AN IMPROVED CORRELATION FOR PREDICTING TWO-PHASE FLOW BOILING HEAT TRANSFER COEFFICIENT IN HORIZONTAL AND VERTICAL TUBES

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ABSTRACT

A new correlating scheme is proposed to predict the two-phase flow boiling heat transfer coefficient in horizontal and vertical tubes. The highlights of the scheme are, (i) the use of additive mechanism of nucleate boiling and convective heat transfer, (ii) different influence of Froude number on the two mechanisms in horizontal flow, and (iii) the introduction of a fluid dependent parameter \( F_{f1} \) in the nucleate boiling term. The proposed correlation does better than any other correlating scheme for the range of fluids tested, including water, refrigerants and cryogenic fluids. The mean deviation for all the data sets considered is 17.1 percent.

INTRODUCTION

Flow boiling is an important mode of heat transfer employed in a number of heat exchange equipments used in the power and process industry. Accurate estimation of the two-phase flow boiling heat transfer coefficients, besides being of critical importance in some cases, usually offers considerable economic saving in the design and operation of these equipments. This paper is aimed at developing a correlation to predict (within about 15-20 percent) the heat transfer coefficient during flow boiling of various fluids, including water, refrigerants and cryogenic fluids, in horizontal as well as vertical tubes.

PREVIOUS WORK

Table I gives some of the important correlations for flow boiling heat transfer coefficient in vertical and horizontal tubes. Following the success of the Martinelli parameter, \( X_{e2} \), in predicting the two-phase pressure drop, Guerrieri and Taitt (1) proposed a heat transfer correlation using \( X_{e2} \). Dengler and Addoms (2) recognized the nucleation effects in flow boiling, and introduced a nucleation factor, \( F_{n} \), in their correlation. Bennett et al. (3) observed a more direct influence of heat flux, \( q \), which was incorporated as a multiplication factor, \( q^{0.11} \) while Uchida and Yamaguchi (4) employed the boiling number \( Bo \), with \( Bo^{0.2} \) as a multiplication factor. Schrock and Grossman (5) employed two additive terms consisting of \( Bo \) and \( X_{e2} \) in their correlation.

Chen (6) proposed an additive mechanism of nucleate boiling and convective heat transfer. He used the Dittus-Boelter correlation for the convective term, and the Forster-Zuber's pool boiling correlation for the nucleate boiling term. A two-phase factor, \( F \), was included in the convective term to represent the two-phase effects, and a suppression factor, \( S \), was included in the nucleate boiling term to account for the suppression of nucleate boiling due to flowing liquid. An elaborate iterative calculation procedure was employed to determine the constants in the equation, using the experimental data of six investigators. Chen's correlation has been recommended by many researchers for general use (e.g. 7, 8). However, it tends to overpredict the effect of nucleation, resulting in large deviations, as reported by several investigators including Anderson et al. (9), Chaddock et al. (10), Jallouk (11), and Mohr and Rüge (12).

Shah (13) proposed a correlating scheme in a chart form. The ratio of two phase to single phase liquid only heat transfer coefficients, \( h_p/h_0 \), was plotted against the convection number \( Co \), with \( Bo \) as a parameter. The chart was divided into two regions - one in which the influence of \( Bo \) is insignificant, and the other in which the influence of \( Co \) is insignificant. Additionally, the Froude number, \( Fr \), was introduced for horizontal tubes. The mean deviation with over 800 data points for water, R-11, R-12, and cyclohexane was 14 percent. Subsequently, Shah (14) proposed correlations to represent the chart within 10 percent.

Recently, Bennett and Chen (15), and Bennett et al. (16) proposed modifications to the original Chen's equation. The two-phase factor \( F \) was derived analytically by relating the wall shear stresses to the pressure drops in the two phase and single phase liquid only flows, and then assuming a linear variation of the thermal diffusivities in the viscous sublayer. The parameter \( S \) was derived by assuming an exponential temperature profile in the bubble growth region, \( X_0 \), near the wall. The final expressions are given in Table I. The agreement with their own water data in vertical tubes and R-11 data in vertical thin-film shell side boiling was reasonably good. Further verification with additional data may be needed before using it as a general correlation for vertical flows.

