Heat Transfer Characteristics in Partial Boiling, Fully Developed Boiling, and Significant Void Flow Regions of Subcooled Flow Boiling

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Subcooled flow boiling covers the region beginning from the location where the wall temperature exceeds the local liquid saturation temperature to the location where the thermodynamic quality reaches zero, corresponding to the saturated liquid state. Three locations in the subcooled flow have been identified by earlier investigators as the onset of nucleate boiling, the point of net vapor generation, and the location where $x = 0$ is attained from enthalpy balance equations. The heat transfer regions are identified as the single-phase heat transfer prior to ONB, partial boiling (PB), and fully developed boiling (FDB). A new region is identified here as the significant void flow (SVF) region. Available models for predicting the heat transfer coefficient in different regions are evaluated and new models are developed based on our current understanding. The results are compared with some of the experimental data available in the literature.

1 Overview and Regions of Subcooled Flow Boiling

Consider a subcooled liquid flowing in a heated channel. As long as the channel wall is below the local saturation temperature of the liquid, heat transfer is by single-phase mode. As the wall temperature exceeds the saturation temperature, boiling can be initiated depending on the wall, heater surface, and flow conditions.

The boiling process in the subcooled flow improves the heat transfer rate considerably over the single-phase value. Subcooled flow boiling has therefore received considerable attention where high-heat-flux cooling is required, such as in emergency core cooling of nuclear reactors, first-wall cooling of fusion reactors, neutron generators for cancer therapy and material testing, high-power electronic applications, cooling of rocket nozzles, and pressurized water reactors (Bergles, 1984; Boyd, 1988).

Figure 1 shows a schematic illustrating important locations and regions of subcooled flow boiling. For the sake of simplicity, the discussion is presented for a circular tube. The discussion is valid for other geometries, and the analysis can be easily extended for other simple geometries using the concept of hydraulic diameter. Liquid enters the tube at **A** under subcooled conditions and the tube wall is below the local saturation temperature. The bulk liquid temperature and the wall temperature vary along the length of the tube. Under a constant heat flux surface boundary condition for a circular tube of diameter D, the bulk fluid temperature variation in the flow direction in the nonboiling region can be obtained from an energy balance over the tube length L. In the single-phase, fully developed, nonboiling region, the heat transfer coefficient α_l is almost constant (neglecting property variation with temperature), and the wall temperature rises linearly and parallel to the bulk liquid temperature. At location **B**, the wall temperature reaches the saturation temperature of the liquid. However, nucleation does not occur immediately, as a certain amount of wall superheat is needed to nucleate cavities existing on the wall.

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The first bubbles appear on the wall at location **C**, which is identified as the *onset of nucleate boiling,* or ONB. The wall temperature begins to level off, as more nucleation sites are activated beyond ONB. Farther downstream, as more sites are activated, the contribution to heat transfer from the nucleate boiling continues to rise while the single-phase convective contribution diminishes. This region is called the *partial boiling* region. At **E** the convective contribution becomes insignificant and the *fully developed boiling,* or FDB, is established. Subsequently, the mean wall temperature remains almost constant in the FDB region until some point where the convective effects become important again due to the two-phase flow in the newly defined *significant void flow* region.

The bubbles generated at the wall immediately following ONB cannot grow due to the condensation occurring at the bubble surface exposed to the subcooled liquid flow. A thin layer of bubbles is formed on the wall. As the bulk liquid temperature increases in the flow direction, the layer becomes populated with more bubbles, whose size also increases with decreasing subcooling. At some location **G**, the bubbles eventually detach from the wall and flow toward the liquid core. Some bubbles condense along the way. Point **G** is identified as the point of *net vapor generation,* or NVG, (also called OSV, *Onset of Significant Void*), prior to which the vapor volumetric flow fraction is insignificant. Heat transfer subsequent to NVG can be considered to be in the two-phase region.

The vapor present in the subcooled flow following NVG is at the saturation temperature. This gives rise to a thermodynamic nonequilibrium condition with the liquid temperature falling below the equilibrium subcooled liquid temperature dictated by the local enthalpy. As heat addition continues downstream, the saturation condition under thermodynamic equilibrium is reached at **H**. A nonequilibrium condition exists and the true liquid temperature is indicated by a dashed line. Flow beyond **H** is covered under saturated flow boiling.

The state of the subcooled liquid can be defined in terms of an equilibrium "quality" based on the liquid enthalpy relative to the saturation state:

$$x = (h_l - h_{l,\mathrm{sat}})/h_{lg} = -c_p \Delta T_{\mathrm{sub}}/h_{lg} \tag{1}$$

