Development of a Flow Boiling Map for Subcooled and Saturated Flow Boiling of Different Fluids Inside Circular Tubes

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Introduction

A clear understanding of the influence of different variables on heat transfer during single-phase flow may be obtained through analytical equations and well-established empirical correlations. The insight provided by these equations and correlations proves useful not only in the design of heat transfer equipment, but also in the development and optimization of augmented surfaces and channel geometries.

Flow boiling heat transfer is more complex than single-phase heat transfer due to the interactions among the two phases and the tube wall in addition to the presence of both convective and boiling modes of heat transfer. As a result, several regions may be identified that are dominated by distinct heat transfer mechanisms. A flow boiling map provides a good way to represent the complex interrelationships among major variables in these regions.

There are three sources of information available for generating a flow boiling map. First, a number of experimental and analytical studies have been reported in the literature on the mechanism of nucleation, bubble growth, bubble departure, and heat transfer under flow boiling conditions.

These fundamental studies are helpful in explaining the heat transfer characteristics of flow boiling systems. The second source of information is available through a large number of experimental investigations performed by researchers under carefully controlled conditions so as to provide much needed data to designers, and to reveal the effect of major operating variables on flow boiling heat transfer. After ascertaining the accuracy of the experimental techniques employed, these data provide a basis for establishing the parametric relationships. Finally, the third source of information is provided by generalized correlations developed from the extensive data sets for different fluids. Since the experimental conditions cannot be easily altered to generate data by varying a single variable at a time while holding other variables constant, a generalized correlation is helpful in covering these gaps. However, extreme caution needs to be exercised in the selection and use of a correlation as its overall accuracy in predicting the heat transfer coefficient may not be sufficient to reveal the correct parametric trends.

Background. Collier (1981) presented the qualitative flow boiling map shown in Fig. 1, depicting the basic relationship between the heat transfer coefficient and the quality, with the heat flux as a parameter. Positive values of quality refer to the saturated two-phase region, while negative values of quality apply to the subcooled region where the quality x is defined as:

\[ x = \frac{(T_\text{sat} - T_\text{in})}{T_\text{sat}} \]  

(1)

Collier’s map is plotted for a single value of mass flux. As will be shown later, his map is relatively specific to water at low pressures, and is representative of only approximate trends in different regions. For example, in the subcooled region, the onset of nucleate boiling is followed by a linear increase in the heat transfer coefficient with x up to x = 0. The heat transfer coefficient in the subcooled region is defined with (T_\text{sat} - T_\text{in}) as the temperature difference. The linear increase in h shown in Fig. 1 does not accurately represent the heat transfer in the subcooled boiling region. The combined effect of nucleate boiling and convective heat transfer in the partial boiling region, and the effect of net vapor generation on h in the subcooled region close to x = 0, are also not represented in his map. In the saturated boiling region, heat transfer is initially shown to be independent of x representing the fully developed nucleate boiling. Subsequently, heat transfer is shown to be entirely by convective mode with no influence of q. Eventually the CHF condition is reached with a drastic reduction in h. The CHF is attained sooner with higher values of q. The in-
fluence of $G$ on heat transfer and CHF in various regions is not included in Collier’s map.

The validity of Collier’s map for water and refrigerants in the saturated boiling region has been investigated by Kandlikar (1988b). The experimental data of Kennen and Cooper (1988) for water, Chawla (1967) for R-11, Jensen and Bender (1986) for R-113, and Jallouk (1975) for R-114 were employed. The trends of a constant $h_{tp}$ in the nucleate boiling region, and an increasing $h_{tp}$ with $x$ in the convective boiling region, as depicted in Collier’s map, were observed to be true only for water near atmospheric pressure. For refrigerants, it was noted that the $h_{tp}$ versus $x$ trend in the convective boiling region was quite different from the ever-increasing trend depicted in Collier’s map. A similar comparison of Collier’s map with the experimental data for different fluids in the subcooled boiling region is not available in the literature.

A number of experimental investigations have represented their data in plots that depict sections of a flow boiling map. One common problem encountered while using these plots is that they are specific to the fluid employed and are generally not applicable beyond the range of conditions covered in the individual experiments. Further, they are plotted in terms of different variables, which are often dimensional.

Objective of the Present Work. The objective of the present work is to develop a flow boiling map to represent the heat transfer coefficient as a function of three major parameters: quality, heat flux, and mass flux. It is desired to present the map in terms of dimensionless parameters. Also, the entire range from the onset of nucleate boiling in the subcooled region up to a quality of 0.8 in the saturated boiling region is to be covered. The flow boiling map will be developed using (i) existing experimental and analytical evidence of the heat transfer mechanisms in different regions, (ii), the trends predicted by generalized correlations, and (iii) available experimental data showing the variation of $h$ with $x$ and other variables. Although it would be desirable to represent the critical heat flux and the dryout region on the map, these are beyond the scope of the present work.

Development of the Flow-Bubbling Map

The final flow boiling map developed in this paper is shown in Fig. 2. It is divided into the subcooled and the saturated boiling regions. The map is applicable to vertical flow with $Re_{a} \geq 2300$, although it can be applied to horizontal flow with a high Froude number, $Fr_{a} > 0.04$. For $Fr_{a} < 0.04$ in horizontal tubes, the map will be able to depict only qualitative behavior since the stratification effects may modify the parametric relationships. The quantitative representation given in the saturated region may be directly applied to practical situations. In the subcooled region, only a qualitative representation is provided since specific fluid properties are needed in various equations for subcooled boiling. The development of the map along with a discussion of the heat transfer behavior in different regions is given in the following sections.

Choice of Coordinates. The functional relationship between the heat transfer coefficient and the three major system parameters (quality, heat flux, and mass flux) will be displayed in the flow boiling map.

