EXTENDING THE APPLICABILITY OF THE FLOW BOILING CORRELATION TO LOW REYNOLDS NUMBER FLOWS IN MICROCHANNELS

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ABSTRACT

As microchannels are applied in flow boiling applications, it is becoming apparent that the Reynolds number based on all liquid flow could approach values below 100. The earlier work by Kandlikar and Steinke (2002, 2003) provided modifications to the Kandlikar correlation (1990,1991) by extending the range of the correlation to all-liquid Reynolds numbers in the range 1000 – 3000.

The present work utilizes the newly available data on flow boiling in microchannels that cover the all-liquid flow Reynolds number between 50 – 500. A new correlation is developed in this range that is able to predict the flow boiling heat transfer coefficient and its trends with quality, heat flux and mass flux accurately within less than 15 percent mean deviation. It is noted that the correlation simply accounts for the change of the flow boiling mechanism without incorporating any additional empirical constants. The heat transfer mechanism during flow boiling at such low Reynolds numbers is altered considerably indicating strong presence of nucleate boiling mode of heat transfer.

INTRODUCTION

The flow boiling heat transfer in small diameter passages is being applied in many advanced designs, including electronics cooling, fuel cell heat exchangers, and other high heat flux dissipation devices. With ongoing research in this area around the world on flow boiling inside microchannels, experimental data is becoming available on local heat transfer coefficient as a function of heat flux and mass flux in channels smaller than 200 µm. The channel size classification used in this work follows the recommendations of Kandlikar and Grande (2002) given below:

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

The flow in microchannels is generally in the laminar region as the mass flux employed is generally low due to high pressure drop experienced especially during flow boiling conditions. Thus the all-liquid Reynolds number is on the order of only a few hundreds or lower.

In two recent investigations, Kandlikar and Steinke (2002, 2003) extended the range of applicability of the Kandlikar (1990,1991) correlation 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. The following recommendations were made:

\[
\begin{align*}
\text{Re}_{LO} &\geq 3000 \quad \text{Turbulent region} \\
3000 > \text{Re}_{LO} &\geq 1600 \quad \text{Transition region} \\
1600 > \text{Re}_{LO} &\quad \text{Laminar region}
\end{align*}
\]

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
Laminar region - Laminar flow equation, \((Nu=constant)\)
Transition region - Depends on other flow parameters; a linear interpolation between \( Re_{LO} \) of 1600 and 3000 is recommended.
In the above work, the following correlation by Kandlikar (1990, 1991) is employed:

\[
\begin{align*}
    h_{TP} &= \text{larger of } \begin{cases} 
    h_{TP,NBD} \\
    h_{TP,CBD}
    \end{cases} \\
    h_{TP,NBD} &= 0.6683C_0^{0.2}(1-x)^{0.8}f_2(F_{Re,LO})h_{LO} + 1058.0Bo^{0.7}(1-x)^{0.8}F_{Fr,LO}h_{LO} \\
    h_{TP,CBD} &= 1.136C_0^{0.8}(1-x)^{0.8}f_2(F_{Re,LO})h_{LO} + 667.2Bo^{0.7}(1-x)^{0.8}F_{Fr,LO}h_{LO}
\end{align*}
\]

(1)

For flow boiling in small diameter tubes, the effect of tube orientation is negligible and the Froude number effect in the above correlation is deleted by setting \( f_2(F_{Fr,LO}) = 1 \). The single-phase, all-liquid flow heat transfer coefficient \( h_{LO} \) is given by the following correlations by Petukhov and Popov (1963), and Gnielinski (1976) respectively.

\[
\begin{align*}
    h_{LO} &= \frac{Re_{LO} \Pr_L f(2/k_L)}{1+12.7(Pr_L^{2/3} - 1)(f/2)^{0.5}} \text{ for } 10^4 \leq Re_{LO} \leq 5 \times 10^6, \\
    h_{LO} &= \frac{(Re_{LO} - 1000) \Pr_L f(2/k_L)}{1+12.7(Pr_L^{2/3} - 1)(f/2)^{0.5}} \text{ for } 3000 \leq Re_{LO} \leq 10^6
\end{align*}
\]

(3)

and

\[
\begin{align*}
    h_{LO} &= \frac{(Re_{LO} - 1000) \Pr_L f(2/k_L)}{1+12.7(Pr_L^{2/3} - 1)(f/2)^{0.5}} \text{ for } 3000 \leq Re_{LO} \leq 10^6
\end{align*}
\]

(4)

Figure 1 to 3 shows the comparison of the correlation prediction with experimental data of Lin et al. (2001) in the laminar flow region. The refrigerant is R-141b, and the tube diameters used are 1.1 mm and 2 mm. The all liquid flow Reynolds number ranges from 1970 to 1156. The flow is laminar. For the constant heat flux condition, \( Nu_{LO} \) is estimated to be 4.36 for a circular tube. The Dittus–Boelter correlation is also to show the effect of turbulence in range of Reynolds number below 3000.
OBJECTIVES OF THE PRESENT WORK

The present work is aimed at studying the recent flow boiling data in microchannels ($D_h \leq 200 \mu m$) in an effort to extend the applicability of the Kandlikar (1990, 1991) correlation. The major factor being the low Reynolds number encountered with all liquid flow in these channels.

