The 2006 CHF look-up table


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Abstract

CHF look-up tables are used widely for the prediction of the critical heat flux (CHF). The CHF look-up table is basically a normalized data bank for a vertical 8 mm water-cooled tube. The 2006 CHF look-up table is based on a database containing more than 30,000 data points and provides CHF values at 24 pressures, 20 mass fluxes, and 23 qualities, covering the full range of conditions of practical interest. In addition, the 2006 CHF look-up table addresses several concerns with respect to previous CHF look-up tables raised in the literature. The major improvements of the 2006 CHF look-up table are:

• An enhanced quality of the database (improved screening procedures, removal of clearly identified outliers and duplicate data).
• An increased number of data in the database (an addition of 33 recent data sets).
• A significantly improved prediction of CHF in the subcooled region and the limiting quality region.
• An increased number of pressure and mass flux intervals (thus increasing the CHF entries by 20% compared to the 1995 CHF look-up table).
• An improved smoothness of the look-up table (the smoothness was quantified by a smoothness index).

A discussion of the impact of these changes on the prediction accuracy and table smoothness is presented. The 2006 CHF look-up table is characterized by a significant improvement in accuracy and smoothness.

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1. Introduction

The critical heat flux (CHF) normally limits the amount of heat transferred, both in nuclear fuel bundles and in steam generators. Failure of the heated surface may occur once the CHF is exceeded. The number of empirical CHF correlations has increased over the past 50 years and has reached well over 1000, just for tubes cooled by water. The present proliferation of CHF prediction methods clearly indicates that the CHF mechanism is complex; no single theory or equation can be applied to all CHF conditions of interest. The complexity involved in predicting the CHF increases significantly when additional factors such as transients, non-uniform flux distributions, and asymmetric cross sections are introduced. This has led to the development of the CHF look-up table.

The CHF look-up table is basically a normalized data bank, that predicts the CHF as a function of the coolant pressure \( P \), mass flux \( G \) and thermodynamic quality \( X \). An updated version of the CHF look-up table is appended to this paper.

The CHF look-up table method has many advantages over other CHF prediction methods, e.g., (i) simple to use, (ii) no iteration required, (iii) wide range of application, (iv) based on a very large database, and (vi) eliminates the need to choose among many CHF prediction methods currently available for tubes cooled by water.

Although the CHF look-up table has been quite successful and has been adopted widely, several concerns have been raised, including
During the past 10 years, further enhancements have been made to the CHF look-up table and its database, culminating in the 2006 CHF look-up table. This paper summarizes the enhancements and presents the improvements in prediction accuracy of the 2006 CHF look-up table.

2. Database

Following the development of the 1995 CHF look-up table, a total of 33 new data sets containing 7545 data were acquired and included in the University of Ottawa’s CHF data bank. Not all of these data were used in the derivation of the new CHF look-up table. The database was first subjected to the following screening criteria (summarized in Table 1):

(i) Acceptable values for diameter (D), ratio L/D, pressure (P), mass flux (G) and quality (X).

(ii) Ensuring that the data satisfied the heat balance (reported power should be approximately equal to [flow] × [enthalpy rise]).

(iii) Identification of outliers using the slice method (Durmazay et al., 2004): the “slice” method was introduced to examine all the data behind each table entry in the look-up table. For each nominal look-up table pressure, and nominal mass flux, a CHF versus critical quality plot was created showing all the experimental CHF values falling within the pressure and mass flux ranges of (P_i + P_i)/2 < P_{exp} < (P_{i+1} + P_{i+1})/2 and (G_{j-1} + G_{j})/2 < G_{exp} < (G_{j+1} + G_{j+1})/2 after normalization to P_i and G_j and D = 8 mm. Data that did not obviously agree with the bulk of the data and the previous CHF look-up table were labelled “outliers” and were excluded in the CHF look-up table derivation process. Fig. 1 shows an example of a slice. The same slice approach was used for the CHF versus pressure (P) and CHF versus mass flux (G) plots.