The choice of quality as the abscissa is quite natural since it may be used as an independent variable to represent the fluid state along an evaporator tube. In the subcooled region, the liquid subcooling, $\Delta T_{al} = T_{al} - T_{l}$, is commonly employed in representing the onset of nucleate boiling and other subcooled boiling heat transfer mechanisms. $\Delta T_{al}$ may be nondimensionalized in terms of $x$ under the assumption of constant $c_{p,l}$ in the range $T_{l} < T_{al} < T_{sat}$. Thus, in equation (1) may be expressed as

$$x = -\Delta T_{al} c_{p,l} / q$$

(2)

It may be noticed that $x = 0$ corresponds to the subcooled region, while $0 < x < 1$ falls under the saturated region.

The heat transfer coefficient is usually defined on the basis of the wall to bulk fluid temperature difference. Thus,

**Nomenclature**

- $a, b$: constants in equation (24)
- $Bo$: boiling number $= q / (Gh_{b})$
- $Bo^{*}$: modified boiling number $= (Bo)^{2/3}$
- $c_{p,l}$: specific heat of liquid, $J/kg \cdot K$
- $D$: inside diameter of tube, m
- $f$: friction factor, given by equation (10)
- $f_{1}, f_{2}$: functions described by equations (10) and (38), respectively
- $F_{p}$: fluid-dependent parameter, given in Table 3
- $Fr_{a}$: Froude number with all flow as liquid $= G_{a}^{2} / (g^{2}D)$
- $G$: mass flux, kg/m²s
- $g$: acceleration due to gravity, m/s²
- $h$: heat transfer coefficient, W/m²·K
- $h_{l}$: heat transfer coefficient with only liquid fraction flow, W/m²·K
- $h_{b}$: heat transfer coefficient with total flow as liquid, equation (7), W/m²·K
- $h_{Tp}$: heat transfer coefficient during two-phase flow with $T_{u} - T_{l}$ as the temperature difference, W/m²·K
- $i$: enthalpy, J/kg
- $i_{sat}$: enthalpy of liquid at saturation, J/kg
- $i_{v}$: enthalpy of vaporization, J/kg
- $k$: thermal conductivity, W/m·K
- $m, n, p$: constants in equations (24)–(29)
- $P$: pressure, Pa
- $Pr_{l}$: Prandtl number of liquid $= \nu_{l} / k_{l}$
- $q$: heat flux, W/m²
- $q_{b}$: heat flux with total flow as liquid $= h_{b}(T_{u} - T_{l})$, W/m²

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The flow boiling map developed for subcooled and saturated flow boiling in circular tubes with \( h_{TP}/h_0 \) versus \( x \) as coordinates.

\[
h_{TP} = q/(T_w - T_f) = \begin{cases} g/\Delta T_{sat} \Delta T_{sub} & \text{for } T_f < T_{sat} \\ g/\Delta T_{sat} & \text{for } T_f = T_{sat} \end{cases}
\]

The two heat transfer coefficients defined by equations (3) and (4) are related in the subcooled region by

\[
h_{TP} = h_{TP}(1 + \Delta T_{sub}/\Delta T_{sat}) \quad \text{for } x < 0
\]

or

\[
h_{TP} = [1/h_{TP} + x\rho/(\epsilon_{sol}q)]^{-1} \quad \text{for } x < 0
\]

Alternatively,

\[
h_{TP} = [1/h_{TP} - x\rho/(\epsilon_{sol}q)]^{-1} \quad \text{for } x > 0
\]

and in the saturated region by

\[
h_{TP} = h_{TP} \quad \text{for } 0 \leq x \leq 1
\]

In the present flow boiling map, \( h_{TP} \) is chosen over \( h_{TP} \) to represent the heat transfer coefficient since it retains the physical concept of the heat transfer coefficient. It also offers certain advantages in nondimensionalizing the heat transfer coefficient, as well as in simplifying the representation of the subcooled region.

In order to represent a number of different fluids on the same map, it is essential to nondimensionalize the heat transfer coefficient. In the saturated flow boiling region, \( h \), the single-phase heat transfer coefficient, with only the liquid fraction flowing in the tube, is frequently employed as a non-dimensionalizing parameter. In the subcooled region, the use of \( h_0 \), the single-phase heat transfer coefficient with total flow as liquid, instead of \( h \), is more appropriate since there is no net equilibrium vapor fraction present in the flow. Use of \( h_0 \) in the saturated region as well is in fact more desirable since the variation in \( h_{TP}/h_0 \) with \( x \) clearly represents the variation in the two-phase heat transfer coefficient, unlike \( h_{TP}/h \), which is affected by the variation in \( h \) with \( x \).

The ordinate of the map is therefore chosen to be \( h_{TP}/h_0 \). Kandlikar (1988a, 1990a) used the Dittus–Boelter correlation for calculating \( h_{TP} \), but later Kandlikar (1990b) showed that the Petukhov–Popov (1963) and Grjebinski (1976) correlations for \( h_0 \) are better able to account for the Prandtl number effect for different fluids. These correlations are therefore employed here. \( h_0 \) is then given by:

\[
P_{TP}/P_{TP} \quad \text{for } 0.5 \leq Pr \leq 2000 \text{ and } 10^4 \leq Re_0 \leq 5 \times 10^6.
\]

**Nomenclature (cont.)**

- \( h_0 \): Reynolds number based on only the liquid fraction flow = \( [GD(1-x)/\mu] \)
- \( Re_0 \): Reynolds number based on all flow as liquid = \( [GD/\mu] \)
- \( r_{max} \): maximum cavity radius, m
- \( T \): temperature, °C
- \( T_f \): bulk mean temperature, °C
- \( T_w \): wall temperature, °C
- \( T_{sat} \): saturation temperature, °C
- \( \Delta T_{sat} \): wall superheat = \( (T_w - T_{sat}) \), °C
- \( \Delta T_{sub} \): liquid subcooling = \( (T_{sat} - T_f) \), °C
- \( \Delta T \): temperature difference

**Subscripts**

- A-G: corresponding to points A-G on Fig. 4
- B: bulk fluid
- f: liquid with only liquid fraction flow
- g: vapor
- L: liquid
- \( h \): latent
- li: with total flow as liquid
- on: onset of nucleate boiling
- sat: saturated
- sub: subcooled
- sup: superheated
- \( x \): quality at the location
- \( x^* \): quality at the location

