PREDICTION OF VOID FRACTION IN SUBCOOLED FLOW BOILING

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Abstract

The information on heat transfer and especially on the void fraction in the reactor core under subcooled conditions is very important for the water-cooled nuclear reactors, because of its influence upon the reactivity of the system. This paper gives a short overview of subcooled boiling phenomenon and indicates the simplifications made by the RELAP5 model of subcooled boiling. RELAP5/MOD3.2 calculations were compared with simple one-dimensional models and with high-pressure Bartolomey experiments [8].

Nomenclature

cf - specific heat of the fluid, J/kgK
C - constant
\( \theta \) - bubble diameter
F - convective factor from Chen's correlation
G - mass flux, kg/m²s
k \_ - thermal conductivity, W/MK
h - enthalpy, J/kg
h \_ - heat transfer coefficient to the single phase liquid, W/m²K (eq.5,6)
Nu - Nusselt number
Pe - Peclet number
p - pressure, bar
S - dissipative factor from Chen’s correlation
St - Stanton number
T - temperature, K

Greek letters

\( \rho \) - density, kg/m³
\( \psi \) - parameter in (eq.5)
\( \dot{V} \) - volumetric mass exchange rate, kg/m³s
\( \Delta T_{sat} \) - wall superheat, \( T_w-T_{sat} \) K
\( \Delta T_{sub} \) - liquid subcooling, \( T_{sat}-T_f \) K

Subscripts

f - fluid
g - vapor
sat - saturated
sub - subcooled
in - inlet
\( w_f \) - wall to fluid
\( w_f \) - interfacial

1. Phenomenological description of subcooled flow boiling

The term "subcooled boiling" is mainly associated with the simplification of the boiling phenomenon in the single dimension, since boiling in a vertical channel is typically a multidimensional phenomenon [1]. Subcooled flow boiling in a heated channel 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, which corresponds to the saturated liquid state. The thermodynamic or equilibrium quality [2] is defined as liquid enthalpy relative to the saturation state.

\[
x = \frac{(h_f - h_{f,sat})}{(h_{g,sat} - h_{f,sat})} = \frac{c_f \Delta T_{sub}}{(h_{g,sat} - h_{f,sat})} \quad (1)
\]

Equation (1) results in a negative equilibrium quality for the subcooled boiling region.
Important locations and regions of subcooled boiling in the heated circular tube are illustrated in figure 1 and discussed in the further text. Kandlikar's [3] phenomenological description of subcooled boiling regions is presented here:

**Single phase region (A-B):** Subcooled liquid enters the tube at location A. As long as the wall temperature is lower than local saturation temperature of the liquid, the heat transfer is single-phase. Wall temperature rises linearly and parallel to the bulk liquid temperature. The wall temperature reaches the saturation temperature of the liquid at location B, defining the beginning of the subcooled boiling region. Nucleation does not occur immediately, since certain amount of wall superheat is required for the onset of nucleation.

**Partial nucleate subcooled boiling region (C-E):** Location C, where the first bubbles appear, is identified as the Onset of Nucleate Boiling (ONB). After the ONB point the wall temperature begins to flatten. Further downstream, as more and more bubble sites occur, the contribution to heat transfer from the nucleate boiling continues to rise and the single-phase convective contribution decreases. This transition region between locations C and E is referred to as partial nucleate boiling.

**Fully developed subcooled boiling region (E-G):** Finally the entire wall surface is covered by bubble sites at the location E, establishing the Fully Developed Boiling (FDB), where the convective heat transfer contribution reduces to zero. As the subcooled liquid in the fully developed boiling approaches to the saturation state, a location G is reached, where bubbles detach from the wall and penetrate into the liquid core. This point is called the point of Net Vapor Generation (NVG), where the void fraction begins to be significant.

