RECLAMATION

*Managing Water in the West*

# Comparison of Physical and Numerical Modeling of Air Entrainment of Hydraulic Jumps in Closed Conduits

**Research and Development Office**
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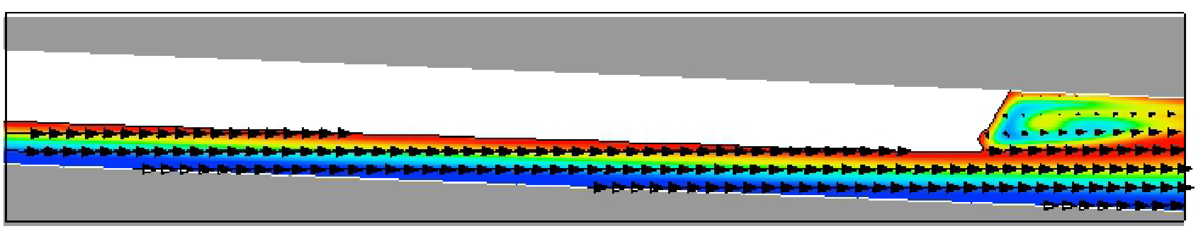


**U.S. Department of the Interior**
**Bureau of Reclamation**
**Research and Development Office**

**September 2016**

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A comparison of numerical modeling was made to physical data of air entrained by a hydraulic jump in a closed conduit. Results showed that a good comparison can made between numerical and physical model results if key control parameters in the numerical model can be calibrated. Air demand was most sensitive to the air entrainment coefficient. A good comparison was made for coefficients between 0.15 and 0.20 which caused numerical results to fall within the same data scatter as the physical results.

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**Peer Reviewer:** I have reviewed the assigned items/sections(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

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# Acknowledgements

This research project was conducted in collaboration with Flow Science Inc. utilizing their Flow 3D™ software.

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# Introduction

The main objective of this research project was to determine if air demand can be accurately predicted using numerical modeling tools. Air entrainment by hydraulic jumps in pipes is a complicated process that involves three dimensional turbulent mixing of air and water. Current practice requires large scale physical models to predict the amount of air entrained into a pipe which is important for adequate air vent design. While good agreement has been found between physical model and prototype (Falvey, 1980), physical modeling can be expensive and time consuming. Advances in numerical modeling software make it feasible to predict air entrainment in hydraulic jumps which could greatly benefit air demand analyses for design and decision making purposes. This report summarizes a comparison of numerical model results using Flow 3D$^{TM}$ software to a physical model of a hydraulic jump in a pipe (Mortensen *et al*, 2011).

# Test Approach

## Physical Data

Numerical modeling was compared to a comprehensive data set from a physical model study conducted at Utah State University in 2010. This study identified a relationship between the volumetric flow rate of air (air demand) entrained by a hydraulic jump and Froude number ($F_r$, see Eq. 1). All tests were for the condition of a hydraulic jump that goes from open channel to pressurized pipe flow in several different pipe sizes. A detailed description of the physical model study and results are documented in Mortensen, *et al* (2011).

$$F_r = \frac{v}{\sqrt{g y_e}} \qquad \text{Eq. 1}$$

Where:
$v$ = approach velocity upstream of hydraulic jump
$g$ = gravitational acceleration
$y_e$ = effective depth (cross-sectional water flow area divided by water surface width)

## Numerical Model

Version 10.1 of Flow 3D$^{TM}$ was used to model air demand of a hydraulic jump going from open channel to pressurized pipe flow. Reclamation modeled test runs using pipe sizes of 3-inch, 12-inch, and 24-inch diameter within a $F_r$ range of approximately 3 to 9. This was done using both methods of air entrainment modeling in Flow 3D; volume fraction and variable density (Hirt, 2012).

As part of a collaboration, Flow Science, Inc. completed test runs in parallel to Reclamation using a 12-inch diameter pipe within a $F_r$ range of 3.5 to 9.3. A description of their model setup is documented in the Appendix of this report. Air demand results for a given $F_r$ from numerical test runs were compared to the physical model data.

# Results

Results from test runs made by Reclamation were variable and did not show any consistent trends (Figure 1). A likely cause is that an incorrect value for the surface tension of the water was used during modeling due to a conversion error in the Flow 3D unit conversion software.

