LARGE OPEN REGION INTERFACIAL DRAG MODELING PACKAGE IN COBRA-IE

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ABSTRACT

COBRA-IE is a three-field subchannel analysis code that was originally based on the COBRA-TF code series. The default interfacial drag model in COBRA-IE has been assessed against a wide range of pressure drop data taken in confined geometries and has been shown to perform very well. The difference in interfacial drag behavior for confined flow paths compared to large open regions where the bubbles are not constrained by the physical geometry of the flow path has been well documented in the open-literature. Therefore, a dedicated interfacial drag model for large, open regions has been developed and implemented in COBRA-IE. This alternative interfacial drag model is based on the drift flux formulation and is activated by user input. A combination of the Kataoka-Ishii and the Zuber-Findley drift-flux correlations has been implemented in COBRA-IE to calculate the weighted mean drift velocity and distribution parameter. The implementation of the model is described in this paper and the interface functions to transition between the drift flux and two-fluid formulations are emphasized.

An assessment of the predictive capability of COBRA-IE for the transient level swell phenomena for the experiments performed by General Electric (GE) has been performed. Level swell is an important phenomenon for reactor safety analysis because it impacts water distribution within the reactor vessel during the blowdown phase of the transient as well as the residual inventory available to provide core cooling. The initial assessment of the code using the default interfacial drag modeling package showed an over-prediction of the level swell and liquid carryover for the GE experiments, which is indicative of an over-prediction of the interfacial drag for these situations. In addition to using the new code to reexamine the GE Level Swell experiment, assessments of the new model have been performed using the steady-state void fraction data collected in the Beattie-Sugawara, and Smith experiments and are presented in this paper.

KEYWORDS
COBRA-IE, interfacial drag, void fraction, assessment

1. INTRODUCTION

Interfacial drag is one of the mechanisms that couples the field momentum equations together in a multi-field analysis formulation. The interfacial drag influences the resultant field velocities, volume fractions, and interfield mass transfer. Accurately characterizing the interfacial drag is important to the prediction of entrained fraction, liquid carryover, dryout, and level swell phenomena. The GE Level Swell experiments [1] represent a standard benchmark which have been used to assess the interfacial drag models in many reactor safety analysis codes

The GE Level Swell experiments were performed using a small (D=0.305 m) and a large vessel (D=1.219 m). This paper will focus on run 1004-3 from the small vessel. This experiment has been extensively used in the assessment of interfacial drag in reactor safety codes [2-5]

A schematic of the experimental facility for the small vessel blowdown tests is shown in Figure 1. The experimental vessel was constructed from a length of 12 inch, schedule 80 pipe. The volume of the vessel is 0.28 m^3. In an attempt to prevent liquid from being entrained out of the test, the blowdown pipe was connected near the top of the vessel. The depressurization rate was controlled via an orifice in the blowdown line which was 0.00952 m for the run considered in this paper.