(iv) Identification of duplicate data using the “slice” method (the same data sets may have been reported by more than one author).

(v) Removal of data sets which display a significant scatter and generally disagree with the bulk of the data. These “bad” data sets may be due to “soft” inlet conditions, which can give rise to flow instabilities or a poorly performed experiment (e.g., large uncertainties in instrumentation).

As can be seen from Table 1, a total of 8394 data points, representing 25% of the total number of CHF data available, were considered unsuitable for use in the 2006 CHF look-up table derivation and were removed through the screening process.

3. Skeleton table

The derivation of the CHF look-up table requires a skeleton table to provide the initial estimate of the CHF look-up table values. The skeleton CHF values are used for evaluating the slopes of CHF versus P, G or X. The slopes are used for extrapolating selected CHF measurement to the surrounding look-up table values of P, G and X as was described by Groeneveld et al.
Table 1
Data selection criteria for look-up table derivation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1995 selection criteria</th>
<th>2006 selection criteria</th>
<th>Number of data removed due to 2006 selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td># of data in the database</td>
<td>25,630</td>
<td>33,175</td>
<td></td>
</tr>
<tr>
<td># of data sets in the database</td>
<td>49</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>$D$ (mm)</td>
<td>$3 &lt; D &lt; 25$</td>
<td>$3 &lt; D &lt; 25$</td>
<td>1420</td>
</tr>
<tr>
<td>$P$ (kPa)</td>
<td>$100 &lt; P &lt; 20,000$</td>
<td>$100 &lt; P &lt; 21,000$</td>
<td>37</td>
</tr>
<tr>
<td>$G$ (kg m$^{-2}$s$^{-1}$)</td>
<td>$0 &lt; G &lt; 8000$</td>
<td>Same</td>
<td>912</td>
</tr>
<tr>
<td>$X$</td>
<td>$X_{CHF} &lt; 1.0$</td>
<td>Same</td>
<td>368</td>
</tr>
<tr>
<td>Inlet temperature (°C)</td>
<td>$T_{in} &gt; 0.01$</td>
<td>Same</td>
<td>10</td>
</tr>
<tr>
<td>$L/D$, $X_{in} &lt; 0$</td>
<td>$L/D &gt; 80$</td>
<td>$L/D &gt; 50$ for $X_{cr} &gt; 0$, $L/D &gt; 25$ for $X_{cr} &lt; 0$</td>
<td>2214</td>
</tr>
<tr>
<td>Heat balance</td>
<td>Error &gt; 5%</td>
<td>Error &gt; 5%</td>
<td>619</td>
</tr>
<tr>
<td>Other data removal criteria</td>
<td>Duplicates</td>
<td>Duplicates</td>
<td>1284</td>
</tr>
<tr>
<td># of data accepted for LUT derivation</td>
<td>23,114</td>
<td>24,781</td>
<td>Total of above: 8394</td>
</tr>
</tbody>
</table>

(1996). The skeleton table also provides the default CHF values at conditions where no experimental data are available.

The skeleton table is primarily based on the 1995 CHF look-up table but with corrections to the subcooled region. These corrections were necessary because the skeleton table for the 1995 CHF look-up table was primarily based on the Katto equation (1992), which was subsequently found to contain discontinuities or trend reversals at certain conditions as shown in Fig. 1.

Values in the skeleton table for $G = 0$ kg m$^{-2}$s$^{-1}$ and $X < 0$ are predicted using the Zuber (1959) correlation with the correction factor derived by Ivey and Morris (1962). The skeleton table values for $G > 300$ kg m$^{-2}$s$^{-1}$ and $X < 0$ are either maintained or replaced with the predicted values by Hall and Mudawar (2000) equation, based on a visual observation of the plots produced by slicing the look-up table and the data trends (Durmayaz et al., 2004).