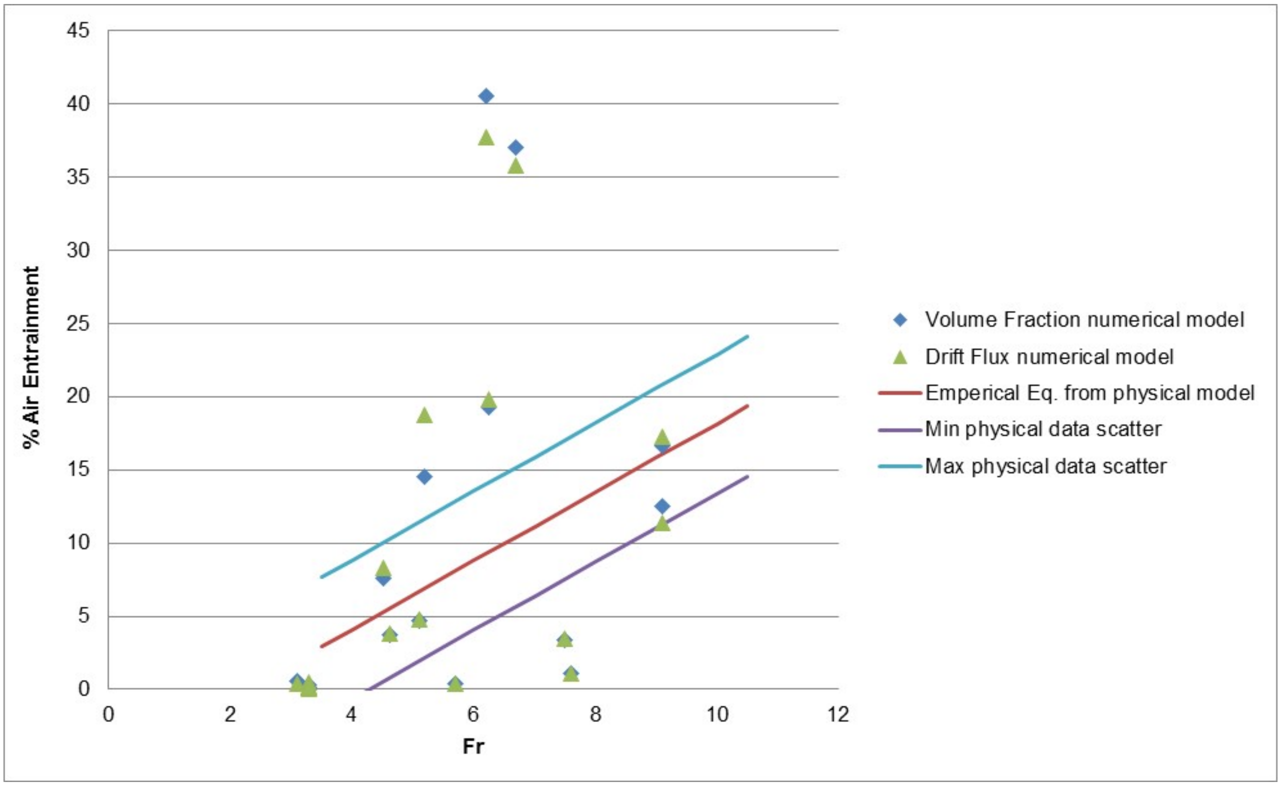


Figure 1 Air demand vs Fr for numerical test runs made by Reclamation.

Test runs made by Flow Science Inc. showed consistent air demand trends with $F_r$ and also that the air entrainment coefficient could be adjusted to match numerical and physical results within the same data scatter (Figure 2, Appendix). A full description of test results from Flow Science Inc. is given in the Appendix.

# Conclusions

Results showed that a good comparison can made between numerical and physical model results if key control parameters in the numerical model can be calibrated. Air demand was most sensitive to the air entrainment coefficient. A good comparison was made for coefficients between 0.15 and 0.20 which caused numerical results to fall within the same data scatter as the physical results for a $F_r$ range of 3 to 8. However, for $F_r$ greater than 8 the numerical model significantly over-estimated air demand which may have been due inaccurate representations of the flow at greater turbulence levels.

Further investigation was postponed as a new version of Flow 3D will be released in the near future which will include a more comprehensive air entrainment model. A repeat comparison using the updated version is recommended after it has been released. An additional comparison will not only determine how to calibrate key parameters for accurate results but will also identify the range for which these parameters are valid. To date, accurate numerical results can only be attained by calibration to physical data. Further comparisons may extend the known range for which the air entrainment model can accurately be applied.

