

Improved Accuracy for Two-Phase Downflow Scenarios

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Abstract

Problems have been reported for very high downflows in small and intermediate pipes in the bubbly and slug flow regimes. When the flow rate is near critical, the calculated mass flow rate depends strongly on the flow orientation for small and intermediate pipes, whereas the flow rate is nearly independent of flow direction for large pipes. At very high flow rates, the flow is expected to be nearly homogenous and hence to be nearly independent of flow direction. The flow rates calculated by RELAP5-3D agree with this expectation except for downflow in small and intermediate pipes, where the calculated flows in the downward direction are about 20% lower than the flows in the upward and horizontal directions. The problem was traced to an extrapolation of the EPRI drift flux correlation beyond the range of its database. The problem was corrected by creating a very high downflow regime. The EPRI correlation is replaced by the Zuber-Findlay churn turbulent and Kataoka-Ishii drift flux correlations in the very high downflow regime for small and intermediate pipes.

Summary

RELAP5-3D predicts critical flow rates that are about 20% lower in downflow than in upflow or horizontal flow for small and intermediate pipes. The lower mass fluxes for downflow in small and intermediate pipes were caused by the calculation of a large slip ratio at the break orifice. The large slip ratios for downflow were caused by the drift parameters from the EPRI drift flux correlation. The EPRI drift flux correlation is based on steam/water tests that were conducted at relatively low downflow rates. The calculated results with the EPRI correlation are judged to be incorrect when extrapolated to very high downflow. The calculated critical flow rates are judged to be too low, the slip ratios are judged to be too high, and the void fractions are judged to be too low at very high downflows in small and intermediate pipes. Therefore, a very high downflow regime was created in RELAP5-3D. The code transitions to the very high downflow regime when the mass flux exceeds 1500 kg/s-m^2 . Since the code currently applies the Zuber-Findlay churn turbulent and Kataoka-Ishii drift flux correlations for very high downflow in large pipes, these same correlations were applied for very high downflow in small pipes, intermediate pipes, and rod bundles to maximize consistency with the current design philosophy of the code.

The code modifications that implement the very high downflow regime into RELAP5-3D were extensively tested using pipes of various sizes and orientations, Marviken test data, scaled Marviken test data, normal code installation problems, and the developmental assessment cases. The verification testing showed that the downflow modifications provided improved results for very high downflow, but had negligible or relatively small effects on most of the installation problems and developmental assessment cases.

1.0 Introduction

RELAP5-3D currently selects different interphase drag correlations depending on pipe orientation, pipe size, and mass flux. The primary orientations considered are horizontal, vertical up, and vertical down. The pipe sizes considered are small ($D \leq 0.018$ m), intermediate ($0.018 < D \leq 0.08$ m), and large ($0.08 < D$). The mass fluxes considered are low ($G \leq 50$ kg/s-m²), medium ($50 < G < 100$ kg/s-m²), and high ($100 \text{ kg/s-m}^2 \leq G$).

Problems have been reported for very high downflows in small and intermediate pipes in the bubbly and slug flow regimes. When the flow rate is near critical, the calculated mass flow rate depends strongly on the flow orientation for small and intermediate pipes, whereas the flow rate is nearly independent of flow direction for large pipes. For small and intermediate pipes, calculated flows in the downward direction are about 20% lower than the flows in the upward and horizontal directions. At very high flow rates, the flow is expected to be nearly homogenous and hence to be nearly independent of flow direction. The flow rates calculated by RELAP5-3D agree with this expectation except for downflow in small and intermediate pipes.

For high downflow rates in small and intermediate pipes, RELAP5-3D uses the EPRI drift flux correlation (Chexal et al. 1997). The EPRI correlation for downflow is based on the steam/water data of Petrick (1962) and the air/water data of Oshinowo and Charles (1974), Sokolov et al. (1969), and Beggs (1972). The mass flux in Petrick's steam/water data varies from 163 to 1,125 kg/s-m², while the air/water data from Oshinowo and Charles and Sokolov et al. varies from 150 to 2,000 and 780 to 2,000 kg/s-m², respectively. Beggs studied many different orientations, including horizontal, vertical up, vertical down, and inclined pipes with angles ranging from 5 to 85° from vertical in both the up and down directions. Chexal et al. report that the mass flux for the Beggs data varies from 60-5,200 kg/s-m², but the range for the vertical downflow data is not given. The problems that have been reported in RELAP5-3D were for steam-water at very high downflow. The mass flux was about 25,000 kg/s-m², which greatly exceeds the range of the data on which the EPRI correlation is based.

Volume 4 of the code manual (RELAP5 Development Team 2009) describes problems that were encountered in the original developmental assessment calculations when the EPRI correlation was used to simulate Marviken critical flow tests (Ericson et al., 1979a and 1979b). The Marviken tests simulated the blowdown of a large tank through a large discharge pipe. Critical flow occurred at the exit of the discharge pipe and very high downflow rates were obtained in the discharge pipe. The EPRI correlation provided poor predictions of the Marviken tests. Thus, the Zuber-Findlay (1965) churn turbulent bubbly and Kataoka-Ishii (1987) drift flux correlations were used instead for large pipes. Simulations of the Marviken tests using the EPRI correlation are shown later in this report. Simulations of small and intermediate pipes at very high downflows with the EPRI correlation show similar problems to those observed with the Marviken tests.

Although the EPRI correlation fits the existing downflow data well within the range of its database, extrapolation of the correlation to very high downflow rates results in predictions of slip ratios that are judged to be too large. An excessively high slip ratio results in the prediction of gas velocities that are too high and void fractions that are too low. An excessively high slip ratio also results in the prediction of critical flow rates that are too low when the Ransom-Trapp critical flow model is used. Unfortunately, these conclusions are based on engineering judgment because experimental data are not available to prove them. Nevertheless, the results presented in this report are judged to be sufficiently compelling to justify replacing the EPRI correlation for very high downflow cases. To maximize consistency with previous code versions, the Zuber-Findlay

churn turbulent and Kataoka-Ishii drift flux correlations are now used for small pipes, intermediate pipes, and rod bundles when the downflow mass flux exceeds $1,500 \text{ kg/s-m}^2$. An interpolation between the EPRI correlation and the churn turbulent bubbly/Kataoka-Ishii correlations is used when the mass flux is between 1250 and 1500 kg/s-m^2 . As with previous versions, the churn-turbulent bubbly correlation is used at low non-dimensional gas flow rates, the Kataoka-Ishii correlation is used at high non-dimensional gas flow rates, and an interpolation is used at intermediate gas flow rates.

The analysis described in this report indicates that the EPRI correlation provides reasonable predictions for very high upflow rates. Therefore, no changes were made to the code for upflow cases.

The engineering judgment developed during this task was based on an analysis of very high mass flux test cases, Petrick's steam/water downflow data, and Marviken critical flow tests. Analyses of these cases are provided in Section 2 of this report. The code modifications required to implement the changes to the very large downflow logic are described in Section 3. Verification testing is described in Section 4. Conclusions and references are provided in Sections 5 and 6, respectively.

2.0 Evaluation of the EPRI Correlation

The evaluation of RELAP5-3D for downflow was based on analyses of several cases, including very high mass flux, Petrick's steam/water downflow data, and the Marviken critical flow tests, which are described in Sections 2.1, 2.2, and 2.3, respectively.

