>Average Deviation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>D &gt; 3</td>
<td>Mini (We\textsubscript{GT}&lt;100)</td>
<td>225</td>
<td>69.6</td>
<td>53.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20.5</td>
<td>-53.5</td>
</tr>
<tr>
<td></td>
<td>Macro (We\textsubscript{GT}&gt;100)</td>
<td>2153</td>
<td>29.1</td>
<td>25.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-20.9</td>
<td>-10.9</td>
</tr>
<tr>
<td>D ≤ 3</td>
<td>Mini (We\textsubscript{GT}&lt;100)</td>
<td>230</td>
<td>25.1</td>
<td>38.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-17.1</td>
<td>-38.0</td>
</tr>
<tr>
<td></td>
<td>Macro (We\textsubscript{GT}&gt;100)</td>
<td>840</td>
<td>16.9</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-7.6</td>
<td>-6.8</td>
</tr>
</tbody>
</table>

3.2 Saturated Boiling Prior to CHF

Shah [6] compared an extensive database (range of parameters listed in Table 2) with his general correlation [17] which had been well-validated with data for macro channels. The database included 4761 data points from 137 studies from 81 sources. As was the case for condensation, most of the data for small diameter channels were satisfactorily predicted but some at low flow rates were underpredicted. The deviations increased with decreasing Weber number but its effect was countered by increasing boiling number Bo. Eventually, the boundary between mini and macro channels was found to be at F =1 as given in Eq. (7). Figure 1 shows the boundary as given by Eq. (7).
Figure 1. We_{GT} for transition between mini and macro channels during saturated boiling in channels according to Eq. (7) according to Shah correlation [6].

Table 4 shows the mean absolute deviations (MAD) of Shah correlation [17] and three other correlations below and above $F = 1$. The correlations of Gungor and Winterton [21], Liu and Winterton [22], are among the most verified for macro channels. The correlation of Kim and Mudawar [23] was validated with data for tube diameters 6.5 mm and smaller. It is seen that MAD for all four increases greatly when $F > 1$. Further, all four underpredict at $F > 1$ by 20 to 34 % for all diameters.

Table 4: Deviations of various correlations for saturated boiling heat transfer in mini and macro regimes proposed by Shah [6]

<table>
<thead>
<tr>
<th>$D$, mm</th>
<th>Channel Mini or macro</th>
<th>$N$</th>
<th>Mean Absolute Deviation (MAD), %</th>
<th>Average Deviation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 3</td>
<td>Mini $F &gt; 1$</td>
<td>66</td>
<td>24.7</td>
<td>32.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-24.7</td>
<td>-32.5</td>
</tr>
<tr>
<td></td>
<td>Macro $F \leq 1$</td>
<td>2283</td>
<td>22.4</td>
<td>26.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-7.3</td>
<td>9.2</td>
</tr>
<tr>
<td>&lt;= 3</td>
<td>Mini $F &gt; 1$</td>
<td>348</td>
<td>30.5</td>
<td>27.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-29.8</td>
<td>-24.7</td>
</tr>
<tr>
<td></td>
<td>Macro $F \leq 1$</td>
<td>2155</td>
<td>20.0</td>
<td>23.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-2.2</td>
<td>-9.1</td>
</tr>
</tbody>
</table>

It is seen in Table 2 that data for $F > 1$ (mini channel) included diameters up to 6.4 mm and Bd up
to 13.7. The data for $F \leq 1$ (macro channels) include diameters down to 0.38 mm and Bond numbers down to 0.15. Hence the criteria based on Bond number and diameter are not satisfactory. The criterion of Li and Wu [15] listed in Table 1 was also evaluated during this data analysis. It was found quite unreliable.

In view of the above $F = 1$ can be considered a reliable criterion for the boundary between mini and macro channels for saturated boiling prior to CHF. Macro channel correlations may be used when $F \leq 1$. The other criteria are not satisfactory for the prediction of heat transfer during saturated boiling prior to CHF.

### 3.3 Subcooled Boiling Prior to CHF

Shah [24] presented a correlation for subcooled boiling heat transfer in channels. He validated the correlation with a large and varied database. The range of parameters is listed in Table 2. It is seen in Table 2 that the data included diameters as small as 0.176 mm and Bond number down to 0.025. The 1340 data points from 68 data sets from 37 sources were predicted with a MAD of only 12.2%. This correlation did not include any factor for surface tension effects. Hence it appears that the boundary of mini channel was not reached in the data analyzed. Figures 2 and 3 show the deviations of the Shah correlation as function of diameter and Bond number. It is seen that there is no effect of diameter or Bond number on the deviations. Thus the various criteria based on diameter and Bond number (and its equivalent confinement number and Eotvos number) are not valid for the prediction of heat transfer during subcooled boiling.

