STUDY OF THE RELAP5/MOD3.2 WALL HEAT FLUX PARTITIONING MODEL

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INTRODUCTION:

The performance of the subcooled boiling model adapted in RELAP5/MOD3.2 computer code has been assessed in detail for low-pressure conditions and it has been found that the void fraction profile is underpredicted. Alternate remedial measures to be utilized while dealing with low-pressure flow boiling conditions to obtain reasonable void fraction predictions have been recommended.

In general, any subcooled boiling model is composed of individual sub-models that account for the different physical mechanism that govern the overall process, as the wall vapor generation, interfacial shear and condensation etc. The wall heat flux partitioning model is one of the important sub-models that is a constituent of any subcooled boiling model. The function of this model is to apportion the wall heat flux to the different components (as the single/two phase fluid or bubble), as the case may be, in a two-phase flow-boiling scenario adjacent to a heated wall. The "pumping factor" approach is generally followed by most of the wall heat flux partitioning models, for partitioning the wall heat flux.

In this work, the wall heat flux partitioning model of RELAP5/MOD3.2 computer code is studied; in particular, the "pumping factor" formulation in the present code version is assessed for its performance under low-pressure conditions. In addition, three different "pumping factor" formulations available in the literature have been introduced into the RELAP5/MOD3.2 code. Simulations of two low-pressure subcooled flow boiling experiments (discussed in reference 9) were performed with the refined code versions to determine the appropriate pumping factor to be used under these conditions.
RELAP5/MOD3.2 WALL HEAT FLUX PARTITIONING:

A brief introduction on the modeling of the subcooled flow boiling phenomenon is available in reference 6 and the various components of the RELAP5/MOD3.2 subcooled boiling model are discussed in detail in references 4 and 11. In the next few sections, the functioning of the wall heat flux partitioning model is presented.

In RELAP5/MOD3.2 [10], the wall heat flux is arbitrarily partitioned into two components,

\[ Q_w = Q_{\text{conv}} + Q_{\text{boil}} \]  

where \( Q_{\text{conv}} \) is a portion of the wall heat transfer treated as convective heat flux and \( Q_{\text{boil}} \) is that portion that results in the saturated pool boiling from the liquid phase. The boiling heat flux, \( Q_{\text{boil}} \), is further partitioned as

\[ Q_{\text{boil}} = Q_{\text{evap}} + Q_{\text{pump}} \]

where \( Q_{\text{evap}} \) is a portion of the boiling heat flux that is assigned vapor formation and \( Q_{\text{pump}} \) is the heat flux that is assigned to the agitation caused due to bubble growth and detachment phenomenon (the ebullition cycle), and, is popularly referred to in the literature as the pumping heat flux.

The ratio of the pumping to the evaporation component of the wall heat flux is called as the “pumping factor” and is represented as

\[ \delta = \frac{Q_{\text{pump}}}{Q_{\text{evap}}} \]  

In the RELAP code, the bubble departure point is first determined using the Saha and Zuber method [10] of predicting the necessary conditions for voids to exist. The Saha-Zuber correlation uses the local Peclet (Pe) number to decide whether the heat flux at the bubble departure point should be related to the Nusselt number (Nu) (low flow) or Stanton number (St) (high flow). The enthalpy corresponding to this point is denoted as the critical enthalpy, \( h_{\text{cr}} \), in the RELAP code and is calculated as

\[ h_{\text{cr}} = \begin{cases} h_{\text{f, sat}} - StC_p/0.0065 & \text{for } Pe > 70000 \\ h_{\text{f, sat}} - NuC_p/455 & \text{for } Pe \leq 70000 \end{cases} \]

As the bulk liquid enthalpy, \( h \), increases above the critical enthalpy, \( h_{\text{cr}} \), a fraction of the total wall heat flux is assumed to generate vapor while the remaining part is used to heat up the bulk liquid. The evaporation fraction \( \chi \) of the total wall heat flux is then determined as follows. If the minimum of the bulk liquid enthalpy, \( h \), and the saturation enthalpy, \( h_{\text{f, sat}} \) is greater than the critical enthalpy, \( h_{\text{cr}} \), then the fraction \( \chi \) is...
where the quantity $\varepsilon$ is the pumping factor, which is calculated by the code as

$$
\varepsilon = \frac{\bar{n}_r \left( h_{sat} - \min(h_f, h_{sat}) \right)}{\bar{n}_s h_{fg}}
$$

(6)

Finally, the wall vapor generation rate per unit volume $\Gamma_w$ is calculated using the above parameters as

$$
\dot{\Lambda}_w = \frac{q_f \dot{A}_w}{V \left[ \max(h_{sat} - h_f, 10^4 J/Kg) \right]}
$$

(7)

where $V$ is the cell volume and $A_w$ is the wall heat transfer area.