For $0 < G < 500$ kg m$^{-2}$s$^{-1}$ and $X < 0$, the table CHF values are established using a linear interpolation between those at zero flow and 500 kg m$^{-2}$s$^{-1}$. This provides a smooth transition.

Compared to the 1995 look-up table three additional pressures (2, 4 and 21 MPa) and one mass flux (750 kg m$^{-2}$s$^{-1}$) were added to the look-up table. The skeleton CHF values for conditions of 2 and 4 MPa pressures and of 750 kg m$^{-2}$s$^{-1}$ mass flux were obtained from linear interpolation. The skeleton CHF values for 21 MPa were interpolated using the CHF versus pressure trend of the Zuber equation, which was found to approximately agree with CHF versus $P$ trends for flow boiling (Groeneveld et al., 1986).

4. Derivation of the CHF look-up table

The primary building blocks for the CHF look-up table are the screened database, described in Section 2, and the skeleton table, described in Section 3. The following steps were taken in the look-up table derivation process:

- The 1995 CHF look-up table, modified as described in the previous section, was used as the skeleton table.
- The expanded database was screened as described in Section 2.
- The effect of tube diameter on CHF is accounted for using the diameter correction factor: $CHF_D/CHF_{D=8mm} = (D/8)^{-1/2}$ for the range of $3 < D < 25$ mm. Outside this range the diameter effect appears to be absent (Wong, 1994).
- For each set of look-up table conditions (each combination of $P_x$, $G_y$, and $X_z$), all experimental data falling within the range $P_{x-1} < P_{exp} < P_{x+1}$, $G_{y-1} < G_{exp} < G_{y+1}$...
and $X_{z-1} < X_{\text{exp}} < X_{z+1}$ were selected. Each experimental CHF point was corrected for the differences in pressure $(P_{\text{exp}} - P_x)$, mass flux $(G_{\text{exp}} - G_x)$ and quality $(X_{\text{exp}} - X_z)$ using the slopes of the skeleton table. The corrected point was given a weight, which was proportional to $[1 - \{(P_{\text{exp}} - P_x)(G_{\text{exp}} - G_x)(X_{\text{exp}} - X_z))/((P_{x+1} - P_x) (G_{z+1} - G_x)(X_{z+1} - X_z))]$ for each of the quadrants surrounding $P_x$, $G_x$ and $X_z$ and the weighted averaged CHF value for all corrected data surrounding each table entry was used to replace the skeleton CHF value.

The updated CHF table is not smooth and displays an irregular variation (without any physical basis) in the three parametric ranges: pressure, mass flux and quality. These fluctuations are attributed to data scatter, systematic differences between different data sets, and possible effects of second-order parameters such as heated length, surface conditions and flow instability. Sharp variations in CHF were also observed at some of the boundaries between regions where experimental data are available and regions where correlations and extrapolations were employed. Prior to finalizing the look-up table, a smoothing procedure developed by Huang and Cheng (1994) was applied. The principle of the smoothing method is to fit three polynomials to six table entries in each parametric direction. The three polynomials intersect each other at the table entry, where the CHF value is then adjusted. This resulted in a significant improvement in the smoothness of the look-up table. A third-order polynomial was used for the smoothing of the 1995 CHF look-up table. However, recent comparisons have shown that a first-order polynomial results in a smoother table with no significant loss in prediction accuracy, see Table 2 (the smoothness index and root-mean-square (rms) values will be discussed in Section 5.2).

Applying the smoothing process to the table entries at all conditions suppressed the discontinuity at the boundaries of the limiting quality region (LQR), as described in Appendix A, resulting in non-representative trend to the experimental data. To maintain the physical trend of the table entries at the LQR, an intermediate table was created that maintained the more abrupt changes at the boundaries of the LQR, extrapolated to the nearest look-up table qualities. Also between the maximum quality of the LQR and $X = 0.9$ a gradual change towards the skeleton table values was applied. Some smoothing needed to applied subsequently to avoid a fluctuation in CHF with pressure and mass flux. Fig. 2 illustrates the intended change in the look-up table prior to applying the additional smoothing.