Kandlikar and Thakur (17) proposed a correlation using \( h_p/h_0 \), \( Bo \), \( Co \) and \( Fr \). The additive mechanism of nucleate boiling and convective mechanism was employed for the entire range of parameters. For the horizontal flow, the Froude number, \( Fr \), was used to account for the asymmetric film distribution along the circumference. This asymmetric distribution affects both, the nucleate boiling, and the convective heat transfer, though to a different degree. This fact was accounted for by employing different exponents for \( Fr \) in the two terms. Kandlikar and Thakur compared their correlation with other correlations, including Shah's chart correlation, and obtained better results (mean deviation of 13.3 percent against 14 percent with Shah's chart).
correlation) with the data for water, R-11, R-113, and cyclohexane.

In the present paper, additional data for cryogenic fluids and refrigerants is compared with the correlation developed in ref. (17). An improvement in the heat transfer model is suggested to include a wider range of fluids.

DEVELOPMENT OF THE CORRELATION

In an evaporator tube, heat is transferred from the wall to the fluid by three means: (i) nucleate boiling in the liquid adjacent to the wall, (ii) convection from the wall to the liquid, followed by surface evaporation at the liquid-vapor interface, and (iii) convection from the wall to the vapor. The third term is usually quite small in comparison to (i) and (ii), except in the post-burnout region. The heat transfer is thus by two mechanisms: (a) nucleate boiling and (b) forced convection to liquid, both of which are present to a varying degree depending on the flow conditions. It is, therefore, reasonable to assume an additive mechanism, as originally proposed by Chen (6):

$$h_{TP} = h_{conv} + h_{nucl}$$

The choice of the parameters representing each term on the right hand side of the Equation (1) is made on the basis of the heat transfer mechanism involved, and the success of a particular parameter in previous investigators' correlations. For the convective term, Chen used a two-phase multiplication factor $F_{p}$, which is given as a function of $X_{et}$. The Martinek parameter $F_{p}$ has been widely used to represent the convective term, as seen from Table 1. Shah used a modified parameter, called Convection number $C_{o}$, which is similar to $X_{et}$, but neglects the vapor viscosity effects. In the present work, $C_{o}$ is used to represent the convective term, primarily because of its success in Shah's chart correlation.

The second term on the right hand side of the Equation (1) represents nucleation effects. Chen used Forster-Zuber's pool boiling correlation with a suppression factor $S$, while Chawla (18) used Stephen's correlation, and Jallouk (11) tried Roosjen's correlation. Mohr and Runge (12) obtained the nucleate boiling contribution in their flow boiling data for Neon, after subtracting the convective contribution calculated from an equation that was fitted to their own results for convective boiling. The nucleate boiling contribution obtained in this manner was plotted against $\Delta T$. A large scatter in the data was obtained, and Mohr and Runge concluded that $S$, instead of $\Delta T$, should be used to correlate the nucleate boiling contribution. This was further confirmed when the nucleate boiling term in Schrock and Grossman's correlation, employing $B_{o}$ ($= q/\sqrt{G}$) as a parameter, correlated their data very well, while Chen's and Chawla's nucleate boiling terms, employing $\Delta T$ as a parameter, resulted in large scatter. In the present study, therefore, $S_{o}$ is employed to represent the nucleate boiling contribution.

In a previous work (17), this author presented a correlation (refer Table 1) using experimental data for water, R-11, R-113 and cyclohexane (19, 20, 18, 21) for vertical as well as horizontal tubes. In the present work, the applicability of the correlation is checked against additional data for R-12 (22), R-114 (11), Nitrogen (23), and Neon (12).

Figure 1 shows a comparison of the Jallouk's experimental values of $h_{TP}$ for R-114 in vertical tubes versus the predicated values using equations given in ref. (17). Large systematic deviations (>40 percent) are observed throughout the range. Still larger deviations are obtained with Shah's correlation (14) as seen from a similar comparison shown in Figure 2. The same trend was observed with the Nitrogen and Neon data. This clearly indicated that the correlations given in ref. (14) and (17) may not be applicable to other fluids.

