Chapter 6

Conclusions and future work

In this chapter all conclusions are comprehensively outlined in the sequence of presentation of information in various preceding chapters. Also the future work to be carried out is specified.

6.1 Conclusions

The following conclusions are arrived at from the present work in Chapters 2 through 5.

6.1.1 Chapter 2

Boiling studies for different conditions for wide ranges of pressures are available in the literature. But the correlations are conservatively applicable to certain ranges of parameters.

In this chapter, the author took up the task of presenting generalized correlation for nucleate boiling on horizontal cylindrical heating elements and the presentation distinctly makes use of a new parameter known as Kakac Number\(^6\), \( \text{Kakac Number} = \frac{PD}{\mu_l h_{liq}^{1/2}} \). The physical significance of the Kakac number is shown to be the net effect of the

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\(^6\) Kakac number has been named after Sadic Kakac, who is a renowned researcher in the field of boiling and two-phase flow.
dynamics of bubble growth, the flow of the medium around the bubble and the energies involved in dilatation and the thermal input into the bubble to sustain the growth. Usage of Kakac number yielded successful correlation covering wide ranges of pressure from a low value of 1 bar to near critical values of the given liquid.

The comprehensive correlation as proposed by the author is as follows:

\[
\frac{q_w}{\mu h_s} \sqrt{\frac{\sigma}{(\rho_l - \rho_v) g}} = 3.8 \times 10^6 \left( \frac{D}{\delta_i} \right)^{1.22} \left( \frac{\rho}{\rho_i} \right)^{0.72} \left( \frac{PD}{\mu h_s^{1/2}} \right)^{0.55} \left( \sqrt{\frac{\sigma}{(\rho_l - \rho_v) gD^2}} \right)^{1.65}
\]

With ranges of

Water:

1 bar < \( P \) < 200 bar \( (P_{cr}=221 \text{ bar}) \)
4.9 mm < \( D \) < 6.94 mm
260 mm < \( L \) < 262 mm
Material: 18 % Ni, 8 % Cr steel

Ethyl Alcohol:

1 bar < \( P \) < 60 bar \( (P_{cr}=64 \text{ bar}) \)
4.9 mm < \( D \) < 6.94 mm
260 mm < \( L \) < 300 mm
Material: 18 % Ni, 8 % Cr steel
6.1.2 Chapter 3

Having established the correlation, the author of the present thesis felt the need to establish the validity of the criteria in correlation for different configurations and medium and hence experimental studies have been planned and conducted for a liquid-surface combination of Forane-Copper. The configuration of the test section employed is a cylinder of following dimensions:

D=42 mm, L=12.7 mm

The experimental results are made use of along with the data of Borishansky et al.\textsuperscript{12}(1966) for water and ethyl alcohol and the following correlation is predicted with the same criteria employed in chapter 2 and an accuracy of \(\pm 16\%\) AD and \(\pm 20\%\) S.D.

Besides the Kakac number, \(K_a \left( \frac{PD}{\mu L^{1/2}} \right)\) happens to be a contribution which enables to arrive at a correlation with minimum deviation as can be seen from plots.

6.1.3 Chapter 4

In power generation two important instances are found to exist in practice Viz., Fast burnout and slow burnout. In nuclear power generation, the prevailing high heat fluxes will lead to unwanted fast burnout (\(X<0\)), which results in the physical damage of the tube. In slow burnout, though the temperature rise in the wall of a steam generating
tube is not high, the phenomena leads to unwanted occurrence of scaling of even highly soluble salts present in the feed water.