# References

Falvey, H. T. (1980). *Air-Flow in Hydraulic Structures.* Denver, CO: Bureau of Reclamation.

Hirt, C. W. (2012). *Modeling Turbulent Entrainment of Air at a Free Surface.* Technical Note FSI-03-TN61-R: Flow Science, Inc. .

Mortensen, J. D., Barfuss, S. L., & Johnson, M. C. (2011). Scale effects of air entrainment by hydraulic jumps within closed conduits. *Journal of Hydraulic Research*, Vol. 49, pp. 90-95.

# Appendix: Flow Science Summary Report

# FLOW-3D Air Entrainment Validation Summary
# January 6, 2016

We have completed our tests of the air entrainment model and are sending you an update of the results and our plans for further testing. Based on our previous discussions, USBR's goal is to identify a value of the air entrainment coefficient and/or other model setup parameters that can be used to match existing physical model measurements for the case of a hydraulic jump within a closed pipe. Previous testing of FLOW-3D by USBR found inconsistent results for the amount of entrained for different pipe sizes, Froude numbers, and various other numerical input settings. This report summarizes the results of Flow Science's efforts to identify suitable model setup procedure and parameter values for the air entrainment model.

The FLOW-3D air entrainment model is explained in tech note FSI-03-TN61. To summarize, the model entrains air into the fluid flow by two different methods. The first method estimates air entrainment at a turbulent free surface by comparing the turbulent kinetic energy to the resisting force of surface tension. The second method accounts for air entrainment resulting from a jet of water impinging on a free surface. The impinging jet is converted to an equivalent turbulent kinetic energy to quantify the total volume of air entrained. In the current test case of a hydraulic jump in an enclosed pipe, air entrainment at a turbulent free surface is the dominant process. Therefore, any model parameter affecting turbulent kinetic energy at the free surface will also affect the amount of entrained air calculated by the model. The parameters that we identified as most important to this process are the air entrainment coefficient, mesh size, turbulence model, and drift-flux model bubble size. We tested various combinations of each of these parameters by comparing how they affected the percent of air entrained. The results allowed us to determine the best values of these parameters for calibrating to the physical modeling data. The following is a discussion of our model setup procedure, the range of variables tested, model results, and summary of our recommendations for future use of the air entrainment model.

## Model Setup

The initial model testing was completed using the 12 inch diameter pipe size, and geometry defined using the STL files provided by USBR. The air entrainment model was activated, including options for bulking and buoyancy. The range of values we tested for the air entrainment coefficient were 0.01, 0.1, 0.15, 0.25, 0.5, 0.75, and 0.9. The ranges of mesh sizes and Froude numbers we tested are provided in tables 1 and 2. The RNG and k-w turbulence models were both tested with a maximum mixing length 0.5 ft (half the pipe diameter). The second order density evaluation method and the drift flux model were also activated. The bubble sizes (ft) tested within the drift flux model were 0.00625, 0.0.125, 0.025, and 0.05. All of the remaining default values for numerical options were retained.

Table 1 Mesh sizes used for grid convergence testing of the 12 in diameter pipe model runs.

| Mesh Name | Mesh Size (ft) | Mesh Size (in) | Cells/Pipe Diameter |
|---|---|---|---|
| Coarse | 0.1667 | 2 | 6 |
| Medium | 0.1111 | 1.33 | 9 |
| Fine | 0.0833 | 1 | 12 |

Table 2 Specified inlet and outlet boundary conditions for a given Fr.

| Volume Flow Rate (cfs) | Downstream Pressure BC (ft) | Average Froude Number |
|---|---|---|
| 1.5 | 9.5 | 3.5 |
| 2.5 | 9.5 | 4.8 |
| 3.0 | 9.5 | 4.5 |
| 3.5 | 10.0 | 5.0 |
| 4.5 | 11.0 | 6.3 |
| 5.5 | 11.0 | 7.6 |
| 7.5 | 11.0 | 9.3 |

## Mesh Size Test Results

We first performed a simple test to compare the effects of refining the mesh size. We started with a coarse mesh size of 2 inches and tested two additional refinements of 1.33 in and 1 in. Using a baffle, we measured the percent air entrained at the downstream end of the pipe and compared the results between the different mesh sizes. Two tests were performed using a high and low value of the air entrainment coefficient. For each of the test cases we found no significant difference in the amount of air entrained between mesh sizes. We continued to use only the medium sized mesh for all subsequent model runs.