2.1 Very High Mass Flux

Problems with the use of the EPRI correlation for simulating problems with very high downflow rates can be illustrated using the simple model shown in Figure 1. The model consists of a time-dependent volume that supplies a two-phase steam/water mixture to a pipe with three control volumes. An orifice connects the discharge of the pipe to another time-dependent volume that is held at atmospheric pressure. Critical flow is obtained at the orifice, which results in very high flow rates through the pipe. Calculations were performed for three different orientations, horizontal, vertical up, and vertical down, and three different pipe sizes, small, intermediate, and large. The pressure and quality supplied to the pipe were 11.7 MPa and 0.01 , respectively. The orifice area was adjusted so that the mass flux was about $25,000 \text{ kg/s-m}^2$ based on the internal area of the small, intermediate, and large horizontal pipes. The orifice and the internal pipe junctions were in the same size category (small, intermediate, or large) for each case. The length-to-diameter ratios of the pipe were the same so that the pressure drop within the pipe was approximately the same for the small, intermediate, and large pipes. The geometries of the test cases are summarized in Table 1.

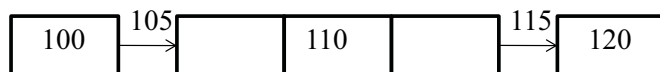


Figure 1. Nodalization for the test cases at very high mass flux.

Table 1. Geometries for the test cases at very high mass flux.

Pipe parameters				Orifice parameters
Size	Diameter (m)	Area (m ²)	Length (m)	Area (m ²)
Small	0.01	7.854e-5	0.06	4.987e-5
Intermediate	0.05	1.963e-3	0.30	1.247e-3
Large	0.20	3.142e-2	1.20	1.995e-2

Figure 2 shows the calculated steady mass flux at the second internal junction in the pipe for each case. The mass fluxes in the horizontal and upflow cases were nearly identical, with a maximum variation of 1.5%, for all three pipe sizes. The downflow mass flux was also in excellent agreement with the values from the horizontal and upflow cases for the large pipe, but was only about 78% of the horizontal value for the small and intermediate pipes.¹ The lower mass fluxes for downflow in the small and intermediate pipes were caused by the calculation of a large slip ratio at the orifice as shown in Figure 3. The slip ratio, which is the vapor velocity divided by the liquid velocity, was about 1.9 for very high downflow in the small and intermediate pipes, whereas the slip ratio for all other cases was less than 1.1. The large slip ratios for downflow in the small and intermediate pipes originated from the large distribution coefficients predicted by the EPRI correlation. The Ransom-Trapp critical flow model predicts significantly lower flow rates than the homogeneous equilibrium model when large slip ratios are calculated.

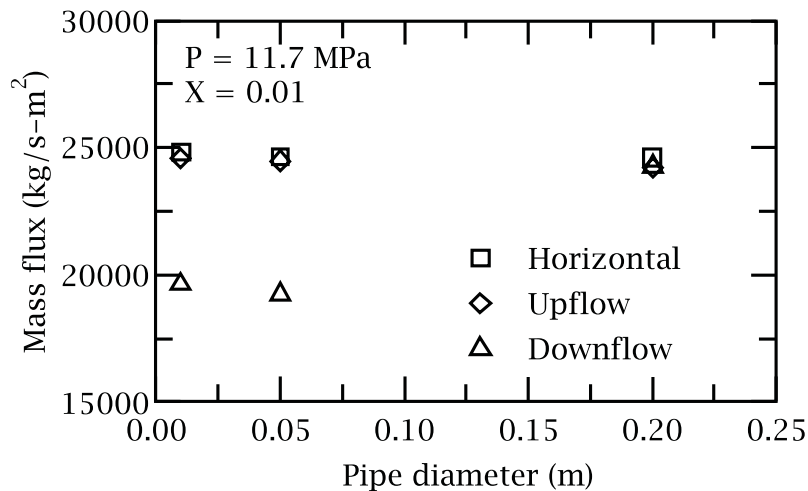


Figure 2. Calculated mass flux in the pipe.

¹ During this analysis two errors were found in the EPRI correlation as implemented in RELAP5-3D for downflow and another error was found in the calculation of the hydraulic diameter at the orifice. These errors are described in Appendix A. The results presented in Figure 2 are from the uncorrected code, RELAP5-3D Version 3.0.2t. The error corrections had a negligible effect for the horizontal and upflow cases. For the downflow cases, the error corrections had small (4%) and significant effects (13%) on the small and intermediate pipes, respectively, and a negligible effect on the large pipe.

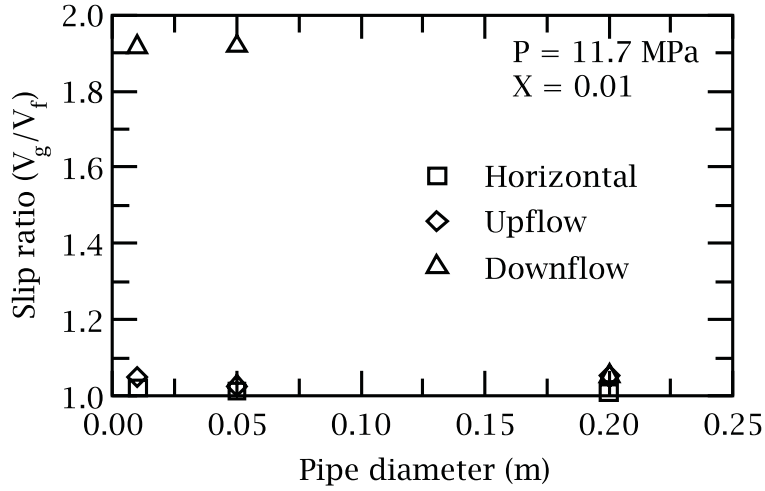


Figure 3. Calculated slip ratios at the orifice for very high downflow.

2.2 Petrick's Steam/Water Downflow Data

Petrick (1962) measured void fractions for downflow in steam-water at three different pressures ranging from 4.1 to 10.3 MPa. The Petrick experiments were the only steam/water downflow data used to develop the EPRI drift flux correlation that is used in RELAP5-3D. The following analysis is based on Petrick's lower pressure (4.1 MPa) data, which are given in Table D-1 of his report. The measured ranges of mass flux and flow quality were 237 to 1150 kg/s-m² and 0.0008 to 0.055, respectively.

A linear regression analysis was performed to determine best-estimate values for the distribution coefficient, C_0 , and drift velocity, v_{gj} , from the experimental data. According to the drift flux model, the gas velocity, v_g , can be calculated as

$$v_g = C_0 j + v_{gj},$$

where j is the total superficial velocity. For this analysis, the positive direction is defined upwards, which implies that the drift velocity is positive and that the steam and superficial velocities are negative for downflow. The least-squares fit to the Petrick data at 4.1 MPa was with $C_0 = 1.11$ and $v_{gj} = 0.417$ m/s. Figure 4 shows that the linear fit matches Petrick's data reasonably well (the R^2 value was 0.982). The distribution coefficient is the slope of the line shown in the figure while the drift velocity is the y-intercept. The fitted values from the current analysis of the Petrick data are reasonably close to those shown in Figure 11 of Ishii (1977) ($C_0 = 1.15$ and $v_{gj} = 0.52$ m/s).