Jallouk (11) observed similar systematic deviations with his data for R-114 using Chen's correlation. He attributed these deviations to the Forster-Zuber's pool boiling correlation. The pool boiling data for R-11, R-113 and R-114 could not be correlated with Forster-Zuber's correlation. However, when an additional multiplication factor for each fluid was applied in the pool boiling correlation, all the pool boiling data was very well correlated. These factors are given in Table 2, for R-11, R-13 and R-114. When Jallouk applied the same multiplication factor of 1.899 for R-114 to the Chen's nucleate boiling term, it resulted in considerable improvement in correlating his own R-114 flow boiling data.

In the present work, a similar form of equation as suggested in ref. (17), is used on the basis of the additive mechanism described by equation (1). The deficiency of all the previous equations in predicting the pool boiling term was taken care of by incorporating a fluid dependent correction factor, $F_{p}$. This factor is similar to the correction factor given in Table 2, which is obtained by comparing the pool boiling data with the Forster-Zuber pool boiling correlation. It may be expected to find this correction factor, $F_{p}$, to be dependent on the fluid-surface combination, cavity sizes, and their distribution on the heating surface. But in the absence of any such categorical data, $F_{p}$ is believed to be only fluid dependent, and its value close to $F_{p}$ for pool boiling. The resulting correlation in its final form is:

**Vertical flow**

$$h_{TP} = D(1+C)D_{p}^{2}h_{p}^{2} + D(Bo)^{4}h_{p}F_{p}$$

**Horizontal flow**

$$h_{TP} = D(1+C)(25Fr_{p})D_{p}^{2}h_{p}^{2} + D(Bo)^{4}(25Fr_{p})^{2}h_{p}F_{p}$$

The single phase liquid-only transfer coefficient $h_{p}$ is calculated by the Dittus-Boelter equation

$$h_{p} = 0.023(G_{1-x})^{0.8}Fr_{p}^{0.4}$$

All the properties are evaluated at the saturation temperature.

The constants $D_{1-6}$ and $F_{p}$ for each fluid are evaluated using the experimental data of Mumm (17) and...
Wright (18) for water, Jallouk (11) for R-114, Chawla (16) for R-11, Steiner and Schlunder (21) for Nitrogen, Mohr and Runge (12) for Neon, and Bandel and Schlunder (22) for R-12. Initial guess value for \( f_{g} \) for a particular fluid is assigned by comparing the pool boiling data for that fluid with the Forster-Zuber's correlation. For example, the initial guess values of \( f_{g} \) for R-11 and R-114 are 1.389 and 1.899 respectively, as obtained from Table 2. Using these \( f_{g} \) values, the constants D1-D6 are evaluated by employing a steepest gradient ascent technique to minimize the overall r.m.s. error. The constants D1-D6 are then used to determine the refined values of \( f_{g} \) for each fluid, using individual data sets, by a simple search technique. The full procedure is repeated to determine the new values of the constants, D1-D6. Any further iterations for \( f_{g} \) and the constants D1-D6 are found unnecessary. The final values of the constants are given in Table 3, and the \( f_{g} \) values for the five fluids tested are given in Table 4. Table 5 shows the ranges of parameters for the data used in developing the correlation.

It may be noted in equations (2) and (3) that the values of constants D1-D4 are the same for vertical as well as horizontal orientations. The only difference in the case of horizontal orientation is the presence of the Froude number terms, which disappears at \( Fr > 0.04 \), giving the same correlation as vertical orientation.

RESULTS AND DISCUSSION

The proposed correlation, equations (2) and (3), is compared with the data used in its development. Figure (3) shows the result of comparison of the experimental heat transfer coefficients with the predicted values using the proposed correlation. It may be seen that the agreement is very good.

The ratio \( \frac{h_{exp}}{h_{pred}} \) is plotted against the three correlating parameters, Co, Bo and Fr in Figures (4), (5) and (6) respectively. A large number of points could not be represented due to overcrowding near the line \( \frac{h_{exp}}{h_{pred}} = 1 \). It can be seen that the errors are quite evenly spread on the positive and negative sides for each particular data set. Also, the agreement is equally good over the entire range for the parameters Co, Bo and Fr.