Table 3 Results of the grid convergence tests comparing % air entrainment for each mesh size.

| Mesh Name | % Air Entrained Inflow = 2.54 Air Coeff. = 0.5 | % Air Entrained Inflow = 2.54 Air Coeff. = 0.2 |
|---|---|---|
| Coarse | 12 | 5.1 |
| Medium | 11 | 5.4 |
| Fine | 13 | 3.7 |

## Air Entrainment Coefficient Test Results

We tested a range of air entrainment coefficients as a function of Froude number to determine if there is a single air entrainment coefficient value that is sufficiently accurate for full range of the physical data. For these comparisons, we used the medium mesh size, RNG turbulence model, and a drift flux bubble size of 0.025 ft. The results in Figure 2 show the percent air entrainment as a function of Froude number and colored by air entrainment coefficient value.

For values of Fr < 7.5, a nearly linear trend is observed between Froude and % air entrainment for all of the values of the air entrainment coefficient. The effects of changing the air entrainment coefficient are having the expected behavior, in that increasing its value increases the % air entrainment and effectively shifting the plotted trend higher on the y-axis. The air entrainment coefficient values of 0.2-0.25 appear to be the best fit to the physical data. However, as Froude number increases to values greater than 8, the linear trend between Froude and air entrainment coefficient begins to break down. For these larger values of Froude number, % air entrainment begins increasing rapidly with Froude number and no longer follows the linear trend observed for lower Froude numbers.