The final CHF look-up table is included as Appendix B. Four levels of shading have been applied to highlight regions of uncertainty. The unshaded entries represent areas that were derived directly from the experimental data and hence have the least uncertainty. The light grey regions represent calculated values based on selected prediction methods that provide reasonable predictions at neighboring conditions where experimental data are available. The uncertainty in this region depends on the level of extrapolation from data-based regions. It is expected to be small at conditions slightly beyond the range of data but becomes large as the extrapolation is further beyond this range. The medium grey regions represent conditions where CHF values were often impossible to obtain, including (i) conditions where critical flow may exist, and (ii) coolant enthalpies where the bulk of the liquid starts to become solid ($T_{\text{bulk}} < 0.01$) and (iii) $G = 0$ where the concept of flow quality becomes imaginary. Those regions are included only to improve interpolation accuracy of other regions. Extrapolation into medium grey region should be avoided. Finally the entries having a black background represent the LQR, where rapid changes in CHF versus quality curve can be observed. Note that the LQR does not occur at all pressures and mass fluxes. Because of space limitations CHF values at some intermediate pressures are not shown in Appendix B.

![Fig. 2. Illustration of derivation of 2006 CHF look-up table values at the LQR.](image-url)
5. Look-up table prediction accuracy and smoothness

5.1. Prediction accuracy

There are two methods for assessing the prediction accuracy of the CHF look-up table: (i) based on constant local conditions (i.e., constant critical quality), and (ii) based on constant inlet conditions (i.e., constant inlet temperature or inlet enthalpy). Method (i) is sometimes referred to as the direct substitution method (DSM), while method (ii) is also referred to as the heat balance method (HBM).

The CHF prediction based on constant local conditions is the simplest to apply. The predicted CHF for each experimental data point in question \((D_{\text{exp}}, P_{\text{exp}}, G_{\text{exp}}, X_{\text{exp}})\) is first found using the CHF look-up table at local flow conditions for a tube of 8-mm diameter using direct interpolation between matrix values of \(P\), \(G\), and \(X\). Next, the CHF is corrected for the diameter effect as follows:

\[
\text{CHF}(D_{\text{exp}}, P_{\text{exp}}, G_{\text{exp}}, X_{\text{exp}}) = \text{CHF}(D = 8, P_{\text{exp}}, G_{\text{exp}}, X_{\text{exp}}) \left( \frac{D_{\text{exp}}}{8} \right)^{-1/2} \quad (5.1)
\]

The CHF prediction based on constant inlet conditions is obtained via iteration with the heat-balance equation using the following steps:

- Estimate the heat flux (if unsure how to make an estimate, assume \(\text{CHF} = 500 \text{ kW m}^{-2}\)).
- Calculate the quality based on the estimated heat flux, mass flux and inlet subcooling:

\[
X = \frac{H - H_l(P_{\text{exp}})}{H_{fg}(P_{\text{exp}})} \approx \frac{\dot{Q}_{\text{est}}}{G_{\text{exp}} H_{fg}(P_{\text{exp}})} \cdot \frac{L_{h,\text{exp}}}{D_{\text{exp}}} - \frac{\Delta H_{h,\text{exp}}(T_{\text{in,exp}})}{H_{fg}(P_{\text{exp}})} \quad (5.2)
\]

Note that the quality as defined above is the thermodynamic quality, which will be negative for subcooled conditions.