COMPARISON WITH OTHER CORRELATIONS

The proposed correlation is compared with the author's previous correlation, ref. (17), and with Shah's chart correlation (13,14) which is recommended by Colliat (8) for predicting flow boiling heat transfer coefficients in horizontal as well as vertical tubes.

Table 6 gives the mean deviation (mean of absolute values of \( h_{exp} - h_{pred} \)) with individual data sets and the comparison of the three correlations. It can be seen from this table that the proposed correlation does better than Shah's chart correlation as well as the author's previous correlation for the new data sets considered (R-114, Nitrogen and Neon). While Shah's chart correlation and the author's previous correlation (17) give very large deviations for R-114 (46 and 45 percent resp.), Nitrogen (57 and 54 percent resp.) and Neon (47 and 42 percent resp.), the proposed correlation results in a mean deviation of less than 20 percent for all data sets except for R-12, and Nitrogen in the range Co>0.65.

A comparison of the Jallouk's R-114 data with the three correlations is shown in Figures 1 and 2. It may be seen that the other two correlations consistently underpredict the \( h_{TP} \) values. Similar results are obtained for R-12, Nitrogen and Neon data.

The proposed correlation results in an average deviation of 17.7 percent for Co>0.65, and 15.4 percent for Co<0.65, considering all the data sets for water, R-11, R-12, R-114, Nitrogen and Neon. Steiner and Schlunder's (21) Nitrogen data is well correlated in the range Co>0.65 (mean deviation 15.0 percent), but results in a rather large deviation of 24.3 percent in the range Co<0.65. Steiner and Schlunder correlated their data using six dimensionless groups. They found that 80 percent of their data was correlated within ±20 percent, while quite large deviations are seen with some of the data points. The dimensionless groups were obtained from dimensional analysis and contain almost all the properties related to the boiling phenomena. In comparison, the present correlation, employing only three dimensionless groups, does quite well.

INFLUENCE OF FRouDE NUMBER

To investigate the influence of Froude number, Chawla's data is considered in greater detail as it covers a very wide range of \( f_{g} \). The proposed correlation for vertical orientation is used without any \( f_{g} \) correction for Chawla's data. The results are plotted in Figure (7). It can be seen from this figure that for \( Fr > 0.04 \), the results are quite good. However, for \( Fr < 0.04 \), it results in consistent overprediction \( h_{exp} < h_{calc} \). As the \( Fr \) decreases below 0.04, larger errors are observed. This may be because of stratification or drying up of the upper portion of the tube inside wall. To take into account this variation, correction factors of \( Fr_{D5} \) and \( Fr_{D6} \) are introduced in the convective and pool boiling terms. However as no correction is needed above \( Fr > 0.04 \), a function 25xFr is used to satisfy this condition. The resulting correlation gives very good results as seen from Figure (5).

INFLUENCE OF \( f_{g} \)

The influence of the multiplication factor \( f_{g} \) in the pool boiling term is investigated in further detail. Jallouk's R-114 date for vertical flow is used to illustrate the influence of \( f_{g} \).

In the proposed correlations, a value of \( f_{g} = 2.150 \) is used for R-114. This results in a mean deviation of 16.9 percent. A comparison of the predicted and experimental values is shown in Figure (1).

Figure (2) shows a similar comparison using \( f_{g} = 1.699 \) for R-114 from Table 2. It may
be seen that the agreement is fair, with a mean deviation of 20.4 percent. However, neglecting this correction factor ($F_{fl} = 1.0$) results in a mean deviation of 49.4 percent.

It may be seen that the values of $F_{pool}$ boiling and $F_{fl}$ given in Tables 2 and 4 are quite close, 1.389 and 1.35 for R-11, and 1.899 and 2.15 for R-114 respectively. This fact may be utilized while extending the applicability of the proposed correlation to other fluids. Any reliable experimental results for flow boiling of that fluid may be used to determine $F_{fl}$ by employing simple curve fitting techniques. In the absence of any flow boiling information for the new fluid, $F_{pool}$ boiling may be used in place of $F_{fl}$ in Equations (2) and (3), without great loss of accuracy.