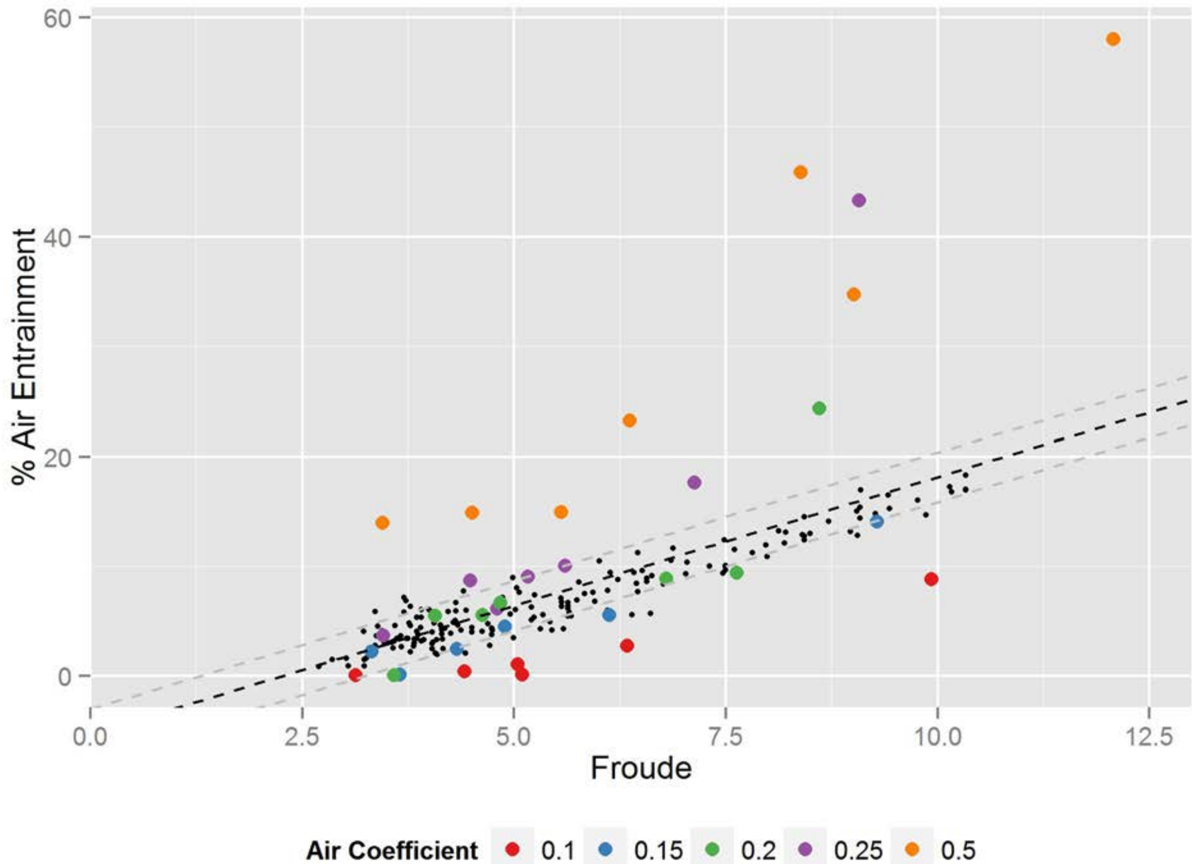


Figure 2 Results of air entrainment coefficient tests comparing the % air entrainment as a function of Froude number. In all tests turbulence model is fixed to RNG and drift flux bubble size fixed to 0.025 ft.

## Turbulence Model Test Results

The RNG and k-w turbulence models were evaluated for a range of Froude numbers and air entrainment coefficient values. Figure 3 illustrates the effects of the turbulence model on the amount of entrained air. The plots are paneled by volume inflow rate which represents Froude number. In each panel the percentage of air entrainment is plotted as a function of air entrainment coefficient to account for the interacting effects of these two variables. The results show that the RNG model consistently produces higher values of entrained air than the k-w model. Further, the difference in the percentage of air entrainment between the two turbulence models also generally increases with the air entrainment coefficient and Froude number.

Another interesting observation regarding the effect air entrainment coefficient can be made from Figure 2, where air entrainment is plotted as a function of the entrainment coefficient. This plot shows that the slope of the line increases with the volume inflow rate (Froude number). This indicates the increasing sensitivity and importance of the air entrainment coefficient for flows with higher Froude numbers, mirroring what was observed in Figure 2.