![Figure 2: Mean absolute deviations of Shah correlation [24] with data sets for subcooled boiling, as function of channel hydraulic diameter.](image)

As seen in Figure 1, the highest value of $W_{EGT}$ for transition to mini channel is about 140 for saturated boiling. The minimum Weber number was 156 in the data for subcooled boiling. Hence analysis of subcooled data at lower $W_{EGT}$ is needed to determine whether the threshold value given by Eq. (7) for saturated boiling is also applicable to subcooled boiling.
3.4 Dispersed Flow Film Boiling

Shah [25] presented a correlation for dispersed flow film boiling in horizontal and vertical tubes which was validated with a large and varied database whose range of parameters is listed in Table 2. These included 1481 data points from 50 data sets from 38 sources. This correlation did not have any factor for surface tension effects. The data included diameters as low as 0.98 mm. Figure 4 shows the deviations of the Shah correlation with data as a function of tube diameter.

It is seen that deviations at small diameters are comparable to those at larger diameters. Thus the mini/macro transition criteria based on diameter are found invalid. The data included Bond numbers down to 2. Some of the criteria listed in Table 1 have transition to mini channel at Bd < 2. Analysis of data at Bd < 2 is needed to see whether these criteria are applicable to dispersed

Figure 3: Mean absolute deviations of Shah correlation [24] with data sets for subcooled boiling, as function of Bond number.

Figure 4: Mean absolute deviations of Shah correlation [25] with the data sets for film boiling in horizontal and vertical tubes as a function of tube diameter.
flow film boiling heat transfer. The minimum $W_{GT}$ in these data was 32. This indicates that the boundary found by Shah for saturated boiling, Eq. (7), is not applicable to dispersed flow film boiling.

### 3.5 Critical Heat Flux (CHF)

Shah [26, 27] analyzed a wide range of data to test his correlation for vertical tubes, Shah [28] for applicability to small diameter channels and to adapt it for horizontal channels. The range of data analyzed is listed in Table 2. The original vertical tube correlation was found to be in good agreement with small diameter channels’ data. The new correlation for horizontal channels also showed good agreement with data for all channel sizes. Neither the vertical tube correlation nor the correlation for horizontal channels included any factor for the effect of surface tension. The data included diameters down to 0.13 mm and Bond numbers down to 0.026. Figures 5 and 6 show the deviations of the Shah correlation with data. It is seen that deviations have no relation to diameter or Bond number. Hence the various criteria based on diameter and Bond number listed in Table 1 were found to be inapplicable. The minimum $W_{GT}$ in the data was 6. Hence the criterion of Eq. (7) for saturated boiling heat transfer is also not applicable.

As all the data analyzed show no effect of surface tension, the threshold for mini channel was not reached. It remains to be found.

![Figure 5: Deviations of Shah correlation [26, 28] with data sets for CHF in channels as a function of channel diameter.](image)

**Conclusions**

1. Literature was reviewed to identify the various criteria proposed for transition from macro (conventional) channels to mini channels. Most of those found are based on diameter alone or only on Bond number and its alternative forms, confinement number and Eotvos number.

2. To determine the limits of applicability of correlations for macro channels to mini channels, wide ranging databases for CHF and heat transfer during condensation, saturated boiling, sub cooled boiling, and film boiling, in channels were compared to well-validated correlations based on data for macro channels. The data included diameters down to 0.13 mm.

3. It was found that the deviations of correlations are not related to diameter alone or to Bond
number alone. Hence such criteria are not generally valid for heat transfer or CHF.

4. For heat transfer during condensation and saturated boiling prior to CHF, the criteria proposed by Shah [5, 6] are supported by the results with several correlations based on macro channel data. Hence these may be considered reliable as the limits of applicability of macro channel correlations.

5. Comparison of data for sub cooled boiling, film boiling, and CHF with well-validated correlations for macro channels showed no limit to their applicability even though the diameters and Bond numbers were very small. Hence the limits of applicability of microchannel correlations for them remain to be found.

Figure 6: Deviations of the Shah correlation (1987, 2015) with data sets for CHF in channels as a function of Bond number.

References


[9] S. G. Kandlikar, Fundamental issues related to flow boiling in mini channels and micro channels,


Biographical information

Dr. Mirza M. Shah is an engineering and research consultant. His research interests include heat transfer during boiling, condensation, and in fluidized beds. His general predictive techniques for heat transfer during boiling and condensation are widely used and are included in most reference works. Dr. Shah’s analytical formulas for evaporation from water pools are extensively used for design and energy analyses. His engineering work has also included HVAC, refrigeration, and energy systems. He has over 75 publications including research papers and chapters in handbooks. He is Fellow of ASHRAE and ASME and licensed Professional Engineer in California and New York. He obtained his doctorate degree from the University of Sunderland in UK. For details, see www.mmshah.org.