CONCLUSIONS

The proposed correlation, Equations (2) and (3) along with Tables 3 and 4, is based on an additive mechanism of nucleate boiling and convective heat transfer. It is developed using the experimental data of seven investigators for water, refrigerants R-11, R-12, R-114, and cryogenic fluids Nitrogen and Neon. It is applicable to vertical as well as horizontal orientations. This correlations does better than all the available correlations with a mean deviation of 17.1 percent for all the data sets tested.

The proposed correlation may be extended to other fluids by first evaluating the value of $F_{fl}$ using the flow boiling data for that fluid. Alternatively, if no such flow boiling data is available, $F_{fl}$ may be obtained, as a first approximation, by comparing the pool boiling data for that fluid with the Forster-Zuber's pool boiling correlation.

NOMENCLATURE

$Bo$ = Boiling number $q/G$ h$_{fg}$
$C_p$ = Specific heat
$Co$ = Convection number \((1-x)\frac{0.8 \times P_g}{P_f}\)
$D$ = Diameter of tube
$D_1-D_6$ = Constants in Equations (2) and (3)
$F_{fl}$ = Fluid dependent multiplication factor in Equations (2) and (3), given in Table 4
$f_{pool}$ = Pool boiling multiplication factor for Forster-Zuber's correlation, Table 2
$F_r$ = Froude number with all flow as liquid, $G^2/gP_g$
$G$ = Mass flux
$g$ = Acceleration due to gravity
$h_{TP}$ = Two-phase heat transfer coefficient
$h_l$ = Single-phase liquid only heat transfer coefficient
$h_e$ = Single-phase all flow as liquid, heat transfer coefficient
$k$ = Thermal conductivity
$Pr$ = Prandtl number, $C_p\nu/k$
$q$ = Heat flux
$Re$ = Reynolds number, $GD/\nu$
$X_{tt}$ = Martinelli Parameter, \(\frac{(1-x)}{x} \times \frac{0.9 \times P_g}{P_f} \times \frac{(1-x)}{\mu_g}
\)
$x$ = Dryness fraction
$\mu$ = Dynamic viscosity
$\rho$ = Density

SUBSCRIPTS

conv = convection
exp = experimental
$g$ = liquid
nucl = nucleate boiling
pred = predicted
TP = two-phase

REFERENCES


### TABLE 2
Multiplication factor, $F_{pool boiling}$, for Forster Zuber

<table>
<thead>
<tr>
<th>Fluid</th>
<th>$F_{pool boiling}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-11</td>
<td>1.389</td>
</tr>
<tr>
<td>R-113</td>
<td>1.240</td>
</tr>
<tr>
<td>R-114</td>
<td>1.899</td>
</tr>
</tbody>
</table>

### TABLE 3
Values of the Constants in Equations (2) and (3)

<table>
<thead>
<tr>
<th>Constant</th>
<th>$C_0&lt;0.65$</th>
<th>$C_0&lt;0.65$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1$</td>
<td>1.091</td>
<td>0.809</td>
</tr>
<tr>
<td>$D_2$</td>
<td>-0.948</td>
<td>-0.891</td>
</tr>
<tr>
<td>$D_3$</td>
<td>887.46</td>
<td>387.53</td>
</tr>
<tr>
<td>$D_4$</td>
<td>0.726</td>
<td>0.587</td>
</tr>
<tr>
<td>$D_5$</td>
<td>0.333</td>
<td>0.096</td>
</tr>
<tr>
<td>$D_6$</td>
<td>0.182</td>
<td>0.203</td>
</tr>
</tbody>
</table>

Note: For $Fr_2 > 0.04$, use $D_5=0$ and $D_6=0$

### TABLE 4
Values of $F_{g2}$ in Equations (2) and (3) for Different Fluids

<table>
<thead>
<tr>
<th>Fluid</th>
<th>$F_{g2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1.0</td>
</tr>
<tr>
<td>R-11</td>
<td>1.35</td>
</tr>
<tr>
<td>R-114</td>
<td>2.15</td>
</tr>
<tr>
<td>R-12</td>
<td>2.10</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>3.0</td>
</tr>
<tr>
<td>Neon</td>
<td>3.0</td>
</tr>
</tbody>
</table>

