Assessment of the ATHENA Code for Calculating the Void Fraction of a Lead-Bismuth/Steam Mixture in Vertical Upflow[1]

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ABSTRACT

Lead-bismuth is currently being considered as a coolant for fast reactors designed to produce low-cost electricity as well as burn actinides. Lead-bismuth fluid properties have been added to the ATHENA code so that it can be used in the thermal-hydraulic analysis of lead-bismuth cooled reactors. The capability of ATHENA to calculate the void fraction of a two-component, two-phase mixture of liquid lead-bismuth and steam in co-current upflow was assessed using the El-Boher and Lesin void correlation. The assessment showed that the drift flux correlations currently available in the code predicted trends that were in reasonable agreement with the El-Boher and Lesin void correlation, but the predicted void fractions were significantly too high. For example, the Kataoka-Ishii correlation, which was the best of the available correlations, predicted void fractions that were up to 30% greater than the values from the El-Boher and Lesin correlation. Consequently, the El-Boher and Lesin correlation was implemented in a modified version of ATHENA. The implementation was complicated by the fact that El-Boher and Lesin correlation was an explicit correlation for void fraction rather than a drift flux correlation. An approach was developed so that the code's basic drift flux formulation could be used to easily implement an explicit void correlation. The predictions of the modified code were in excellent agreement with the El-Boher and Lesin void correlation.

INTRODUCTION

Lead-bismuth is currently being considered as a coolant for a variety of reactors designed to produce low-cost electricity and/or burn actinides (1,2,3,4). The economic advantages of lead-bismuth arise from the possibility of developing passively safe reactors with long core lifetimes, possibly in excess of 15 years, combined with lower capital and operating costs. The ability to burn actinides created by the current generation of light water reactors is also an attractive feature of lead-bismuth cooled reactors.

A thermal-hydraulic system analysis capability of lead-bismuth cooled reactors is being developed based on the ATHENA computer code (5). The ATHENA code is incorporated as a compile time option in the RELAP5-3D computer code (6), which in turn is an extension of RELAP5/MOD3 (7). The principal difference between RELAP5 and ATHENA is that RELAP5 was designed to use water as the working fluid while ATHENA allows the use of many different working fluids, including liquid metals. The

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properties of the lead-bismuth eutectic have recently been added (8) to ATHENA. The ATHENA and RELAP5 codes are described further in the following section.

The RELAP5 series of codes has been extensively used and assessed for the thermal-hydraulic analysis of light water reactors. However, the ATHENA code has not been assessed as thoroughly for the non-aqueous fluids. Consequently, the capability of the ATHENA code to predict the void fraction of a mixture of lead-bismuth and steam for vertical upflow was assessed. Two-phase effects are normally not of concern in lead-bismuth cooled reactors because of the high boiling point (1998 K) of the coolant. However, one of the designs being considered (see Reference 2) injects water into the upper plenum region of the reactor to produce steam by direct contact with the lead-bismuth. The ability of the code to predict the void fraction of a mixture of steam and lead-bismuth is also of concern in more conventional designs during a transient initiated by the rupture of a steam generator tube.

The ATHENA code was assessed using the El-Boher and Lesin void correlation (9,10). This correlation was developed for co-current upflow of different mixtures, including water and air, mercury and steam, and lead-bismuth and steam. The lead-bismuth/steam data were taken in the ETGAR-3 facility, which is described in a following section. Subsequent sections describe the El-Boher and Lesin void correlation, an ATHENA input model of the ETGAR-3 facility, assessment results and discussion, and conclusions.

CODE DESCRIPTION

The ATHENA and RELAP5 codes solve separate continuity, momentum, and energy equations for the gas and liquid phases. Each phase can have a different temperature and velocity within a control volume. The difference in velocity between the gas and liquid phases significantly affects the calculated void fraction and thus is of particular interest for this paper. As phase velocity differences are governed by the interfacial friction model, the history and features of the model will be discussed in more detail below.

