Flow boiling in mini- and microchannels offer very high heat transfer capabilities and find applications in many emerging technologies, such as electronics cooling and fuel cells. The low flow rate employed in such geometries, coupled with the small flow channels, often results in a laminar flow with all flow as liquid. Since the single-phase flow with all liquid is in the laminar range, the flow boiling correlations developed for conventional tubes with an inner diameter larger than 3 mm and turbulent flow need to be carefully reviewed. In the present work, flow boiling correlation for large diameter tubes developed by Kandlikar [1, 2] is modified for flow boiling in minichannels by using the laminar single-phase heat transfer coefficient for all liquid flow. The correlation is also extended for flow boiling in microchannels using the nucleate boiling as the dominant part of the original correlation. The trends in heat transfer coefficient versus quality are compared in the laminar and deep laminar regions in minichannels and microchannels. Excellent agreement is obtained between predicted values and experimental data.

The original correlation by Kandlikar [1, 2] on flow boiling heat transfer coefficient was developed using a large data bank consisting of over 10,000 data points. The tube diameter ranged from 3 to 25 mm. All the data was in the turbulent region (ReLO > 3000) considering all flow in the liquid phase. With the current interest in minichannels and microchannels, the correlation is extended to these geometries. The available experimental data is used to verify the validity of the extended correlation.

As the tube diameter becomes smaller, the practical range of all liquid flow Reynolds number (ReLO) falls in the laminar region. Figure 1 shows the range of the Reynolds number as a function of tube diameter using some of the flow boiling data available in literature. It is seen from Figure 1 that for tube diameters below 1 mm, ReLO extends well into the laminar region. For
microchannels with diameters below 200 micrometers, the all-liquid flow is invariably in the laminar region.

The channel size classification used in this work follows the recommendations of Kandlikar and Grande [3] given below:

Conventional channels: $D_h \geq 3$ mm  
Minichannels: $200 \mu m \leq D_h \lt 3$ mm  
Microchannels: $10 \mu m \leq D_h \lt 200 \mu m$  
Transitional Channels: $0.1 \mu m \lt D_h \leq 10 \mu m$  
Transitional Microchannels: $1 \mu m \lt D_h \leq 10 \mu m$  
Transitional Nanochannels: $0.1 \mu m \lt D_h \leq 1 \mu m$  
Molecular Nanochannels: $D_h \leq 0.1 \mu m$

The classification is based on the mean free path of molecules in the single-phase flow, surface tension effects, and flow patterns in the two-phase flow applications. It should be emphasized that the channel size classification is merely a guide to help us identify the channel size ranges in various applications. The operating parameters, such as system pressure, and fluid properties, such as density, viscosity, and surface tension, have a major influence on the flow characteristics. These classifications are not linked to any specific equations. Nevertheless, it serves as a guide in identifying the physical dimensions associated with the flow phenomena in a somewhat general way.

In the present work, the applicability of the Kandlikar correlation [1, 2] is extended to the minichannels and microchannels by suitably accounting for the low Reynolds number values encountered in these geometries.

**ORIGINAL CORRELATION FOR LARGE DIAMETER TUBES ($Re_{LO} > 3000$)**

Flow boiling heat transfer correlations, such as those in Kandlikar [1, 2], utilize the single-phase, all-liquid heat transfer coefficient in predicting the nucleate boiling and convective boiling components as given by the following equation,

$$h_{TP} = \text{larger of } \begin{cases} h_{TP,NBD} \\ h_{TP,CBD} \end{cases}$$

$$h_{TP,NBD} = 0.6683 \text{ Co}^{-0.2}(1 - x)^{0.8} f_2(Re_{LO})h_{LO} + 1058.0 \text{ Bo}^{0.7}(1 - x)^{0.8} F_{Fl}h_{LO}$$

$$h_{TP,CBD} = 1.136 \text{ Co}^{-0.9}(1 - x)^{0.8} f_2(Re_{LO})h_{LO} + 667.2 \text{ Bo}^{0.7}(1 - x)^{0.8} F_{Fl}h_{LO}$$