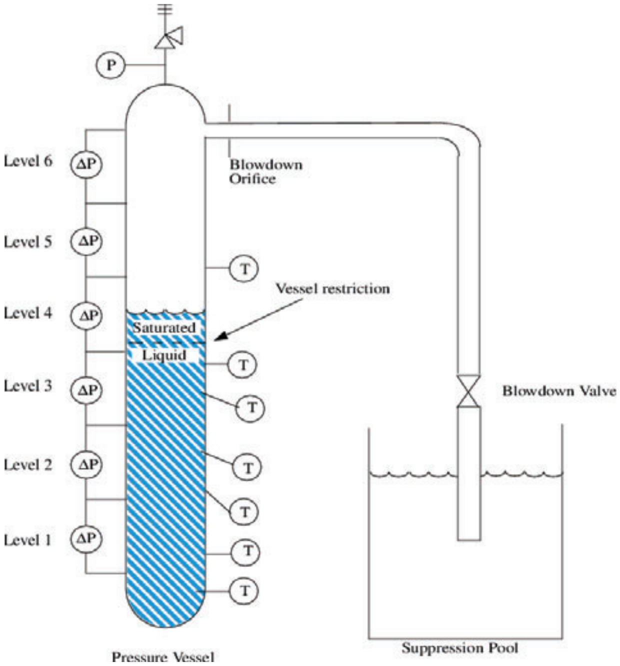

Figure 1. Schematic of GE Level Swell Experiment 1004-3

The instrumentation of the test included one absolute and six differential pressure gauges and several temperatures detectors. As shown in Figure 1, the regions between adjacent pressure taps are referred to as Levels (or segments) and are numbered sequentially starting at the bottom. The differential pressure measurements were used to infer the void fraction in each segment by assuming that hydrostatic head was the only component contributing to the pressure difference. The initial conditions for test number 1004-3 were a system pressure of 6.92 MPa and a water level of 3.167 m. Since the experimental fluid temperatures were not included in the test report, the initial liquid temperature was assumed to correspond to the saturation temperature, 559 K.

During the process of analyzing this experiment with COBRA-IE, it was observed (Figure 2) that for elevations near the two-phase level, the void fraction was significantly over predicted during the plateau regions for Level 4 (10-100 seconds) and Level 5 (10-40 seconds). This over-prediction of void fraction was inconsistent with assessments in geometries with hydraulic diameters that more closely matched the value for typical commercial PWR geometries. The impact of walls on interfacial shear and void fractions has been well established [6-7]. As such, a study is warranted to determine if new models are needed for larger hydraulic diameter regions.

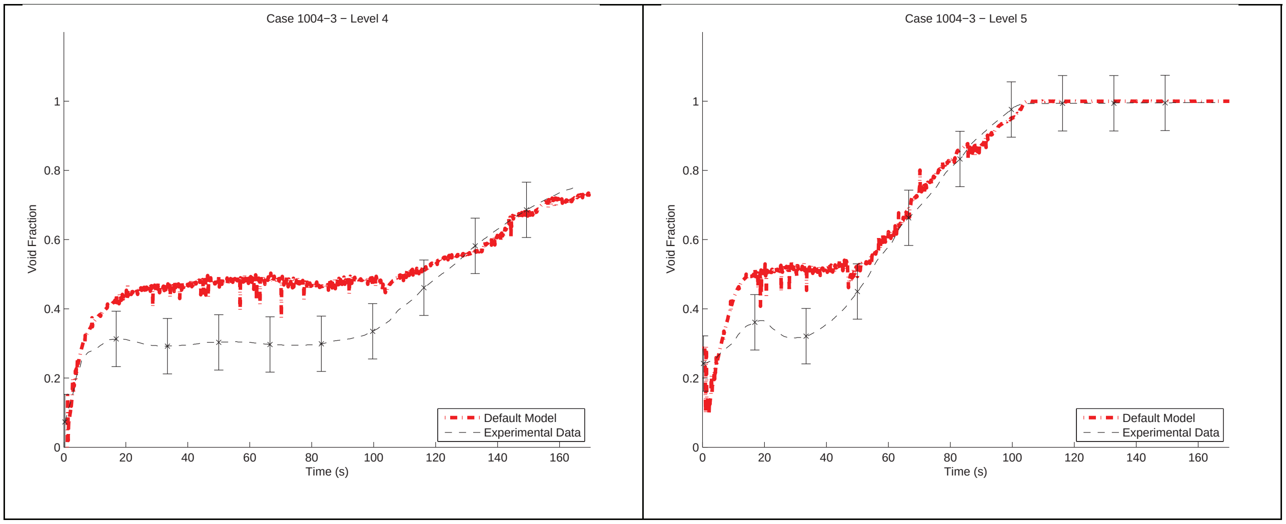

Figure 2. Original COBRA-IE Predictions of Void Fraction in Levels 4 and 5

2. COBRA-IE INTERFACIAL SHEAR BACKGROUND

The momentum equations applied by COBRA-IE employ an interfacial drag component, K_i, which is defined based on the interfacial shear, τ, and relative velocity, U_r, as :

$$K_i = \frac{\tau}{U_r}\frac{A}{\Delta z} \tag{1}$$

where the area in this expression can be the interfacial or projected area, depending on how the drag coefficient or friction factor is quantified in the calculation of shear stress. The interfacial drag components, K_i, are flow-regime dependent. Two formulations are available in COBRA-IE for calculating the interfacial drag:

1) Two-fluid using drag coefficients and
2) Drift flux.