### TABLE 5
Range of Parameters used in Developing Equations (2) and (3)

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Orient.</th>
<th>G</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$kg/m^2-s$</td>
<td>$W/m^2$</td>
</tr>
<tr>
<td>water (19)</td>
<td>horiz. 11.8</td>
<td>340-1400</td>
<td>150-800</td>
</tr>
<tr>
<td>water (20)</td>
<td>vert. 12.0,18.3</td>
<td>1800-11,200</td>
<td>40-280</td>
</tr>
<tr>
<td>R-11 (18)</td>
<td>horiz. 6,14,25</td>
<td>12.2-250</td>
<td>1.3-70</td>
</tr>
<tr>
<td>R-12 (22)</td>
<td>vert. 20</td>
<td>104-441</td>
<td>2-70</td>
</tr>
<tr>
<td>R-114 (11)</td>
<td>vert. 20</td>
<td>600-4410</td>
<td>50-600</td>
</tr>
<tr>
<td>Nitrogen (21)</td>
<td>horiz. 14</td>
<td>40-450</td>
<td>0.3-400</td>
</tr>
<tr>
<td>Neon (12)</td>
<td>horiz. 4,6</td>
<td>76-131</td>
<td>0.3-50</td>
</tr>
</tbody>
</table>

### TABLE 6
Comparisons of Correlations with Experimental Data Mean Deviations, Percent

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Kandlikar and Thakur (17)</th>
<th>Correlation</th>
<th>Wong (23)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>water,hor. (19)</td>
<td>9.8</td>
<td>11.0</td>
<td>18.7</td>
<td>**</td>
</tr>
<tr>
<td>water,vert. (20)</td>
<td>13.4</td>
<td>16.2</td>
<td>15.3</td>
<td>**</td>
</tr>
<tr>
<td>R-11,hor. (18)</td>
<td>14.8</td>
<td>15.5</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>R-12,hor. (22)</td>
<td>53.1</td>
<td>22.5</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>R-14,vert. (11)</td>
<td>45.4</td>
<td>18.1</td>
<td>15.7</td>
<td>**</td>
</tr>
<tr>
<td>R-12,hor. (12)</td>
<td>53.8</td>
<td>24.3</td>
<td>15.0</td>
<td>**</td>
</tr>
</tbody>
</table>

Notes: *mean deviation $= \frac{1}{n} \sum_{i=1}^{n} \frac{|h_{TP,actual} - h_{TP,predicted}|}{100}$