RELAP5 originally calculated phase velocity differences using interfacial drag coefficients and interfacial areas that were calculated from correlations appropriate for the flow regime and the vertical orientation of each control volume. A drift flux model was included into the code during the development of RELAP5/MOD3 because much of the experimental knowledge of two-phase flow in light water reactors was embodied in the drift flux correlations that had been developed during many years of nuclear safety research. The drift flux model was implemented into RELAP5/MOD3 by modifying the definition of relative velocity and calculating a revised drag coefficient using the distribution parameter and the drift velocity from a drift flux correlation. The principal assumption during this adjustment was that the pressure gradient was dominated by hydrostatic and wall friction forces, as terms due to other forces were neglected. The adjustment of the interfacial friction term allowed RELAP5/MOD3 to predict void fractions in agreement with the underlying drift flux correlations. The drift flux model was applied only to vertical control volumes in the bubbly and slug flow regimes. The original interfacial friction model, which was based on drag coefficients, was applied for all other cases. Different drift flux correlations were applied in the bubbly and slug flow regimes depending on the diameter and mass flux of the control volume.

RELAP5/MOD3, RELAP5-3D, and the ATHENA codes all use the same interfacial friction model, which is a combination of the original drag coefficient and drift flux methods.

EXPERIMENTAL FACILITY

The ETGAR-3 facility is illustrated in Figure 1. The facility consisted of two vertical pipes, called a riser and downcomer, that were connected at the bottom with a crossover pipe and at the top with a separator. Tests were conducted by mixing steam with lead-bismuth near the bottom of the riser. The mixture of lead-bismuth and steam then flowed upwards through the riser and into the separator, which returned liquid lead-bismuth to the downcomer. Natural circulation flow was induced by the difference in density between the riser and downcomer pipes. The pipes were 0.203 m in diameter and 7.5 m long.

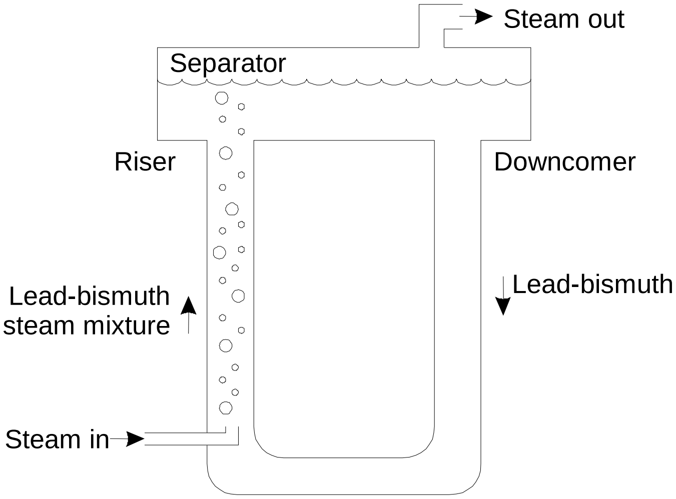

Figure 1. Schematic of the ETGAR-3 facility.

Tests were conducted at a nominal pressure of 3.5×10^5 Pa and a nominal temperature of 443 K. The liquid superficial velocity varied from 0.6 to 1.6 m/s. The ratio of gas superficial velocity to liquid superficial velocity varied from about 0.35 to 5.8. The average flow quality was about 1×10^{-4}.

The pressure in the riser was measured at over twenty locations. The void fraction distribution in the riser was calculated from the measured axial pressure distribution.

VOID CORRELATION

The El-Boher and Lesin void correlation was developed with co-current upflow data from three facilities, including the ETGAR-3 facility that was described in the previous section, an air/water facility, and a steam/mercury facility.

The El-Boher and Lesin correlation is:

$$\alpha = 1/[1+0.27(Q_R)^{-0.69}(Fr)^{-0.177}(\mu_f/\mu_g)^{0.378}(Re/We)^{0.067}] \quad (1)$$

where α is the gas volume fraction, Q_R is the volumetric flow ratio, Fr is the Froude number, μ_f/μ_g is the dynamic viscosity ratio, Re is the Reynolds number, We is the Weber number, and the subscripts f and g refer to the liquid and gas, respectively. The non-dimensional numbers are calculated as

$$Q_R = x\rho_f/[(1-x)\rho_g] = j_g/j_f \quad (2)$$

$$Fr = j_f^2/(gD) \quad (3)$$

$$Re = \rho_f\, j_f\, D/\mu_f \quad (4)$$

$$We = j_f^2\rho_f\, D/\sigma \quad (5)$$

where

x = flow quality
ρ = density
j = superficial velocity
D = pipe diameter
g = acceleration due to gravity
σ = surface tension