The two-fluid formulation is the primary method for quantifying the interfacial drag in COBRA-IE. The drift flux formulation was added to COBRA-IE to improve the predictive accuracy of the code for situations where the bubbles are not constrained by the physical geometry of the flow path. The drift flux formulation is only used to quantify the interfacial drag in bubbly flow situations for a large, open region as identified by user input.

2.1. Drag Coefficient Formulation

The interfacial shear stress between the continuous liquid and gas fields is defined as:

$$\tau_{i,gk} = \frac{1}{2}\mathbb{C}\rho_k\left|U_{r,gk}\right|U_{r,gk} \tag{2}$$

where:

$$\mathbb{C} = \begin{cases} C_D & \text{Drag coefficient (for bubbles or droplets)} \\ f_i & \text{Fiction Factor (for liquid films)} \end{cases} \tag{3}$$

The relative velocity is $U_{r,gk}$. The field density, ρ_k, used in this expression corresponds to the carrier phase (i.e. continuous liquid for bubbly flow). The drag coefficient, C_D, or interfacial friction factor, f_i, is flow regime specific.

It should be mentioned here that drag coefficients for bubbles or droplets are typically quantified using a projected area, but COBRA-IE characterizes flow structure using interfacial area. In terms of projected area, the drag component is defined in COBRA-IE as:

$$K_i = \frac{1}{2} C_D \rho_k |U_r| \left(\frac{A_{proj}}{\Delta z} \right) \tag{4}$$

Assuming spherical bubbles or droplets with characteristic size, D_c, the projected area is equal to:

$$A_{proj} = \pi \left(\frac{D_c}{2} \right)^2 \tag{5}$$

and the interfacial area is equal to:

$$A_i = 4\pi \left(\frac{D_c}{2} \right)^2 \tag{6}$$

Dividing Equation (5) by Equation (6) provides a relationship between projected and interfacial areas:

$$A_{proj} = \frac{A_i}{4} \tag{7}$$

such that Equation (4) can be recast in terms of interfacial area, rather than projected area, as:

$$K_i = \frac{1}{8} C_D \rho_k |U_r| \left(\frac{A_i}{\Delta z} \right) \tag{8}$$

The drag component formulation is used for all channel types and flow regimes in COBRA-IE except for regions that have been identified as a large, open region to calculate the interfacial drag associated with the small and large bubble regimes.

2.2 Drift Flux Formulation

The drift flux formulation is an alternative method of describing the interaction between two fields where the drift velocity describes the slip, or relative movement, between the two fields. Unlike the two-fluid formulation, this method quantifies the interfacial drag between the two fields without requiring an estimate of the interfacial area.

Two different drift velocities are commonly defined in the open-literature [8]. The first is the mean drift velocity, U_{gj}, which is given as:

$$U_{gj} = U_g - j_{tot} \tag{9}$$

where the total superficial velocity, j_{tot}, is defined as the sum of the phasic superficial velocities:

$$j_{tot} = j_g + j_l \tag{10}$$

A relationship between the mean drift velocity, U_{gj}, and the actual relative velocity, $U_{r,gl}$, can then be determined by substituting the definition of superficial velocity $(j_k = U_k \alpha_k)$ into Equation (9):

$$U_{gj} = U_g - \left[U_g \alpha_g + U_l \left(1 - \alpha_g\right)\right] \tag{11}$$

Expanding this result:

$$U_{gj} = U_g\left(1 - \alpha_g\right) - U_l\left(1 - \alpha_g\right) \tag{12}$$

and then applying the definition of relative velocity $\left(U_{r,gl} = U_g - U_l\right)$, yields the desired relationship as:

$$U_{gj} = U_{r,gl}(1 - \alpha_g) \tag{13}$$

The second type of drift velocity is the weighted mean drift velocity, $\langle U_{gj} \rangle$, which is defined as:

$$\langle U_{gj} \rangle = U_g - C_0\, j_{tot} \tag{14}$$

where the distribution parameter, C_0, represents an empirical factor correcting the one-dimensional homogenous theory to account for the fact that the concentration and velocity profiles across the channel can vary independently of one another, with the lighter phase tending to migrate to the higher velocity region.