Hence, we see that the pumping factor is an important parameter in the partitioning of the wall heat flux. As can be seen from its definition, pumping factor $\varepsilon$ is very high just above the critical enthalpy, $h_r$ and approaches zero as the bulk liquid enthalpy goes toward the saturation value. Pumping causes a suppression of the evaporation process and a proper estimation of the pumping factor $\varepsilon$ is therefore necessary to model the subcooled boiling phenomenon.

A detailed survey was undertaken to obtain the various pumping factors that are documented in the literature. Four different formulations of the "pumping factor" available in the literature are summarized in Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>Pumping Factor</th>
<th>Validity</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOWRING$^6$</td>
<td>1962</td>
<td>$3.2 \left( \frac{\rho_f}{\rho_s} \right) \left( \frac{c_{pf}}{h_{fg}} \right)$</td>
<td>1 to 9.5 bar</td>
</tr>
<tr>
<td>GREGORIO AND MERLINI$^6$</td>
<td>1968</td>
<td>$1 + \frac{\rho_f}{\rho_s} \left( \frac{c_{pf}}{h_{fg}} \frac{\Delta T_{sub}(z)}{h_{fg}} \right)$</td>
<td>N/A</td>
</tr>
<tr>
<td>LAHEY$^{11}$</td>
<td>1978</td>
<td>$\frac{\rho_f}{\rho_s} \left( \frac{h_{f, sat} - h_f}{h_{fg}} \right)$</td>
<td>N/A</td>
</tr>
<tr>
<td>ZEITOUN &amp; SHOUKRI$^7$</td>
<td>1997</td>
<td>$0.75 \left( \frac{\rho_f}{\rho_s} \frac{c_{pf}(T_w - T_f)}{h_{fg}} \delta_{th} \right) \frac{D_i}{D_t}$</td>
<td>Low Pressure 1-2 bars</td>
</tr>
</tbody>
</table>
From Collier\(^6\), it can be seen that Bowring was the first to propose a model for subcooled boiling. He also introduced the concept of "Wall heat flux partitioning" and the "pumping factor" approach. Based on experimental data, Bowring suggested different 'pumping factor' formulations for low-pressure and high-pressure conditions. We have used his low-pressure formulation in this study. Gregorio and Merlini have proposed a slightly different formulation for the pumping factor.

RELAP5/MOD3.2 uses the Lahey's mechanistic model\(^{11}\) and "pumping factor" formulation. After formulating his mechanistic model, Lahey used experimental data (high pressure) to balance his evaporation and condensation processes by specifying a condensation parameter and altering his pumping term accordingly.

Zeitoun and Shoukri argue in their work\(^9\) that the previous formulations overestimate the pumping factor due to assumptions that are inherent in their formulations. This results in suppressing the vapor generation process and an underestimation of the void fraction. Hence, they propose a new formulation for the pumping factor. Zeitoun and Shoukri derive their formulation based on the volume of the thermal boundary layer pushed by the nucleating bubbles and the average temperature difference across the thermal boundary layer.

**RELAP5 MODIFICATIONS:**

As with a previous modification\(^5\) to the original code version, the bubbly to slug flow transition criterion was increased to 0.3, to be consistent with experimental observations\(^{10}\). Later, these "pumping factors" were introduced into the RELAP5/MOD3.2 computer code. While the first two pumping factor formulations are simple and easily amenable for implementation in the RELAP code, the last formulation is complicated. Appendix I presents the steps involved in the implementation of the last pumping factor formulation.

**NODALIZATION OF THE EXPERIMENTAL SETUP & SIMULATIONS:**

Two low-pressure subcooled boiling experiments were simulated with the refined code versions. These experiments were chosen so as to reflect different geometry, inlet mass flux and inlet subcooling conditions. Tables 2 and 3 summarize the geometrical details and the parameters of interest for the simulated experiments. The RELAP5/MOD3.2 nodalization of the experimental setup is presented in Fig. 1. More details on the experimental setup and other relevant information on the experiment and can be found in references 2 and 9.