- The first estimate of CHF is calculated from the CHF look-up table at local flow conditions \((D = 8 \text{ mm}, P_{\text{exp}}, G_{\text{exp}}, X)\) corrected for diameter

\[
q_{\text{pred}}(D_{\text{exp}}, P_{\text{exp}}, G_{\text{exp}}, X) = \text{CHF}(8, P_{\text{exp}}, G_{\text{exp}}, X) \left( \frac{D_{\text{exp}}}{8} \right)^{-1/2} \quad (5.3)
\]

- Re-evaluate the quality using the average of the predicted value and the previous heat flux value, and again find the CHF.
- Continue this iteration process until the heat flux value starts converging to a single value.

The prediction errors are calculated for each data point from the database. The mean (arithmetic average) and rms errors are evaluated for data subsets and for the complete database based on either constant local quality and constant inlet condition. The error histograms in Fig. 3 based on the enlarged database show that the 2006 look-up table has a more peaked error distribution. Details of the error distributions are presented in Table 3. The table shows that using the enhanced database, the rms and average errors of the 2006 CHF look-up table are less than those for the 1995 CHF look-up table.

The improvement in prediction accuracy is most pronounced for subcooled conditions \((X < 0)\) and in the limiting quality region \((X_{\text{lim}}' < X < X_{\text{lim}}'')\) where the rms errors based on constant inlet conditions decrease from 11.13 to 7.08% and from 10.88 to 6.71%, respectively. The reductions in error for \(X < 0\) are due to the improvements to the skeleton table for \(X < 0\) (described in Section 3) by reducing the dependence on the Katto equation. The reduction in error in the LQR is primarily due to the maintaining to some degree a sharper variation in CHF values as was shown in Fig. 2. The rms error in Region III was also reduced significantly: from 11.34 to 8.01%.

These error comparisons are based on the total number of data points (i.e., 25,217). The 2006 CHF look-up table has also been compared to additional data obtained at pressures up to 21 MPa, but adding the extra data affects the errors by less than 0.03%.

A separate error analysis of the outliers (as identified by the “slice method”, see Fig. 1) showed that their rms errors are more than three times those of the above table. This indicates that the selection criteria have been effective in removing suspect data.

The error distribution based on the constant inlet-flow conditions approach for the 2006 CHF look-up table with respect to pressure, mass flux and critical quality are shown in Fig. 4. Slight systematic errors are present at low pressures and very low and high mass velocities and high qualities. A more detailed examination showed that the high errors were primarily at pressures less than 250 kPa and mass velocities less than 750 kg m\(^{-2}\) s\(^{-1}\). The scatter among these low flow and low-pressure data is very large due to possible flow instability at these conditions. Table 3 shows the impact on prediction errors after excluding these data from the error analysis. The rms error at constant inlet-flow conditions for the 2006 CHF look-up table reduces from 7.10 to 5.86%.
Table 3
Error statistics of the 1995 and 2006 CHF look-up tables