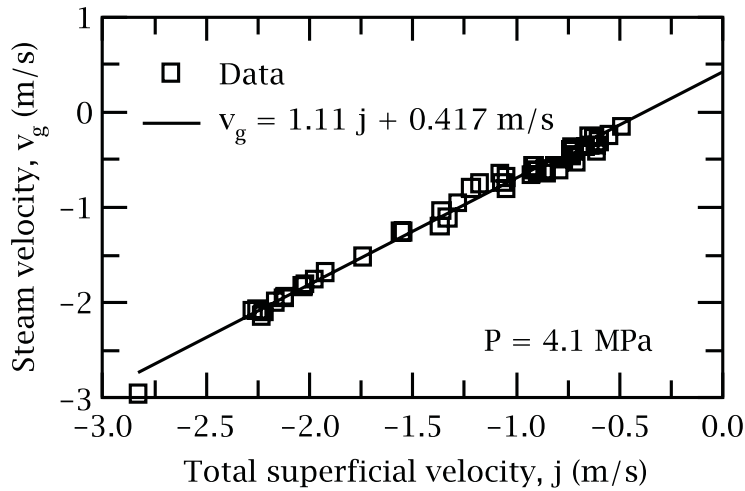


Figure 4. Linear fit to Petrick's data at 4.1 MPa.

Spreadsheet calculations were performed to determine the effect of mass flux on the EPRI correlation for both upflow and downflow using Petrick's hydraulic diameter of 0.0493 m and a pressure of 4.1 MPa. The mass flux was varied from 500 to 25,000 kg/s-m². Note that the larger mass flux used in the calculations is close to the value for critical flow and far exceeds the maximum value from Petrick's experiments. The calculations were performed at a flow quality of 0.03. Figure 5 shows the calculated distribution coefficient from the EPRI correlation for both upflow and downflow along with the linear fit to Petrick's downflow data. The distribution coefficient for upflow is nearly independent of mass flux, while the coefficient for downflow varies significantly with mass flux. The distribution coefficient from the correlation for downflow significantly differs from the linear fit to the downflow data although the distribution coefficient for upflow ($C_0 = \sim 1.13$) agrees closely with the linear fit ($C_0 = 1.11$).

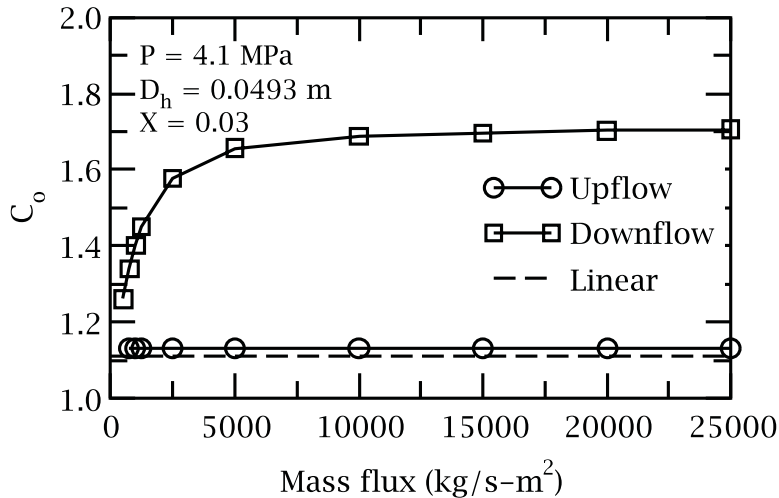


Figure 5. Distribution coefficients versus mass flux at 4.1 MPa.

Figure 6 shows the calculated drift velocity from the EPRI correlation for upflow and downflow along with the linear fit to the downflow data. The drift velocity is nearly independent of mass flux for upflow, but varies significantly with downflow. The drift velocity from the linear fit agrees better with the correlation results for upflow at very high mass fluxes than for downflow.

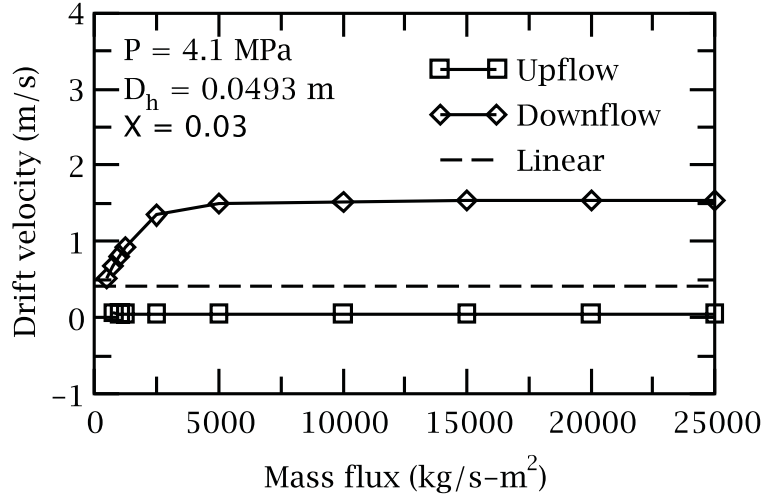


Figure 6. Drift velocity versus mass flux at 4.1 MPa.

Figure 7 shows the calculated void fractions from the EPRI correlation for upflow and downflow along with the linear fit to the downflow data. For downflow, the void fractions from the EPRI correlation agree reasonably well with the linear fit when the mass flux is in the range of the Petrick data (≤ 1150 kg/s-m²). However, at higher mass fluxes, the void fraction from the downflow correlation is significantly less than that from either the upflow correlation or the linear fit to the downflow data. For the range of the Petrick data, the void fractions from the EPRI correlation for downflow are much greater than or about the same as the void fractions for upflow. The void fraction for downflow is never significantly less than the void fraction for upflow in the range of the Petrick data. Although the EPRI correlation fits the Petrick downflow data more accurately than the simple linear fit, the extrapolation of the correlation to very high downflow mass fluxes is judged to be incorrect.

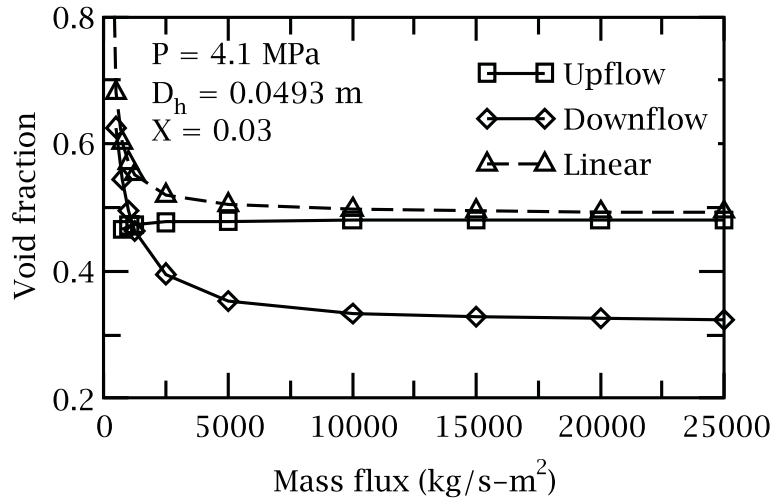


Figure 7. Void fractions versus mass flux at 4.1 MPa.

2.3 Marviken Critical Flow Tests

Volume 4 of the code manual (RELAP5 Development Team 2009) describes problems that were encountered in the original developmental assessment calculations when the EPRI correlation was used to simulate Marviken critical flow tests (Ericson et al., 1979a and 1979b). The Marviken tests simulated the blowdown of a reactor vessel through a large discharge pipe. Critical flow occurred at the exit of the discharge pipe and very high downflow rates were obtained in the discharge pipe. The EPRI correlation provided poor predictions of the Marviken tests. Thus, the Zuber-Findlay (1965) churn turbulent bubbly and Kataoka-Ishii (1987) drift flux correlations were used instead for large pipes.