<table>
<thead>
<tr>
<th>CASE</th>
<th>GEOMETRY</th>
<th>ID (m)</th>
<th>OD (m)</th>
<th>LENGTH (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ANNULUS</td>
<td>0.0127</td>
<td>0.0254</td>
<td>0.3048</td>
</tr>
<tr>
<td>2</td>
<td>PIPE</td>
<td>0.01229</td>
<td>N/A</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 2. Geometrical Configuration of the Cases
Table 3. Experimental Conditions

<table>
<thead>
<tr>
<th>CASE</th>
<th>PRESSURE (Pa)</th>
<th>MASS FLUX (kg/s-m²)</th>
<th>HEAT FLUX (kW-m²)</th>
<th>INLET SUBCOOLING (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.65</td>
<td>367.4</td>
<td>714.4</td>
<td>29.2</td>
</tr>
<tr>
<td>2</td>
<td>1.65</td>
<td>620.2</td>
<td>805.0</td>
<td>44.3</td>
</tr>
</tbody>
</table>

RELAP5 nodalization of the experimental setup is shown in Figure 1. The inlet pressure and temperature conditions were specified at the inlet time dependent volume and the inlet flowrate to the test section was specified using the time dependent junction preceding the inlet single volume. The conditions at the exit of the test section were specified at the time-dependent junction that followed the test section. The pressure in the test section was set at the volume next to the exit of the test section. The test section was divided into an equal number of axial volumes and heat structures, with uniform heat distribution associated with each structure.

RESULTS & DISCUSSIONS:

The results of the studies are presented in Figures 2 and 3. The axial void fraction profile predicted by the code with the different “pumping factors” is compared with the experimental values. It is found that the Lahey’s and Gregorio and Merlini’s “pumping
Figure 2. Void Fraction Profile for Case 1 (Annulus) with Different Pumping Factors

Figure 3. Void Fraction Profile for Case 2 (Pipe) with Different Pumping Factors
factor" formulations underpredicted the void fraction profile for both the cases. However, reasonable void fraction predictions were obtained when Bowring's or Zeitoun and Shoukri's "pumping factor" was used. Therefore, it seems that for low-pressure subcooled flow boiling conditions, it would be more appropriate to use Bowring's or Zeitoun and Shoukri's "pumping factor" formulation.

The possible reasons for obtaining better predictions with Bowring's or Zeitoun and Shoukri's "pumping factor" may be as follows. Since the Bowring's pumping factor formulation is obtained using experimental low-pressure subcooled flow boiling data, it gives reasonable predictions. The Zeitoun and Shoukri's formulation takes into account the changes that occur in the thermal boundary layer and the sauter mean diameter of the bubbles in the determination of the pumping factor. Hence, they are able to capture the physical trend more closely than the other two formulations.

The Lahey's formulation assumed that the liquid enthalpy leaving the control volume is saturated and the liquid volume leaving the heated surface is equal to the volume of the departed bubble. Moreover, the heat transfer is calculated based on the temperature difference between the saturated liquid and the bulk subcooled liquid. In addition, Lahey also proposes a condensation parameter to balance the vapor generation and condensation processes. This condensation parameter is obtained based on high-pressure data. It is felt that the combined result of all the above is an overestimation of the pumping term and the suppression of the vapor generation process for low-pressure conditions.

CONCLUSION:

The "pumping factor" approach and the Wall heat flux partitioning model adopted in the RELAP5/MOD3.2 subcooled boiling model were studied in detail. The performance of three different pumping factor formulations available in the literature was assessed for their suitability for low-pressure subcooled flow boiling conditions. Two low-pressure experiments with different inlet mass flux and inlet subcooling conditions in different geometries were simulated with the refined code versions. The axial void fraction profile predictions obtained with the different pumping factor formulations were presented. The results of the study indicate that the Bowring's and the Zeitoun and Shoukri's pumping factor formulations would be more appropriate for low-pressure conditions.