Based on Equation (9), the relationship between weighted mean, $\langle U_{gj} \rangle$, and mean drift, U_{gj}, velocities is:

$$\langle U_{gj} \rangle = U_{gj} - (C_0 - 1) j_{tot} \tag{15}$$

and then a relationship between the weighted mean drift velocity and the relative velocity can be found as:

$$U_{r,gl} = \frac{(C_0 - 1) j_{tot} + \langle U_{gj} \rangle}{\left(1 - \alpha_g\right)} \tag{16}$$

When defining the interfacial friction in the context of the drift flux, the relative velocity that is used in based on the weighted difference between the phase velocities [9]

$$< U_{r,gl} >= C_1 U_g - C_0 U_l \tag{17}$$

2.3 Conversion from Drift-Flux to Drag Coefficient Formulation

The use of a drift-flux formulation in COBRA-IE requires the ability to convert from drift-flux calculations to a two-fluid formulation. This process requires the ability to equate the calculation of the total interfacial drag force per unit volume for the drift-flux and two-fluid methods. Such a relationship can be derived by first balancing the interfacial drag and buoyancy forces for a steady state bubble traveling at its terminal velocity in the two-fluid construct. This equality can be written in force per unit volume as:

$$\overbrace{C_i\left|U_{r,gl}\right|U_{r,gl}}^{interfacial\ drag} = \overbrace{\alpha_g\left(1-\alpha_g\right)\Delta\rho g}^{buoyancy} \tag{18}$$

Then, applying the definition of mean drift velocity, U_{gj}, given in Equation (13) yields an expression for the interfacial coefficient, C_i, as:

$$C_i = \frac{\alpha_g\left(1-\alpha_g\right)^3\Delta\rho g}{U_{gj}^2} \tag{19}$$

Now, equating the expressions for interfacial force per unit volume for and two-fluid form and the drift flux, using Equations (19) for the drag coefficient and Equation (17) as the relative velocity yields:

$$\overbrace{\frac{\alpha_g\left(1-\alpha_g\right)^3\Delta\rho g}{U_{gj}^2}\left(C_1U_g - C_0U_l\right)^2}^{Drift\ Flux\ Formulation} = \overbrace{\underbrace{\left[\frac{\mathbb{C}}{2}\rho\left|U_{r,gl}\right|\frac{A}{\Delta z}\right]}_{K_i}\frac{U_{r,gk}}{A_{mom}}}^{Two-Fluid\ Formulation} \tag{20}$$

The bracketed term on the right in Equation (20)is denoted as the interfacial friction component, K_i, in COBRA–IE. In order to preserve the directional component of the interfacial drag, the interfacial friction component must be positive. Rearranging the equation, adding subscripts to denote that this equation is solved on the momentum mesh in COBRA-IE, and using an absolute value on the relative velocity with the addition of a small value to prevent dividing by zero yields:

$$K_{i,DF} = \frac{\alpha_{g,j}\left(1.0-\alpha_{g,j}\right)^3\left(\rho_{l,avg}-\rho_{g,avg}\right)g\left(C_1U_g - C_0U_l\right)^2A_{mom}}{U_{gj}^2\left|U_{r,gl}\right| + 3.048x10^{-7}\frac{m}{s}} \tag{21}$$

where:

$$C_1 = \frac{1.0 - min\begin{cases}1.0\\ C_0\alpha_{g,j}\end{cases}}{1.0-\alpha_{g,j}} \tag{22}$$

3 Drift Flux Model Description

In an effort to improve interfacial shear predictions for large regions, a combination of the Kataoka-Ishii [10] and the Zuber-Findley [11] drift-flux correlations has been implemented in COBRA-IE. This method was chosen in part because the RELAP5-3D code [9] utilizes a similar approach for vertically oriented pipes with hydraulic diameters in excess of 8 cm. The RELAP5-3D formulation of the correlations has been adopted. In the adopted method formulation, the Kataoka-Ishii correlation is used for large values of the non-dimensional, superficial velocity, j_g^+, which is defined as:

$$j_g^+ = \frac{\alpha_{g,j}\left|U_g\right|}{U_c} \tag{23}$$

The characteristic velocity, U_c, is defined as:

$$U_c = \left[\frac{\sigma g\left(\rho_{l,avg} - \rho_{g,avg}\right)}{\rho_{l,avg}^2}\right]^{1/4} \tag{24}$$