The single-phase, all-liquid flow heat transfer coefficient $h_{LO}$ is given by the following correlations by Petukhov and Popov [4] and Gnielinski [5], respectively.

$$h_{LO} = \frac{\text{Re}_{LO} Pr_l(f/2)(k_l/D)}{1 + 12.7 (\text{Pr}_L^{1/3} - 1)(f/2)^{0.5}}$$

for $10^4 \leq \text{Re}_{LO} \leq 5 \times 10^6$  

$$h_{LO} = \frac{(\text{Re}_{LO} - 1000) \text{Pr}_l(f/2)(k_l/D)}{1 + 12.7 (\text{Pr}_L^{2/3} - 1)(f/2)^{0.5}}$$

for $3000 \leq \text{Re}_{LO} \leq 10^4$

where $f$ is the friction factor given by

$$f = [1.58 \ln(\text{Re}_{LO}) - 3.28]^2$$

$F_{Fl}$ is a fluid-surface dependent parameter. This parameter represents the nucleation characteristics of the liquid on the given heater surface, which depend on the nucleation site density, fluid properties responsible for nucleation, etc. However, since such information is not available in the flow boiling data, it has been correlated against the fluid-surface combinations for commercial tube surfaces. Table 1 gives the values of $F_{Fl}$ for a number of fluids on copper and brass surfaces.

The Kandlikar correlation [1, 2] was developed using a large data bank consisting of over 10,000 local data points with ten different fluids, including water, refrigerants, and cryogenic fluids. The success of the Kandlikar correlation in accurately representing the trends in heat transfer coefficient versus quality is seen with the high pressure and low pressure data obtained by Schrock and Grossman [6]. Figure 2 compares the flow boiling data from the Schrock and Grossman [6, 7] and Kandlikar [1] correlation. The all-liquid flow heat transfer coefficient is calculated using the turbulent flow correlation. The correlation predicts Schrock and Grossman’s data within less than 10%, and the trends are also well represented.
Table 1 Table of recommended $F_{fl}$ (fluid-surface parameter) values in flow boiling correlation by Kandlikar [1, 2]

<table>
<thead>
<tr>
<th>Fluid</th>
<th>$F_{fl}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1.00</td>
</tr>
<tr>
<td>R-11</td>
<td>1.30</td>
</tr>
<tr>
<td>R-12</td>
<td>1.50</td>
</tr>
<tr>
<td>R-13B1</td>
<td>1.31</td>
</tr>
<tr>
<td>R-22</td>
<td>2.20</td>
</tr>
<tr>
<td>R-113</td>
<td>1.30</td>
</tr>
<tr>
<td>R-114</td>
<td>1.24</td>
</tr>
<tr>
<td>R-134a</td>
<td>1.63</td>
</tr>
<tr>
<td>R-152a</td>
<td>1.10</td>
</tr>
<tr>
<td>R-32/R-132</td>
<td>3.30</td>
</tr>
<tr>
<td>R-141b</td>
<td>1.80</td>
</tr>
<tr>
<td>R-124</td>
<td>1.00</td>
</tr>
<tr>
<td>Kerosene</td>
<td>0.488</td>
</tr>
</tbody>
</table>

$F_{fl} = 1$ for stainless steel tubes for all fluids.

The nucleate boiling and convective boiling contributions are additive in flow boiling. The overall trend in heat transfer coefficient versus quality is that nucleate boiling contribution decreases with quality and convective boiling contribution increases with quality. Depending on the boiling number and the liquid to vapor density ratio, the heat transfer coefficient trends are seen to be increasing, decreasing or flat with an increase in quality. This insight led to the development of a flow boiling map presented by Kandlikar [8].