Calculations of Marviken Test 24 (Ericson et al., 1979b) were performed with RELAP5-3D Version 3.0.2t and two special versions of the code that were created to use the EPRI drift flux correlation in the discharge pipe. In the special versions, variable *dlim* in Subroutine *fdisj* was changed from 0.08 to 1.0 m so that the EPRI correlation would be applied in the discharge pipe, which had a hydraulic diameter of about 0.75 m, and at the break junction, which had a hydraulic diameter of about 0.5 m. The first special version used the EPRI correlation as coded in Version 3.0.2t, which includes the errors described in Appendix A. The second special version included the error corrections listed in Appendix A. The input model for these calculations was based on the model used by Bayless (2011).

Comparisons between measured and calculated results for Marviken Test 24 are shown in Figures 8 through 10, which show steam dome pressure, break mass flow rate, and fluid density in the discharge pipe. Three calculated results are shown in each figure. The first calculated result, which is identified as “RELAP5-3D” in the figures, utilized Version 3.0.2t and applied the Zuber-Findlay and Kataoka-Ishii drift flux correlations in the discharge piping. The second calculated result, which is identified as “EPRI”, used the change to variable *dlim* so that the EPRI correlation as currently coded, including the errors described in Appendix A, would be applied in the discharge pipe. The third calculated result, which is identified as “Cor. EPRI”, used the change to variable *dlim* and the error corrections described in Appendix A.

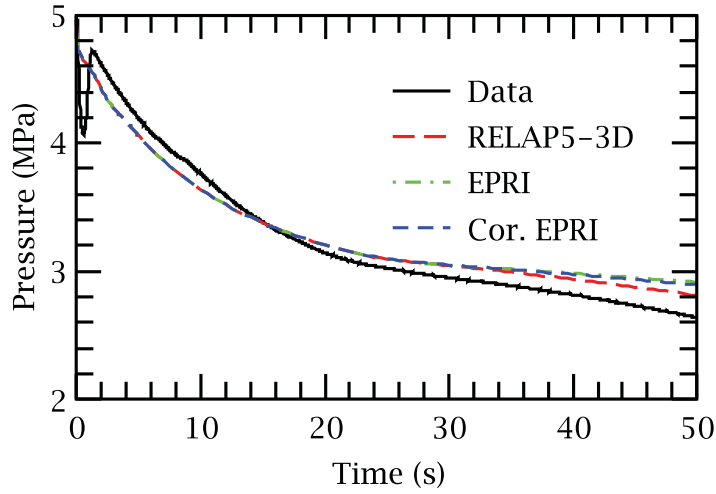


Figure 8. Steam dome pressure in Marviken Test 24.

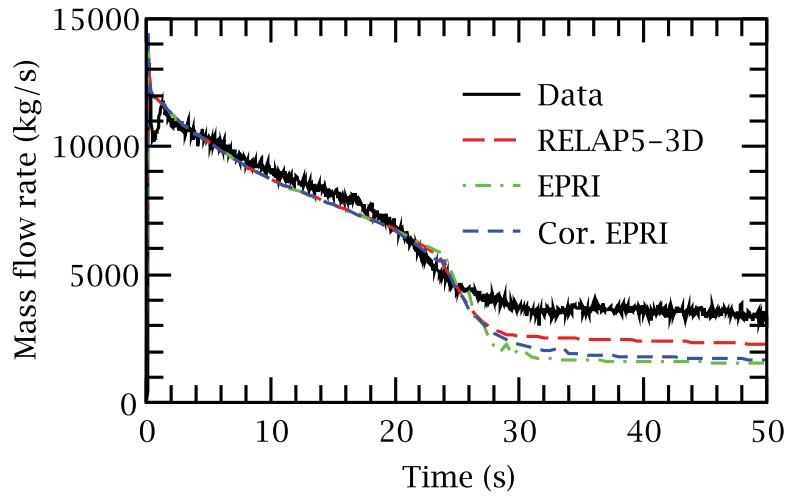


Figure 9. Break mass flow rate in Marviken Test 24.

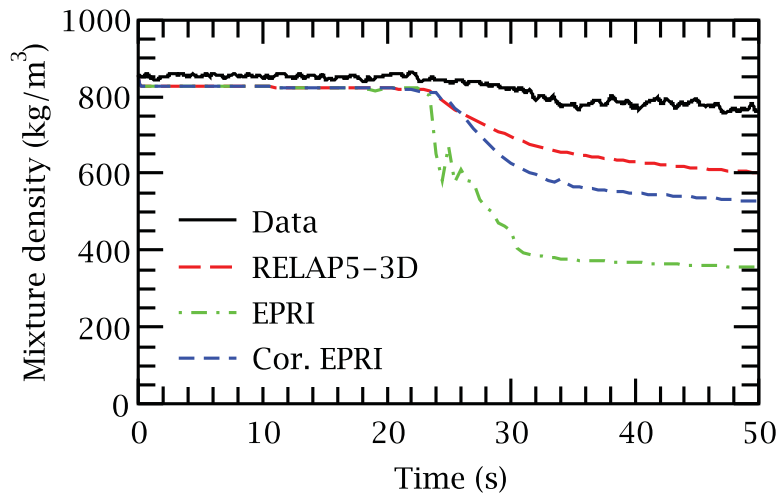


Figure 10. Fluid density in the discharge pipe in Marviken Test 24.

The figures show that all three code versions calculated essentially identical results before 25 s, which corresponds to the period with single-phase break flow. RELAP5-3D provided the best prediction after 25 s, which corresponds to the period of two-phase break flow. The largest improvement was in the break flow, where the calculation with the base code was more than 30% higher than with the EPRI correlation as coded and about 25% higher than the corrected EPRI calculation. The calculation with the corrected EPRI correlation was better than with the uncorrected correlation, particularly in the calculation of fluid density as shown in Figure 10.

Although not shown here, the results for Marviken Test 22 were qualitatively similar to those shown for Marviken Test 24.

Figures 11 and 12 show calculated slip ratios in the discharge pipe and at the break. The slip ratios at both locations were nearer to unity, indicating more homogeneous flow, when the Zuber-Findlay and Kataoka-Ishii correlations were applied. The EPRI correlation calculated a large slip ratio at the break, similar to that shown previously in Section 2.1. However, the EPRI correlation predicted a slip ratio less than unity in the pipe, which caused the lower densities shown in Figure 10. These results differ from those obtained previously in Section 2.1, where the slip ratios at internal pipe junctions were higher with the EPRI correlation, for the small and intermediate pipes. The difference was caused by the prediction of very high drift velocities with the EPRI correlation, about 20 m/s without the error corrections and about 5 m/s with the error corrections, for the large pipe in Marviken. The reduction in drift velocity due to the error correction led to the improved density prediction within the pipe shown in Figure 10. However, both the uncorrected and corrected drift velocities were judged to be unreasonably large.