For both the Kataoka-Ishii and Findley-Zuber correlation, the drift-velocity is defined in terms of the characteristic velocity. In the Kataoka-Ishii correlation, U_{gj} is given by:

$$U_{gj,KI} = C\left(\frac{\rho_{g,avg}}{\rho_{l,avg}}\right)^{-0.157} N_\mu^{-0.562} U_c \tag{25}$$

where the viscosity number, N_μ, is calculated using

$$N_\mu = \frac{\mathrm{\mu_l}}{\sqrt{\mathrm{\rho_l \sigma} L_{cap}}} \tag{26}$$

where the Laplace capillary length, L_{cap}, is equal to:

$$L_{cap} = \sqrt{\frac{\sigma}{g\left(\rho_{l,avg} - \rho_{g,avg}\right)}} \tag{27}$$

The leading coefficient in Equation (25) is given as:

$$C = \begin{cases} 0.0019\, N_{bond}^{0.809} & N_{bond} < 30.0 \\ 0.030 & N_{bond} \geq 30.0 \end{cases} \tag{28}$$

The Bond number, N_{bond}, is defined as:

$$N_{bond} = \frac{D_h}{L_{cap}} \tag{29}$$

For the Findley-Zuber correlation, the drift velocity is given by:

$$U_{gj,FZ} = 1.41\, U_c \tag{30}$$

The two correlations are combined by:

$$U_{gj} = \left[\omega_{j_g^+} U_{gj,KI} + \left(1 - \omega_{j_g^+}\right) U_{gj,FZ}\right] CPM_{U_g} \tag{31}$$

where CPM_{U_g} is a Code Physics Multiplier and has been included in COBRA-IE to provide a means to propagate the uncertainty in the calculation of U_{gj} for use in best-estimate plus uncertainty calculations, and the function, $\omega_{j_g^+}$, is defined as:

$$\omega_{j_g^+} = min \begin{cases} 1.0 \\ max \begin{cases} 0.0 \\ \dfrac{j_g^+ - 0.5}{2.5 - 0.5} \end{cases} \end{cases} \tag{32}$$

This results in the use of the Findley-Zuber correlation for $j_g^+ < 0.5$, the Kataoka-Ishii correlation for $j_g^+ > 2.5$, and a linear transition between the two correlations for the intermediate j_g^+ values.

The RELAP5-3D formulation for the Kataoka-Ishii distribution parameter, C_0, is used. This is given by:

$$C_0 = C_\infty - (C_\infty - 1)\sqrt{\frac{\rho_{g,avg}}{\rho_{l,avg}}} \tag{33}$$

where the term C_∞ is given by:

$$C_\infty = 1 + 0.2\sqrt{\frac{\rho_{l,avg}\sqrt{D_h g}}{G_l + G_g}} \tag{34}$$

and $G_l$and G_g, are mass fluxes for liquid and vapor, respectively.

When implemented in COBRA–IE, the following restriction is placed on the distribution parameter, C_0:

$$C_0 = min \begin{cases} C_0 \\ 1.33 \\ \dfrac{1}{\alpha_{g,j}} \end{cases} \tag{35}$$

The distribution parameter, C_0, is not transitioned between the Kataoka-Ishii and Findley-Zuber correlation in the same manner as the drift velocity. This is justified as the variation in the distribution parameter tends to be much smaller than the change in drift velocity.

The interfacial drag coefficient for the small bubble and large bubble regimes ($\alpha < 0.5$) in channels identified as a Large, Open region (Channel Type 3) are obtained using Equation (21) such that:

$$K_{i,SB} = K_{i,LB} = K_{i,DF} \tag{36}$$

4 Results

To assess the accuracy of this new model, the analysis of the GE Level Experiment was repeated. The new results, for all of the levels, are shown in Figure 5. These results show that the revised model provides excellent agreement with the experimental data. With the revised drift flux model, the predictions of the void fraction for all of the levels are now within the stated experimental uncertainty with the exception of the calculation of the time when the two-phase level is dropping through level 4 (t > 100). It is noted that the new model did not significantly impact the calculation of the void fraction in the lowest two levels, which have the smallest predicted and measured void fractions. The fact that both the new and previous methods provide predictions within the uncertainty band in this region shows that the drift flux formulation does not degrade the accuracy of the code in locations where the default model provided adequately accurate results. The prediction of void fraction in level 3, which previously was just outside of the experimental uncertainty band, is now predicted to fall within experimental uncertainty.