<table>
<thead>
<tr>
<th>Data selection (# of data)</th>
<th>All selected (25,217)</th>
<th>Except ( P &lt; 250 ), ( G &lt; 750 ) (24,552)</th>
<th>( X &lt; 0 ) only (1845)</th>
<th>Region I: ( X &lt; X'_{\text{lim}} ) or no LQR (19,856)</th>
<th>Region II: LQR, ( X'<em>{\text{lim}} &lt; X &lt; X''</em>{\text{lim}} ) (4565)</th>
<th>Region III: ( X &gt; X'_{\text{lim}} ) (796)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995 CHF look-up table</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg. error, ( X = C )</td>
<td>7.63</td>
<td>7.27</td>
<td>-2.95</td>
<td>6.10</td>
<td>13.81</td>
<td>9.40</td>
</tr>
<tr>
<td>rms error ( X = C )</td>
<td>42.96</td>
<td>42.10</td>
<td>18.00</td>
<td>37.42</td>
<td>58.89</td>
<td>57.28</td>
</tr>
<tr>
<td>Avg. error, ( \Delta H_{\text{in}} = C )</td>
<td>0.75</td>
<td>0.62</td>
<td>-2.93</td>
<td>0.505</td>
<td>1.37</td>
<td>1.383</td>
</tr>
<tr>
<td>rms error, ( \Delta H_{\text{in}} = C )</td>
<td>9.18</td>
<td>8.66</td>
<td>11.13</td>
<td>8.62</td>
<td>10.88</td>
<td>11.34</td>
</tr>
<tr>
<td>Smoothness index</td>
<td></td>
<td></td>
<td></td>
<td>0.098</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smoothness rms</td>
<td></td>
<td></td>
<td></td>
<td>0.132</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006 CHF look-up table</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg. error, ( X = C )</td>
<td>4.09</td>
<td>5.81</td>
<td>0.85</td>
<td>2.31</td>
<td>14.53</td>
<td>-12.4</td>
</tr>
<tr>
<td>rms error ( X = C )</td>
<td>38.92</td>
<td>37.21</td>
<td>14.74</td>
<td>31.13</td>
<td>60.8</td>
<td>47.52</td>
</tr>
<tr>
<td>Avg. error, ( \Delta H_{\text{in}} = C )</td>
<td>0.08</td>
<td>0.48</td>
<td>0.10</td>
<td>-0.07</td>
<td>1.14</td>
<td>-2.28</td>
</tr>
<tr>
<td>rms error, ( \Delta H_{\text{in}} = C )</td>
<td>7.10</td>
<td>5.86</td>
<td>7.08</td>
<td>7.15</td>
<td>6.71</td>
<td>8.01</td>
</tr>
<tr>
<td>Smoothness index</td>
<td></td>
<td></td>
<td></td>
<td>0.095</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smoothness rms</td>
<td></td>
<td></td>
<td></td>
<td>0.132</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4. Error distributions for the 2006 CHF look-up table with respect to \( P \), \( G \) and \( X \).
5.2. Smoothness

Fig. 5 compares 3-D representations of the 1995 and 2006 CHF look-up tables for three pressures. Both tables appear reasonably smooth. The only obvious non-smooth trend for the 2006 CHF look-up table was the LQR, which was “smoothed out” in the 1995 CHF look-up table. Aside from the LQR it is difficult to see which region is smoother, making it difficult to judge which of the two tables is smoother. Hence it was decided to quantify the smoothness using the following approach (this approach was not applied to the transition at the LQR boundary).

Since the grid numbers in these CHF look-up tables for $P$, $G$, and $X$ are roughly the same, as a first approximation, the grid indexes were used as the normalized parameters for the look-up table smoothness assessment. Assuming that the look-up table has $P_i$, $G_j$, and $X_m$ as its grid points, with $i = 1, 2, \ldots, I$; $j = 1, 2, \ldots, J$; and $m = 1, 2, \ldots, M$, the local smoothness of the look-up tables is simply presented by the average of the absolute value of the relative slope differences at each direction of a local grid point.

$$\omega_{q_{cr}}(P_i, G_j, X_m) = \frac{1}{3} \left[ \left( \frac{1}{\bar{q}_{cr}} \frac{\partial q_{cr}}{\partial i} \right)_+ - \left( \frac{1}{\bar{q}_{cr}} \frac{\partial q_{cr}}{\partial i} \right)_- + \left( \frac{1}{\bar{q}_{cr}} \frac{\partial q_{cr}}{\partial j} \right)_+ - \left( \frac{1}{\bar{q}_{cr}} \frac{\partial q_{cr}}{\partial j} \right)_- + \left( \frac{1}{\bar{q}_{cr}} \frac{\partial q_{cr}}{\partial m} \right)_+ - \left( \frac{1}{\bar{q}_{cr}} \frac{\partial q_{cr}}{\partial m} \right)_- \right]_{P_i, G_j, X_m}$$