In a subsequent paper, Kandlikar [2] showed that the single-phase heat transfer coefficient $h_{LO}$ should be treated as the single-phase heat transfer coefficient with all flow as liquid at any given section. Based on this concept, Kandlikar successfully extended the correlation to predict the flow boiling heat transfer coefficients in microtubes and compact heat exchanger geometry. The correlation predicts contribution from the nucleate boiling term even under high quality. In an effort to validate the presence of nucleation under high shear conditions, Kandlikar et al. [9] conducted high speed video imaging for water boiling over a 10 mm diameter circular heated rod, placed flush in the 40 mm × 3 mm rectangular channel. The video images showed the presence of bubbles as small as 10 microns evolving rapidly under highly sheared flow conditions.

In the subcooled flow boiling region, the flow boiling was seen as fully developed at higher wall superheats. Considering only the nucleate boiling term in the nucleate boiling dominant part of the correlation, Kandlikar [10] predicted the subcooled flow boiling data.

However, one of the major limitations of the correlation was that it was applicable only to the turbulent flow data (with $Re_{LO}$ in the turbulent region). Following the suggestion made by Kandlikar [2], the extension presented in the following section provides a complete correlation scheme for deep laminar, laminar, and transition region flows in minichannels and microchannels.

CORRELATION EXTENSION TO LAMINAR AND TRANSITION FLOW REGION IN MINICHANNELS ($1600 < Re_{LO} > 3000$)

Table 2 gives the list of selected experimental data for flow boiling heat transfer studies in mini- and microchannels. In two recent investigations, Kandlikar and Steinke [11, 12] extended the range of applicability of the Kandlikar [1, 2] correlation (Eq. (1)) to Reynolds numbers below 3000. It is necessary for the all-liquid flow single-phase heat transfer coefficient to reflect the existing single-phase flow structure. The use of turbulent flow correlations was not appropriate when the flow is laminar. A transition region was identified between Reynolds numbers of 1600 and 3000, and the following recommendations were made:

- Turbulent region: $Re_{LO} \geq 3000$
- Transition region: $1600 \leq Re_{LO} < 3000$
- Laminar region: $Re_{LO} < 1600$

The single-phase heat transfer coefficient for all flow as liquid, $h_{LO}$, was calculated in the above regions as follows:

- Turbulent region: Gnielinski correlation
- Transition region: Depends on other flow parameters— a linear interpolation between $Re_{LO}$ of 1600 and 3000 is recommended.
- Laminar region: Laminar flow equation, $Nu = C$

For flow boiling in small diameter tubes, the effect of tube orientation is negligible, and the Froude number...
Table 2  Selected flow boiling heat transfer studies for mini- and microchannels

<table>
<thead>
<tr>
<th>Author/year</th>
<th>Fluid/heating method</th>
<th>Channel specifications</th>
<th>G, kg/m² s</th>
<th>Reₐ</th>
<th>q'' kW/m²</th>
<th>x</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wambsganss, France, Jendrzejczyk, &amp; Tran [13]</td>
<td>R-113, direct electric heating of tube</td>
<td>Round, D = 2.92 mm</td>
<td>50–300</td>
<td>1,933–2,013</td>
<td>8.8–90.75</td>
<td>0–0.9</td>
<td>Heat transfer identified with various flow patterns; h decreases with increasing x</td>
</tr>
<tr>
<td>Lin, Kew, &amp; Cornwell [14]</td>
<td>R-141b, direct electric heating of tube</td>
<td>Round, D = 1.1 mm, 1.8 mm, 2 mm x 2 mm</td>
<td>93–570</td>
<td>536–2,955</td>
<td>18–72</td>
<td>0.02–1.0</td>
<td>h increases with x at lower q'' and decreases with x at higher q''</td>
</tr>
<tr>
<td>Yen et al. [16]</td>
<td>HCFC 123, Direct electric heating of tube</td>
<td>Round D = 0.51 mm, 0.19 mm</td>
<td>145–295</td>
<td>410–26.9</td>
<td>0.05–0.98</td>
<td>h decreases with increasing x</td>
<td></td>
</tr>
</tbody>
</table>

Effect in the above correlation is deleted by setting $f_2(Fr_{LO}) = 1$.

