ANALYSIS OF THE INTERFACIAL AREA TRANSPORT MODEL FOR INDUSTRIAL 2-PHASE BOILING FLOW APPLICATIONS

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ABSTRACT

One of the most important parameters when using a 2-fluid model to analyze the critical heat flux (CHF) performance of a mixing grid is the interfacial area term. This term is responsible for the rate of phase change and the amount of thermal and mechanical interaction between phases. Accurate closure relations for this term are not fully developed for flow conditions in a rod bundle that contain spacers with mixing vanes and simple support grids. Using the OECD/NRC, Nuclear Power Engineering Corporation (NUPEC) PWR Bundle Tests (PSBT) 5x5 rod bundle steady-state average void fractions are compared to numerical simulations. Predicting the correct void fraction is one aspect in using numerical simulation to predict CHF performance but attention must also be turned to the temperature distribution along the rods, especially the impact of spacers. An analysis is presented which shows the impact of the temperature distribution along the rods for various interfacial area transport model parameters and closure models. With this AREVA demonstrates that it is possible to predict average void and correct temperature distributions with the use of computational fluid dynamics (CFD).

1. INTRODUCTION

The modelling of multi-phase flow in rod bundles with spacers is an important aspect for nuclear fuel design and operation. The use of simulation techniques from 1-D analysis to CFD is a well established field in many industries. Especially in the field of nuclear applications single-phase CFD is already an integral part of the thermal hydraulic method toolbox, see e.g. [1],[2]. Multi-phase CFD is a subject of intense research, methods for nuclear applications are on-going [3],[4].

The purpose of this paper is to highlight the use of numerical simulations for multi-phase applications which can be used for safety analysis, performance prediction and cost savings.

The paper will describe the models used for a 2-phase analysis and highlight areas of numerical sensitivity to achieve stable/converged solutions. With the chosen set of models, the experimental data from the OECD/NRC PSBT 5x5 rod bundle benchmark is used to highlight the ability of the models to predict average void in a rod bundle configuration. Average void prediction in the sub-channels is one important aspect of nuclear applications, but predicting the correct rod temperature distribution close or at critical heat flux (CHF) will also be discussed.

2. PHYSICAL MODELS

The 2-phase simulations are based on the Eulerian multi-phase approach, where the conservation of mass, momentum and energy are solved for each phase. The commercial software tool provided by CD-adapco, STAR-CCM+ v7.04 is used for the standard 2-phase analysis with
custom modelling for the interfacial area and wall boiling models. The conservative relations for mass, momentum and energy used in STAR-CCM+ are given by [5]-[7].

2.1 Interfacial Area Transport Equation

The interfacial area term is very important in the interaction terms between phases for momentum and mass/energy transfer. Ishii [8] summarizes the development of the interfacial area term based on modelling and experimental benchmarks. Before going further it is important to show the relationship between interfacial area and mean bubble diameter, for a spherical bubble the relationship is

\[ d_s = \frac{6\alpha_s}{a_i} \]  

(1)

Where \( d_s \) is the mean Sauter bubble diameter and \( a_i \) is the interfacial area. The easiest method is to assume a constant mean Sauter bubble diameter or a function of sub-cooling, but an advanced method is to solve a transport equation for the interfacial area. Kocamustafaogullari and Ishii [9] developed the Interfacial Area Transport Equation (IATE), based on the concept of a particle number distribution, where this quantity of interfacial area is convected and its source/sink terms are based on collision frequency, efficiency, compressibility and mass transfer. Many source term variants have been developed to describe the break-up and coalescence, by Hibiki and Ishii [10], Wu et al. [11] and Yao and Morel [12] to name a few. The volumetric form of the interfacial area transport equation is given by Yao and Morel [8]

\[
\frac{\partial (a_i)}{\partial t} + \nabla \cdot (\vec{u}_g a_i) = \frac{2}{3} a_i \rho_g \left( \Gamma_{g,i} - \alpha \frac{D\rho_g}{Dt} \right) + \frac{36\pi}{3} \left( \frac{\alpha}{a_i} \right)^2 \left( \phi_n^{CO} + \phi_n^{BK} \right) + \pi a_i^2 \phi_n^{NUC} 
\]  

(2)

The 2 terms on the left hand side represent the unsteady and convective term of the interfacial area. The 1st term on the right hand side represents the change due to condensation/evaporation, but not nucleation at the wall, the 2nd term is based on compressibility of the gas phase followed by coalescence, breakup and nucleation.