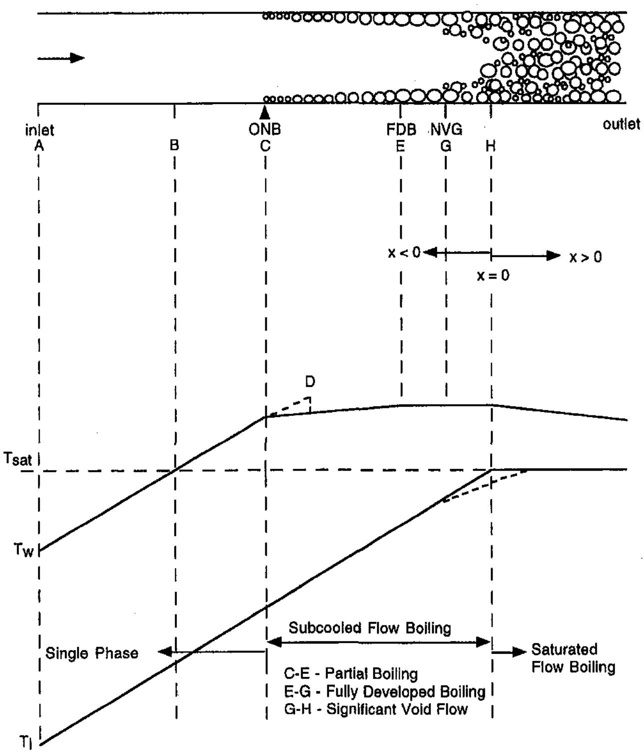

Fig. 1 Schematic representation of subcooled flow boiling

Equation (1) results in a negative quality in the subcooled region. In the single-phase region of the subcooled flow before any boiling is initiated, the heat transfer rate is expressed in terms of the single-phase liquid heat transfer coefficient and the wall-to-liquid temperature difference:

$$\dot{q} = \alpha_l(T_w - T_l) = \alpha_l(\Delta T_{\text{sat}} + \Delta T_{\text{sub}}) \tag{2}$$

Further discussion on the heat transfer rates in different regions is presented in the following sections. Kandlikar (1997) presented a comprehensive summary of heat transfer in different regions. In the present paper, further refinements are incorporated in the nondimensionalizing of ONB criterion, and in the heat transfer models for the *fully developed subcooled flow boiling* and the *significant void flow* regions. Additional data from McAdams et al. (1949) are included in the comparison.

2 Onset of Nucleate Boiling (ONB)

As long as the wall temperature is below the local saturation temperature, nucleate boiling cannot be initiated under steady flow conditions. The bubbles are nucleated on cavities present on the heater surface and require a certain amount of wall superheat depending on the cavity size and the flow conditions. Presence of trapped gases or vapor in the cavities initiates the nucleus formation. Generally, at the beginning of the boiling process at start-up, the cavities are flooded and require a higher degree of wall superheat. Once boiling is initiated, the required superheat to sustain the bubble activity is lower due to the presence of vapor inside the cavities. This behavior is known as the hysteresis effect and is marked for highly wetting liquids such as refrigerants.

In the absence of the hysteresis effect, the nucleation criterion suggested by Hsu and Graham (1961) has shown to predict the nucleation data reasonably well by many later investigators (e.g., Kandlikar and Cartwright, 1995). Bergles and Rohsenow (1964) described the nucleation criterion graphically in terms of the tangency condition and presented an empirical correlation for the ONB condition. Hsu (1962) and Sato and Matsumura (1964) presented equations for $\Delta T_{\text{sat,ONB}}$ and $\dot{q}_{\text{ONB}}$:

$$\Delta T_{\text{sat,ONB}} = \frac{4\sigma T_{\text{sat}} v_{lg} \alpha_l}{\lambda_l h_{lg}} \left[1 + \sqrt{1 + \frac{\lambda_l h_{lg} \Delta T_{\text{sub}}}{2\sigma T_{\text{sat}} v_{lg} \alpha_l}} \right] \tag{3}$$

and

$$\dot{q}_{\text{ONB}} = [\lambda_l h_{lg}/(8\sigma v_{lG} T_{\text{sat}})][\Delta T_{\text{sat,ONB}}]^2 \tag{4}$$

The range of active cavity radii were also presented by Hsu, and Sato and Matsumura. This equation was recently nondimen-

Nomenclature

a, b = constants in Eq. (15)
Bo = boiling number = $\dot{q}/(\dot{m}h_{lg})$
c_p = specific heat, J/kg K
C = const
D = diameter of flow channel, m
D_h = hydraulic diameter of flow channel, m
F_{fl} = fluid-surface parameter in Kandlikar (1990) correlation
f = friction factor
h = enthalpy, J/kg
h_{lv} = latent heat of vaporization, J/kg
m = constant in Eq. (17), given by Eq. (20)
$\dot{m}$ = mass flux, kg/m^{2}s
n = constant in Eq. (20), given by Eq. (22)
Nu = Nusselt number
Pr = Prandtl number
p = constant in Eq. (20), given by Eq. (21)
$\dot{q}$ = heat flux, W/m^{2}K
r_c = cavity radius
r_c^* = nondimensional cavity radius, given by Eq. (5)
Re = Reynolds number
T = temperature, K
v = specific volume, m^3/kg
x = equilibrium quality
x_a = apparent quality, given by Eq. (25)
α = heat transfer coefficient, W/m^{2}K
α^* = α based on wall superheat, W/m^{2}K
δ_t = thickness of the thermal boundary layer thickness = λ/α_1, m
ΔT_{sat} = wall superheat = $T_w - T_{\text{sat}}$, K
ΔT_{sat}^* = nondimensional wall superheat, given by Eq. (6)
ΔT_{sub} = liquid subcooling = $T_{\text{sat}} - T_l$, K
ΔT_{sub}^* = nondimensional liquid subcooling, given by Eq. (7)
λ = thermal conductivity, W/m K
μ = viscosity, N s/m^2
σ = surface tension, N/m

Subscripts

A–E = corresponding to A–E in Fig. 7.
b = bulk
cp = constant property
FDB = fully developed boiling
g = vapor
l = liquid
lo = all flow as liquid
lg = latent
NBD = nucleate boiling dominant
ONB = onset of nucleate boiling
PB = partial boiling
sat = saturated state
sub = subcooled state
SVF = significant void flow
w = wall