The resulting correlation takes the following form:

$$h_{TP,NBD} = 0.6683 \cdot Co^{-0.2} (1 - x)^{0.8} \cdot h_{LO} + 1058.0 \cdot Bo^{0.7} (1 - x)^{0.8} \cdot F_{Fl} \cdot h_{LO}$$

$$h_{TP,CBD} = 1.136 \cdot Co^{-0.9} (1 - x)^{0.8} \cdot h_{LO} + 667.2 \cdot Bo^{0.7} (1 - x)^{0.8} \cdot F_{Fl} \cdot h_{LO}$$

(7)

(8)

For $Re_{LO} < 1600$, the flow is considered as laminar, and the following equation is used for calculating the single-phase all-liquid laminar heat transfer coefficient, $h_{LO}$:

$$h_{LO} = \frac{Nu \cdot k}{Dh}$$

(9)

For the transition region, a linear interpolation between the turbulent single-phase heat transfer coefficient and laminar heat transfer coefficient values is recommended as described earlier. Another fact that is observed in all the flow boiling data with small channels is that the first two or three experimental data points at low qualities always report considerably higher heat transfer coefficient values. This is believed to be due to the increased heat transfer rate associated with the onset of nucleate boiling. This effect is not predicted by the correlation. Also, the correlation is not valid in the liquid deficient region at high qualities, generally observed to be above 0.7 to 0.8.

Figure 3 compares the flow boiling data from Wambsganss et al. [15] with the correlation by Kandlikar [1, 2] using turbulent single-phase correlation. It is seen that the correlation by Kandlikar [3, 4] using a turbulent single-phase heat transfer coefficient yields good agreement. The average deviation between the data and the correlation is 19.7%.

Figures 4–6 compare the flow boiling data from Lin et al. [14] with the correlation by Kandlikar [1, 2]. It is seen that as the Reynolds number is reduced from the transition region ($Re_{LO} = 1970$) to laminar region ($Re_{LO} = 1156$), the data start to yield good agreement with the correlation by Kandlikar [1, 2] using a single-phase all-liquid laminar heat transfer coefficient. The average deviation between the prediction and the data is 21.9%. Although this deviation is somewhat high, it should be recognized that the transition region tends to be quite difficult to predict even for the single-phase flow.

**CORRELATION EXTENSION TO LOW REYNOLDS NUMBER FLOWS IN MINICHANNELS ($410 > Re_{LO} > 100$)**

In a recent work, Kandlikar and Balasubramanian [15] extended the correlation by Kandlikar [1, 2] to

![Figure 3](wambsganss et al. [15] R113 data (points) compared to the present correlation (lines) using turbulent (Dittus-Boelter) single-phase correlation; $Dh = 2.92$ mm, $P_{sat} = 150$ kPa, and $Re_{LO} = 1,995, 2,013, and 1,934$ (Kandlikar et al. [11]).]
Figure 4  Flow boiling data of Lin et al. [14] compared to the correlation by Kandlikar (1990, 1991a) using laminar and turbulent single-phase correlations; \( D_h = 2 \) mm, \( q'' = 40.2 \) kW/m\(^2\), and \( Re_{LO} = 1970 \) (Kandlikar et al. [11]).

Figure 5  Flow boiling data of Lin et al. [14] compared to the correlation by Kandlikar [1, 2] using laminar and turbulent single-phase correlations; \( D_h = 1.1 \) mm, \( q'' = 36.2 \) kW/m\(^2\), and \( Re_{LO} = 1600 \) (Kandlikar et al. [11]).