The most dramatic improvements in accuracy are in the plateaus that exist in levels 4 and 5. During these time periods of 10-100 seconds for level 4 and 10-40 seconds for level 5, the previous predictions were well in excess of the experimental data uncertainty band. The revised model matches the experimental data almost perfectly during these time periods; indicating that the drift flux model can much more accurately predict interfacial shear in this large open region.

Finally, the prediction of the level into and out of the top-most level continues to be predicted with the same outstanding accuracy as the default model.

To ensure that the drift flux formulation provided sufficient accuracy for a wider range of conditions than seen in the GE Level Swell test, two additional data sets were predicted with both the default interfacial shear model and the new drift flux formulation. Each of these experiments provided measured steady-stated void fraction for adiabatic flow in tubes of various sizes. These data sets are from Smith [12] and Beattie [13].

The range of conditions for each experiment is provided in Table I. The pipe sizes used in the Smith experiments are both in excess of the 8 cm demarcation between the standard interfacial shear models and their drift flux method. As such, it is expected that the revised drift flux model should improve the accuracy of these predictions. With a diameter of 7.4 cm, the inclusion of the Beattie data is being included to assess the adequacy of 8 cm demarcation. These predictions will be used to assess the applicability of both the default model and the drift flux model.

Table I - Range of Conditions for Void Fraction Assessments

Experimental Data Source	Fluid	Diameter (cm)	Pressure (MPa)	j_g (m/s)	j_l (m/s)	α $(-)$
Smith	Air-Water	10-15	0.1	0.04-8	0.05-2	0.02-0.71
Beattie	Steam-Water	7.4	7	0.8-24.	0.29-3.4	0.24-0.86

The results from the Smith test are shown in Figure 3. The different symbols represent the data from the three different axial locations for which data was collected in the test. The results indicate that model does improve the accuracy of the predictions. The largest impact is the region where the experimental void fraction is between 30% and 50%. This region falls within the Large Bubble regime within COBRA-IE. When combined with the comparisons from the GE Level Swell experiment, it is clear that the difference in the physical mechanisms between large open regions and confined flow passages is largest in this void fraction range.