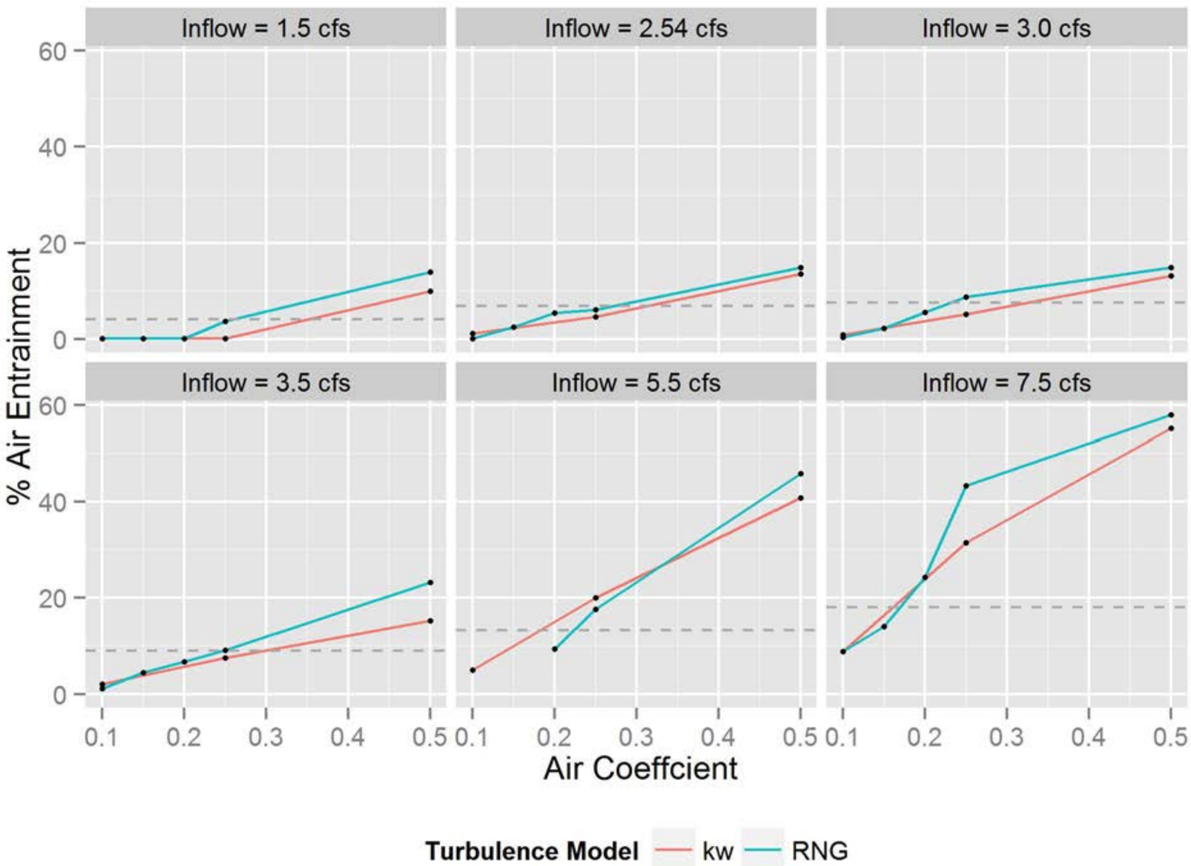


Figure 3 Results of turbulence model tests, comparing the % air entrainment between the RNG and k-w turbulence models over a range of air entrainment coefficients. Interactive effects of Froude number are illustrated by displaying separate panels six different inflow rates.

## Drift Flux – Bubble Size Test Results

With the drift flux model active any entrained air is treated as a dispersed media within the water, accounting for the forces of buoyancy and drag and changes the density profile of the fluid. This model requires the specification of an air bubble size which can potentially affect the modeled hydraulics. The results of testing different bubble sizes are presented in Figure 4. The results show that, while the bubble size did appear to have an effect, no recognizable trend of how bubble size effected % air entrainment was identified. In addition, the bubble size appears to have the greatest effect at higher Froude numbers.