Figure 6  Flow boiling data of Lin et al. [14] compared to the correlation by Kandlikar [1, 2] using laminar and turbulent single-phase correlations; \( D_h = 1.1 \) mm, \( q'' = 34.6 \) kW/m\(^2\), and \( Re_{LO} = 1156 \) (Kandlikar et al. [11]).

Figure 7  Yen et al. [16] data point for HCFC 123 compared to the correlation by Kandlikar [1, 2] using laminar single-phase equation; \( D_h = 0.51 \) mm, \( G = 295 \) kg/m\(^2\) s, and \( Re_{LO} = 410 \) (Kandlikar et al. [15]).

Laminar flow in minichannels. The correlation by given Eqs. (7) and (8) using the single-phase laminar all-liquid flow heat transfer coefficient \( h_{LO} \) is used for the low Reynolds number flow in minichannels. The single-phase laminar all-liquid flow heat transfer coefficient \( h_{LO} \) is given by Eq. (9).

Figure 7 compares the flow boiling data from Yen et al. [16] with the correlation by Kandlikar [1, 2] using a laminar single-phase equation. A circular tube of diameter 0.51 mm (510 µm) is used in these data sets. The data yield reasonable agreement with the correlation but the trend seems to be changing. As the Reynolds number is decreased to lower values, the correlation starts to over predict the data, especially in the high quality region. This indicates that the convective boiling contribution is reduced at a lower Reynolds number.

The agreement with the experimental data is 16.3% in the laminar region above \( Re_{LO} = 400 \). The trend also is undergoing a change from its convective boiling dominant trend of flat or slightly increasing to the nucleate boiling trend of decreasing \( h \) versus \( x \) as the flow Reynolds number decreases, which can be seen from Figures 8 and 9. In this region, the changeover from one trend to another show somewhat contradictory results. However, a further decrease in the Reynolds number leads to the nucleate boiling dominant trend with its characteristic decreasing \( h \) versus \( x \) trend, as shown in the following section.

**CORRELATION EXTENSION TO VERY LOW REYNOLDS NUMBERS IN MICROCHANNELS (Re_{LO} \leq 100)**

In the same work, Kandlikar and Balasubramanian [15] also extended the correlation by Kandlikar [1, 2] to deep laminar flow, \( Re_{LO} \leq 100 \), in microchannels. In
this range, the following correlation is recommended:

\[ h_{TP} = h_{TP, NBD} \]  

(10)

where \( h_{TP, NBD} \) is given by Eq. (7), reproduced below:

\[
h_{TP, NBD} = 0.6683 \, Co^{-0.2}(1 - x)^{0.8} \, h_{LO} + 1058.0 \, Bo^{0.7}(1 - x)^{0.8} \, \Phi_{FB} \, h_{LO}
\]  

(11)

The single-phase laminar all-liquid flow heat transfer coefficient \( h_{LO} \) is given by Eq. (9). The proposed correlation given by Eqs. (10–11) takes into account the nucleate boiling dominant region \( (h_{TP, NBD}) \) of the previous Kandlikar correlation, Eqs. (7–8), without any additional constants. The convective part of the correlation is neglected. The proposed correlation indicates that the flow is dominated by nucleate boiling for \( Re_{LO} \leq 100 \) in microchannels.

A circular tube of diameter 0.19 mm (190 \( \mu \)m) is used in the data sets presented in Figures 8 and 9. The proposed correlation is denoted by the legend Laminar-NBD in figures, which refers to laminar flow with the nucleate boiling dominant correlation. The trend displayed in the data for the low quality region warrants some discussion. Immediately following the nucleation, or the onset of nucleate boiling, the liquid super heat is suddenly released, which results in a very high heat transfer coefficient in the low quality region.

The proposed Kandlikar and Balasubramanian correlation [15] yields excellent agreement, as seen in Figures 8 and 9, which both have \( Re_{LO} \) around 100. Based on this behavior, it can be concluded that the boiling is nucleate dominant for low Reynolds number flow in microchannels \( (Re_{LO} \leq 100) \). The average deviation between the experimental data and the correlation prediction in the deep laminar region is 17.3%.