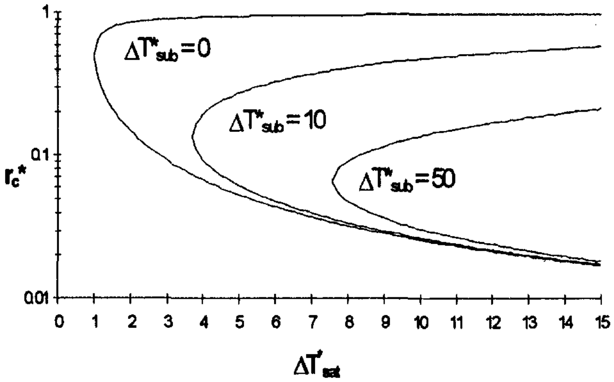

Fig. 2 Nondimensional form of nucleation criterion presented by Kandlikar and Spiesman (1997)

sionalized by Kandlikar and Spiesman (1997) by introducing the following parameters:

$$r_c^* = r_c/\delta_t \tag{5}$$

$$\Delta T^*_{sat} = \Delta T_{sat} h_{lv} \delta_t / (8\sigma T_{sat} v_{lv}) \tag{6}$$

$$\Delta T^*_{sub} = \Delta T_{sub} h_{lv} \delta_t / (8\sigma T_{sat} v_{lv}) \tag{7}$$

The nondimensional form of the active cavity range is then given by the following equation:

$$r^*_{max},\, r^*_{min} = \frac{1}{2}\left[\frac{\Delta T^*_{sat}}{\Delta T^*_{sat} + \Delta T^*_{sub}} \pm \sqrt{\left(\frac{\Delta T^*_{sat}}{\Delta T^*_{sat} + \Delta T^*_{sub}}\right)^2 - \frac{1}{(\Delta T^*_{sat} + \Delta T^*_{sub})}}\,\right] \tag{8}$$

The properties in Eqs. (3)–(8) are evaluated at the saturation temperature and α_l is determined from an appropriate correlation incorporating the wall temperature correction factor. Figure 2 shows the nondimensional plot for the nucleation criterion given by Eq. (8) for three values of ΔT^*_{sub}. Note that $\Delta T^*_{sub} = 0$ corresponds to the saturation condition. Additional factors such as the dissolved gases and surface characteristics further affect the nucleation characteristics.

3 Fully Developed Boiling Region

After ONB, nucleation activity increases along the flow as the liquid subcooling decreases. Heat transfer is by a combination of single-phase convective, and nucleate boiling modes. At some point, heat transfer is essentially by the nucleate boiling mode with little contribution from the single-phase convective mode. This region is called *fully developed boiling* and has been studied extensively for water by earlier investigators in nuclear reactor applications. Table 1 provides a summary of some of the important work reported in literature. Jens and Lottes' (1951) correlation was one of the first ones reported with water data. Thom et al. (1965) later found that this correlation underpredicted their data and proposed a correlation recommended by Collier (1981) and Rohsenow (1985) for water. The Thom et al. correlation agrees well with the low-heat-flux data of Brown (1967) as reported by Rohsenow (1985).

Shah (1977) compiled the available experimental data on twelve fluids from fifteen different sources. The FDB and the *partial boiling* regions are not clearly identified in his correlation; instead he employs the level of subcooling relative to the wall superheat as a criterion and recommends separate correlations for the two regions. The demarcation between the two regions is made by a hand-drawn line through the data sets on a plot of $\Delta T_{sub}/\Delta T_{sat}$ versus Bo.

In the present work, the Kandlikar (1990) correlation for saturated flow boiling heat transfer is re-examined. One of the features of this correlation as reported by Kandlikar (1991) is its ability to predict the trends in α versus x in the low-quality region, explaining the reasons for increasing or decreasing α for different cases. The correlation employed the additive model of the nucleate boiling component and the two-phase convective heat transfer in the saturated boiling region. In the subcooled *fully developed boiling* region, the convective contribution is insignificant and the term representing the nucleate boiling component is expected to represent the total heat transfer coefficient. The heat transfer coefficient α^* in the *fully developed boiling* region is thus given by the following equation derived from the nucleate boiling dominant region of the Kandlikar correlation:

$$\alpha^* = 1058.0 Bo^{0.7} F_{fl} \alpha_{lo} \tag{9}$$

Note that α^* is based on the wall superheat with $\dot{q} = \alpha^* \Delta T_{sat}$, $Bo = \dot{q}/(\dot{m} h_{lg})$. Note that $\dot{m}$ is the total mass flux, kg/m^{2}s. F_{fl} is the fluid-surface parameter, and α_{lo} is the single-phase heat transfer coefficient for all liquid flow (same as α_l in the subcooled region) obtained from Gnielinski (1976) and Petukhov–Popov (1963) correlations along with the property correction factor recommended by Petukhov (1970):

$$\mathrm{Nu}_{lo} = \mathrm{Nu}_{lo,cp}\,(\mu_b/\mu_w)^{0.11} \tag{10}$$

where $\mathrm{Nu}_{lo,cp}$ is the Nusselt number with constant properties obtained from the following equations, and the subscripts b and w refer to the properties at bulk and wall temperatures, respectively.