If we multiply equation 2 by the density of the gas phase, assume steady-state and incompressible gas phase, equation 2 can be rewritten as

\[
\nabla \cdot \left( \alpha_g \rho_g \vec{u}_g \phi \right) = \frac{2}{3} a_i \Gamma_{g,i} \rho_g \left( S_{CO} + S_{BK} \right) + \rho_g \pi a_i^2 \phi_n^{NUC} 
\]  

(3)

where the \( \frac{36\pi}{3} \left( \frac{\alpha}{a_i} \right)^2 \) term is incorporated into the \( S_{CO}, S_{BK} \) source terms for coalescence/break-up and \( \phi \) is a passive scalar related to interfacial area by \( a_i = \phi \alpha \). Equation 3 is the final form implemented in STAR-CCM+ using passive scalar transport equation.
2.1.1 IATE Break-up and Coalescence Source Terms

In equation 3 it is interesting to examine the two source terms for break-up and coalescence for any potential numerical difficulties. There are many different models available for break-up and coalescence, but for simplicity only 2 will be examined, Hibiki and Ishii [10] and Yao and Morel [12].

The source terms for break-up and coalescence allow for singularities to occur, e.g. when the void fraction $\alpha$ approaches $\alpha_{\text{max}}$.

Using material properties at 135 bars for water/steam and assuming two different mean bubble diameters (0.1 and 1mm) and two values for turbulent dissipation rate of water $\epsilon = 1$ and 1000 m$^2$/s$^3$ (typical sub-channel and near rod values), Figure 1 compares the sum of the break-up and coalescence source term. For the Yao and Morel model for large bubbles, the source term shows no singularity, because the term $\frac{\text{We}}{\text{We}_{\text{crit}}}$ ($\text{We}_{\text{crit}} = 1.24$) or the interaction time is dominant compared to the free travelling time. As the bubble diameter gets smaller and volume fraction increases a singularity is found in the Yao and Morel model, not because $\alpha_{\text{max}} = \alpha$ like in the Hibiki and Ishii model but because the free travelling time and interaction term offset each other resulting in a near zero value. The break-up and coalescence models were originally not devised for flow parameters reaching values that lead to these unphysical singularities. However, during the iterative numerical solutions of the governing equations such values might be reached during intermediate solution steps. Therefore it is essential for a stable numerical implementation of these terms, to provide stability measures, such as smoothing, suppressing the singularity or by setting $\alpha_{\text{max}}$ to a number slightly greater than 1. These techniques have no physical meaning; therefore it is necessary to evaluate the effect on the 2-phase results. A detailed discussion of the numerical techniques and evaluation of these techniques is out of the scope of this paper.
2.2 Wall Boiling

As the interfacial area is an important term for 2-phase modelling an equally important aspect is the wall boiling models which generate the amount of void, but which is also a source term for the IATE model (last term in equation 3).

In STAR-CCM+ the wall heat flux is composed of 4 components \([3]\), liquid contribution based on single-phase turbulent convection, portion responsible for producing bubbles \(q_{\text{evap}}\), portion of heat due to the influx of cooler liquid after a bubble as departed (quenching), and a vapour contribution to heat flux, based on single-phase turbulent convection.

STAR-CCM+ has 2 different sub-models for wall boiling but there is also the ability to implement user defined models, *e.g.* Model Set 3 in Table 1.

<table>
<thead>
<tr>
<th>Wall Boiling</th>
<th>Model Set 1</th>
<th>Model Set 2</th>
<th>Model Set 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucleation site number density</td>
<td>Lemmert-Chawla</td>
<td>Hibiki-Ishii</td>
<td>Kocamustafaogullari-Ishii</td>
</tr>
<tr>
<td>Bubble departure diameter</td>
<td>Tolubinsky-Kostanchuk</td>
<td>Kocamustafaogullari</td>
<td>Kocamustafaogullari-Ishii</td>
</tr>
<tr>
<td>Bubble departure frequency</td>
<td>Cole</td>
<td>Cole</td>
<td>Cole</td>
</tr>
</tbody>
</table>

Table 1 - Summary of sub-models for wall boiling.