**CONCLUSION**

1. The work by Kandlikar and Steinke [11, 12] extends the range of the correlation by Kandlikar [1, 2] to laminar and transition flow in minichannels by introducing the use of the fully developed laminar and transition flow equations for the all-liquid flow heat transfer coefficient. The new sets of equations are given by Eqs. (7–8) with an appropriate single-phase correlation for \( h_{LO} \).

2. The transition between the laminar and turbulent flow, as seen through the single-phase all-liquid flow correlation, is not well defined. In general, the flow with \( Re_{LO} < 1600 \) may be treated as fully developed laminar flow, while the flow may be considered in the transition region for \( 1600 \leq Re_{LO} < 3000 \). The Gnielinski correlation is applicable for \( Re_{LO} > 3000 \). An appropriate interpolation scheme needs to be developed in the transition region.

3. The experimental data for 0.51 mm diameter tubes (minichannel) for low laminar flow \( (450 > Re_{LO} > 150) \) was well correlated using the Kandlikar correlation [1, 2] with \( h_{LO} \) calculated from laminar flow equation.

4. The experimental data for 0.19 mm diameter tubes (microchannel) for deep laminar flows \( (Re_{LO} \leq 100) \) was also well correlated using the proposed correlation, which uses only the nucleate boiling dominant part of the Kandlikar correlation, Eqs. (10–11). The average deviation between the experimental data and the correlation in various regions is found to be less than 20%.

5. Based on the data sets investigated using the proposed correlation, it is concluded that boiling is more nucleate dominant for low Reynolds number flows \( (Re_{LO} \leq 100) \) in microchannels.
6. More experimental data is needed to verify the nucleate boiling dominant effect in the low Reynolds number flow in minichannels. Also, the exact transition to the NBD region at a Reynolds number of 100 in microchannels is expected to undergo further refinement as new data become available in this range of flow.

**NOMENCLATURE**

- \( A_s \): heat transfer surface area, m²
- \( B_0 \): boiling number, \( q''/(G \ i_{LG}) \)
- \( C_0 \): convection number, \( (\rho_G/\rho_L)^{0.5} \ ((1 - x)/x)^{0.8} \)
- \( D_h \): tube diameter, mm
- \( f \): fanning friction factor
- \( F_f \): fluid-surface parameter
- \( F_r \): Froude number
- \( G \): mass flux, kg/m² s
- \( h_{LO} \): all-liquid flow single-phase heat transfer coefficient, W/m²°C
- \( h_{TP} \): two-phase heat transfer coefficient, W/m²°C
- \( i_{LG} \): specific enthalpy, J/kg
- \( k \): thermal conductivity of liquid, W/m°C
- \( L \): length of tube, m
- \( N_u \): Nusselt number
- \( P_{avg} \): test section average pressure, kPa
- \( q'' \): heat flux, W/m²
- \( Re_{Lo} \): all-liquid flow Reynolds number
- \( T \): temperature, °C
- \( X \): quality

**Greek**

- \( \mu \): viscosity, Ns/m²
- \( \rho \): density, kg/m³

**Subscripts**

- \( \text{avg} \): average
- \( \text{TS} \): test section
- \( \text{NBD} \): nucleate boiling dominant
- \( \text{CBD} \): convective boiling dominant

**REFERENCES**


in widely accepted correlations for different geometries, he started to look at the problem from a fundamental perspective. Using the high-speed photography techniques, he demonstrated that small bubbles are released at a high frequency under flow conditions. He is also working in the area of binary flow boiling and bubble formation in inkjet printing application. He has worked extensively in the area of microchannels. He has given a number of invited and keynote talks nationally and internationally. He is the founder and chair of ASME Rochester Heat Transfer Chapter and the Heat in History Editor of Heat Transfer Engineering.

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