$h_{TP,actual} - h_{TP,predicted} \times 100$

$n$ - number of data points

** indicates no data available in this range
<table>
<thead>
<tr>
<th>Author</th>
<th>Fluid</th>
<th>Correlation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Guerrieri and Taiti [1] 1956</td>
<td>Cyclohexane, vertical upflow</td>
<td>$h_{TP} = 3.4 \left( \frac{1}{\eta} \right) 0.45 h_{\eta}$</td>
<td>mean deviation of 11.1% with own data</td>
</tr>
<tr>
<td>2. Dengler and Addoms [2] 1956</td>
<td>water, vertical upflow</td>
<td>$h_{TP} = 3.5 \left( \frac{1}{\eta} \right) 0.5 F_{DA} h_{\eta}$</td>
<td>mean deviation of 30.5% with own data</td>
</tr>
<tr>
<td>3. Bennett, et. al. [3], 1959</td>
<td>water, vertical annuli upflow</td>
<td>$h_{TP} = 0.64 \left( \frac{1}{\chi} \right) 0.74 h_{\eta}(q)0.11 \chi_{tt}$</td>
<td>mean deviation of 11.9% with own data</td>
</tr>
<tr>
<td>4. Uchida and Yameguchi [4], 1966</td>
<td>R-12, Horizontal</td>
<td>$h_{TP} = 17.5 (80)0.2 \left( \frac{1}{\chi_{tt}} \right) 1.67$</td>
<td>mean deviation of 11% with own data</td>
</tr>
<tr>
<td>5. Schrock and Grossman [5] 1962</td>
<td>water, vertical upflow</td>
<td>$h_{TP} = 7400[80+1.5k10^{-4} \left( \frac{1}{\chi_{tt}} \right) \chi^{2/3}] h_{\eta}$</td>
<td>mean deviation of 35% with own data</td>
</tr>
<tr>
<td>6. Chen [6] 1966</td>
<td>water, refrigerants and organic fluids, vertical</td>
<td>$h_{TP} = h_{conv} + h_{nucl}$ see ref.[8] for details</td>
<td>mean deviation of 12% with data of six investigators</td>
</tr>
<tr>
<td>7. Chawla [16] 1967</td>
<td>R-11, Horizontal</td>
<td>$h_{conv} = k_{e} C_{L}(R_{k} - F_{k}) C_{2} \frac{C_{p}}{2} \rho_{g} 0.8 Re_{k}0.35 Pr_{k}0.42$</td>
<td>not widely tested with other's data</td>
</tr>
<tr>
<td>8. Steiner and Schlunder [21] 1977</td>
<td>Nitrogen, Horizontal</td>
<td>$h_{nucl} - from Stephehn's correlation, see ref. [16] 80% data falls within ± 20%</td>
<td></td>
</tr>
<tr>
<td>9. Shah [13] 1976</td>
<td>water, refrigerant, cyclohexane, vertical &amp; horizontal</td>
<td>In a chart form 90% data falls within ± 30%</td>
<td>mean deviation 14% with 17 data sources</td>
</tr>
<tr>
<td>10. Bennett and Chen [15] and Bennett [16], et.al, 1980</td>
<td>water, R-11 similar to Chen (6) with modified F and S, see ref [15].</td>
<td>$Nu_{TP} = 1.05 \times 10^{-2} k_{1} k_{2} k_{3} k_{4} k_{5} k_{6} F_{Wet}$</td>
<td>water and R-11 thin film evaporation data agrees well.</td>
</tr>
<tr>
<td>11. Kandlikar and Thakur [17], 1982</td>
<td>water, refrigerant cyclohexane, vertical &amp; horizontal</td>
<td>$h_{TP} = B1(C0)^{B2}(25R_{k})^{B3} h_{\eta} + B3(80)B4(F_{k})^{B5} h_{\eta}$</td>
<td>mean deviation 13.7% - same data as used by Shah</td>
</tr>
</tbody>
</table>
Fig. 1 Comparison of Correlations with Jallouk's (11)
- Proposed Correlation
- Correlation in ref. (12)
(h in W/m²·°C)

Fig. 2 Comparison of Correlations with Jallouk's (11)
R-114 data
- Using \( F = \frac{\text{pool boiling}}{1.899} \) in the proposed correlation
- Shah's (14) correlation
(h in W/m²·°C)

Fig. 3 Comparison of the Proposed Correlation with Experimental Data
- Vertical orientation (19, 20, 11)
- Horizontal orientation (18, 23, 12, 22)
(h in W/m²·°C)

Fig. 4 Influence of Co on \( \frac{h_{\text{exp}}}{h_{\text{pred}}} \) (proposed correlation)
- Mumm (19)
- Wright (20)
- Chawla (18)
- Jallouk (11)
- Steiner and Schlunder (22)
- Mohr and Kunze (12)
- Bandel and Schlunder (22)
Fig. 5 Influence of Bo on $h_{\text{exp}}/h_{\text{pred}}$ (proposed correlation)
- Hume (19), Wright (20), Chawla (18)
- Jallonk (11), Steiner and Schlunder (23),
- Mohr and Runge (12),
- Bandel and Schlunder (22)

Fig. 6 Influence of Fr on $h_{\text{exp}}/h_{\text{pred}}$ (proposed correlation)
- Chawla (18), Steiner and Schlunder (23)
- Mohr and Runge (12),
- Bandel and Schlunder (22)

Fig. 7 Influence of Fr on $h_{\text{exp}}/h_{\text{pred}}$ using proposed vertical tube correlation (no Fr term) for Chawla's (18) horizontal tube R-11 data