**Abbreviations**

- CBD: convective boiling dominant
- FDB: fully developed boiling
- NBD: nucleate boiling dominant
- NVG: point of net vapor generation
- ONB: onset of nucleate boiling
- PB: partial boiling
- SAT: saturated
- SPL: single-phase forced convection with liquid

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Subcooled Boiling Region

![Diagram showing wall and fluid temperatures in the subcooled boiling region](image)

\[ \text{Nu} = h_D k_D / D = Re_D Pr (f/2) / (11.07 + 12.7(P_r^{2/3} - 1)(f/2)^{2/3}) \] (8)

Gnielinski (1976)

For \( 0.5 \leq P_r \leq 2000 \) and \( 2200 \leq Re_D < 10^{5} \),

\[ \text{Nu} = h_D k_D / D = (Re_D - 1000)Pr (f/2)^{2} / \left[ 1 + 12.7(P_r^{2/3} - 1)(f/2)^{2/3} \right] \] (9)

The friction factor \( f \) in equations (8) and (9) is given by

\[ f = \left( 1.58 \ln(Re_D) - 3.28 \right)^{-1} \] (10)

Based on the above discussion, \( h_{fp}/k_D \) is chosen to represent the nondimensionalized heat transfer coefficient along the ordinate, and \( x \) is chosen to represent the fluid state along the abscissa.

Subcooled Region

A representative sketch showing the wall and bulk fluid temperatures in the subcooled region is shown in Fig. 3. The subregions displayed in Fig. 3 are generally of no interest in refrigerant evaporator design, but are of relevance in applications such as steam generators, nuclear reactors, and cooling systems for magnets and electronic equipments.

As a necessary condition for the onset of nucleate boiling, the wall temperature at a given location must be equal to or greater than the local saturation temperature, or \( T_w \geq T_{sat} \).

The maximum value of \( \Delta T_{w,\text{on}} \) for the condition is satisfied occurs at a quality \( x^* \) and the following relations apply:

\[ T_w = T_{sat} \] (11)

\[ \Delta T_{w,\text{on}} = q / h_D \] (12)

Combining equations (2) and (12), \( x^* \) may be expressed as

\[ x^* = -q(x^*)/h_D = Bo/St_D \] (13)

where \( Bo \) is the boiling number, \( Bo = q/(G_{f}l_D) \), and \( St_D \) is the Stanton number with total flow as liquid, \( St_D = h_D / (G_{f}l_D) \).

The region with \( T_w < T_{sat} \) lies entirely in single phase flow. The nondimensionalized heat transfer coefficient in this region is given by

\[ h_{fp}/k_D = 1 \] (14)

As \( T_w \) exceeds \( T_{sat} \), a nonboiling region may still exist over some length since nucleation is not initiated until the onset of nucleate boiling, or ONB, is reached.

Onset of Nucleate Boiling, ONB. The wall superheat and \( q \) at ONB are governed by the superheat requirements to activate a cavity on the surface. Assuming the availability of all cavity sizes, Bergles and Rohsenow (1964) proposed that nucleation would occur when the temperature in the liquid at the interface of a hemispherical bubble attains the minimum temperature required to nucleate the cavity. This condition is reached when the liquid temperature profile near the wall is normal to the curve representing the temperature required to activate the cavity as a function of the cavity radius.

Murphy and Bergles (1972) compared the theoretical results for incipient nucleation heat flux for R-113 with and without dissolved air on copper surfaces. The equation for \( \Delta T_{w,\text{on}} \) for pure liquids is derived as

\[ \Delta T_{w,\text{on}} = \left( \frac{R \alpha \rho_{\text{sat}}}{k_L} \right) \left( \frac{dp}{dT}_{\text{sat}} \right)^{-1/2} \] (15)

The other condition that should be satisfied at ONB is given by the single-phase forced convection relation just prior to ONB

\[ q_{on} = h_D (T_w - T_j) = h_D (\Delta T_{sat} + \Delta T_{w,\text{on}}) \] (16)

At ONB, \( q_{on} \) and \( q_{sat} \) are equal, and the solution of equations (15) and (16) yields the values of \( T_{sat} \) and \( q_{sat} \) at ONB.

The above equations may still be applied when dissolved gases are present in the liquid by calculating the \( T_{sat} \) and the slope \( dp/dT \) at the saturation condition corresponding to the mixture. Murphy and Bergles (1972) obtained satisfactory agreement with their data using equation (15) for the case of decreasing heat flux. For the case of increasing heat flux, a nucleation hysteresis was observed for R-113, which is a low surface tension fluid. For such fluids, the initiation of nucleation is inhibited at lower wall superheats by the nonavailability of all decreasing sizes due to increased wetting of the surface. With a given maximum cavity size \( r_{max} \) available on the surface, Murphy and Bergles obtained a modified equation for ONB as

\[ \Delta T_{w,\text{on}} = \frac{q_{on}}{h_D} \Delta T_{sat} + 2 \alpha \Delta T_{sat} \] (17)

Murphy and Bergles could correlate their ONB data for R-113 by employing an \( r_{max} \) of 42.7 \( \mu \)m. In the presence of dissolved gases, the saturation temperature and the slope of the saturation curve need to be modified as suggested by Murphy and Bergles.

From equations (2) and (16), the quality at ONB may be expressed in terms of \( \Delta T_{w,\text{on}} \) as

\[ x_{\text{on}} = -q / h_D = \Delta T_{w,\text{on}} G_{f} / k_L \] (18)

Alternatively, introducing \( x^* \) from equation (13), we can write

\[ x_{\text{on}} = x^* + \Delta x^* \] (19)

where \( \Delta x^* \) is given by

\[ \Delta x^* = \Delta T_{w,\text{on}} G_{f} / k_L \] (20)

\( \Delta T_{w,\text{on}} \) in equation (20) is obtained from equation (15), or if \( r_{max} \) for the particular surface is known, equation (17) may be employed.