In this context, the model of Mozharov\textsuperscript{92} (1959) is further extended to obtain a correlation for the evaluation of slow burnout heat flux. The correlation is as follows:

$$\frac{q_{ch}}{\mu_h g} = 2.74 \left( \frac{\rho}{\rho_v} \right)^{1.7} X^{0.116} (1-X)^{2.65} \left( \frac{V'}{V} \right)^{0.35} \left( \frac{P}{P_{cr}} \right)^{0.95}$$

Satisfying the ranges

$$100 < P < 200 \text{ Bar}, \ 8 < D < 10 \text{ mm}, \ 0.25 < L < 2.1 \text{ m}$$

Besides the performance of the steam generating tubes for mist flow conditions is theoretically analyzed and the author has proposed a model to estimate the wall temperature of steam generating tube. The success of the theoretical analysis is established by comparing the model with the data of Era et al.\textsuperscript{39} (1967) for $P=70$ Bar and $D=6$ mm.

6.1.4 Chapter 5

In micro-electronics and Fusion reactor components where the coolant is in sub-cooled condition, thermal dissipation of high heat fluxes generated is also of utmost importance and hence the author bestowed evaluation of the critical heat flux for fast burnout with emphasis for diameter of the tubes less than 3mm and different flow conditions. In this correlation as well, the Kakac number, $K_a \left( \frac{PD}{\mu_h h_1} \right)$. 
proved to be of utmost significance and the standard deviation in correlating the data is found to be within accepted limits.

The following correlations are proposed by the author for fast burnout and the correlations proposed by the author are compared with some of the empirical and dimensionless correlations of other authors and the present correlation seemed to satisfy successfully nearly 3050 data points gathered from various sources in the literature,

For diameters in the range $0.25 < D < 3 \, \text{mm}$ and around 1300 data points,

$$\frac{q_{st}}{\mu_h h_s} = 0.045 \text{Re}^{0.68} \left[ \frac{PD}{\mu_h h_s^{1/2}} \right]^{0.123} \left[ \frac{D}{L} \right]^{0.45}$$

$$\frac{q_{st}}{\mu_h h_s} = 0.12 \text{Re}^{0.72} \left[ \frac{P}{P_{cr}} \right]^{0.17} \left[ \frac{D}{L} \right]^{0.5}$$

For all diameters ranging from $0.8 \, \text{mm}$ to $37.5 \, \text{mm}$ and total 3050 data points,

$$\frac{q_{st}}{\mu_h h_s} = 0.071 \text{Re}^{0.62} \left[ \frac{PD}{\mu_h h_s^{1/2}} \right]^{0.17} \left[ \frac{D}{L} \right]^{0.5}$$

$$\frac{q_{st}}{\mu_h h_s} = 0.125 \text{Re}^{0.75} \left[ \frac{P}{P_{cr}} \right]^{0.23} \left[ \frac{D}{L} \right]^{0.42}$$

$$\frac{q_{st}}{\mu_h h_s} = 0.075 \text{Re}^{0.65} \left[ \frac{PD}{\mu_h h_s} \right]^{0.15} \left[ \frac{C_p (T_s - T_i)}{h_s} \right]^{0.22} \left[ \frac{D}{L} \right]^{0.5}$$
The criterion used in evaluation of critical heat flux is extended to slow burnout and a successful correlation has been obtained. Besides, introduction of the surface tension parameter of Mozharov (1959) gave an improved correlation purporting the model that the onset of critical conditions might be due to the combined effect of heat flux and high velocity vapor leading to physical destruction of the liquid film. The following correlations are predicted for slow burnout with an accuracy of ± 18% AD and ± 20% SD.

\[
\frac{q_{mD}}{\mu_i h_i} = 0.000537 \left[ \frac{PD}{\mu_i h_i^{1/2}} \right]^{0.84} \left[ \frac{L}{D} \right]^{0.4} \left[ \frac{GD}{\mu_i} \right]^{-0.787} \frac{(1-X)}{X}^{-0.177}
\]

\[
\frac{q_{mD}}{\mu_i h_i} = 0.2383 \times 10^4 \left[ \frac{PD}{\mu_i h_i^{1/2}} \right]^{0.8} \left[ \frac{L}{D} \right]^{0.41} \left[ \frac{GD}{\mu_i} \right]^{0.75} [1-X]^{1.11} \left[ \frac{\sigma D_{p_x}}{\mu_i^2} \right]^{-0.46}
\]

In all the cases both for evaluation of heat transfer coefficient in pool boiling and critical heat flux in flow boiling in sub-cooled and saturated conditions, Kakac number, \( K_a \left( \frac{PD}{\mu_i h_i^{1/2}} \right) \) has been universally used and this number gave successful correlations.