Petukhov and Popov (1963) found, for $0.5 \le \mathrm{Pr} \le 2000$ and $10^4 \le \mathrm{Re}_{lo} \le 5 \times 10^6$:

$$\mathrm{Nu}_{lo} = \frac{\mathrm{Re}_{lo}\mathrm{Pr}_l(f/2)}{[1.07 + 12.7(\mathrm{Pr}^{2/3} - 1)(f/2)^{0.5}]} \tag{11}$$

Gnielinski (1976) found, for $0.5 \le \mathrm{Pr} \le 2000$ and $2300 \le \mathrm{Re}_{lo} < 10^4$:

$$\mathrm{Nu}_{lo} = \frac{(\mathrm{Re}_{lo} - 1000)(f/2)\mathrm{Pr}_l}{[1 + 12.7(\mathrm{Pr}^{2/3} - 1)(f/2)^{0.5}]} \tag{12}$$

where f is the friction factor given by the following equation:

$$f = [1.58 \ln(\mathrm{Re}_{lo}) - 3.28]^{-2} \tag{13}$$

The heat transfer coefficient in the FDB region of the subcooled flow is expressed in terms of the temperature difference between the wall and the fluid, or $\dot{q} = \alpha^* \Delta T_{sat} = \alpha_{\mathrm{FDB}}(\Delta T_{sub}$

Table 1 Some important correlations for fully developed heat transfer in subcooled flow boiling

Investigator Year	Fluid	Correlation	Comments
McAdams et al. (1949)	water	$\dot{q} = C\,(\Delta T_{sat})^{3.86}$	Perhaps the first reported correlation for *FDB*. The constant C depends on the dissolved air content.
Jens and Lottes (1951)	water	$\Delta T_{sat} = 25\,\dot{q}^{0.25}\exp(p/62)$; p - bar, $\dot{q}$ - MW/m^2, T - K	Earlier correlation, modified by later investigators.
Thom et al. (1965)	water	$\Delta T_{sat} = 22.65\,\dot{q}^{0.5}\exp(p/87)$; p - bar, $\dot{q}$ - MW/m^2, T - K	$\dot{q} \propto \Delta T_{sat}^2$ from the correlation, data indicates an exponent of 3, tested for low heat flux water data.
Mikic and Rohsenow (1969)	water	$\dot{q} = 1.89\times10^{-4}\, \bullet\, g^{1/2} h_{lg}^{1/2} \rho_l^{17/8} c_{p,l}^{19/8} \rho_g^{1/8} (\Delta T_{sat})^3 / [\sigma^{9/8} (\rho_l - \rho_g)^{3/8} T_{sat}^{1/8}]$	Developed for pool boiling, includes surface effects, recommended by Rohsenow (1985) for *FDB*.
Shah (1977)	R-11, R-12, R-113, water, other fluids.	$\dot{q} = [230\,(\dot{m}\, h_{lv})^{-0.5}\, \alpha_{lo}\, \Delta T_{sat}]^2$ α_{lo} from Dittus-Boelter correlation	$\dot{q} \propto \Delta T_{sat}^2$, not supported by data; no clear distinction between *partial* and *fully developed boiling*; hand-drawn line through data to include the effect of subcooling.
Present work	water, refrigerants	$\dot{q} = [1058\,(\dot{m}\, h_{lv})^{-0.7} F_{fl}\, \alpha_{lo}\, \Delta T_{sat}]^{1/0.3}$ α_{lo} from Gnielinski, and Petukhov and Popov correlations; F_{fl} - fluid-surface parameter, given by Kandlikar (1991).	Represents correct dependence of $\dot{q}$ on ΔT_{sat}; compares well with Bergles and Rohsenow's (1964), McAdams et al. (1949) and Del Valle and Kenning (1985) water data, and other refrigerant data.

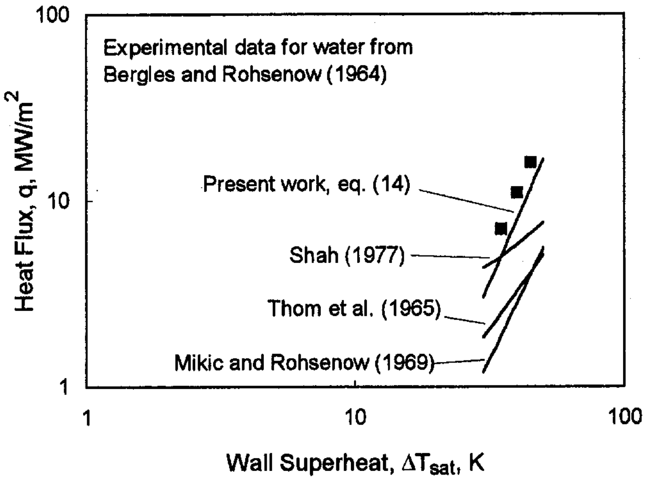

Fig. 3 Comparison of *fully developed boiling* correlations with experimental data from Bergles and Rohsenow (1964); subcooled water, 4.5 m/s flow velocity, 109-72°C subcooling, 2.2 bar pressure.