Equations (13), (19), and (20) may be utilized in examining the effects of \( q \) and \( G \) on \( x_{\text{on}} \) at ONB. As \( q \) increases, \( x_{\text{on}} \) decreases since the required wall superheat to activate a cavity is attained at lower fluid temperatures. An increase in \( G \) however has an opposite effect since the single-phase heat transfer is improved and the temperature profile in the fluid near the wall becomes steeper. This causes the temperature at the top surface of a nucleating bubble to be lower, thereby delaying the nucleation until the bulk fluid temperature \( T_f \) increases. The influence of \( q, G, h_D \), and the fluid properties is represented by \( Bo \) and \( St_D \) as shown in Fig. 2.

For low surface tension fluids such as freons, the ONB is delayed during start-up when the heat flux is gradually increased. The improved heat transfer immediately following ONB causes \( T_w \) to reduce suddenly with a corresponding increase in the heat transfer coefficient. Since this phenomenon

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is strongly dependent on the fluid and the wall conditions, it is not shown in the flow boiling map. The reader is urged to check for the temperature excursion at ONB when it is of significance in their particular application.

Partial Subcooled Boiling. Immediately following the point of ONB, an increasing number of nucleation sites become active as $\Delta T_{sub}$ is reduced, until the heat transfer is predominantly by the nucleating boiling mechanism. This region is called the partial subcooled boiling region. A number of different schemes have been proposed in the literature to predict the heat transfer in this region. For example, Bowring (1962) proposed a model that sets the limiting value of $q$ at fully developed boiling as 1.4 times the heat flux at the intersection of the extended single-phase $q$ versus $\Delta T_{sub}$ curve with the fully developed $q$ versus $\Delta T_{sub}$ curve. In the partial boiling region, the single-phase contribution was assumed to be equal to $h_{p} \Delta T_{sub}$. Another method proposed by Bergles and Roberson (1964) employs a superposition technique in which the fully developed boiling curve is used as an asymptotic limit for the partial boiling region. Further details of the two models may be found from Collier (1981).

A major problem while using the two models described above in the flow boiling map arises from the complexity in evaluating various terms in the correlating schemes. This difficulty is avoided in the new model described here, which employs equation (15) proposed by Murphy and Bergles (1972) for $\Delta T_{sub}$ONB and $q_{ONB}$ is calculated from $q_{ONB} = h_{ONB} \Delta T_{sub}$ONB. The heat flux at FDB is calculated from the Bowring model. In the region $q_{ONB} = q < q_{ONB}$, the wall superheat is calculated from an equation derived to yield the correct limiting heat flux values at ONB and FDB, as well as provide the same slope at these two points. The details of the model and the construction of the map in the partial boiling region are described below.

Figure 4 shows a representative $q$ versus $\Delta T_{sub}$ plot in the subcooled region. The curve ABCD represents the single-phase heat transfer relation for liquid at a fixed subcooling corresponding to a quality, say $x_1$. Corresponding values of $q_{ONB}$ and $\Delta T_{sub}$ONB are calculated by solving equations (15) and (16), and ONB is located at point C in Fig. 4. (Note that equation (17) should not be employed for this construction.) The fully developed boiling curve is represented by EF. Point D is then obtained at the intersection of the two curves.

The single-phase heat transfer along the curve ABCD is described by

$$ q_{AB} = h_{l}(\Delta T_{sat} + \Delta T_{sub}) = h_{l}(\Delta T_{sat} - x_{s}h_{f}/c_{p}) $$

Equation (2) has been employed in equation (21) to express $\Delta T_{sub}$ in terms of $x$.

The fully developed curve is obtained from a correlation by Shah (1977). It is described later under a section on fully developed subcooled boiling, and is given by equation (32). Simultaneous solution of equations (21) and (32) for a given $x_1$ gives the value of $q_{ONB}$ at location D. $q_{ONB}$ is then obtained from

$$ q_{ONB} = 1.4q_{ONB} $$

Equation (22) was obtained by Forster and Creff (1959) on the basis of the experimental data covering a wide range of conditions and fluids. Bowring (1962) employed it in his model for the partial boiling region. The wall superheat $\Delta T_{wall}$ may be obtained from

$$ \Delta T_{wall} = q_{ONB}/h_{ONB} $$

where $h_{ONB}$ in the fully developed boiling region may be obtained from equation (32). Point E can now be located on the FDB curve.

The region between C and E is identified as partial boiling region. The slope of the $q$ versus $\Delta T$ curve varies from 0 in the single-phase region ABC to 2 in the fully developed boiling region E. The $q$ versus $\Delta T$ relation in the partial boiling region may be approximated as

$$ q = a + b(\Delta T_{sat})^m $$

where $a$ and $b$ are the dimensional constants corresponding to $x_{s}$, and can be obtained from the boundary conditions: $q = q_{ONB}$ at $x = 0$, $\Delta T_{wall} = \Delta T_{ONB} - \Delta T_{sat}$, and $q = q_{E}$ at $\Delta T_{wall} = \Delta T_{wall}$. The values of $a$ and $b$ are given by

$$ b = (q_{E} - q_{ONB})/(\Delta T_{wall} - \Delta T_{sat}) $$

$$ a = q_{ONB} - b\Delta T_{wall} $$

The exponent $m$ in equation (24) is allowed to vary linearly from $m = 1$ at $q = q_{ONB}$ to $m = 2$ at $q = q_{E}$ by employing the following equation:

$$ m = n + pq $$

The constants $n$ and $p$ may be calculated as

$$ p = 1/(q_{E} - q_{ONB}) $$

$$ n = 1 - p/q_{ONB} $$

Since $a$, $b$, and $p$ in equations (24)–(29) are dimensional constants, a consistent set of units should be employed. Efforts to nondimensionalize these equations resulted in quite cumbersome expressions.

The construction of the partial boiling region on the flow boiling map is given in Fig. 2. The construction proceeds as follows:

(i) Locate $X_{ONB}$ on the map for the given conditions. Consider $x > x_{ONB}$.

(ii) Obtain $q_{ONB}$ at the intersection of the two curves.

(iii) If the heat flux flux $q > q_{ONB}$, the point lies in or beyond the fully developed region. Partial boiling equations do not apply.