The studies presented by the author are already brought out in the contemporary literature as publications to establish the usefulness and credibility to the work.
6.2 Future work

As a continuation of the present studies, the author aims at doing future work in improving the boiling heat transfer coefficients and enhancement of critical heat flux in thermal equipment operating at high pressure and temperatures. The author feels that the change in physical properties of the coolant would be helpful in operating the equipment under high heat flux conditions. It is a hope that addition of certain nano-particles to the coolant will change the characteristic bubble dynamics and the heat dissipation mechanism from the heated wall can be by far improved and hence the author aim him attention to work theoretically and experimentally in finding out the effect of nano materials on the thermal management of the heat transfer equipment.
List of tables

Table 3.1: Test runs from the experiment.

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<td>18.85</td>
<td>188890</td>
<td>56.34</td>
<td>10020.69</td>
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</tbody>
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$P_s$ — System Pressure, $T_w$ — Wall Temperature, $\Delta T$ — $T_w - T_b$, $q$ — Wall heat flux, $T_b$ — Bulk Temperature and $h$ — Heat transfer coefficient.
Table 4.1: Data of water for saturated flow boiling ($X > 0$)

<table>
<thead>
<tr>
<th>S. No</th>
<th>Data</th>
<th>Pressure data</th>
<th>Mass Flux, $G$ [Kg/m$^2$.s]</th>
<th>$q_{ev}$ [MW/m$^2$]</th>
<th>Dryness fraction, $X$</th>
<th>Diameter, D- mm</th>
<th>Length, L- m</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Peskov et al. [96] (1961) For water in horizontal tubes</td>
<td>100 - 200</td>
<td>491 - 5541</td>
<td>0.58 - 4.923</td>
<td>0.003 - 0.431</td>
<td>8 - 10</td>
<td>0.25 - 2.1</td>
<td>250</td>
</tr>
</tbody>
</table>
### Table 5.1: General Sub-cooled data of all authors (X<0)