ACKNOWLEDGEMENTS:

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APPENDIX I

The pumping factor proposed by Zeitoun and Shoukr³ is of the form

\[ 0.75 \left( \frac{\hat{n}_t}{\hat{n}_s} \right) \left( \frac{c_{st}(T_w-T_r)}{h_b} \right) \left( \frac{d_{sm}}{d_{sm}} \right) \]  --(1)

where \( \delta_{in} \) is the thickness of the thermal boundary layer displaced by the bubble and \( d_{sm} \) is the Sauter mean diameter of the bubble. The thickness of the thermal boundary layer \( \delta_{in} \) is calculated from the following approximation

\[ \hat{a}_{in} = \frac{K(T_w-T_r)}{q} \]  --(2)

From RELAP5/MOD3.2 Code Manual, Vol. IV, we see that the Sauter mean diameter \( d_{sm} \) of the bubble can be expressed as

\[ d_{sm} = \frac{6d'}{2.4} \]  --(3)

where \( d' \) is the most probable droplet diameter. However, the most probable droplet diameter \( d' \) and the mean droplet diameter \( d_0 \) are related by

\[ d' = \frac{2d_0}{3} \]  --(4)

Using (3) and (4), if we relate the Sauter mean diameter, \( d_{sm} \), and the mean droplet diameter, \( d_0 \), we obtain

\[ d_{sm} = \frac{10d_0}{6} \]  --(5)

However, it is assumed in RELAP5/MOD3.2 that the mean droplet diameter, \( d_0 \), is half the maximum bubble diameter, \( d_{max} \), and, the maximum bubble diameter for bubble breakup is specified in terms of the critical Weber number, which is 10 for the case of bubbly flow.

The result of the first assumption is the following expression that relates the Sauter mean diameter, \( d_{sm} \), and the maximum bubble diameter, \( d_{max} \),

\[ d_{sm} = \frac{10}{12} d_{max} \]  --(6)

Using the definition of the Weber number and the second assumption, we can arrive at a relation between the critical Weber number and the maximum bubble diameter, \( d_{max} \),
By substituting (7) in (6), we can express the sauter mean diameter of the bubble, \( d_{\text{sa}} \), in terms of the physical properties and flow conditions

\[
\begin{align*}
\frac{d_{\text{sa}}}{d_\text{max}} &= \frac{100}{\hat{n}_f v_f^2} \\
\text{(8)}
\end{align*}
\]

On substituting the expressions for the thickness of the thermal boundary layer, (2), and the bubble sauter mean diameter, (9), into the expression for the pumping factor, (1), the result is

\[
\hat{\alpha} = 0.09 \frac{\hat{n}_f k C_{\text{eff}} (T_w - T_f)^2 v_f}{q h \hat{n}_g} \\
\text{(9)}
\]

The above expression was implemented into the RELAP code.
NOMENCLATURE:

\( \tilde{n}_f \) - density of the liquid phase
\( \tilde{n}_g \) - density of the gas phase
\( h_r \) - enthalpy of the liquid phase
\( h_{\text{fsat}} \) - saturation enthalpy of the liquid phase
\( h_{\text{fg}} \) - latent heat of vaporization
\( \delta \) - surface tension of the liquid
\( c_{pf} \) - specific heat capacity of the liquid phase
\( k_f \) - thermal conductivity of the liquid phase
\( \tilde{a}_h \) - thickness of the thermal boundary layer
\( d_{\text{sm}} \) - sauter mean diameter of the bubbles
\( T_w \) - wall temperature
\( T_f \) - fluid temperature
\( v_g \) - velocity of the gas phase
\( v_f \) - velocity of the liquid phase
\( v_r \) - relative velocity, \( v_g - v_f \)
\( \tilde{a} \) - pumping factor
\( \tilde{\alpha} \) - evaporative fraction of the wall heat flux
\( \tilde{\bar{A}}_w \) - wall vapor generation rate per unit volume
\( q \) - wall heat flux
\( q_{\text{conv}} \) - convective heat flux
\( q_{\text{boil}} \) - convective heat flux
\( q_{\text{pump}} \) - pumping heat flux
\( \Delta T_{\text{sub}}(z) \) - inlet Subcooling at any axial location \( z \), i.e., \( T_{\text{in}}(z) - T_f(z) \)
REFERENCES:


(7) B. Donevski and M. Shoukri, "Experimental Study of Subcooled Flow Boiling and Condensation in Annular Channel", Thermo Fluids Report No. ME/89/TF/R1, Department of Mechanical Engineering, McMaster University, Hamilton, ON, Canada, 1989.