**Significant void flow region (G-H):** From NVG point onward the flow is considered as two-phase mixture. That means that two-phase heat transfer can be considered and boiling becomes very similar to the saturated flow boiling. The conditions for the NVG location are of particular interest for the RELAP5 computer code. Saturation condition under thermodynamic equilibrium is reached at point H, where the bulk liquid temperature becomes equal to the liquid saturation temperature. However, some subcooled liquid is still locally present in the liquid core.
2. Correlations for subcooled boiling flow

Considering the phenomenological description, Kandlikar [3] divides subcooled boiling into 3 regions. For the sake of simplicity, we will adopt the rough subdivision of the subcooled boiling region into two main regions [2]. In the highly subcooled region, just subsequent to the ONB point, the generated vapor remains as discrete bubbles attached to the wall surface whilst growing and collapsing. Voidage in this region is essentially a wall effect.

At lower subcoolings, at the NVG point (or FDB point by Griffith et al) the bubbles detach from the surface and move through the slightly subcooled liquid. This region is called significant void flow region [3] and voidage in this region is considered as a bulk fluid effect.

2.1. Highly subcooled region (partial boiling and fully developed boiling)

Onset of nucleate boiling

The required wall superheat to initiate bubble nucleation was suggested by many authors, Davis and Anderson [2], Frost and Dzakowic [2], Hsu et al [3]. The Bergles and Rohsenow nucleation criterion is widely used [2]:

\[
(\Delta T_{\text{sat}})_{\text{ONB}} = 0.556 \left( \frac{q_{\text{ONB}}}{1082P^{0.156}} \right)^{0.463} \rho^{0.274}
\]  

(2)

Partial subcooled boiling region

In the partial boiling region, nucleation and single phase convection processes occur simultaneously. Bowring [2] suggests that:

\[
q = q_{\text{SPL}} + q_{\text{SCB}}.
\]  

(3)

The Bowring method implements the superposition of a single phase forced convection component \(q_{\text{SPL}}\) and a subcooled boiling component \(q_{\text{SCB}}\), where \(q\) is the total average wall surface heat flux. Fully developed (FDB) region is reached when convection component \(q_{\text{SPL}}\) reduces to zero. The variation of the single-phase heat flux component \(q_{\text{SPL}}\) with reducing the local subcooling can be described by the Jens and Lottes correlation [4]. The Bowring procedure is detaily explained in Collier [2]. Jens-Lottes relationship between \(\Delta T_{\text{sat}}\) and \(q\):

\[
\Delta T_{\text{sat}} = \psi q^n = 25q^{0.25}e^{-0.62}
\]  

(4)

The subcooling for the FDB point is then calculated by the Bowring formula:

\[
\Delta T_{\text{sub(FDB)}} = \left[ \frac{q}{1.4h_{fo}} \right] - \psi \left[ \frac{q}{1.4} \right]^n
\]  

(5)

2.2. Significant void flow region

Onset of significant void flow region or NVG point

After the point of first bubble departure (also NVG point), significant void is present in the subcooled liquid and the void rises very rapidly even though the bulk liquid may still be in a highly subcooled state. There are several experimental correlations for this point available in the literature. Griffith et al. [2] suggest that the transition to the significant void region is associated with the onset of FDB region, while Bowring [2] calculates the point of first
bubble detachment. A very simple method for calculating the NVG point is the Saha and Zuber criterion \[2\], which is also used by the RELAP5 code. Griffith et al. and Bowring criteria for subcooling are given by equations (6) and (7), respectively, while the Saha-Zuber correlation adopted for use in RELAP5 code is listed among constitutive equations in table 1.

\[
\Delta T_{\text{sub} (FDG)} = \frac{q}{5h_f}, \quad \text{(Griffith et al.)} \ [2]
\]

\[
\Delta T_{\text{sub} (ZG)} = (14 + 0.1p) \frac{q\rho_f}{G}, \quad \text{(Bowring) [2]}
\]

2.3. Void fraction estimation

There are only a few models for wall void fraction estimation in the highly subcooled boiling region, where bubbles do not penetrate into the bulk subcooled flow. One of them is the model proposed by Griffith et al \[2\]. However this model becomes incorrect at low pressures below 20 bar, since the bubble diameter becomes a function of pressure as well.

In the significant void flow region, there are several methods of calculating the void fraction. Collier \[2\] states the model proposed by Bowring and empirical methods of Thom, Zuber and Levy.