<table>
<thead>
<tr>
<th>S. No</th>
<th>Data</th>
<th>Pressure, Bar</th>
<th>Mass Flux, KG/m² s</th>
<th>q&lt;sub&gt;e&lt;/sub&gt; MW/m²</th>
<th>Inlet Temp, T&lt;sub&gt;i&lt;/sub&gt;, °C</th>
<th>Diameter D - mm</th>
<th>Length - m</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ENEA</td>
<td>1.019 - 85</td>
<td>9,167 - 43, 130</td>
<td>3.8896 - 60.579</td>
<td>1.14 - 242</td>
<td>0.584 - 25.4</td>
<td>0.063 - 0.61</td>
<td>756</td>
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<tr>
<td>2</td>
<td>Boyd&lt;sup&gt;15&lt;/sup&gt; (1990)</td>
<td>4.5 - 16.6</td>
<td>757 - 40, 560</td>
<td>1.3959 - 41.5</td>
<td>18 - 20</td>
<td>3 - 10.2</td>
<td>0.289 - 1.17</td>
<td>36</td>
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<tr>
<td>3</td>
<td>Bergles&lt;sup&gt;6&lt;/sup&gt; (1963)</td>
<td>1.3 - 22.7</td>
<td>8,438 - 41, 180</td>
<td>18.7 - 123.8</td>
<td>6 - 85</td>
<td>0.33 - 2.67</td>
<td>0.00177 - 0.0666</td>
<td>210</td>
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<tr>
<td>4</td>
<td>Ormstt&lt;sup&gt;2&lt;/sup&gt; (1964)</td>
<td>9 - 32</td>
<td>5,004 - 90000</td>
<td>6.37 - 227.95</td>
<td>1 - 205</td>
<td>0.4 - 2</td>
<td>0.0112 - 0.056</td>
<td>310</td>
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<tr>
<td>5</td>
<td>Knoebl&lt;sup&gt;15&lt;/sup&gt; (1974)</td>
<td>1.8 - 7.37</td>
<td>3,915 - 13, 657</td>
<td>3.3327 - 11.425</td>
<td>0.3 - 104.8</td>
<td>9.52 - 9.53</td>
<td>0.609</td>
<td>376</td>
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<tr>
<td>6</td>
<td>Gambill&lt;sup&gt;15&lt;/sup&gt; (1968)</td>
<td>0.92 - 85</td>
<td>7,057 - 12, 285</td>
<td>7.025 - 54.338</td>
<td>5 - 35.85</td>
<td>3.18 - 7.75</td>
<td>0.0191 - 0.584</td>
<td>33</td>
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<td>7</td>
<td>Thorgerson&lt;sup&gt;15&lt;/sup&gt; (1974)</td>
<td>4.458</td>
<td>4,175 - 13, 420</td>
<td>4.2084 - 12.383</td>
<td>1 - 80</td>
<td>3.05 - 11.7</td>
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<tr>
<td>8</td>
<td>Narai et al.&lt;sup&gt;44&lt;/sup&gt; (1987)</td>
<td>1 - 15</td>
<td>4300 - 29, 900</td>
<td>4.65 - 69.89</td>
<td>15 - 78</td>
<td>1 - 6</td>
<td>0.01 - 0.1</td>
<td>147</td>
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<td>9</td>
<td>Ziegarnik&lt;sup&gt;134&lt;/sup&gt; (1981)</td>
<td>5 - 30</td>
<td>2500 - 20, 600</td>
<td>3.478 - 32.6</td>
<td>0.5 - 134</td>
<td>3.15 - 4</td>
<td>0.0805 - 0.25</td>
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Table 5.2: ENEA data for water in vertical channel

<table>
<thead>
<tr>
<th>No</th>
<th>Data</th>
<th>Pressure Bar</th>
<th>Mass Flux, G, KG/m².s</th>
<th>q₀, MW/m²</th>
<th>Inlet, Temp, Tᵢ °C</th>
<th>Diameter, D mm</th>
<th>Length, L m</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Data of water in vertical channel</td>
<td>0.953-51</td>
<td>2018-49673</td>
<td>3.988-67.593</td>
<td>18-80</td>
<td>0.25-8</td>
<td>0.01-0.16</td>
<td>320</td>
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<td>2</td>
<td>Data of R-12 in vertical tubes</td>
<td>6.6-29.3</td>
<td>385-1558</td>
<td>2.8e-2-92.592</td>
<td>26-90</td>
<td>7.72</td>
<td>1.18-2.3</td>
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### Table 5.3: Sub-cooled Data of water in Light water reactor