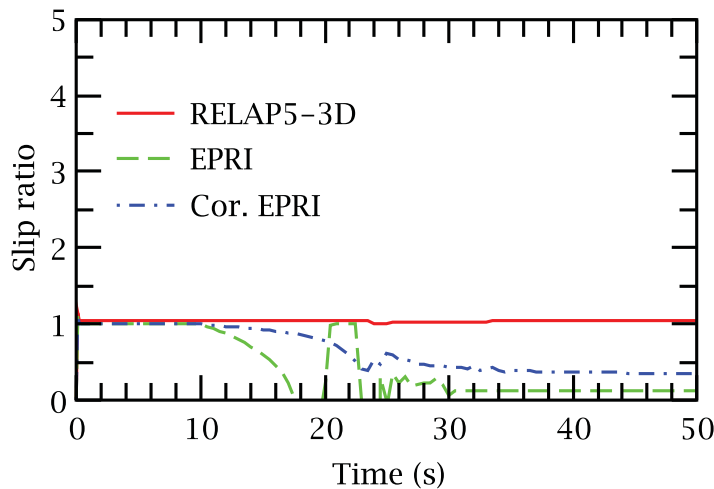


Figure 11. Slip ratio in the discharge pipe in Marviken Test 24 .

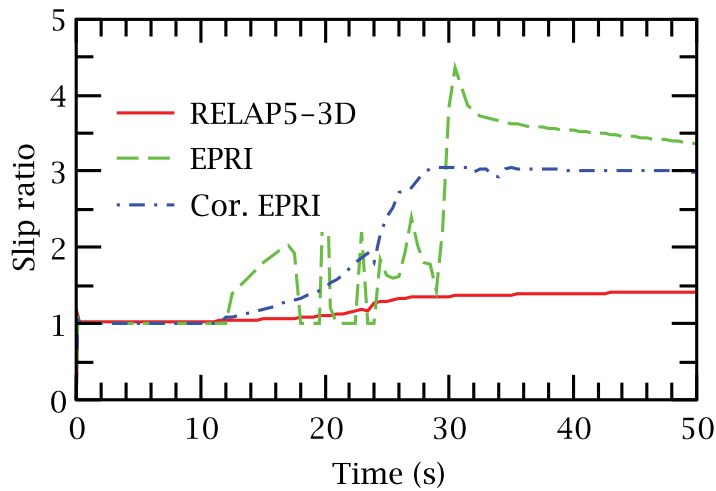


Figure 12. Slip ratio at the break junction in Marviken Test 24.

In summary, the combination of the Zuber-Findlay and Kataoka-Ishii correlations provide a significantly better simulation of Marviken Test 24 than both the corrected and uncorrected EPRI correlations. The results with the EPRI correlation would have been even worse if the distribution coefficient from the EPRI correlation had not been limited to 1.33 as described in Volume IV of the code manual.

3.0 Code Modifications

The evaluation of the EPRI correlation for very high downflow conditions is described in Section 2. A summary of the evaluation is provided below.

Section 2.1 shows that critical flow calculations using the EPRI drift flux correlation as currently coded in RELAP5 were about 20% lower for downflow than for the horizontal and upwards directions. The lower mass fluxes for downflow in the small and intermediate pipes were caused by the calculation of a large slip ratio at the break orifice. The large slip ratios for downflow were caused by the large distribution coefficients predicted by the EPRI correlation. The Ransom-Trapp critical flow model predicts significantly lower flow rates than the homogeneous equilibrium model when large slip ratios are calculated. The calculated void fraction and the critical flow rate were judged to be too low for very high downflows.

Section 2.2 determined the effect of mass flux on the EPRI correlation for both upflow and downflow using representative conditions from Petrick's steam/water downflow tests. The maximum mass flux was $25,000 \text{ kg/s-m}^2$, which far exceeds the maximum value from Petrick's experiments. For upflow, the EPRI correlation calculates drift parameters that are nearly independent of mass flux, while the drift parameters for downflow vary significantly with mass flux. The upflow drift parameters agree well with a linear fit of Petrick's data when extrapolated to very high mass fluxes. For downflow, the drift parameters from the EPRI correlation agree reasonably well with the parameters from the linear fit within the range of Petrick's data, but agree poorly when extrapolated to very high mass fluxes. For the range of the Petrick data, the calculated void fractions from the EPRI correlation for downflow are generally much greater than the calculated void fractions for upflow and are about the same at the maximum mass flux in the

database. The extrapolation of the correlation to mass fluxes above about 1500 kg/s-m^2 yields void fractions that are much lower than for upflow and are judged to be too low.

Section 2.3 showed that the Zuber-Findlay and Kataoka-Ishii correlations provided a significantly better simulation of Marviken Test 24 than the corrected and uncorrected EPRI correlations. The calculated two-phase break mass flow rate with the base code was about 25% higher than with the corrected EPRI correlation and more than 30% higher than with the uncorrected EPRI correlation. The calculated slip ratio at the break junction was much higher with the EPRI correlation. The calculated slip ratio from the EPRI correlation was judged to be too high and caused the lower break flow rate. Section 2.1 showed that similar behavior was obtained for small and intermediate pipes. Therefore, the EPRI correlation is judged to predict too high of slip ratios for very high downflow, which can lead to a significant underprediction of break flow rates.

The application of the EPRI correlation to Marviken Test 24 results in a significant underprediction of the critical two-phase flow. The root cause is the over-prediction of the slip ratio at the break. Although the Marviken test is applicable for the large pipe regime in RELAP, similar results are expected for small and intermediate pipes.

The range of mass flux in the steam/water database of the EPRI correlation extends to 2100 kg/s-m^2 for upflow, which is approximately a factor of two greater than the range for downflow, but can be far less than the critical mass flux. However, the drift parameters are nearly constant for upflow and thus the EPRI correlation calculates nearly homogeneous results when extrapolated to very high mass fluxes. Therefore, no changes are needed for upflow. For downflow, however, the drift parameters vary significantly with mass flux. The extrapolation of the distribution coefficient leads to the calculation of high slip ratios, such as seen in small and intermediate pipes shown in Section 2.1. The extrapolation of the drift velocity can lead to the calculation of slip ratios less than unity for large pipes, particularly when the distribution coefficient is limited to 1.33 as in RELAP5-3D.

The calculated results with the EPRI correlation are judged to be incorrect for very high downflow. The calculated critical flow rates are judged to be too low, the slip ratios are judged to be too high for small and intermediate pipes, and the void fractions are judged to be too low at very high downflows. Although the air/water database of the EPRI correlation may extend to 5000 kg/s-m^2 for downflow, the results shown in Figure 7 are judged to be incorrect above 1500 kg/s-m^2 . Therefore, the EPRI correlation will be replaced outside of the range of its steam/water database. Since the code currently applies the Zuber-Findlay churn turbulent and Kataoka-Ishii drift flux correlations for very high downflow in large pipes, these same correlations will be applied for very high downflow in small pipes, intermediate pipes, and rod bundles to maximize consistency with the current design philosophy of the code.

Very high downflow is defined as a mass flux above 1500 kg/s-m^2 . An interpolation between the EPRI correlation and the very high downflow correlations will begin at a mass flux of 1250 kg/s-m^2 , which is approximately the upper limit of the steam/water database for the EPRI correlation. The interpolation between the EPRI correlation and the very high downflow correlations is similar to that currently done in the transition regions between the EPRI correlations and the low flow correlations in small and intermediate pipes. The transitions between the churn turbulent and Kataoka-Ishii correlations within the very high downflow regime will be modeled the same as in the current code for intermediate and large pipes.

The new map for the drift flux correlations applied for vertical bubbly and slug flows is shown in Table 2. The new map is implemented through changes to Subroutine *fidisj*. The interpolation

region between high downflows and very high downflows is set by variables $gdvhl$ and $gdvhh$, whose values can be easily changed if necessary.