Equation (1) predicted the data from the ETGAR-3 facility with a root-mean-square (rms) error of 10.87% and the data from all three facilities with a rms error of 11.77%. Reference 9 also reported that Equation (1) was tested against data from other facilities that used air/water, steam/mercury, freon/mercury, and nitrogen/mercury mixtures. The rms error for all the data was 11.97%. The overall range of the correlation was reported to be between 0.08 and 0.83 for void fraction, 0.016 and 0.203 m for diameter, and 0.09 to 2.58 m/s for liquid superficial velocity. The temperature varied from ambient to 443 K.

Although Equation (1) was based on over 3400 data points from the ETGAR-3 facility, only limited data were presented in Reference 9. For the purposes of this paper, Equation (1) will be used as a substitute for the underlying data.

ATHENA INPUT MODEL

The ATHENA input model of the ETGAR-3 facility is illustrated in Figure 2. The model represented only the 7.5-m long riser pipe, which was all that was necessary to assess the code's prediction of void fraction. Liquid lead-bismuth and gas were introduced into the bottom of the riser with time-dependent junctions, component 505 for the liquid and component 515 for the gas. The pressure at the top of the riser was specified with a time-dependent volume (component 535). The riser was divided into 17 control volumes using a pipe (component 520) and a branch (component 530). The lower 7.0 m of the riser was modeled with 14 control volumes that were each 0.5 m long. The upper 0.5 m of the riser was divided into three smaller control volumes so that the pressure in these control volumes nearly equaled that of component 535, which was set at the nominal ETGAR-3 pressure. The void fraction from the uppermost volume of component 520 was used in the comparisons with the El-Boher and Lesin correlation that are shown later.

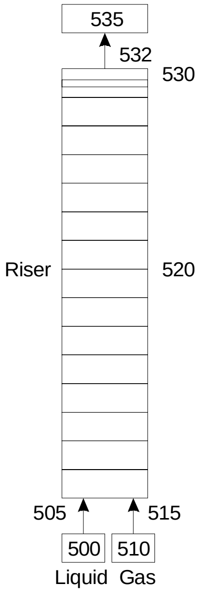

Figure 2. ATHENA model of the ETGAR-3 facility.

The steam injection in the ETGAR-3 facility was simulated using a mixture of ideal, non-condensable gases. The mass fractions of these non-condensable gases were set so that the density of the mixture equaled that of steam at nominal ETGAR-3 conditions. The steam injection could not be simulated using the normal water property tables available in ATHENA because the code allows the use of only one working fluid, which in this case was lead-bismuth, in a hydrodynamic system. The use of non-condensable gases to simulate steam is acceptable because steam would not condense at the operating pressure and temperature of the ETGAR-3 facility.

RESULTS

ATHENA calculations were performed by holding the liquid flow rate constant and varying the gas flow in steps over the range tested in the ETGAR-3 facility. The steps were long enough to allow steady conditions to be reached. The calculations were performed at nominal conditions for ETGAR-3. Specifically, the liquid superficial velocity was set to 1.1 m/s, the pressure at the top of the riser pipe was set to 3.5×10^5 Pa, and the liquid and gas inlet temperatures were set to 443 K.

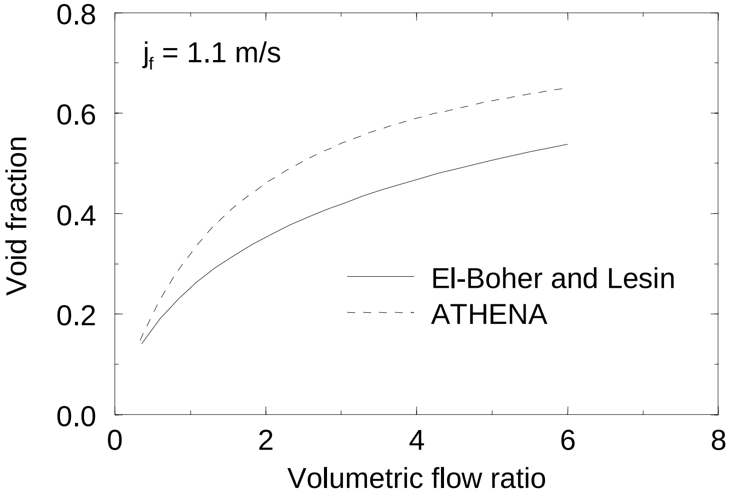

Figure 3. A comparison of the El-Boher and Lesin correlation with ATHENA.