Before using these models in a CFD simulation it is important to examine \(q_{\text{evap}}\) as a function of wall superheat. Assuming the material properties at 135 bars and that the liquid temperature is equal to the saturation temperature, sub-cooling is zero, the various model sets can be plotted as a function of super heat. In Figure 2 the Model Sets 1 and 3 behave very similar: step increase in \(q_{\text{evap}}\) and than levelling out as the super heat increases. Even though Model Sets 1 and 3 are similar in terms of \(q_{\text{evap}}\), the bubble departure diameter is different by a factor of 100, where the Kocamustafaogullari-Ishii model is driven mainly by the reference pressure, therefore being 100 times smaller than the Tolubinsky-Kostanchuk model, which is mainly driven by sub-cooling and the reference diameter of 0.6mm.
2.3 Interfacial Momentum Closure Models

The interfacial momentum closure models used for the simulations are the drag model based on Wang and turbulent dispersion. Additional closure models are examined in section 4.2.

3. RESULTS OECD/PSBT BENCHMARK

3.1 Geometry/Boundary Conditions

The boundary conditions and spacer location are given by [14]. It is based on the test assembly B5, which is a 5x5 rod bundle, uniformly heated with 7 spacers with mixing vanes, 8 simple support grids and 2 spacers with no mixing vanes. Five different test cases were examined, which represent a range of operating pressure from 75-167 bars and a range of average void from near zero to 56%. A summary of the cases used for the CFD simulations can be found in Table 2.

<table>
<thead>
<tr>
<th>Test Case</th>
<th>5_1121</th>
<th>5_2442</th>
<th>5_5311</th>
<th>5_3321</th>
<th>5_3332</th>
</tr>
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<tbody>
<tr>
<td>Pressure [bar]</td>
<td>164</td>
<td>147</td>
<td>73.5</td>
<td>122</td>
<td>122</td>
</tr>
<tr>
<td>Inlet Temperature [°C]</td>
<td>316.9</td>
<td>263</td>
<td>193.8</td>
<td>271.8</td>
<td>277.3</td>
</tr>
<tr>
<td>Heat Flux (kW/m²)</td>
<td>1096</td>
<td>733</td>
<td>1285</td>
<td>1098</td>
<td>914</td>
</tr>
<tr>
<td>Mass Flux [kg/m²]</td>
<td>4156</td>
<td>1386</td>
<td>2242</td>
<td>3072</td>
<td>2219</td>
</tr>
</tbody>
</table>

Table 2 - Summary of PSBT operating conditions for CFD simulations.

The mesh consists of 121 million trimmed cells; Figure 3 shows the mesh resolution for the spacer with mixing vanes and simple support grid.
3.2 Average Void prediction

The results for all simulations are based on models presented in section 2. For all runs, the solution was considered converged when the percent error in mass imbalance
\[
\left( \frac{m_{g,\text{in}} + m_{\text{f,lin}} + m_{g,\text{out}} + m_{\text{f,out}}}{m_{g,\text{in}} + m_{\text{f,lin}}} \right) \times 100
\]
was less than 1% and the average void was no longer changing at the 3 monitoring locations (2.216, 2.699, and 3.177m in the test section). Figure 4 shows an example of the average void convergence history for the 5_2442 case (all other cases show similar behaviours).

One set of comparison with experimental data is to examine the average void in all sub-channels and compare with chordal measurement, Figure 5. There is good agreement between the level of the void at the 3 locations as well as the distribution, the edges having lower void compared to the center. Figure 6 compares the predicted average void in the 4 central sub-channels with experiment based on the 3 monitoring locations at 2.216, 2.699, and 3.177m in the test section. Figure 6 shows for all 5 test cases the 2-phase models are able to predict average void within the uncertainty of the experimental value.
Figure 5 - Comparison of average void based on run 5_2442. Top: CFD results of average void in each sub channel, Bottom: void distribution image in rod bundle by chordal measurement[15].

Figure 6 - Comparison of average void between CFD and experiments [16] for the 5 PSBT test cases.
4. RESULTS OF 2X1 SUBCHANNEL WITH SPACER NEAR CHF

In section 3 the prediction of average void with CFD was shown to work within the uncertainty of the experiment based on the OECD/PSBT benchmark. Another aspect of CHF prediction is the rod temperature; therefore a 3-span, 2x1 sub-channels case was built using the OECD/PSBT geometries. The interest of this study is to examine how the different closure models effect rod temperature for a rod bundle with spacers and support grids. In the following section no conclusion should be drawn on which is the best model or coefficients, but rather an examination of the effect these models have on rod temperature near DNB conditions.