3. RELAP5 correlations for subcooled boiling region

RELAP5 disregards the wall voidage region between the ONB point and the NVG point. Thus the fluid flow in the upstream of the NVG point is treated as single-phase flow and two-phase flow downstream. In Table 1 RELAP5 constitutive equations for subcooled boiling are listed \[5\]. Here only the main closure equations for the energy conservation equations are given, since we assume that the relative motion of phases is of minor importance for the subcooled boiling \[6\].

<p>| Table 1: RELAP5/MOD3.2 constitutive equations for subcooled boiling flow region |
|---------------------------------|---------------------------------|</p>
<table>
<thead>
<tr>
<th>Constitutive equations</th>
<th>Reference/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vapor generation rate on the wall</strong></td>
<td>Lahey’s [5] mechanistic model is used to capture the effect of thermal gradient in the wall boundary layer. Liquid near the wall is preheated and flashes to vapor.</td>
</tr>
<tr>
<td>[ \Gamma_w = \frac{q_w}{h_f} ] Ch = \frac{\min(h_f, h_{f,w}) - h_w}{(h_{f,w} - h_w)(1 - \varepsilon)} \rho_f(h_{f,m} - \min(h_f, h_{f,m})) \rho_s(h_{s,m} - h_{f,m}) ] X = \frac{\varepsilon}{\rho_s}</td>
<td>Saha-Zuber [5] correlation is used to calculate the critical enthalpy ( h_r ) of the subcooled fluid, where RELAP5 starts treating the fluid as two-phase flow. The correlation is valid for pressures from 1.01 to 138 bars. At low flow rates the bubble detachment occurred at constant Nu number (thermally controlled), while at high flow rates the bubble departure is hydrodynamically induced at a fixed St number. The Pe = 70000 is the switch between thermally or hydrodynamically controlled bubble departure.</td>
</tr>
<tr>
<td><strong>Net vapor generation point (NVG)</strong></td>
<td>Saha-Zuber [5] correlation is used to calculate the critical enthalpy ( h_r ) of the subcooled fluid, where RELAP5 starts treating the fluid as two-phase flow. The correlation is valid for pressures from 1.01 to 138 bars. At low flow rates the bubble detachment occurred at constant Nu number (thermally controlled), while at high flow rates the bubble departure is hydrodynamically induced at a fixed St number. The Pe = 70000 is the switch between thermally or hydrodynamically controlled bubble departure.</td>
</tr>
<tr>
<td>[ h_w = \begin{cases} \frac{S t C_f}{0.0065} &amp; Pe &gt; 70000 \ \frac{N u C_f}{455} &amp; Pe \leq 70000 \end{cases} ]</td>
<td>All heat flux from the wall during subcooled boiling process is consumed to vapor generation and liquid heating, thus ( Q_{w} = 0 ). Heat</td>
</tr>
<tr>
<td><strong>Wall heat transfer saturated flow boiling:</strong></td>
<td>All heat flux from the wall during subcooled boiling process is consumed to vapor generation and liquid heating, thus ( Q_{w} = 0 ). Heat</td>
</tr>
</tbody>
</table>

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subcooled flow boiling:

\[ T_{sa} < T_f < (T_{sa} - 5), \quad F' = F - 0.2(T_{sa} - T_f)(F - 1) \]

\[ T_f < T_{sa} - 5, \quad F' = 1 \]

- Interfacial heat transfer
  - Interface heat transfer coefficient (for bubbly flow):
    \[ h_t = \frac{C\phi(h_g' - h_f')d}{2\left(1 - \frac{1}{\rho_g'/\rho_f'}\right)} \]
    \[ \phi = \begin{cases} \frac{v_f}{v_g}, & v_f \leq 0.61 \text{m/s} \\ 0.61, & v_f > 0.61 \text{m/s} \end{cases} \]
    \[ C = \begin{cases} 65 - 5.69 \cdot 10^{-4}(p - 10^3), 10^3 \leq p \leq 10^6 \text{ Pa} \\ 0.25 \cdot 10^8 - 10^{-14}, 10^6 < p \leq 17.7 \cdot 10^6 \text{ Pa} \end{cases} \]
  - Volumetric interface heat transfer coefficient:
    \[ H_{if} = h_{if}A, \quad A_i = 3.6\sigma/d, \text{ interface surface area} \]