Table 2. Drift flux void fraction correlations for vertical bubbly-slug flow.

Flow rates	Rod bundles	Narrow rectangular channels	Small pipes $D \leq 0.018\text{m}$	Intermediate pipes $0.018\text{m} < D \leq 0.08\text{m}$	Large pipes $0.08\text{m} < D$
High upflow rates $G \geq 100$ $\text{kg/m}^2\cdot\text{s}$	EPRI (2) (eprij)	Griffith (2) (griftj)	EPRI (3) (eprij)	EPRI (9) (eprij)	Churn-turbulent bubbly flow (14) transition (15) Kataoka-Ishii (16) (katokj)
Medium upflow rates $50 \text{ kg/m}^2\cdot\text{s} < G < 100 \text{ kg/m}^2\cdot\text{s}$			Transition ^a (5)	Transition ^a (13)	
Low upflow, downflow, and countercurrent flow rates $-50 \text{ kg/m}^2\cdot\text{s} \leq G \leq 50 \text{ kg/m}^2\cdot\text{s}$			Zuber-Findlay slug flow (4) (zfslgj)	Churn-turbulent bubbly flow (10) transition (11) Kataoka-Ishii (12) (katokj)	
Medium downflow rates $-100 \text{ kg/m}^2\cdot\text{s} < G < -50 \text{ kg/m}^2\cdot\text{s}$			Transition ^a (5)	Transition ^a (13)	
High downflow rates $-1250 \leq G \leq -100$ $\text{kg/m}^2\cdot\text{s}$			EPRI (3) (eprij)	EPRI (9) (eprij)	
Transition $-1250 < G < -1500$ $\text{kg/m}^2\cdot\text{s}$	Transition ^a (17)		Transition ^a (21)	Transition ^a (25)	
Very high downflow rates $G \leq -1500 \text{ kg/m}^2\cdot\text{s}$	Churn-turbulent bubbly flow (18) transition (19) Kataoka-Ishii (20) (katokj)		Churn-turbulent bubbly flow (22) transition (23) Kataoka-Ishii (24) (katokj)	Churn-turbulent bubbly flow (26) transition (27) Kataoka-Ishii (28) (katokj)	

a. Interpolation is applied between different flow rates.

4.0 Verification Testing

The verification testing for the code modifications described in Section 3 and the error corrections described in Appendix A was more extensive, systematic, and rigorous than for previous modifications. The verification testing included the calculations described in Section 2, the code installation problems, and the developmental assessment calculations described by Bayless (2011). The testing using the installation and developmental assessment problems is described by Davis (2012).

The effects of the code modifications for the very large downflow case from Section 2.1 are shown in Figures 13 and 14. The code modifications resulted in more nearly homogeneous flow for the cases with very high downflow in small and intermediate pipes and caused them to be more like the horizontal and upflow cases. Normalized to the horizontal cases, the difference in

mass flux decreased from more than 20% with the original code to 1.1% and 3.5% with the modified code for the small and intermediate pipes, respectively. The slip ratio at the orifice decreased from more than 1.9 to less than 1.1.

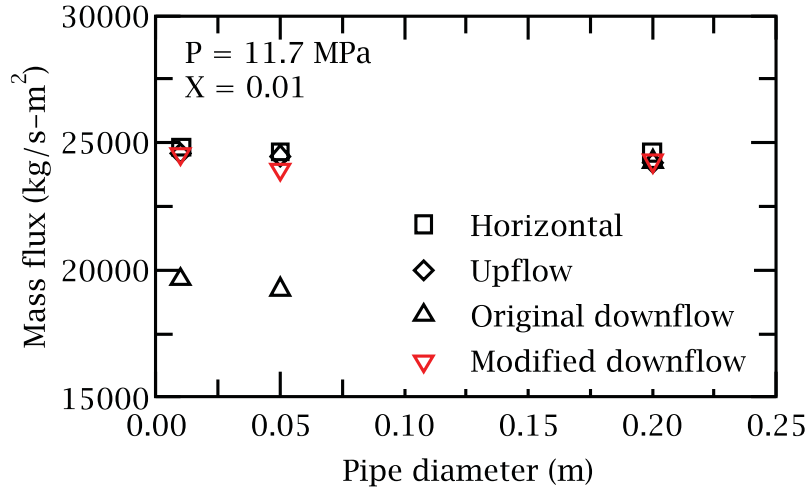


Figure 13. The effect of code modifications on the calculated mass flux in the pipe.

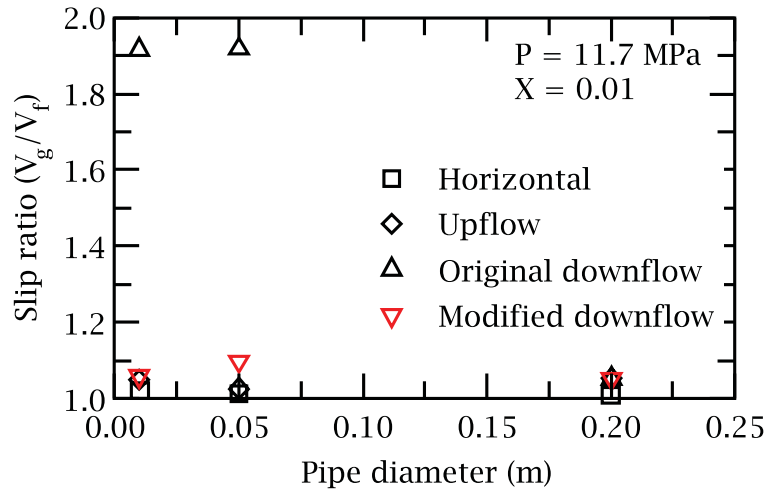


Figure 14. The effect of code modifications on the calculated slip ratios at the orifice.

The experimental steam/water database is limited for very large downflows. The code modifications for very large downflows in small and intermediate pipes were therefore based on engineering judgment rather than direct comparisons with experimental data. The lack of experimental data obviously causes problems regarding verification of the modifications. To obtain representative data, the Marviken geometry was scaled by an area factor so that RELAP5-3D considered the discharge pipe to be of intermediate or small size. This was accomplished by

multiplying all the flow areas in the Marviken input model by a factor of 0.01 to produce an intermediate discharge pipe and by a factor of 0.0004 to produce a small discharge pipe. This approach is equivalent to the full-height, full pressure scaling rationale often used to design small-scale experimental facilities (see Condie et al., 1987, for example). This scaling rationale preserves the ratio of the break area to system volume and the time scale of the experiment.

Comparisons between RELAP5-3D with the input model scaled to an intermediate pipe and the scaled Marviken data are shown in Figures 15 through 17. The measured break mass flow rate was scaled by the area ratio, but the pressure and fluid density were not changed because the full-pressure scaling rationale is designed to preserve the thermodynamic properties of the fluid. Two calculated results are shown, one from RELAP5-3D Version 3.0.2t, which contains the original logic for very high downflows, and the second using the modified logic described in this report. The calculated results for the intermediate sized pipe are similar to those shown previously for the actual Marviken test. The pressure with the modified logic is slightly lower in the two-phase region and is in slightly better agreement with the data. The break flow with the modified logic is about 40% higher and is in much better agreement with the scaled data. The fluid density is slightly lower with the modified logic, and in somewhat worse agreement with the data, but is very similar to that shown previously in Figure 10 for the full-scale Marviken data.