(5.4)

where “+” refers to the forward slope, and “-” refers to the backward slope, $q_{cr}$ is the CHF, and $\bar{q}_{cr}$ is the average CHF at its corresponding interval. The smoothness index for the entire look-up table is defined as the overall average of the local smoothness at all internal grid points.

$$\Omega_{q_{cr}} = \frac{\sum_{i=2}^{I-1} \sum_{j=2}^{J-1} \sum_{m=2}^{M-1} \omega_{q_{cr}}(P_i, G_j, X_m)}{(I-2)(J-2)(M-2)}$$

(5.5)

The rms of the smoothness is calculated in a similar manner:

$$\text{rms}_{q_{cr}} = \sqrt{\frac{\sum_{i=2}^{I-1} \sum_{j=2}^{J-1} \sum_{m=2}^{M-1} \left[ \omega_{q_{cr}}(P_i, G_j, X_m) - \Omega_{q_{cr}} \right]^2}{(I-2)(J-2)(M-2)}}$$

(5.6)

Table 3 shows that the smoothness index and the rms of the smoothness for the 2006 CHF look-up table are improved compared to the corresponding values for the 1995 CHF look-up table.
6. Conclusions and final remarks

The tube CHF database has been expanded since the derivation of the 1995 CHF look-up table with 33 additional data sets containing 7545 new data points.

The screening process of the CHF data has been enhanced significantly resulting in a larger fraction (~25%) of data being excluded from the table development.

The 2006 CHF look-up table is a significant improvement over the 1995 CHF look-up table; the rms errors were reduced and the smoothness of the look-up table was improved. The largest improvements in prediction accuracy was obtained in the subcooled CHF region where local subcooling trend now agrees better with the Hall–Mudawar equation, and in the limiting quality region where the smoothing has been removed. The rms errors decreased by approximately 4% in these regions.

Despite the large number of CHF studies performed in directly heated tubes during the past 50 years, significant gaps in the data remain, where CHF predictions are based on extrapolation and models predictions. Additional CHF experiments are required to fill these gaps.

Acknowledgements

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Appendix A. Limiting quality region

The limiting quality phenomenon (LQR) is characterized by a fast decrease in CHF with an increase of steam quality. The LQR usually occurs in the intermediate steam quality region. To illustrate the limiting quality phenomenon, Doroshchuk et al. (1970) and Bennet et al. (1967) divided the critical heat flux versus quality curve into three regions as is illustrated in Fig. A1. The annular flow regime occurs in all three regions, but it is postulated (e.g. Bennet et al., 1967) that in region I the primary mechanism responsible for CHF occurrence is droplet entrainment from the thick liquid film. This mechanism is quite effective in reducing the film thickness thus depleting the annular film flow rate until the film breaks down. Region III in characterized by a very thin liquid film which is replenished by deposition from the entrainment laden vapor stream. Since the entrainment rate from a thin liquid film is virtually zero, CHF occurs when the evaporation rate \( \frac{q}{H_{fg}} \) exceeds the deposition rate, which explains the low CHFs in region III. The intermediate region II is referred to as the limiting quality region because of the steep CHF versus X slope.

Peng et al. (2004) reviewed the available literature on the LQR and, using the UofO data bank, he tabulated the LQR boundaries. A similar approach was recently undertaken at the University of Ottawa using Durmayaz’s et al. (2004) “slice” method. The boundaries were defined as shown in Fig. A1(b): the point where the slope first showed a significant change \( \left( \frac{q_{cr} X_{lim}}{X} \right) \) was considered typical of the start of the LQR while the point of the next slope change combined with a low CHF \( \left( \frac{q''_{cr} X''_{lim}}{X''} \right) \) was considered the end of the LQR.

Appendix B. 2006 CHF look-up table

![Fig. A1. Schematic representation of the limiting quality region.](image-url)
<table>
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<tr>
<th>Pressure [kPa]</th>
<th>Mass Flux [kg m⁻² s⁻¹]</th>
<th>CHF [kW m⁻²]</th>
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References