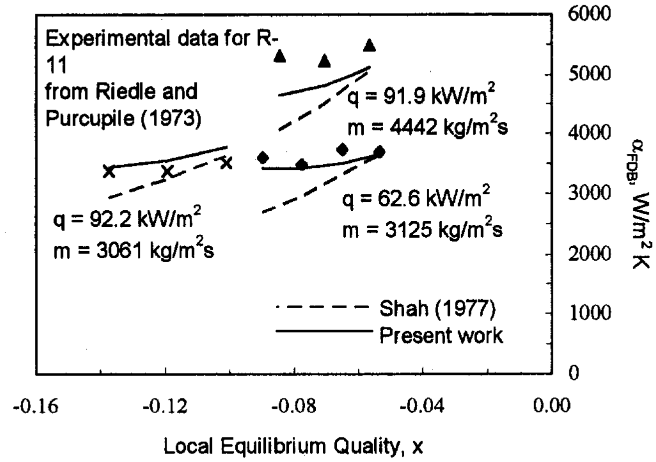

Fig. 4 Comparison of present work, Eq. (9), and Shah (1977) correlations with Riedle and Purcupile (1973) experimental data in the *fully developed boiling* (FDB) region

$+\ \Delta T_{sat}$). Combining the definition of α^* and Bo with Eq. (9) results in the following expression for $\dot{q}$ in the FDB region:

$$\dot{q} = [1058(\dot{m}h_{lg})^{-0.7}F_{fl}\alpha_{lo}\Delta T_{sat}]^{1/0.3} \tag{14}$$

The present correlation given by Eq. (14) and the other correlations listed in Table 1 are compared with the experimental data of Bergles and Rohsenow (1984) for water flowing in an annulus over a heated stainless steel tube. The results are shown in Fig. 3. The Thom et al. (1965) correlation considerably underpredicts the results. This was also noted by Rohsenow (1985) who reported that the Thom et al. correlation is able to predict Brown's (1967) data, which are in the low heat flux range. The pool boiling curve represented by the Mikic and Rohsenow (1969) correlation is below the FDB curve, but has the same slope as the experimental FDB data. The Shah (1977) correlation underpredicts the results, and exhibits a lower slope. The dependence of $\dot{q}$ on ΔT_{sat} is expressed through an exponent of 3.86 by McAdams et al. (1949), whereas it is 2.0 in the correlations of Shah and Thom et al., and 3.33 in the present work. The present work agrees closely with the data and displays the same trend as seen from Fig. 3.

To compare the present correlation with the Shah (1977) correlation further, the refrigerant data by Riedle and Purcupile (1973) employed in Shah's correlation development are used. The FDB region is identified by the method described in the next section. Figure 4 shows the results of the comparison in the FDB region for R-11 under two different conditions. The agreement with both the Shah correlation and the present work is excellent; the absolute mean error with the Shah correlation is 14.5 percent, while it is 13.0 percent with the present work. The data points close to $x = 0$ sometimes show larger deviation as they may fall under the *significant void flow* region. Use of the saturated flow boiling correlation (Kandlikar, 1990) with the nonequilibrium quality calculated from Saha and Zuber (1974) improves the results, and is discussed in greater detail in section 6.

To verify the FDB model given by Eq. (14) further, it is compared with the data reported by McAdams et al. (1949). They conducted experiments with subcooled flow of water at 2.07, 4.14, and 6.2 bar pressures in annuli with an inner diameter of 6.35 mm, and jacket diameters of 4.32 mm, 10.92, and 18.54 mm ID tubes. The corresponding hydraulic diameters were 4.32, 12.19, and 13.21 mm. Water velocity was varied from 0.3 m/s to 11 m/s.

Figures 5 and 6 show the comparison of the McAdams et al. (1949) data for two conditions with the present model in the PB and FDB regions. The steep vertical line represents the present model given by Eq. (14) in the FDB region. As can be seen, the agreement is excellent.

4 Location of FDB

Figure 7 shows a plot of $\dot{q}$ versus T_w at constant subcooling. **A-B** lies in the single-phase region, with ONB starting at **C**, and the *fully developed boiling* beginning at **E**. The location **E** where the FDB begins has been investigated by many investigators, and the model by Bowring (1962) is widely recommended. In the present work, the same model is employed. The intersection of the extension of the single-phase line **A-B-F** given by Eqs. (2) and (10)–(13), and the fully developed boiling curve E-F-G given by Eq. (14) identifies **F**, and $\dot{q}_F$ is obtained by solving the two-equation sets:

$$1058F_{fl}(\dot{m}h_{lg})^{-0.7}\dot{q}_F - \dot{q}_F^{0.3} - 1058\alpha_{lo}F_{fl}(\dot{m}h_{lg})^{-0.7}\Delta T_{sub} = 0 \tag{15}$$

An iterative scheme is needed to solve Eq. (15) for $\dot{q}_F$ at given

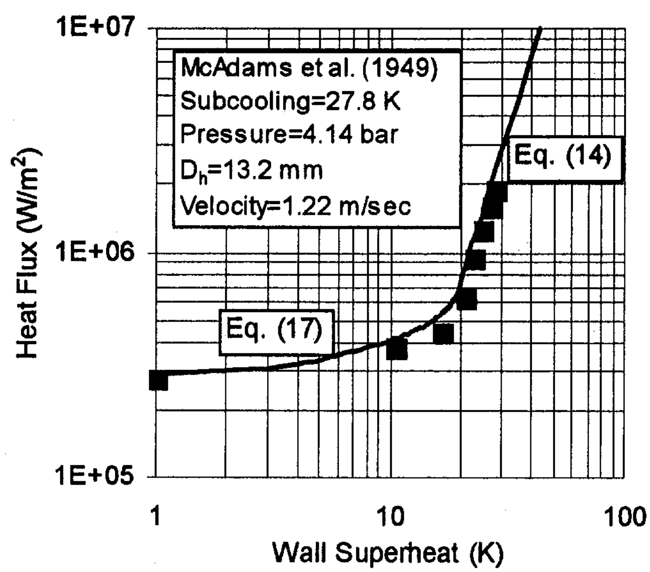

Fig. 5 Comparison of the present model, Eqs. (17) and (14), with McAdams et al. (1949) data in the *partial boiling* and the FDB regions, water velocity 1.22 m/s