Figure 3 compares calculated results from ATHENA with the El-Boher and Lesin correlation. The trends calculated by ATHENA were in reasonable agreement with Equation (1). However, the calculated void fractions exceeded the values from the correlation by up to 30%.

ATHENA used the Kataoka-Ishii drift flux correlation (11) to calculate the results shown in Figure 3. Several other drift flux correlations are available in the code depending on the geometry and mass flux, including Chexal and Lellouche (12), Zuber-Findlay slug (13), and Zuber-Findlay churn-turbulent bubbly (14). Results from all of these correlations are compared with the El-Boher and Lesin correlation in Figure 4. Of the correlations available in the code, the Kataoka-Ishii correlation agrees best with Equation (1). However, as stated previously, the void fractions predicted with the Kataoka-Ishii correlation exceeded those from Equation (1) by up to 30%.

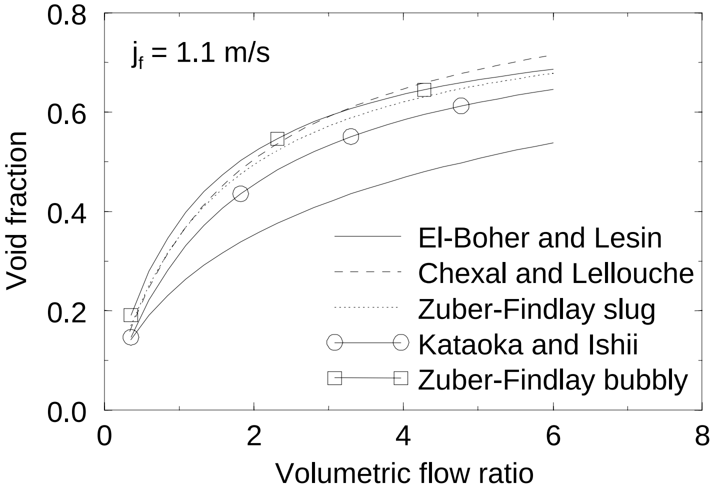

Figure 4. A comparison of the El-Boher and Lesin correlation with several drift flux correlations.

DISCUSSION

Based on the results shown in Figure 3 and 4, it was decided to implement the El-Boher and Lesin correlation into ATHENA. One method to implement the correlation might be to try to use it directly within the code. However, the code obtains the void fraction through a simultaneous solution of a system of six differential equations based on the continuity, momentum, and energy equations for the gas and liquid phases. The code's solution for the void fraction cannot be replaced with an explicit void correlation, such as the El-Boher and Lesin correlation, without fundamentally altering the code's solution scheme. Thus, a direct implementation of the El-Boher and Lesin correlation is not feasible given the structure of the code.

Another way to implement the El-Boher and Lesin correlation would be to convert it into a drift flux formulation. The gas velocity, v_g, can be written (13) as

$$v_g = j_g / \alpha = C_0 j + v_{gj} \qquad (6)$$

where C_0 is the distribution parameter, v_{gj} is the (constant) drift velocity, and j is the total superficial velocity

$$j = j_g + j_f \qquad (7)$$

The gas velocity predicted by the El-Boher and Lesin correlation is shown as a function of total superficial velocity in Figure 5. The figure also shows the results of a linear regression fit that determined optimal values of the coefficients C_0 (1.48) and v_{gj} (1.17 m/s). According to Equation (6), the gas velocity should be a linear function of total superficial velocity if C_0 and v_{gj} are constant. Since the gas velocity obtained from the El-Boher and Lesin correlation was nearly linear, correlations for C_0 and v_{gj} could be developed that would allow the drift flux model to match the El-Boher and Lesin correlation reasonably well. However, Equation (6) with the optimal coefficients predicts gas velocities that are too large, and hence void fractions that are too small, compared to the correlation at low and high values of superficial velocity. Thus, even though the comparison between the El-Boher and Lesin correlation and Equation (6) with constant coefficients is reasonable in the region shown, the two curves would diverge as the superficial velocity is extrapolated. Furthermore, it could be relatively complicated to develop correlations for C_0 and v_{gj} based on the El-Boher and Lesin correlation.