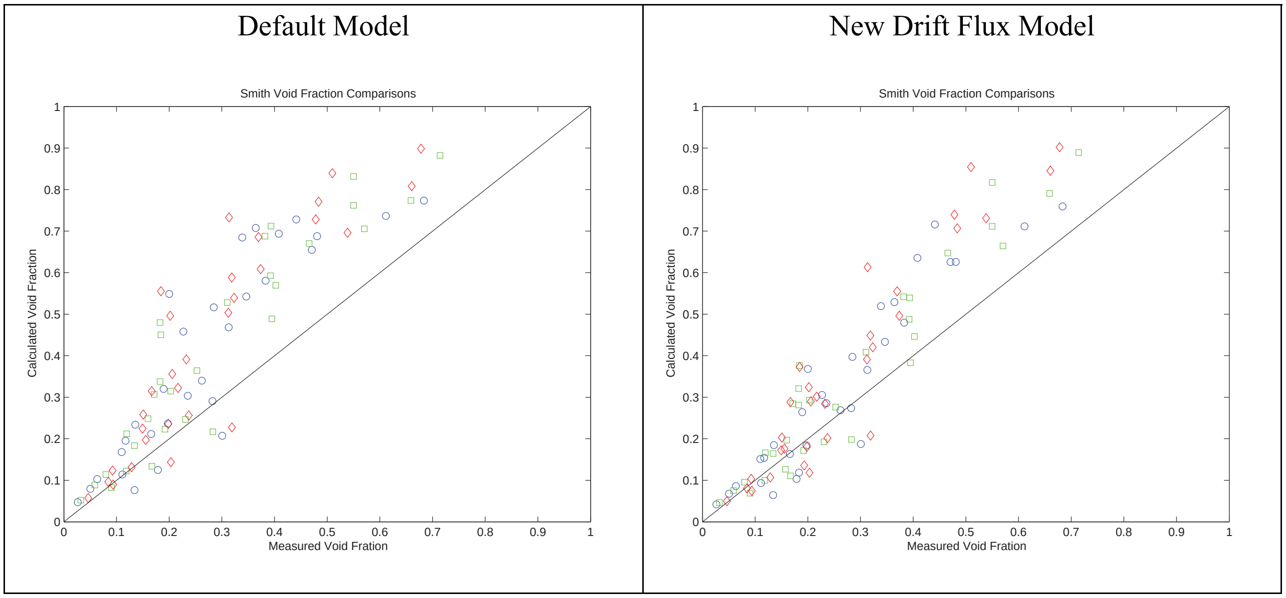

Figure 3. Comparison of Void Fraction Predictions for Smith Experiments

Statistical information concerning the accuracy of the standard and drift flux model is presented in Table II. The results indicate that the mean error in the predicted void fraction is reduced by approximately a factor of 2 for both the complete data and for just the data that falls with the range where the drift flux model is being used, $0 < \alpha < 0.5$.

Table II – Comparison of Both Models with Smith Data

		Default Model		New Drift Flux Model	
	N	Mean Error	Mean Abs(Error)	Mean Error	Mean Abs(Error)
All Data	93	0.132	0.143	0.072	0.094
$\alpha_{exp} < 0.5$	87	0.132	0.124	0.067	0.098

The comparison with the Beattie data is shown in Figure 4. This figure shows the results from the new model and the default model provide very similar results. This is an indication that the 8 cm value is appropriate for switching between the default physical models that are used in the default physical models and the new drift flux models.

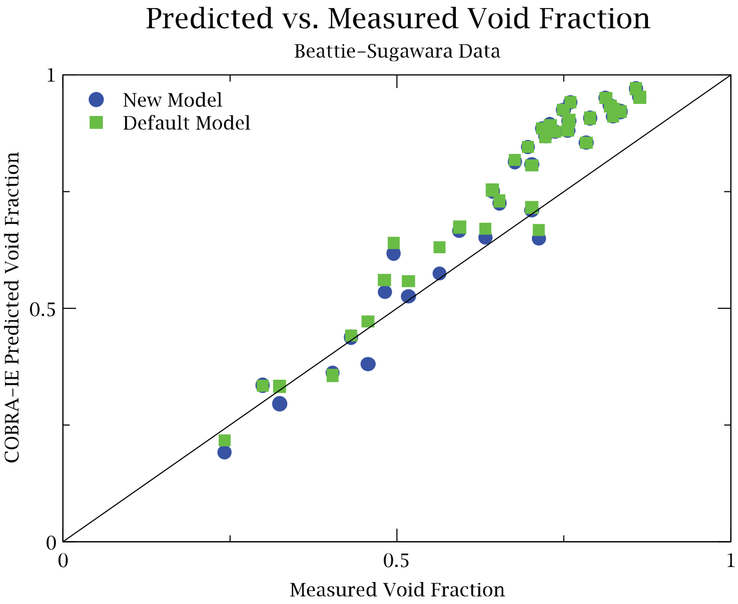

Figure 4. Comparison of Drift Flux and Default Model for Beattie Data

5 Conclusions

As a result of poor predictions of the GE Level Swell experiment it was determined that the default interfacial shear models utilized in COBRA-IE caused a significant overprediction of void fraction for flow within large, unconfined geometries. The default model, which has been validated against data more consistent with commercial PWR core geometry hydraulic diameters, is insufficient to model larger geometries. A drift flux formulation was implemented in the form of an equivalent interfacial friction factor.

The results of the revised code have been validated using data from three different experimental facilities. The results from the GE Level Swell experiments now show that with the exception of one 60 second period, the void fraction predictions are now within the experimental uncertainty band for all of the levels. This is a marked improvement over the default model set.

The comparisons to the Smith data, which have diameters of 10 and 15 cm, show that the mean error has been significantly reduced for new model when compared to the previous model. When combined with the GE Level Swell data, validation is provided for steady-state and transient condition; air-water and steam-water fluids and a range of superficial gas and liquid velocities. The comparisons with the Smith data indicate that the issues with the standard model may be related to the large bubble flow regime within COBRA-IE.