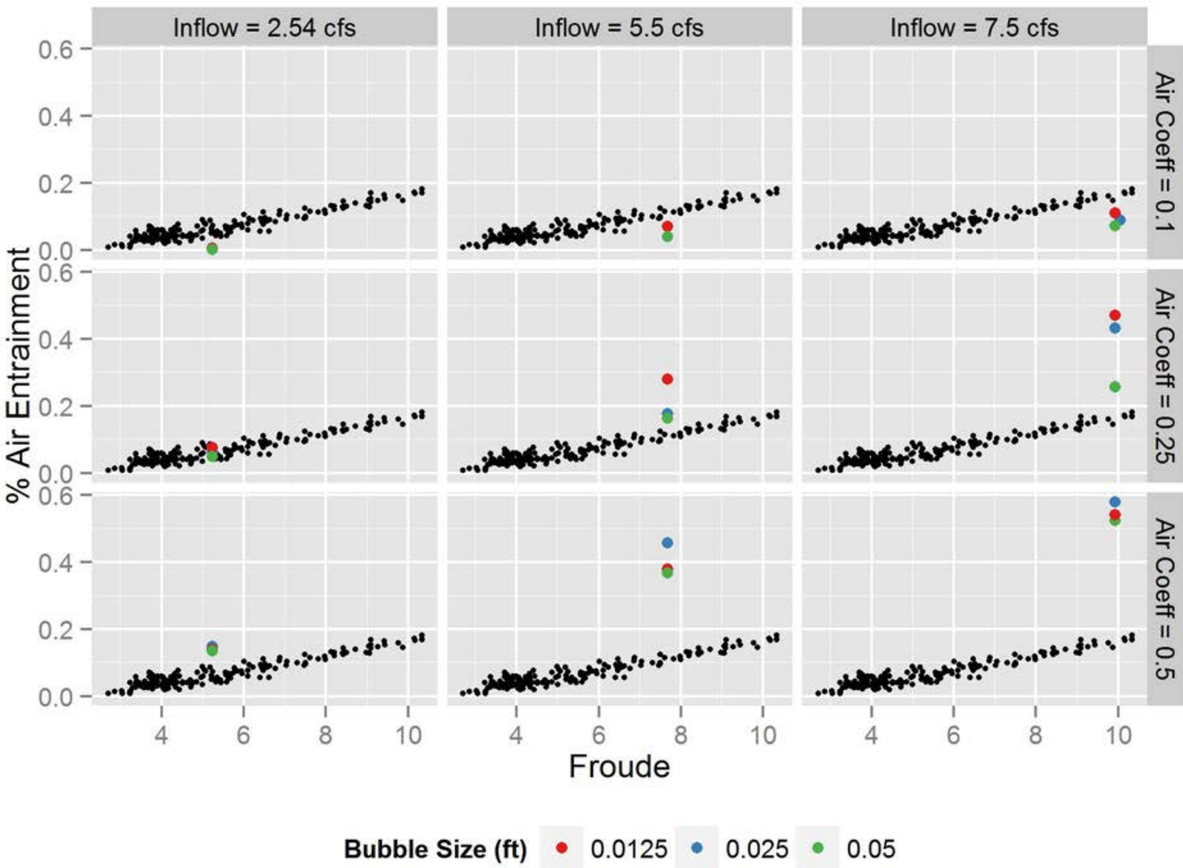


Figure 4 Results of drift flux bubble size test comparing the % air entrainment as a function of Froude number. Interactive effects of Froude number and air entrainment coefficient value are illustrated through the panel plot. Each panel column represents a different inflow rate and each panel row represents a different air entrainment coefficient value.

## Summary and Recommendations

The mesh tests show that the air entrainment model is not very sensitive to mesh size, especially as compared to previous versions of the model. Since the coarse mesh size compared well with fine mesh, we elected to use the medium mesh size throughout the remainder of the tests because the computational time was more manageable. Using a mesh size of approximately 10 cells across the pipe diameter should be suitable to resolve the hydraulics and percent air entrainment for the case of a hydraulic jump in an enclosed pipe.

The air entrainment coefficient tests provided the most useful information. When varying only the Froude number and holding all other parameters constant, we found that we were able to get consistent results for the percent of air entrained. By increasing the air entrainment coefficient value you can observe an increasing trend of percent air entrained with increasing Froude. As the air entrainment coefficient is increased the percent air increases as expected. For lower Froude (< 8) numbers the relationship appears nearly linear, which allows for calibration of the air entrainment coefficient with the physical data. For Froude numbers less than 8, the data in Figure 1 indicates that the best value of the air entrainment coefficient value of 0.2-0.25 for the case of a hydraulic jump in a pipe.

For higher Froude numbers (Fr > 8) the linear relationship breaks down as percent air entrainment increases rapidly with Froude number. Because the air entrainment is mainly a function of turbulent kinetic energy, the cause of the rapid increase may be attributed to an overestimation of the kinetic turbulent energy by the turbulence model. Another potential cause is that the model structure of the air entrainment calculation may be missing or over simplifying an important physical process that affects the actual air entrainment at higher Froude numbers. We are currently investigating the cause of this rapid increase in air entrainment, and will be working to improve the model for future releases. Until the exact cause is identified we would recommend using the air entrainment model for the ranges of input variables specified in this report.

The turbulence model tests show that the percent air entrainment when using the RNG and k-w models follow the same general trend. For small values of Froude number, these two models match very closely, but for higher values of Fr the differences can become significant. Even though these produced relatively similar results, we recommend using the RNG model because of faster computation times.

The drift flux bubble size tests yielded little useful information. We were not able to detect a noticeable trend in the percent air entrained when changing the bubble size. For future use, we recommend keeping the bubble size relatively small (~0.010) compared the size of the mesh cell size. Additional best practice items include setting the maximum mixing length for the turbulence model. The physically maximum mixing length is the pipe diameter, but there are arguments that exist to set this as low as 7% of pipe diameter. For all of our testing, we set the value to half the pipe diameter. We performed several sensitivity tests and found that there were no differences in the results when maximum mixing lengths of 0.7, 0.5, and 1 were used.

For future testing it would also be very valuable to have data from the physical model that includes the upstream flow rate and downstream water surface elevation for each measured value of air entrainment. The location of the jump is a function of these two boundary conditions. Additionally, we found that the jump location is very sensitive to the air entrainment coefficient. The data that was provided by USBR did not include the downstream water surface elevation; therefore we needed to assume a value for each of the FLOW3D model runs. If both boundary conditions were known then we could use the jump location as another potential method to calibrate the air entrainment coefficient. If additional physical modeling is completed we would recommend collecting both volume inflow rate and downstream water surface elevation for possible future FLOW3D modeling.

Finally, when reviewing the USBR input files we noticed an error with the surface tension coefficient that could explain some of the unexpected results. The standard value for water at 20° C is 0.005 slugs/$s^2$, but was set to 0.16 slugs/$s^2$ for all of the USBR simulations, possibly due to a unit conversion error. This had a significant effect on the amount of entrained and is a possible reason why the USBR model results showed inconsistencies.