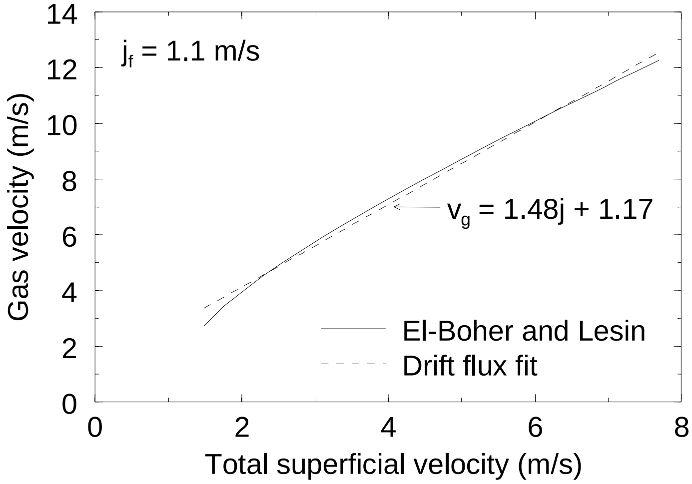

Figure 5. A drift flux fit to the El-Boher and Lesin correlation.

Rather than convert Equation (1) to a drift flux correlation, the El-Boher and Lesin correlation was implemented in a modified version of ATHENA by making a minor change to the way that the code applies the drift flux model. Specifically, solving Equation (6) for C_0 yields

$$C_0 = (j_g/\alpha - v_{gj})/j \tag{8}$$

Since j_g and j can be computed at each junction and α can be obtained from Equation (1), C_0 can be determined if v_{gj} is known. Of the correlations available in the code, the Kataoka-Ishii correlation's prediction of drift velocity was in the best agreement with the 1.17 m/s value obtained from the fit to the El-Boher and Lesin correlation. Consequently, the Kataoka-Ishii correlation was used to calculate v_{gj}. Figure 6 shows the solution to Equation (8) for nominal ETGAR-3 conditions. Note that the values of C_0 shown depend on the assumed drift velocity and would differ if a different drift velocity correlation had been used. However, the actual values of C_0 are not as important to the prediction of void fraction as the combined values of C_0 and v_{gj}.

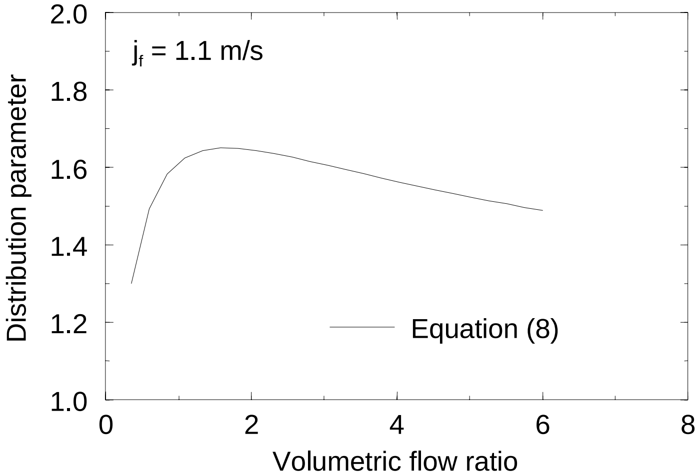

Figure 6. Distribution parameter as a function of volumetric flow ratio.

The calculation of C_0 from Equation (8) is a departure from the current implementation of drift flux models in ATHENA. Currently, C_0 depends only on fluid properties and, in some correlations, on mass flux. Because the gas flow generally does not significantly affect the mass flux, C_0 is currently independent, or nearly independent, of the gas flow. However, the solution to Equation (8) depends directly on the gas superficial velocity, as well as the total superficial velocity.