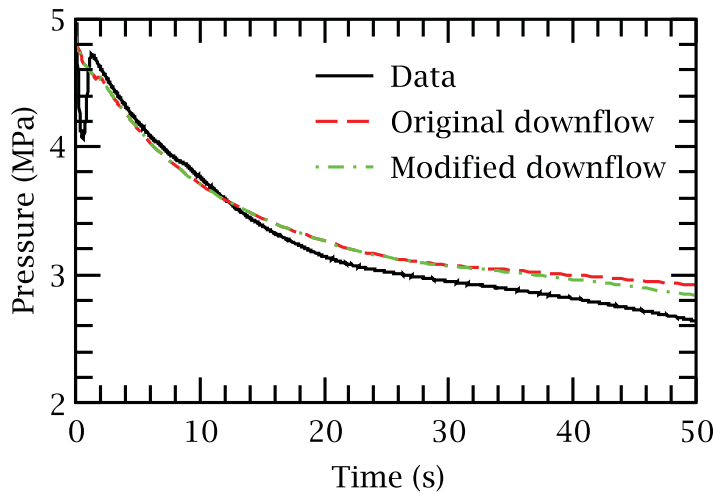


Figure 15. Steam dome pressure in Marviken Test 24 scaled to an intermediate sized pipe.

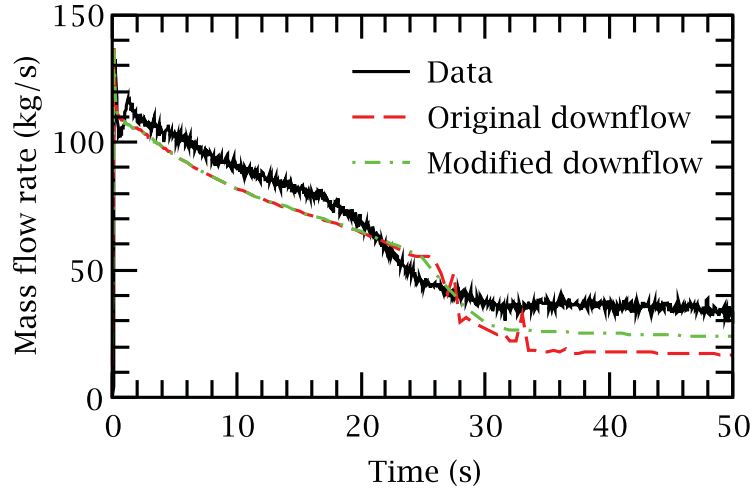


Figure 16. Break mass flow rate in Marviken Test 24 scaled to an intermediate sized pipe.

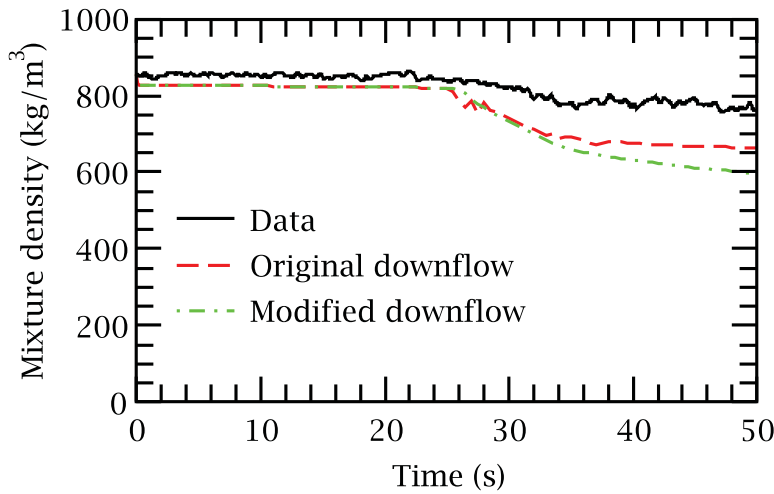


Figure 17. Fluid density in the discharge pipe in Marviken Test 24 scaled to an intermediate pipe.

The comparison between RELAP5-3D with the input model scaled to a small pipe and the scaled Marviken data are shown in Figures 18 through 20. The calculated results for the small pipe are less similar to the scaled Marviken data than for the intermediate pipe. One of the disadvantages of the full-height scaling rationale is that the friction in the discharge pipe becomes more important as the pipe diameter decreases. This scaling distortion significantly reduced the calculated break flow compared to the scaled value from the test prior to 20 s, and delays the start of the two-phase break flow regime to about 40 s in the calculation. A related, but much smaller, scaling distortion can be seen in Figure 16 for the intermediate pipe before 20 s. Even with the scaling distortion, the trends in the break flow rates are similar to those shown previously. The calculated break flow rate with the modified logic is higher, and in better much agreement with the scaled data. The flow at the break is also more homogeneous with the modified logic. Although the calculated density in the two-phase region is higher with the original logic, and in better agreement with the data, this was partially due to the scaling distortion in friction in the

discharge pipe. The higher mass flow rate in the calculation with the code modifications caused a higher frictional pressure drop in the discharge pipe, which led to more flashing and a lower fluid density.

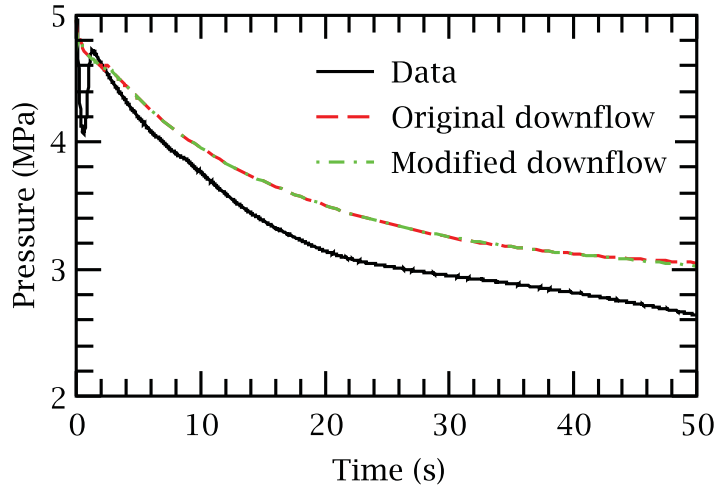


Figure 18. Steam dome pressure in Marviken Test 24 scaled to a small pipe.

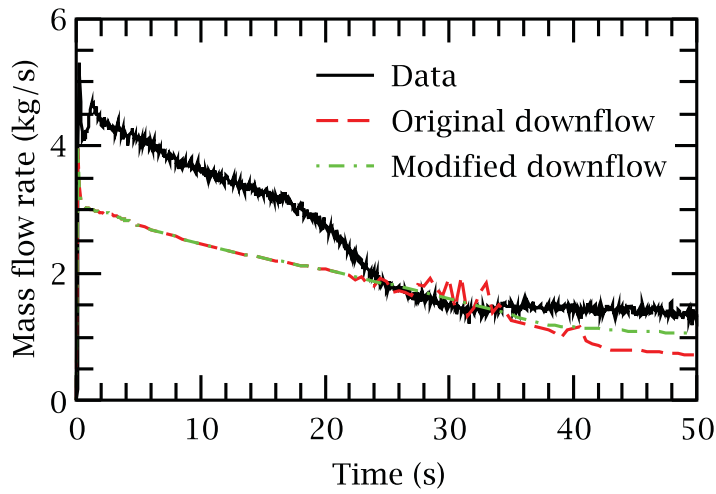


Figure 19. Break mass flow rate in Marviken Test 24 scaled to a small pipe.