Finally, the Beattie data shows that for a pipe diameter of 7.4 cm, both models provide very similar results. This is an indication that the 8 cm value that is used in RELAP5-3D to transition between their standard model set and the revised drift flux model set is appropriate.

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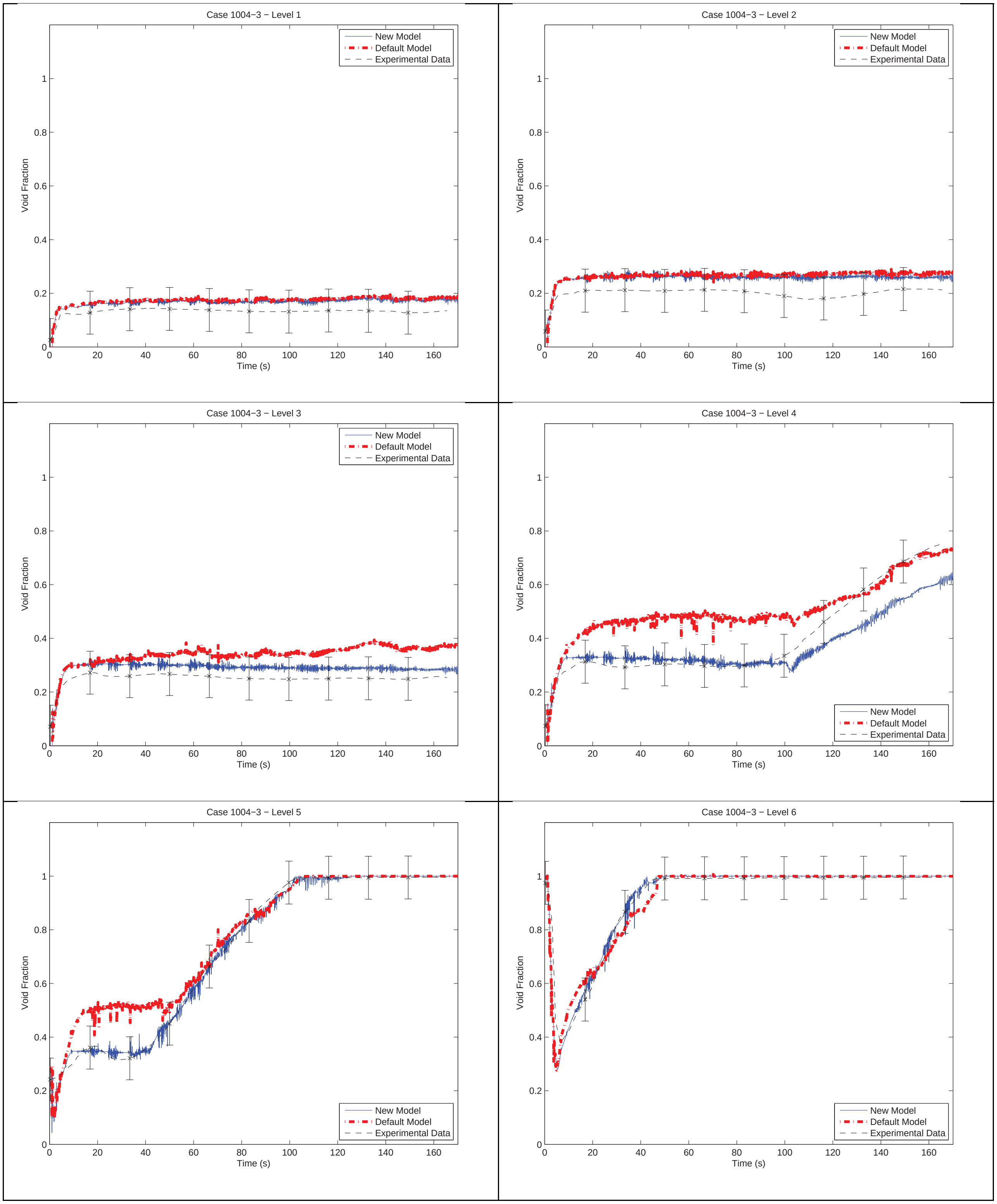

Figure 5. Comparison of Void Fraction for New and Default Interfacial Shear Models