(iv) Solve equations (24) and (27) to obtain $\Delta T_{wall}$ for the given $q$, $h_{ONB}$ is then obtained from $h_{ONB} = q/\Delta T_{wall}$. Knowing $h_{ONB}$, locate $h_{FDB}/h_{ONB}$ corresponding to $x_{s}$ on the flow boiling map.

(v) Consider $x > x_{s}$ and follow steps (i) through (vii). Continue the procedure for higher values of $x$ until the condition in step (vii) has been attained.

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The procedure described above satisfies the two limiting conditions, one at the ONB and the other at the beginning of the fully developed boiling. Further, by varying the slope of the $q$ versus $\Delta T_{sat}$ curve in the partial boiling region from 1 to 2, smooth transitions are obtained near points C and E in Fig. 4.

For some conditions with very low Bo, such as Bo, and Bo, it may be noted that the saturated liquid state may be reached before the FDB is attained. Under extreme conditions for very low values of Bo, even the ONB state may not be reached before $x=1.0$. However, these situations are generally of no practical interest.

**Fully Developed Subcooled Boiling, FDB.** The fully developed subcooled boiling occurs as the boiling curve enters the region of low subcooling dominated by nucleate boiling. Bergles and Rohsenow (1964) experimentally obtained the fully developed subcooled boiling curve for flow boiling and compared it with the pool boiling curve employing the same stainless steel heater rod surface. Their results are shown in Fig. 5. It can be seen that the two curves are quite different, implying that the basic mechanism in pool boiling is altered due to the imposed flow.

A number of correlations have been proposed in the literature specifically for water; for example, the equation by Jens and Lottes (1951) is widely used. Another correlation by Bjorge et al. (1982) covers the entire range of subcooled and saturated boiling, but is not tested extensively for fluids other than water. A correlation developed by Shah (1977) is based on experimental data for water, refrigerants, alcohols, methanol, and carbon tetrachloride. Shah's correlation in the fully developed boiling region may be expressed as:

$$h_{TP}/h_s = f_1(Bo)$$

where $f_1(Bo)$ is given by

$$f_1(Bo) = \begin{cases} 230 \text{Bo}^{0.5} & \text{for Bo} > 3.0E-5 \\ 1 + 46 \text{Bo}^{0.5} & \text{for Bo} \leq 3.0E-5 \end{cases}$$

Combining equations (6), (13), and (30), $h_{TP}/h_s$ may be expressed as

$$h_{TP}/h_s = \left[1/f_1(Bo) + x/x^*\right]^{-1}$$

A comparison of Shah's correlation with the experimental data of Rohsenow and Clark (1951) shows a reasonable agreement as seen from Fig. 6.

The FDB region is plotted on the flow boiling map in Fig. 2 using equation (32). As Bo increases, the FDB region starts at lower values of $x$ and the curve shifts higher indicating the availability of more nucleation sites similar to pool boiling heat transfer behavior with increasing heat flux.

**Point of Net Vapor Generation.** As the subcooled liquid in the fully developed boiling approaches the saturation state corresponding to $\Delta T_{sat} = 0$ or $x = 0$, a point is reached where net vapor generation occurs in the flow. The flow of the two-phase mixture from this point onward affects the nucleate boiling and the convective boiling components much the same way as in the saturated flow boiling. The fully developed nucleate boiling at some point begins to be affected by the two-phase flow, and the convective heat transfer contribution to the two-phase mixture is progressively improved with increasing $x$.

The point of net vapor generation is predicted from a correlation by Saha and Zuber (1974). The subcooling at this point is given by the following equation:

$$\Delta T_{sub,NVG} = \begin{cases} 0.0022 \left(qD/k_f\right)/\text{Re}_0 \text{Pr}_f \leq 70,000 \\ 153.8 \frac{q}{Gr_p^{0.5}} \text{Re}_0 \text{Pr}_f > 70,000 \end{cases}$$

The quality at NVG may be obtained from equations (2) and (33) as

$$x_{NVG} = \begin{cases} -0.0022 \text{Bo} \text{Re}_0 \text{Pr}_f \text{Re}_0 \text{Pr}_f \leq 70,000 \\ -153.8 \text{Bo} \text{Re}_0 \text{Pr}_f > 70,000 \end{cases}$$

Based on the above criteria, the value of $\Delta T_{sub,NVG}$ is calculated to be 31.9°C, and the corresponding $x_{NVG}$ is 0.229 for the conditions of the experimental data of Rohsenow and Clark shown in Fig. 6.

In the region from the point of NVG to $x = 0$, the flow effects may become important as $x$ approaches 0. Further investigations in this area are needed to confirm the effect of NVG on the heat transfer in the subcooled boiling region. In the meantime, a linear relation between $h_{TP}$ and $x$ is employed with $h_{TP}$ varying from $h_{TP,NVG}$ obtained from equation (32) to $h_{TP,x=0}$ obtained from the saturated boiling correlation given by equation (35).

**Saturated Boiling Region.**

The behavior of $h_{TP}$ with $x$ in the saturated region is quite complex. As Bergles (1988) notes, “In general, the prediction of heat transfer in the quality region is an elusive business that requires much more attention.” The intuitive trend of increasing $h_{TP}$ with $x$ is observed for certain fluids, while for other fluids, a decreasing trend is noted. Further, for the same fluid, different investigators obtained different trends.
An investigation by Kandlikar (1988b) explains these differences in the observed trends. As an extension of this study, specific parameters have been identified in this paper, which enable us to predict the correct trend for a given fluid under a given set of operating conditions.

The saturated boiling region is represented on the flow boiling map in Fig. 2 for $x \geq 0$. The two heat transfer coefficients, $h_{TP}$ and $h_{FP}$, are identical in this region since $T_f = T_{sat}$. The $x$ range from 0.0 to 0.8 is included on the map, although it should be noted that a CHF condition may deprive the wall surface of a liquid film, thereby severely deteriorating the heat transfer. In some cases with large values of Bo, CHF is reached even in the subcooled region. Comprehensive surveys on this topic are given by Collier (1981), Rohsenow (1985), and Bergles (1988). The location of CHF depends on a number of parameters such as inlet subcooling, tube length, and pressure besides the three main parameters, $h$, $q$, and $G$. The reader is urged to check the CHF condition before using the flow boiling map.