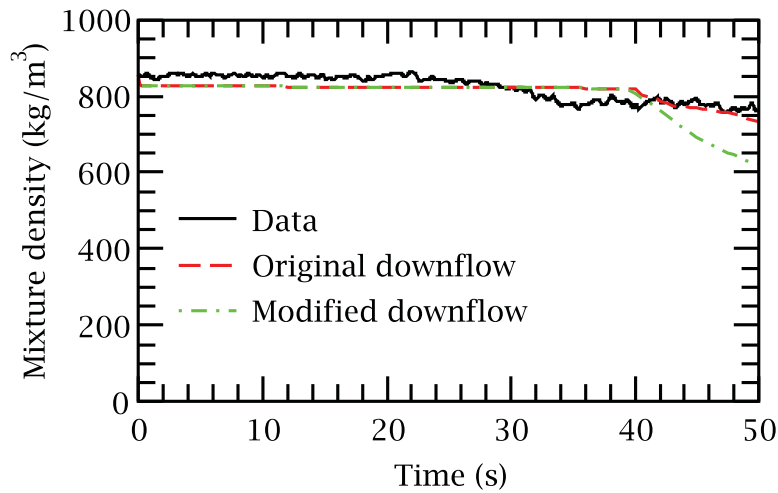


Figure 20. Fluid density in the discharge pipe in Marviken Test 24 scaled to a small pipe.

Overall, the results of the scaled calculations for Marviken Test 24 are consistent with those shown in Sections 2.1 and 2.3. The use of the EPRI correlation results in the calculation of larger slip ratios at the break and smaller break flows. The larger slip ratios cause the calculation of lower void fractions and higher fluid densities in the discharge pipe.

5.0 Conclusions

RELAP5-3D predicts critical flow rates that are about 20% lower in downflow than in upflow or horizontal flow for small and intermediate pipes. The lower mass fluxes for downflow in the small and intermediate pipes were caused by the calculation of a large slip ratio at the break orifice. The large slip ratios for downflow were caused by the drift parameters from the EPRI drift flux correlation.

The EPRI drift flux correlation is based on Petrick's steam/water downflow tests, which were conducted at relatively low downflow rates. The calculated results with the EPRI correlation are judged to be incorrect when extrapolated to very high downflow. The calculated critical flow rates are judged to be too low, the slip ratios are judged to be too high, and the void fractions are judged to be too low at very high downflows in small and intermediate pipes. Therefore, the EPRI correlation will be replaced outside of the range of its steam/water database. Since the code currently applies the Zuber-Findlay churn turbulent and Kataoka-Ishii drift flux correlations for very high downflow in large pipes, these same correlations will be applied for very high downflow in small pipes, intermediate pipes, and rod bundles to maximize consistency with the current design philosophy of the code.

The experimental database for the EPRI correlation does not include very high upflows. However, the EPRI correlation is judged to provide reasonable results when extrapolated to very high upflow. Therefore, no changes are needed for upflow.

The code modifications that implement the very high downflow regime into RELAP5-3D were extensively tested using pipes of various sizes and orientations, Marviken test data, scaled Marviken test data, normal code installation problems, and the developmental assessment cases. The verification testing showed that the downflow modifications provided improved results for very high downflow, but had negligible or relatively small effects on most of the installation problems and developmental assessment cases.

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APPENDIX A – ERROR CORRECTIONS

Two errors were found in the EPRI correlation as implemented in RELAP5-3D for downflow during this analysis. Another error was found in the calculation of the hydraulic diameter at an orifice junction that is modeled with the abrupt area change model. These errors are discussed in more detail below.

The EPRI drift flux correlation currently implemented in RELAP5-3D is not entirely consistent with the current version of the correlation described by Chexal et al. (1997) for downflow. The EPRI correlation implemented in RELAP5/MOD3 was based on Chexal and Lellouche (1986). The EPRI correlation was revised in 1991 (Chexal et al., 1991), and again in 1997 (Chexal et al., 1997). The implementation of the EPRI correlation in RELAP5-3D was revised by Riemke (2000) to be consistent with the 1997 version of the correlation. There were numerous changes between the 1986 and 1997 versions of the EPRI correlation. However, two of these changes were unintentionally not implemented in the 2000 upgrade. The missing changes were related to constants C_3 and C_{10} that are used in the calculation of the drift velocity. The first error was that the constant C_3 was calculated as

$$C_3 = 2(C_{10}/2)^{B^2},$$

but should have been calculated as

$$C_3 = \min(10, 2(C_{10}/2)^{B^2}).$$

The second error was that the third term in C_{10} was calculated as

$$C_{10} (\text{term3}) = (D_1/D_h)^{0.1} \text{abs}(Re_f)^{0.001},$$

but should have been calculated as

$$C_{10} (\text{term3}) = 0.26 (D_1/D_h)^{0.1} \text{abs}(Re_f)^{0.001}.$$

These errors affect the calculation of the drift velocity for downflow, but not for upflow.

The countercurrent logic of the EPRI correlation is not fully implemented in RELAP5-3D because it slowed the code down for certain problems. Instead, the countercurrent logic is based on the downflow logic. Therefore, the corrections to the downflow portion of the logic will also affect results during countercurrent flow.

These errors affect two-phase downflow results in small pipes, intermediate pipes, and rod bundles for all code versions released after 2000. Both errors cause the calculated drift velocity to be too large for downflow. The missing factor of 0.26 on the third C_{10} term causes the calculated drift velocity to be too large by about 10% at a liquid Reynolds number of 1E6 and by about 20% at a Reynolds number of 1E5. The missing limit of 10 on C_3 affects results when the liquid Reynolds number is greater than 1.2E6 to 1.4E6 for hydraulic diameters of 0.01 m and 0.08 m, respectively.

The third error is related to an incorrect junction hydraulic diameter that is used in the interphase drag calculations when the abrupt area change model is used at an area reduction. As shown in Equation 6.1-18 of Volume 4 of the manual (RELAP5-3D Code Development Team, 2009), the throat diameter, D_T , is currently calculated as

$$D_T = D_j(A_T/A_j)^{0.5},$$

where A_T is the throat area, D_j is the junction hydraulic diameter, and A_j is the printed junction area, which is the minimum of the two adjacent volume areas for an abrupt change. The basis for this equation is provided by Rimeke (1989). Riemke states “In order to account for a valve whose area can change during a calculation, or an abrupt area change, the junction phasic velocities (vel_{gj} and vel_{fj}) were divided by the throat ratio ($athrot$), and the resulting physical velocities (vel_{gjt} and vel_{fjt}) were used. Similarly, the junction diameter ($diam_j$) was multiplied by the square root of the throat ratio (\sqrt{athrot}).” The above logic is correct for the modification of the phasic velocities. However, the logic is not correct for the throat diameter at an abrupt area change with an area reduction. In this case, the junction hydraulic diameter defaults to the value calculated from the input junction area, which is the correct value for cylindrical geometry. Therefore, multiplication by the square root of the throat ratio is not correct. To account for the effect of valve movement, the throat diameter should be calculated as

$$D_T = D_j(A_T/A_F)^{0.5},$$

where A_F is the full open valve area that the user entered into the input model.

This last error exists in all code versions since RELAP5/MOD3.0. The error could affect any two-phase problem in which the abrupt area change model is applied at area reductions.

The code errors did not significantly affect the installation test problems described in Appendix C or the developmental assessment cases described in Appendix D.

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