4.1 Geometry/Boundary Conditions

The boundary conditions are taken from test case 5_2442, which is shown in Table 2: the heat flux is slightly increased by about 3% to get closer to DNB conditions, but the CFD inlet condition remains sub-cooled. Figure 7 shows the geometry of the 3-span case and the periodic matching that was used to study rod temperature; it consists of 2 spacers and 3 simple support grids. Because the model is a 2x1 sub-channel with mixing vanes, it is necessary to introduce periodic boundaries for the correct cross-flow field to be established, the 3 different periodic matches (P1-P1, P2-P2, and P3-P3), can be seen in Figure 7.

Figure 7 - Geometry of the 3 spans, 2x1 sub-channel using the NUPEC spacer with vanes and simple support grid. Lower Right: 3 Periodic boundary conditions and associated matching

4.2 Circumferential Averaged Rod Temperature

Based on experiments within AREVA it is well established that for uniform heating the highest temperatures occur at the end of heated length (EOHL) and the simple support grid has a small effect. Examining all the different closure models and model coefficients, a parametric study could involve a huge matrix of comparisons, thus the purpose here is to highlight the differences found from changing a few parameters and models. Using the lower center rod, every 5mm a circumferential average temperature is made for the entire length of the 3 spans.
Figure 8 shows the effect of rod temperature for 2 different wall boiling models; Model Sets 1 and 3 (refer to Table 1 for a description). In the region of the high temperatures, the mean bubble diameter for Model Set 1 is about 10 times higher, evaporation rates are also higher and a higher void content is found near the wall compared with Model Set 3, therefore the rod heat flux is going into the vapour contribution of heat flux, causing the temperature to be higher. The position of the temperature peaks is occurring after the spacer, not at EOHL.

Figure 9 shows the effect of changing the coefficients in the source term for the IATE equation, break-up and coalescence. When changing the break-up coefficients there is very little change in the rod temperature, but when increasing the coalescence source term coefficients there is a distinct increase in temperature. Increasing the coalescence source term has the effect of decreasing the interfacial area, which corresponds to a slightly higher evaporation rate in cells which are slightly superheated, thus there is an increase in the rod. This is the same reason why Model Set 1 has higher temperatures; lower interfacial area due to the larger bubble departure diameter. The reason why changing the break-up had a small effect is because the coalescence term is the dominating factor in these cells near the wall.

Figure 10 shows the effect of changing different closure laws with respect to wall temperature. The reference case is based on boiling Model Set 3 and increasing the coalescence source terms, (Figure 9). The largest effect is seen by the lift model, which is showing the higher temperatures near the end of span compared to after the spacer; this effect is in line with experimental results for uniform heating. Adding the wall force models negates the benefit of the lift force and
changing the drag law or adding particle induced turbulence has a small effect on the wall temperature distribution.

Another interesting fact is that for all the different temperature profiles in Figure 10, the average void at various cross-sections are all within 1% of each other, which is below the uncertainty in void measurements, thus all models would provide the same average void prediction.

The main reason for the change in the wall temperature distribution by using the lift model is because it redistributes the void along the wall. Figure 11 shows that for the reference case there is a peak in void after the spacer, thus resulting in high temperatures, for the lift case the void is maximum near the end of a span, thus resulting in higher temperatures in this region.

5. CONCLUSION

The source terms for the IATE model for interfacial area were examined in this paper. It was concluded that numerical techniques are needed to ensure stability of CFD runs for industrial
applications. A comparison of 3 different boiling sub-models was examined, demonstrating that Model Set 3 has an advantage in stability and realistic bubble departure diameters for PWR conditions. The 2-phase Eulerian multi-phase model in STAR-CCM+ along with the IATE for bubble distribution and the boiling Model Set 3 showed good agreement with predicting average void within the uncertainty of the OECD/PSBT experiment.

Examining the circumferential average rod temperature for different models resulted in interesting conclusions that can not be gained by looking at average void alone. The largest impact for rod temperature is the boiling models chosen, but not necessary from the evaporation heat flux but more from the bubble departure diameter that goes into the source term for interfacial area. Changing the coalescence source term has a greater impact than the break-up term in the considered flow regimes. The closure models for drag and particle induced turbulence have a small effect on rod temperature, but the addition of a lift model brings the correct temperature distribution. With this AREVA demonstrates that it is possible to predict average void and correct temperature distributions with the use of computational fluid dynamics.

6. REFERENCES