The development of the flow boiling map in the saturated boiling region is based on a correlation presented by Kandlikar (1988a, 1990a). The parametric trends predicted by the Kandlikar correlation and five other correlations were compared by Kandlikar (1988b) with some of the existing experimental data. It was found that the Kandlikar correlation closely represented the trends and also gave the lowest mean deviations for over 5000 data points considered. Further confirmation of the trends predicted by the Kandlikar correlation are obtained in the present study by comparing with additional data. The Kandlikar correlation (1988a, 1990a) is given by

$$h_{TP}/h_0 = \text{maximum of} \begin{cases} h_{TP}/h_0 \text{NBD} \\ h_{TP}/h_0 \text{CBD} \end{cases}$$

(35)

where the subscripts NBD and CBD refer to the nucleate boiling dominant and convective boiling dominant regions given by

**Nucleate boiling dominant (NBD) region:**

$$h_{TP}/h_0 \text{NBD} = 0.685(\rho_v/\rho_0)^{0.14}x^{0.2}(1-x)^{0.8}f_1(F_r)$$

**Conveective boiling term**

$$+ 1058.0 \text{Bo}^{0.6}F_r(1-x)^{0.8}$$

(36)

**Nucleate boiling term**

**Convective boiling dominant (CBD) region:**

$$h_{TP}/h_0 \text{CBD} = 1.1360(\rho_v/\rho_0)^{0.14}x^{0.75}(1-x)^{0.8}f_3(F_r)$$

**Conveective boiling term**

$$f_1(F_r)\text{ in equations (36) and (37) is a fluid-dependent parameter, which is set equal to 1.0 for water. On the basis of a data bank consisting of over 5000 data points, Kandlikar (1988a, 1990a) obtained F_r values for refrigerants R-11, R-12, R-123, R-22, R-113, R-114, and R-122.}$$

$$\text{Table 3 lists the values of F_r for water and these seven refrigerants.}$$

The accuracy of the experimental setup and the data reduction procedure employed in obtaining the data needs to be ascertained before using them in verifying the trends in $h_{TP}$ versus $x$. It is suggested that a fluid-dependent parameter, which is set equal to 1.0 for water. On the basis of a data bank consisting of over 5000 data points, Kandlikar (1988a, 1990a) obtained $F_r$ values for refrigerants R-11, R-12, R-123, R-22, R-113, R-114, and R-122. Table 3 lists the values of $F_r$ for water and these seven refrigerants.

The accuracy of the experimental setup and the data reduction procedures employed in obtaining the data needs to be ascertained before using them in verifying the trends in $h_{TP}$ versus $x$. Five investigations covering a wide range of parameters for water, R-12, R-22, R-113, R-114, and R-122A have been evaluated here. The results of the evaluation are presented in Tables 1 and 2.

The ranges of operating conditions of the five investigations by Jalouk (1975), Jensen and Bensler (1986), Jung et al. (1989), Kenning and Cooper (1988), and Khanpara (1986) are presented in Table 1. The data by Jung et al. and Khanpara were obtained for horizontal tubes, but since the Froude number in their experiments was high, $F_r > 0.04$, the effect of gravity would be negligible. Table 2 gives the details of the experimental setup and data reduction procedures employed in these investigations. It may be noted that four investigators employed electrically heated stainless steel or copper tubes, while Jalouk employed a 12-mm-thick copper tube in ten sections, each individually heated with insulated nichrome wire wound around the tube. This results in a boundary condition that is probably closer to a constant wall temperature condition than a constant heat flux condition. A comparison with Jalouk's data showed that all the correlations were underpredicted consistently by about 10 percent over the entire quality range.

Another observation may be made regarding the experimental accuracy reported in Table 2. Although the investigators report an accuracy within 10 to 15 percent, larger deviations may be expected for small values of wall to fluid temperature differences.

### Table 1 Operating ranges of parameters employed by different experimental investigators

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Year</th>
<th>Fluid</th>
<th>Orientation</th>
<th>$D$, mm</th>
<th>$p$, bar</th>
<th>$x$</th>
<th>$q$, kW/m²</th>
<th>$G$, kg/m²s</th>
<th>Bo × 10⁶</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jalouk</td>
<td>1975</td>
<td>R-114</td>
<td>Vert-up</td>
<td>4.4-14.8</td>
<td>0.007-0.71</td>
<td>0.8-62.1</td>
<td>157-1313</td>
<td>0.05-24.02</td>
<td>547</td>
<td></td>
</tr>
<tr>
<td>Jensen and Bensler</td>
<td>1986</td>
<td>R-113</td>
<td>Vert-up</td>
<td>8.1</td>
<td>2.7-7.2</td>
<td>0.001-0.71</td>
<td>6.7-51.1</td>
<td>165-1523</td>
<td>0.035-12.65</td>
<td>1264</td>
</tr>
<tr>
<td>Jung et al.</td>
<td>1989</td>
<td>R-12</td>
<td>Hor</td>
<td>9.1</td>
<td>3.26</td>
<td>0.040-0.551</td>
<td>10-35</td>
<td>250-720</td>
<td>0.50-8.30</td>
<td>205</td>
</tr>
<tr>
<td></td>
<td>R-22</td>
<td>Hor</td>
<td>9.1</td>
<td>3.95</td>
<td>0.072-0.68</td>
<td>10-35</td>
<td>250-720</td>
<td>0.68-8.33</td>
<td>409</td>
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</tr>
<tr>
<td></td>
<td>R-114 Hor</td>
<td>9.1</td>
<td>2.57</td>
<td>0.072-0.68</td>
<td>10-35</td>
<td>250-720</td>
<td>1.56-8.17</td>
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</tr>
<tr>
<td></td>
<td>R-12A Hor</td>
<td>9.1</td>
<td>3.35</td>
<td>0.034-0.68</td>
<td>10-35</td>
<td>250-720</td>
<td>0.47-7.11</td>
<td>126</td>
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<td></td>
</tr>
<tr>
<td>Kenning and Cooper</td>
<td>1988</td>
<td>Water</td>
<td>Vert-up</td>
<td>9.6</td>
<td>1.6-5.9</td>
<td>0.004-0.671</td>
<td>52-417</td>
<td>123-689</td>
<td>0.39-11.3</td>
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<tr>
<td>Khanpara</td>
<td>1986</td>
<td>R-113</td>
<td>Hor</td>
<td>8.7</td>
<td>3.3-3.4</td>
<td>0.15-0.8</td>
<td>17-40</td>
<td>248-600</td>
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<tr>
<td></td>
<td>R-22</td>
<td>Hor</td>
<td>8.7</td>
<td>3.9-9.2</td>
<td>0.0-0.88</td>
<td>22-40</td>
<td>271-559</td>
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</table>