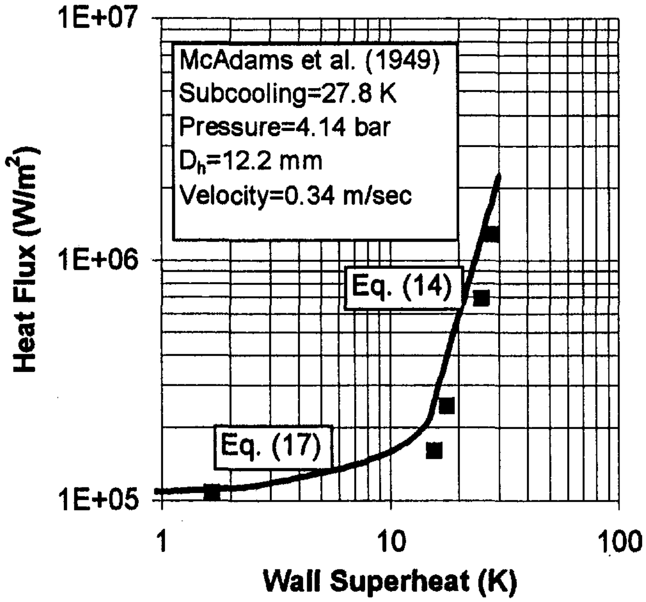

Fig. 6 Comparison of the present model, Eqs. (17) and (14), with McAdams et al. (1949) data in the *partial boiling* and the FDB regions, water velocity 0.34 m/s

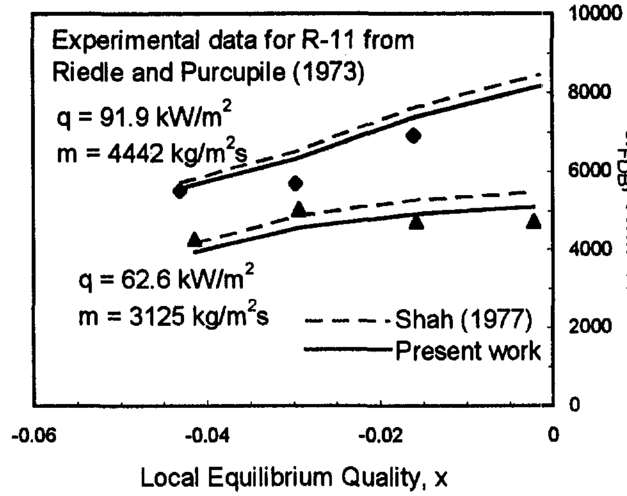

Fig. 8 Comparison of present work, Eqs. (15)-(22), and Shah (1977) correlation with Riedle and Purcupile (1973) data for R-11 in the *partial boiling* region

values of $\dot{m}$ and ΔT_{sub}. After locating **F**, $\dot{q}_E$ is obtained from the Bowring (1962) model given by the following equation:

$$\dot{q}_E = 1.4\,\dot{q}_F \tag{16}$$

The wall superheat at **E** can be calculated from the FDB equation, Eq. (14).

5 Partial Boiling Region

The *partial boiling* region is identified as the region between **C**, where ONB begins, and **E**, where FDB begins, as shown in Fig. 7. The heat transfer in this region is calculated by slightly modifying the procedure outlined by Kandlikar (1991) as follows.

The heat flux $\dot{q}_E$ at **E** is obtained from Eq. (14), and $\dot{q}_C$ at **C** is obtained from Eqs. (3) and (4) at ONB. In the *partial boiling* region **C-E**, the following equation is employed:

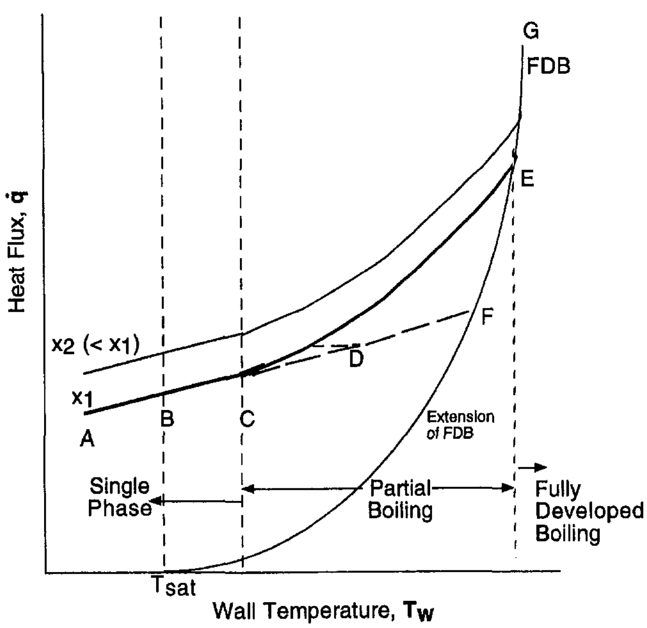

Fig. 7 Heat transfer in *partial boiling* region

$$\dot{q} = a + b(T_w - T_{sat})^m \tag{17}$$

The constants a and b are obtained from the known heat fluxes at **C** and **E**:

$$b = \frac{\dot{q}_E - \dot{q}_C}{(\Delta T_{sat,E})^m - (\Delta T_{sat,C})^m} \tag{18}$$

and

$$a = \dot{q}_C - b(\Delta T_{sat,C})^m \tag{19}$$

The exponent m is treated as a constant in Eqs. (17)–(19), and is determined as follows:

$$m = n + p\dot{q} \tag{20}$$

where the constants n and p are obtained by matching the slopes of $m = 1$ at **C** to $m = 1/0.3$ at **D**:

$$p = (1/0.3 - 1)/(\dot{q}_E - \dot{q}_C) \tag{21}$$

and

$$n = 1 - p\dot{q}_C \tag{22}$$

This procedure assures smooth transitions from the single-phase region to the *partial boiling* region, and then to the FDB region. The gradual change in the slope also reflects the fact that an increasing number of nucleation cavities are activated as wall superheat increases.

The model outlined above for heat transfer in the *partial boiling* region is compared with the experimental data of Riedle and Purcupile (1973) for R-11 for three conditions. In the experiments, the liquid temperature increases as it is heated along the length of the tube. The results are therefore plotted on α versus x coordinates, where $\alpha = \dot{q}/(\Delta T_{sub} + \Delta T_{sat})$. Figure 8 shows a comparison of the present model and Shah's (1977) correlation with Riedle and Purcupile's data. This data set was used in the correlation development by Shah. As can be seen from Fig. 8, the present model results in a slightly better agreement than the Shah correlation. For the entire data set, the absolute mean error with the Shah correlation is 11 percent, while it is 7.9 percent with the present method. It may be noted that the present model utilizes the earlier correlations for the FDB and ONB conditions, and that no additional empirical

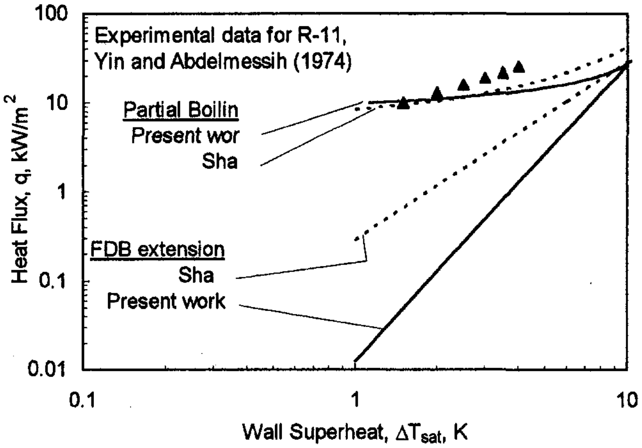

Fig. 9 Comparison of present work, Eqs. (15)–(22), and Shah (1977) correlation with Yin and Abdelmessih (1974) data for R-11 in the *partial boiling* region; 1.4 bar and 611 kg/m²s

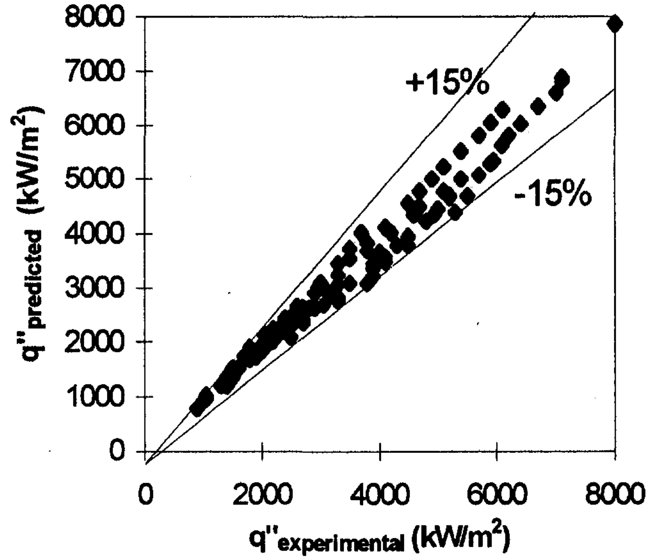

Fig. 11 Comparison of the present work using the nonequilibrium quality in the Kandlikar (1990) correlation with subcooled water data by Del Valle and Kenning (1985) for 0.2 mm heater thickness

constants are introduced. Figures 9 and 10 show similar comparisons with Yin and Abdelmessih's (1974) data for R-11, and Hino and Ueda's (1985) data for R-113, respectively. The local subcooling for the each data point was not available, and it is suspected that some of the data points, especially in Fig. 9, may be under the *fully developed boiling* region. Further improvement is expected from the present model after correcting each data point for the local subcooling.

Comparison of McAdams et al. (1949) data in the PB region can also be seen from Figs. 5 and 6. The agreement is seen to be excellent. It can be seen that the Bowring's model for the transition to FDB is also well represented.

6 Significant Void Flow Region

The point of net vapor generation identifies the location in the subcooled flow where the net void fraction begins to be significant. It is postulated by Kandlikar (1997) that the two-phase flow effects would become important and the saturated flow boiling correlations should be applicable. Although the thermodynamic quality is negative in this region, the nonequilibrium quality based on the void fraction would be positive. An apparent quality, x_a, is therefore introduced to account for the nonequilibrium effects.