- Mean bubble diameter \( d_o = \frac{d_{max}}{2} \)

- Vapor generation rate in the volume with two-phase flow
  \[ \Gamma = \frac{H_g(T_g - T_s) + H_f(T_f - T_s)}{h_f' - h_g'} \]
  \[ h_f' = h_f, \quad h_g' = h_g, \quad T_g < 0, \text{ condensation} \]
  \[ h_f' = h_f, \quad h_g' = h_g, \quad T_g > 0, \text{ evaporation} \]

Example

The RELAP5 prediction of the subcooled boiling was assessed on the example of a high-pressure circular tube with the length \( L = 3.66 \text{ m} \) and diameter \( D = 0.01016 \text{ m} \). Conditions are presented in the table 2:

<table>
<thead>
<tr>
<th>Table 2: Example conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pressure at exit, ( p )</strong></td>
</tr>
<tr>
<td><strong>Heat flux, ( q )</strong></td>
</tr>
<tr>
<td><strong>Mass flux, ( G )</strong></td>
</tr>
<tr>
<td><strong>Inlet temperature, ( T_{in} )</strong></td>
</tr>
</tbody>
</table>

The RELAP5/MOD3.2 model of the vertical tube consisted of the 36 nodes with time dependent volumes at the inlet and outlet of the tube. RELAP5 wall and fluid temperature distributions were compared with the temperature estimations calculated by the Bowring method from Jens-Lottes correlation, equation (4). The wall superheat at the ONB point was derived from equation (2). FDB subcooling was calculated by equation (5).

<table>
<thead>
<tr>
<th>Table 3: ONB point calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ONB point</strong></td>
</tr>
<tr>
<td>( Z_{ONB} (m) )</td>
</tr>
<tr>
<td>( \Delta T_{SAL} (\text{°C}) )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4: FDB point calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FDB point</strong></td>
</tr>
<tr>
<td>( \Delta T_{SUB}(\text{°C}) )</td>
</tr>
<tr>
<td>( \Delta T_{SAL}(\text{°C}) )</td>
</tr>
</tbody>
</table>

The comparison of temperature distributions is shown in figure 2. The wall temperature calculated by RELAP is continuous and exceeds the Jens-Lottes wall temperature for almost
15 °C at the saturated boiling point. The wall temperature distribution in figure 5 and the heat transfer comparison [7] show that RELAP does not take into account the changed heat transfer conditions in the partial subcooled boiling region.

![Graph showing temperature distributions](image)

**Figure 2:** Comparison of temperature distributions; RELAP5/MOD3.2 prediction versus Jens-Lottes correlation for conditions in table 2

Figure 3 presents the void fractions calculated by RELAP5 and void fractions derived from empirical methods of Thom et al. and Bowring. Thom et al. and Bowring empirical calculations of this example are presented in [7]. The NVG locations and subcoolings are compared in table 5 and figure 3.

**Table 5: NVG point**

<table>
<thead>
<tr>
<th>NVG point</th>
<th>Griffith (Z_{FDD}=Z_{NVG})</th>
<th>Bowring (Z_d)</th>
<th>Saha-Zuber (RELAP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z_{NVG} (m)</td>
<td>2.85</td>
<td>2.86</td>
<td>2.70</td>
</tr>
<tr>
<td>(\Delta T_{sub} \degree{C} )</td>
<td>6.95</td>
<td>5.00</td>
<td>9.75</td>
</tr>
</tbody>
</table>

![Graph showing void fraction predictions](image)

**Figure 3:** Comparison of void fraction predictions in the significant void flow region

The Saha-Zuber criterion used in the RELAP5 code, allows vapor generation in the bulk liquid at lower subcooling than Griffith or Bowring correlation. Thus, the NVG point occurred earlier, as presented in figure 4. The void fraction estimations by Thom et al. and Bowring are also lower than RELAP5 void fractions.
4. Bartolomey experiments

The RELAP5/MOD3.2 model of subcooled boiling was compared to 3 high-pressure Bartolomey experiments [8] with the conditions from table 6:

**Table 6: Experiment conditions**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Length ( L ) (m)</th>
<th>Tube inside diameter ( D ) (m)</th>
<th>Pressure at exit, ( p ) (bar)</th>
<th>Heat flux, ( q ) (kW/m(^2))</th>
<th>Mass flux, ( G ) (kg/m(^2)s)</th>
<th>Inlet temperature, ( T_{in} ) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. 1</td>
<td>1.5</td>
<td>0.012</td>
<td>147.5</td>
<td>1130</td>
<td>2123</td>
<td>583</td>
</tr>
<tr>
<td>Exp. 2</td>
<td>1.16</td>
<td>0.012</td>
<td>68.9</td>
<td>770</td>
<td>1467</td>
<td>519</td>
</tr>
<tr>
<td>Exp. 3</td>
<td>1.24</td>
<td>0.012</td>
<td>68.9</td>
<td>790</td>
<td>405</td>
<td>421</td>
</tr>
</tbody>
</table>

The RELAP5/MOD3.2 prediction of void fraction is compared against experimental data in figures 4 to 6. The RELAP5 nodalization model of the tube consisted of 15 nodes. The modified nodalization density did not have a significant influence on the results [7]. The abscissa on figures 4 to 6 is the thermodynamic quality \( x \). The ONB and NVG points indicated in figures are obtained from Bergles-Rohsenow and Bowring correlations, respectively. The comparison of thermodynamic qualities \( x \) for the RELAP5 and Bowring NVG points is given in table 7.

**Table 7: Comparison of ONB and NVG points**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>RELAP</th>
<th>Rohsenow (ONB)</th>
<th>Bowring (NVG)</th>
<th>RELAP</th>
<th>Rohsenow (ONB)</th>
<th>Bowring (NVG)</th>
<th>RELAP</th>
<th>Rohsenow (ONB)</th>
<th>Bowring (NVG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_{ONB} )</td>
<td></td>
<td>-0.265</td>
<td></td>
<td></td>
<td>-0.460</td>
<td></td>
<td></td>
<td>-0.172</td>
<td></td>
</tr>
<tr>
<td>( x_{NVG} )</td>
<td>-0.082</td>
<td>-0.072</td>
<td>-0.119</td>
<td>-0.098</td>
<td>-0.06</td>
<td>-0.045</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5:** Void fraction versus thermodynamic quality; experiment 1

**Figure 6:** Void fraction versus thermodynamic quality; experiment 2

**Figure 7:** Void fraction versus thermodynamic quality; experiment 3
5. Conclusions

The subcooled boiling region can be roughly divided into two main regions: highly subcooled region (voidage in this region represents a wall effect) and significant void flow region (voidage in this region is considered as bulk fluid effect). The subcooled boiling is at least a 2D phenomenon. Thus the simplifications made by RELAP5 were assessed:

- RELAP5 does not take into account the wall voidage in the highly subcooled region. The RELAP5 code treats the fluid in this region (from ONB to the NVG point) as single-phase flow.
- The RELAP5 wall temperature after the ONB point exceeds significantly the wall temperature calculated by the Jens-Lottes correlation, which considers changed heat transfer conditions after the ONB point.

The RELAP5 computer code uses the Saha-Zuber correlation to determine the location of the NVG point, where the fluid is treated as a two-phase flow. Comparison with Bowring correlations for NVG point on the Bartolomey experiments [8] shows earlier appearance of RELAP5 NVG point, which also fits better to the experimental data.

Comparison of RELAP void fraction with the experimental void fraction shows slight underprediction of RELAP5/MOD 3.2 calculations after the NVG point. We also presume that RELAP5 does not predict the experimental wall voidage, although the location of experimental NVG point is not clearly evident from the available experimental data.

This study shows that there is a need for multidimensional modeling of the subcooled boiling phenomenon, especially in the highly subcooled boiling region. Our future activities will therefore deal with 2D modeling of the subcooled flow boiling.

References

3. S.G. Kandlikar, “Heat transfer characteristics in partial boiling, fully developed boiling, and significant void flow regions of subcooled flow boiling”, FED-Vol. 244, ASME 97, 1997
7. B.Končar, “One-dimensional models of subcooled flow boiling”, draft seminar No.1 for the postgraduate study in Nuclear Engineering, Ljubljana, 1998