NA = data not available, $h_{TP}$ data derived from figures.
<table>
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<tr>
<th>Investigator</th>
<th>Year</th>
<th>Fluid</th>
<th>Tube material</th>
<th>Wall thickness, mm</th>
<th>Heating element</th>
<th>$T_w - T_f$ °C</th>
<th>$T_f$</th>
<th>$T_w$</th>
<th>Measuring technique and accuracy</th>
<th>Comments</th>
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</thead>
<tbody>
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<td>Jallouk</td>
<td>1975</td>
<td>R-114</td>
<td>Copper</td>
<td>12.55</td>
<td>Wire wrap</td>
<td>2.2-13.8</td>
<td>18.4</td>
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<td>Thrempl in fluid, ±0.2°C</td>
<td>Thrempl in fluid, ±0.2°C</td>
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<td>Turbine flow meter, ±6 percent</td>
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<td>Average h over 25 cm sections</td>
<td>Average h over 25 cm sections</td>
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<tr>
<td>Jensen and Bensler</td>
<td>1986</td>
<td>R-113</td>
<td>SS</td>
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<td>0.6-15.1</td>
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<td>SS</td>
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<td>1.9-8.4</td>
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<td>Two 4-m-long test sections connected by U-tube</td>
<td>Two 4-m-long test sections connected by U-tube</td>
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<tr>
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<td>R-114</td>
<td>SS</td>
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<td>Variable area flow meters, ±3 percent</td>
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<td>Guard heater to reduce losses</td>
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<tr>
<td>Khanpara</td>
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<td>R-113</td>
<td>Copper</td>
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<td>Tube wall</td>
<td>2-4 (NA*)</td>
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<td>From $P_{at}$, ±0.4 °C</td>
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<td>Voltage and current, ±4 percent</td>
<td>Voltage and current, ±4 percent</td>
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<td>Single-phase tests done to check accuracy</td>
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<td>Single-phase tests done to check accuracy</td>
<td>Single-phase tests done to check accuracy</td>
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</tbody>
</table>

*NA = not available, $h_{TP}$ data derived from figures.
Table 3 Fluid-dependent parameter \( F_\rho \) in the Kandikdar correlation

<table>
<thead>
<tr>
<th>Fluid</th>
<th>( F_\rho )</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>
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<tr>
<td>R-131B</td>
<td>1.31</td>
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<tr>
<td>R-22</td>
<td>2.20</td>
</tr>
<tr>
<td>R-13</td>
<td>1.90</td>
</tr>
<tr>
<td>R-114</td>
<td>1.24</td>
</tr>
<tr>
<td>R-152a</td>
<td>1.10</td>
</tr>
</tbody>
</table>

In some cases this difference is as small as 0.6°C, which is of the same order of magnitude as the accuracy of temperature difference measurements. This is suspected to be a major reason for erratic behavior in some of the data from these sources. An accurate estimation of \( x \) is desired especially in the region where \( h_{TP} \) varies strongly with \( x \), as in the case of R-114 data at low pressures obtained by Jallouk (1975). Since \( x \) is determined from a heat balance over a long preheater section, the error associated with the measured values of temperature, pressure, electrical power input, and the heat losses influence the determination of \( x \).

The experimental data by Jung et al. (1989) and Khanpara (1986) were not used in the development of the Kandikdar correlation. A mean deviation of less than 20 percent was observed with R-113 and R-22 data sets by Khanpara, and R-12, R-22, R-114, and R-152a data sets by Jung et al. The trends in these data sets also agreed with those predicted by the Kandikdar correlation, as will be shown later.

To represent equation (35) on the flow boiling map in Fig. 2, three parameters are needed: \( \rho_1/\rho_2 \), \( Bo* \), and \( F_\rho \). A modified boiling number \( Bo^* \) is introduced to include the effect of \( Bo \) and \( F_\rho \). \( Bo^* \) is defined by

\[
Bo^* = Bo \left( \frac{F_\rho}{F_\rho_{ref}} \right)^{0.7}.
\]

The variation of \( h_{TP}/h_0 \) with \( x \) is plotted for three values of \( \rho_1/\rho_2 \) and two values of \( Bo^* \) covering the range of parameters commonly employed in the refrigeration, power, and process industries. The influence of these parameters in various regions is discussed in the following sections.

Nucleate Boiling Dominant (NBD) Region. The nucleate boiling dominant region exists at lower values of \( x \) in the saturated boiling region in Fig. 2. Here \( Bo^* \) is seen as the major influencing parameter. As \( Bo^* \) increases, the contribution due to nucleate boiling increases and consequently \( h_{TP}/h_0 \) increases.

The trend in \( h_{TP}/h_0 \) versus \( x \) is also influenced by the magnitude of Bo. At higher values of Bo, the convective contribution is small compared to the nucleate boiling component. The primary trend of decreasing \( h_{TP}/h_0 \) with \( x \) associated with the nucleate boiling component is clearly seen. As \( \rho_1/\rho_2 \) decreases, the convective contribution becomes less significant and the range of the nucleate boiling dominant region is extended to higher values of \( x \). At lower values of \( Bo^* \) however, the contribution due to the nucleate boiling component is not very large and the \( h_{TP}/h_0 \) versus \( x \) trend is influenced by the increasing trend of the convective boiling contribution with \( x \).