A modified version of ATHENA was created that implemented the solution to Equation (8) using the El-Boher and Lesin and Kataoka-Ishii correlations. Figure 7 shows predictions from the modified code and the El-Boher and Lesin correlation for the range of liquid flows tested in the ETGAR-3 facility. The results from the modified code are in excellent agreement with the El-Boher and Lesin correlation.

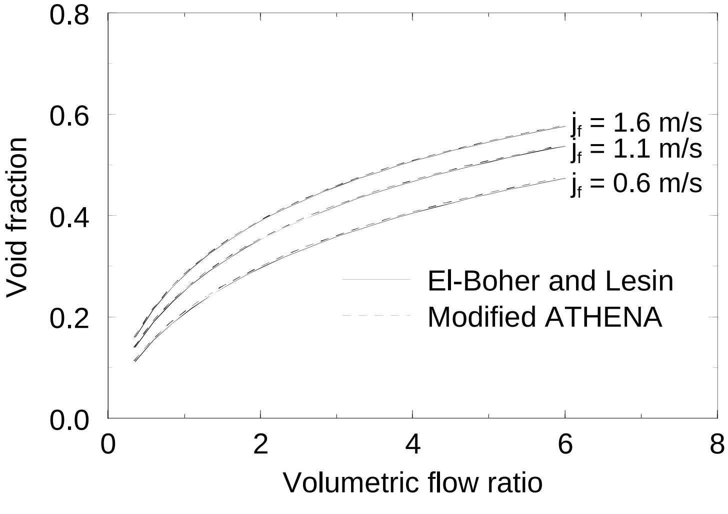

Figure 7. A comparison of the El-Boher and Lesin correlation with the modified ATHENA code.

The modified version of ATHENA applies the El-Boher and Lesin correlation only for systems containing lead-bismuth and for control volumes in the bubbly and slug flow regimes in vertical upflow. The original drag coefficient model is applied for all other cases. The range of the El-Boher and Lesin correlation, which was given previously, limits the code's range of applicability for those calculations using the correlation. Of course, care should be taken when extrapolating any correlation outside of the range of its database. Particular care should be taken when extrapolating an empirical correlation, such as the El-Boher and Lesin correlation.

The failure of the drift flux correlations presently available in ATHENA to accurately predict the void fraction data generated in the ETGAR-3 facility is not surprising since the correlations were primarily developed for two-phase mixtures of air and water or steam and water. Properties of the steam/lead-bismuth mixture are significantly different than those of air/water and steam/water. For example, the gas-to-liquid density ratio for the lead-bismuth/steam mixture in the ETGAR-3 facility is about 7 times smaller than for air/water at atmospheric pressure and about 300 times smaller than for steam/water at 7 MPa. The gas-to-liquid viscosity ratio for the lead-bismuth/steam mixture is about 4 times smaller than for air/water and about 40 times smaller than for steam/water. Thus, the steam/lead-bismuth fluid properties represent a substantial extrapolation from those for which the water-based correlations were developed. The failure of the water-based correlations to predict the data from the ETGAR-3 facility is probably not caused by a diameter effect. Although the 0.203-m diameter of the ETGAR-3 facility is relatively large, it is within the range of diameters for which the Kataoka-Ishii correlation was developed.

CONCLUSIONS

The drift flux correlations presently available in ATHENA did not adequately represent the void fraction data generated in the ETGAR-3 facility. The available drift flux correlations provided reasonable trends, but predicted void fractions that were significantly greater than those predicted by the El-Boher and Lesin correlation.

The El-Boher and Lesin correlation was successfully implemented into a modified version of ATHENA. The modified code was able to reproduce the results from the El-Boher and Lesin correlation. Since the correlation was developed using mixtures of lead-bismuth and steam, it is expected that the modified code should give more accurate results for the analysis of reactors cooled by lead-bismuth. Of course, care should be taken if the correlation is extrapolated outside of the range of its database.

The method described here could presumably be used to implement any explicit correlation for void fraction into the ATHENA or RELAP5 codes for those cases in which the codes apply the drift flux model, which includes vertical control volumes in bubbly and slug flow. The method could not be used to implement void fraction correlations developed for horizontal components or for vertical components in the annular flow regime because the drift flux model is not applied for these cases.

ACKNOWLEDGMENTS

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