<table>
<thead>
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<th>S. No</th>
<th>Data</th>
<th>Pressure Bar</th>
<th>Mass Flux, G, KG/m².s</th>
<th>q, MW/m²</th>
<th>Inlet, Temp, Tᵢ, °C</th>
<th>Diameter, d, mm</th>
<th>Length, L, m</th>
<th>Count</th>
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<tr>
<td>1</td>
<td>HTPS</td>
<td>140 – 152</td>
<td>741.2 - 4311.2</td>
<td>1.56 - 4.8114</td>
<td>72.5 - 280</td>
<td>10 – 17</td>
<td>1.008 - 2</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>Thompson¹¹⁸</td>
<td>33.9 – 103.2</td>
<td>3808 - 10390.4</td>
<td>3.354 -10.16</td>
<td>199.56 -250</td>
<td>10.26</td>
<td>0.762 - 0.794</td>
<td>64</td>
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<tr>
<td></td>
<td>(1964)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>3</td>
<td>Lee¹¹ (1988)</td>
<td>38.53 – 111</td>
<td>2040 - 4161.6</td>
<td>3.93 - 7.722</td>
<td>178.7 -252.9</td>
<td>5.588 - 0.77</td>
<td>0.216 - 0.87</td>
<td>16</td>
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<tr>
<td>4</td>
<td>ENEA DATA</td>
<td>33.46-206.6</td>
<td>512.7 - 18362</td>
<td>1.104-14.77</td>
<td>20 - 354.03</td>
<td>1.905 - 7.46</td>
<td>0.035 - 1.98</td>
<td>190</td>
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Table 5.4: General sub-cooled data of Small diameter tubes (0.25 < D < 3 mm):

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<th>S. No</th>
<th>Data</th>
<th>Pressure Bar</th>
<th>Mass Flux, G KG/m².s</th>
<th>qₑ武警, MW/m²</th>
<th>Inlet Temp, T₀ °C</th>
<th>Diameter, D- mm</th>
<th>Length, L- m</th>
<th>Count</th>
</tr>
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<tr>
<td>1</td>
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<td>1 - 23</td>
<td>4032 - 43,139</td>
<td>6 - 56.808</td>
<td>3 - 130</td>
<td>0.584 - 3.1</td>
<td>0.1 - 0.289</td>
<td>311</td>
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<tr>
<td>2</td>
<td>Narai et al.²⁴ (1987)</td>
<td>1.01 - 10.5</td>
<td>4300-29, 911</td>
<td>4.656 - 69.89</td>
<td>15 - 78</td>
<td>1 - 3</td>
<td>0.01 - 0.101</td>
<td>124</td>
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<tr>
<td>3</td>
<td>Bergles² (1963)</td>
<td>1.31 - 22.8</td>
<td>8438-41, 810</td>
<td>18.7 - 123.8</td>
<td>6 - 85</td>
<td>0.33 - 2.67</td>
<td>0.00177 - 0.066</td>
<td>210</td>
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<tr>
<td>4</td>
<td>Ornatski²⁷ (1964)</td>
<td>9.81 - 32.5</td>
<td>5004 - 90,000</td>
<td>6.37 - 227.95</td>
<td>1.5 - 205</td>
<td>0.4 - 2</td>
<td>0.0112 - 0.056</td>
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Table-5.5: Sub-cooled data for small diameter vertical channel (courtesy ENEA):

<table>
<thead>
<tr>
<th>S. No</th>
<th>Data</th>
<th>Pressure Bar</th>
<th>Mass Flux, G KG/m².s</th>
<th>( q_{cr} ) MW/m²</th>
<th>Inlet Temp, ( T_i ) °C</th>
<th>Diameter, D- mm</th>
<th>Length, L- m</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ENEA</td>
<td>1-23</td>
<td>2923-49, 673</td>
<td>6.8695 – 67.593</td>
<td>18.6 – 45</td>
<td>0.25 – 3</td>
<td>0.1</td>
<td>90</td>
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</table>

Table 5.6: Light water reactor sub-cooled data of various authors for small diameter tubes:

<table>
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<tr>
<th>S. No</th>
<th>Data</th>
<th>Pressure Bar</th>
<th>Mass Flux, G KG/m².s</th>
<th>( q_{cr} ) MW/m²</th>
<th>Inlet Temp, ( T_i ) °C</th>
<th>Diameter, D- mm</th>
<th>Length, L- m</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(Courtesy ENEA)</td>
<td>13.78 - 190</td>
<td>818.7-15, 776</td>
<td>1.104- 21.4225</td>
<td>52 – 354</td>
<td>1.14 - 3</td>
<td>0.0114-0.696</td>
<td>220</td>
</tr>
</tbody>
</table>
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Fig. 2.2 Predictions from Rohsenow Correlation\textsuperscript{103, 87} (1952, 1969) for Stainless-steel ethyl alcohol combination.
Fig. 2.3 Validation of Pioro's correlation\textsuperscript{100, 101} (2004) with Experimental data.
Fig. 2.4 Validation of Foster-Zuber (1955) correlation with experimental data.
Fig. 2.5 Validation of Borishansky correlation\textsuperscript{11} (1969) with the data of Ethyl alcohol.
Fig. 2.6 Validation of Borishansky correlation\textsuperscript{11} (1969) with the data of water.
Data of Borishansky et al. (1966)
Number of data points = 468

- △ Water [1 < P < 200 bar]
- ▼ Ethyl Alcohol [1 < P < 60 Bar]
  4.99 < D < 6.94 mm

Fig. 2.7 Comparison of Kichigin et al. (1966) correlation with the data of Borishansky et al. (1966).
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Fig. 2.11 Validation of Experimental data with the present correlation

Eq. (2.12)
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Fig. 3.3 A generalized correlation with the data of Borishansky et al. (1966) and present experimental data.
Fig. 3.4 Comparison of present Experimental data with the correlation of Rohsenow et al.\textsuperscript{103, 87} (1952, 1969).
Forane-Copper combination
No of Data points: 105
D=12.7 mm
L=42 mm
modified values of $C_{sf}$ and $m$
$C_{sf}^* = 9.286 \times 10^3$ and $m = 3.12$

Fig. 3.5 Validation of Pioro et al. correlation\textsuperscript{100,101} (2004) with the present experimental data.
Fig. 3.6 Validation of Labuntsov correlation (1972) with the present experimental data.
Fig. 3.7 Validation of Kruzhilin correlation \textsuperscript{74, 75} (1949) with a modified constant with the present experimental data.

---

Forane-Copper combination
No of Data points: 125
D=12.7 mm
L=42 mm

Original value of constant recommended by Kruzhilin is $c=0.082$
Corrected value of constant to fit the data of Forane $c=1.64$
Fig. 4.1: Comparison of Moshkov (1999) results with the predictions of Levan et al. (1975) for mass velocity.
Average Deviation=19% \( (G \frac{2}{D} \cdot \Delta p)_J^{12} = 115(X/1-X)^{14} \)
Standard Deviation=24% \( G \sim p \cdot V^n \)
100 Bar < P < 200 Bar
8mm < D < 10mm
500 < G < 5500 Kg/m²s
0.25m < L < 2.1m
Data of Peskov et al. (1966)

Fig. 4.2 Validation of Critical Heat Flux Correlation.
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- $L_4$: Mist flow region

$Z=0$, $X=0$
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0.2 < D < 3-mm
Total number of points - 1340
Average Deviation: 18 %
Data Courtesy ENEA
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Dimensionless parameter.
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Correlation [56, 57] [2000]
Fig. 5.11. Comparison of present correlations for \(D<3\) mm with Mudawar et al. Correlation\(^56,57\) [2000]

Mudawar Equation [2000]:

\[
\begin{align*}
\text{Bo} &= C_1(\text{We})^{C_2} \left(\frac{\rho_2}{\rho_d}\right)^{C_3} \left[1-C_4(\rho_2/\rho_d)^{C_5} X_{\text{ex}}\right] \\
\text{We} &= \left(\frac{G^2 D}{\nu \rho}\right)
\end{align*}
\]

Mudawar et al.\(^57\) (2000) equation

Equation 5.8

Equation 5.9

Re, Reynolds number based on inlet conditions
Fig. 5.12 Comparison of present correlations with Tong\textsuperscript{119} [1968] and Modified Tong\textsuperscript{20} [1994] Correlations
Plate 3: experimental setup of Boiling Heat Transfer
Plate 3-4 Slug bubble regime of nucleate boiling in a test run