The density ratio \( \rho_1/\rho_2 \) affects only the convective component as seen from equations (36) and (37). Since the contribution due to the convective component at high values of Bo is quite small in the nucleate boiling region, the effect of varying \( \rho_1/\rho_2 \) from 1000 to 10 is not significant. However, at low values of Bo, the convective contribution is quite large. Here the effect of density ratio can be clearly seen. At \( \rho_1/\rho_2 = 1000 \), \( h_{TP}/h_0 \) increases with \( x \), while at \( \rho_1/\rho_2 = 10 \), \( h_{TP}/h_0 \) decreases with \( x \).

Convective Boiling Dominant (CBD) Region. In the convective boiling dominant region, the trend of \( h_{TP}/h_0 \) with \( x \) is strongly influenced by the trend of the convective boiling component, which depends on \( \rho_1/\rho_2 \) as seen from equation (37). For a given \( x \), a higher value of \( \rho_1/\rho_2 \) results in a larger vapor volume and a higher velocity of the two-phase mixture. The result is similar to an apparent increase in \( G \) in a single-phase flow causing the convective contribution to increase with the density ratio.

As \( x \) increases, the convective contribution increases, and with a higher density ratio, \( h_{TP}/h_0 \) increases rapidly with \( x \). This trend becomes even more pronounced for lower values of \( Bo^* \) where the nucleate boiling contribution is small. Increasing \( Bo^* \) at a fixed value of \( \rho_1/\rho_2 \) causes the \( h_{TP}/h_0 \) curve to become less steep due to the increasing contribution from the nucleate boiling component, which tends to decrease with increasing \( x \).

Comparison With Trends From Experimental Data. The trends seen in the saturated boiling region of Fig. 2 may be confirmed by inspecting the experimental data for water at low and high pressures corresponding to the high and low values of \( \rho_1/\rho_2 \), respectively. Figure 7 shows the experimental data points of Kenning and Cooper (1988) corresponding to \( \rho_1/\rho_2 = 930 \) and almost the same value of Bo. The data and the correlation both display an increasing trend in \( h_{TP} \) with \( x \). On the same plot Morzov's (1969) data and the predicted curve from the Kandikdar correlation are also shown for approximately the same Bo but at a lower value of \( \rho_1/\rho_2 = 40 \). Here, \( h_{TP} \) is almost independent of \( x \). The influence of \( \rho_1/\rho_2 \) is clearly seen from this comparison.

Further comparison of the \( h_{TP}/h_0 \) versus \( x \) trend at moderate values of \( \rho_1/\rho_2 \) is carried out by employing recent data for refrigerants R-113 reported by Khanpara (1986) and for R-22 by Khanpara et al. (1986). These data sets were not employed in the development of the Kandikdar correlation. Figure 8 shows two sets of Khanpara's R-113 data at \( \rho_1/\rho_2 = 59.4 \) and approximately the same Bo. Two observa-
Fig. 8 Comparison of the Kandlikar (1990a) correlation with the saturated flow boiling data of Khaparna (1986) for R-113

![Graph showing comparison](image)

Khaparna's (1986) R-113 data, $\rho_f/\rho = 59.4$

- $G=90$ kg/m$^2$, $q=24.1$ kW/m$^2$, $Bo=0.00905$
- $G=150$ kg/m$^2$, $q=38.1$ kW/m$^2$, $Bo=0.0105$

Kandlikar (1990a) correlation: $h_{fp}/h_0 = \frac{90}{105}^{1/3}$

Fig. 10 Comparison of the Kandlikar (1990a) correlation with the saturated flow boiling data of Jalkaus (1975) for R-114

![Graph showing comparison](image)

Jalkaus (1975) R-114 data

- $G=100$ kg/m$^2$, $q=28.3$ kW/m$^2$, $Bo=0.0105$
- $G=150$ kg/m$^2$, $q=49.9$ kW/m$^2$, $Bo=0.013$

Kandlikar (1990a) correlation: $h_{fp}/h_0 = \frac{100}{150}^{1/3}$

Fig. 9 Comparison of the Kandlikar (1990a) correlation with the saturated flow boiling data of Khaparna (1986) for R-22

![Graph showing comparison](image)

Khaparna's (1986) R-22 data, $\rho_f/\rho = 29.4$

- $G=424$ kg/m$^2$, $q=7.66$ kW/m$^2$, $Bo=0.096$
- $G=520$ kg/m$^2$, $q=9.97$ kW/m$^2$, $Bo=0.13$

Kandlikar (1990a) correlation: $h_{fp}/h_0 = \frac{424}{520}^{1/3}$

Fig. 10 Comparison of the Kandlikar (1990a) correlation with the saturated flow boiling data of Jalkaus (1975) for R-114

Conclusions

The interrelationships between the heat transfer coefficient and other major variables during subcooled and saturated flow boiling in circular tubes are investigated. Representative correlating schemes along with some of the reliable experimental data sources on water and refrigerants have been utilized in understanding the underlying heat transfer mechanisms. The parametric behavior during flow boiling is represented in a flow boiling map, which is plotted as $h_{fp}/h_0$ versus $x$ with the modified boiling number, $Bo^*$, and $\rho_f/\rho$ as parameters. The location of CHF is not shown on the map.

In the subcooled boiling region, the onset of nucleate boiling (ONB) and the point of net vapor generation (NVG) have been located. The heat transfer during partial boiling, fully developed subcooled boiling, and beyond the NVG point are represented on the flow-boiling map. The effects of $q$, $G$, and different fluids are represented by $Bo^*$ and $\rho_f/\rho$. A new model is developed to represent the heat transfer in the partial boiling region. The need for further investigation in the region between the NVG and $x=0.5$ has been pointed out.

In the saturated flow-boiling region, the nucleate boiling and the convective boiling dominant regions are displayed. The density ratio, $\rho_f/\rho$, and $Bo^*$ are identified as the major system parameters to represent the effects due to different fluids, operating pressure, $q$, and $G$. The location of CHF is not shown on the map. It is believed that the map will prove to be useful in the design and optimization of various flow-boiling experiments, and also in understanding the underlying mechanisms while developing flow-boiling models for other geometries or for enhanced surfaces.