NEW CORRELATION

For Reynolds number in the range of $3000 < Re < 100$ the following correlation by Kandlikar (1990,1991) is employed:

$$ h_{TP} = \text{larger of } \begin{cases} \frac{h_{TP,NBD}}{h_{TP,CBD}} \\ h_{TP,CBD} \end{cases} \quad (5) $$

$$ h_{TP,NBD} = 0.6683C_0^{-0.2}(1-x)^{0.8}h_{LO} + 1058.0B\sigma^{0.7}(1-x)^{0.8}F_Rh_{LO} $$

$$ h_{TP,CBD} = 1.136C_0^{-0.9}(1-x)^{0.8}h_{LO} + 667.2B\sigma^{0.7}(1-x)^{0.8}F_Rh_{LO} $$

(6a, 6b)

The single-phase laminar all-liquid flow heat transfer coefficient $h_{LO}$ is given by,

$$ h_{LO} = \frac{Nuk}{D_h} \quad (7) $$

For Reynolds number below and equal to 100 ($Re \leq 100$) the following Kandlikar Correlation is proposed,

$$ h_{TP} = h_{TP,NBD} \quad (8) $$

$$ h_{TP,NBD} = 0.6683C_0^{-0.2}(1-x)^{0.8}h_{LO} + 1058.0B\sigma^{0.7}(1-x)^{0.8}F_Rh_{LO} $$

(9)

where the laminar $h_{LO}$ is calculated by eq.(7).

The new correlation takes into account the nucleate boiling dominant region ($h_{TP,NBD}$) of the previous Kandlikar correlation (1990,1991) without any addition of extra constants. The convective part of the correlation is neglected. The new correlation indicates that the boiling is nucleate dominant for $Re_{LO} \leq 100$ in Microchannels.

DETAILS OF DATA SET INVESTIGATED

The experimental data sets of Yen et al. (2002) using HCFC-123 in stainless steel tubes of internal diameter 0.19 mm and 0.51mm is investigated. The tube diameter of 0.19 mm tube can be classified as a microchannel and 0.51mm tube can be classified as minichannel under the classification scheme introduced earlier.

As the data for microchannels in the channel diameters of less than 200 µm is becoming available, it is seen that the Reynolds number with all liquid flow often falls in the range below 100. The present investigation focuses on this range of Reynolds number.
RESULTS

Figures 5 to 9 compare the correlation by Kandlikar (1990,1991) with the data by Yen et al. (2002). For these data sets, laminar single phase heat transfer coefficient; eq. (7), is used with constant Nusselt number of 4.36. The correlation is denoted by the legend titled as Laminar in the following figures.

For data sets in Figs. 5 and 6, the correlation by Kandlikar (1990,1991) using laminar single phase heat transfer coefficient yields excellent agreement. As the Reynolds number is decreased to values lower than 200 the correlation starts to over predict the data.

The new correlation proposed here, eq. (8), is used for the data sets which have Re close to 100. The new correlation is denoted by the legend Laminar-NBD meaning laminar flow with nucleate boiling dominant correlation. The results are discussed next.
The new Kandlikar correlation (2003) yields an excellent agreement as seen in Figs. 8, 9, and 10, which all have Re around 100. Based on this behavior it can be concluded that the boiling is nucleate dominant for low Reynolds number flow in microchannels.

CONCLUSIONS

1. The experimental data for 0.51mm diameter tubes (minichannel) for Reynolds number ranging between 450 to 150 where correlated well using the Kandlikar correlation (1990,1991) with $h_{LO}$ calculated from the laminar flow equation.

2. The experimental data for 0.19mm diameter tubes (microchannel) for Reynolds numbers around 100 was also well correlated using the new correlation proposed in this work using only the nucleate boiling dominant part of the Kandlikar correlation, eq.(8).

3. Based on the data sets investigated using the new correlation proposed here, it is concluded that the boiling is more nucleate dominant for low Reynolds number flows in microchannels.

4. 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 Reynolds number of 100 is expected to undergo further refinement as new data becomes available in this range of flow.

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NOMENCLATURE

$A_s$ – heat transfer surface area, m$^2$
$Bo$ – boiling number, $= q/(G_i L_G)$
$Co$ – convection number, $= (\rho_G/\rho_L)^{0.5} ((1-x)/x)^{0.8}$
$D_h$ – tube diameter, m
$f$ – friction factor
$Fr$ – Froude number
$h_{LO}$ – all-liquid flow single-phase heat transfer coefficient, W/m$^2$ °C
$h_{TP}$ – two-phase heat transfer coefficient, W/m$^2$ °C
$i_{L_G}$ – latent heat of vaporization, J/kg
$k$ – thermal conductivity of liquid, W/m°C
$L$ – length of tube, m
$Nu$ – Nusselt number
Pavg- Test section average pressure, kPa
q, q” – heat flux, W/m²
Reₙₙₙₙ – all liquid flow Reynolds number
T – temperature, °C
x - quality

Greek

µ  Viscosity (Ns / m²)
ρ  Density (kg/m³)

Subscripts

avg  Average
TS  Test Section
NBD- Nucleate boiling dominant
CBD-Convective boiling dominant

REFERENCES