Saha and Zuber (1974) correlations are employed to locate the thermodynamic quality x_{NVG} at location **G** shown in Fig. 1.

$\text{Re}_{lo}\text{Pr}_l < 70{,}000$:

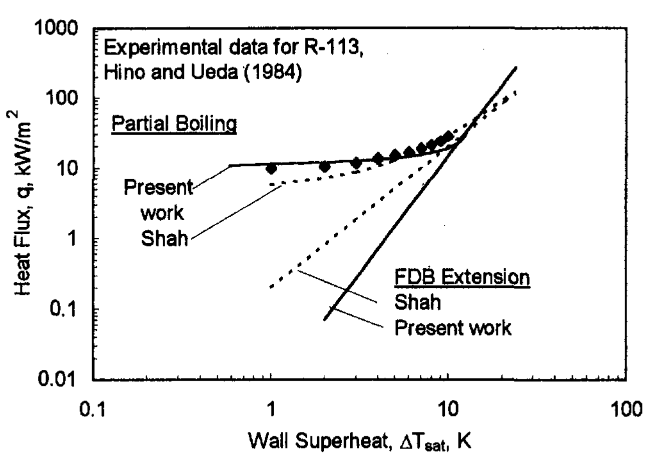

Fig. 10 Comparison of present work, Eqs. (15)–(22), and Shah (1977) correlation with Hino and Ueda (1984) data for R-113 in the *partial boiling* region; 1.47 bar and 515 kg/m²s

$$x_{\text{NVG}} = -0.0022\,\frac{\dot{q}D}{\rho_l h_{lg} \kappa_l} = -0.0022 Bo\ \text{Re}_{lo}\text{Pr}_l \quad (23)$$

$\text{Re}_{lo}\text{Pr}_l > 70{,}000$:

$$x_{\text{NVG}} = -154 Bo \quad (24)$$

The apparent quality in the *significant void flow* region beyond x_{NVG} is obtained from a correlation also recommended by Saha and Zuber (1974):

$$x_a = \frac{x - x_{\text{NVG}} \exp(x/x_{\text{NVG}} - 1)}{1 - x_{\text{NVG}} \exp(x/x_{\text{NVG}} - 1)} \quad (25)$$

where x is the actual thermodynamic quality (negative value in the subcooled region).

The apparent quality x_a is then used in the Kandlikar (1990) correlation for saturated flow boiling. Kandlikar (1997) have proposed the model given above and compared the available experimental data for water and refrigerants from literature. Figure 11 shows the results of comparison with the subcooled flow boiling data obtained by Del Valle and Kenning (1985) for a heater thickness of 0.2 mm and three different velocities. The experimental data are obtained for the flow of water in a rectangular channel. Del Valle and Kenning compared their data with the available models for the fully developed boiling and found large errors (predicted heat fluxes were lower by a factor of over two). The data reported by Del Valle and Kenning correspond to the thermocouple location toward the exit of the test section located 130 mm from the inlet. In the present analysis, their data are corrected to obtain the local temperature and the equilibrium quality by applying the heat balance equation over the heated length between the inlet section and the thermocouple location. It can be seen from Fig. 11 that the agreement is excellent for all three velocities.

7 Additional Remarks

The experimental data reported in literature on subcooled boiling should be used with caution. In applying the equations and models in this region, it is essential to determine the local subcooling at the section where wall temperature is measured. In many data sets, including Del Valle and Kenning (1985), the subcooling at the inlet to the test section is reported. As the liquid flows through the test section, it gets heated and the local subcooling decreases in the flow direction. This effect is quite significant in long test sections under high-heat-flux conditions.

8 Conclusions

Subcooled flow boiling is divided into three regions, *partial boiling, fully developed boiling,* and a newly defined *significant void flow* region. A comprehensive methodology with appropriate correlations is presented to predict the heat transfer in each region. Highlights of the proposed methodology are given below.

(*a*) The onset of boiling is determined from the bubble nucleation criterion proposed by Hsu and Graham (1961). The nondimensional form of equations presented by Kandlikar and Spiesman (1997) provide a clear way to study the parametric effects.

(*b*) Bowring's (1962) method is employed to identify the beginning of the *fully developed boiling* region.

(*c*) The nucleate boiling component in the Kandlikar correlation (1990) for saturated flow boiling in the nucleate boiling dominant region is employed to describe the heat transfer in the *fully developed boiling* region.

(*d*) The method proposed by Kandlikar (1991) is slightly modified/corrected for heat transfer in the *partial boiling* region.

(*e*) The Saha and Zuber (1974) correlation is used to determine the location of the NVG point and the nonequilibrium quality at a given section in the *significant void flow* region.

(*f*) The correlation for the nucleate boiling dominant (NBD) region in the Kandlikar (1990) correlation is used to calculate the heat transfer coefficient in the *significant void flow* region using the nonequilibrium quality.

(*g*) It is recommended that the nonequilibrium quality be employed, instead of the thermodynamic equilibrium quality, in the low-quality saturated flow boiling region as well for estimating the heat transfer coefficient using the Kandlikar (1990) correlation.

The methodology described in (*b*)–(*f*) has been compared with some of the available experimental data on water and refrigerants with very good agreement, generally within less than 10–15 percent.

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