A Computational Assessment of Gas Jets in a Bubbly Co-Flow

[1]Melissa Fronzeo*, [1]Michael Kinzel

[1]The Pennsylvania State University, University Park, PA, USA

Abstract

In this effort, Computational Fluid Dynamics (CFD) is used to investigate the dynamics of gas jetted into an internal pipe flow. Specifically, we aim to understand the resulting cavity and resulting interaction modes that drive the gas to mix with the exterior flow. In order to vary the bubbly flow, the pipe fluid is treated as a weighted mixture of air and water with the volume fraction of air being a controlled variable. The velocity of the external flow and the mass flow rate of the air jetted in the flow are also varied to obtain a global understanding of the variation. These variations indicate the occurrence of several flow regimes of the primary cavity forming at the jet exit, as the jet gas interacts with the bulk pipe flow. Results of the weighted air/water mixture are compared to previous results involving only water as the bulk pipe flow. The overall results provide insight into the various flow regimes that occur.

Introduction

In the present effort, we consider the primary breakup mechanism in a cavity that initiates gas mixing within a pipe co-flow. The diagram in Figure 1 indicates the scenario being investigated, which indicates flow through a pipe with a sting-mounted body that is used to inject and mix gas into the pipe flow. In general, gas jets expelled into a gaseous flow are well understood. However, the mechanisms of multiphase gas jets expelled into a liquid are less understood than single phase jets, with the majority of the studies relating to gas jetted into a quiescent liquid. When it comes to gas jets expelled into a liquid co-flow, or even bubbly liquid, the field of study is even smaller. Despite this, understanding the dynamics of the jet-liquid interactions are important to industrial uses such as underwater cutting and chemical mixing [1]. In this effort, a parametric study of this multiphase flow system is investigated using CFD, which has been previously used and validated in regards to similar multiphase jets applications [2-4].

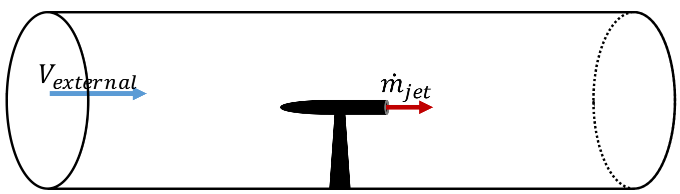


Figure 1: Pipe geometry

In previous work from the authors, the variation of the freestream liquid velocity and the mass-flow rate of the gaseous jet were investigated [2,3]. This data was then used to identify different regimes based on the gas-liquid interactions, and subsequently create a regime map of these interactions. Results indicated that the interaction involves at least five-different dynamic modes. In those studies, pure water was used as the freestream liquid, hence, the conditions do not include free-stream gas content that is expected to occur with recirculation or when placing injection ports in parallel. The present effort expands on the previous work in order to develop a more generalized understanding of submerged jets by also considering variations in the freestream liquid properties. Specifically, the liquid is varied by using a weighted mixture of air and water. Such mixture variation, controlled by a volume fraction parameter, leads to density, compressibility, and viscosity changes in the freestream flow. For these various free-stream conditions, parametric evaluations of freestream velocity and jet-mass-flow rate are still evaluated creating a three-dimensional set of data. In these efforts, previously used regime analysis methods are applied to identify the flow regimes for each data set. The result is a three-dimensional matrix of data with parametric variations in the freestream velocity, jet mass-flow rate, and free-stream gaseous volume fraction.

Methods

The present work was performed within the commercial code, Star-CCM+ [5]. The physical modeling for the gas jet and varying freestream liquid was previously used and validated for gas jetted into water [2]. The modeling was specifically validated against the experimental data found in Weiland's PhD dissertation [1]. All of the simulations are conducted using 2D axisymmetric modeling, with a time-resolving flow model. The previous work conducted on air jetted into water classified several multiphase regimes of the gas-liquid interactions, with infographics in Figure 2:

- Mode 1: Shedding Jet: Large bubble ejections; gas is attached to the nozzle (Figure 2(e)).

*Corresponding Author, Melissa Fronzeo: maf5524@psu.edu

- Mode 2: Toroidal Cavity: Small gaseous cavity; liquid enters cavity in constant stream, ejections of gas pockets, often in toroidal vortex form. (Liquid entering the cavity indicated by dotted lines in Figure 2(a)).
- Mode 3: Pulsating Cavity: Medium gaseous cavity; large interface waves; liquid enters cavity in small pockets (indicated by dotted lines and circles in Figure 2(b)).
- Mode 4: Stable Cavity: Large gaseous cavity; little to no liquid enters cavity; small interface waves (Figure 2(c)).
- Mode 5: Over-Ventilated Cavity: Small gaseous cavity; large bubble ejections from end of cavity (Figure 2(d)).

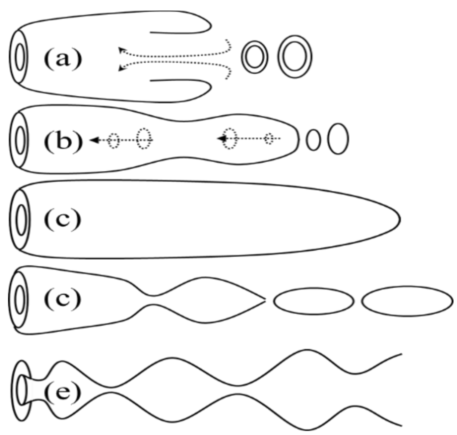
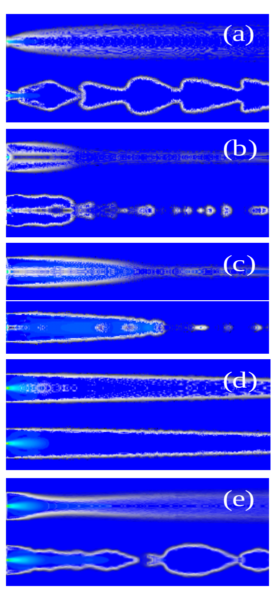
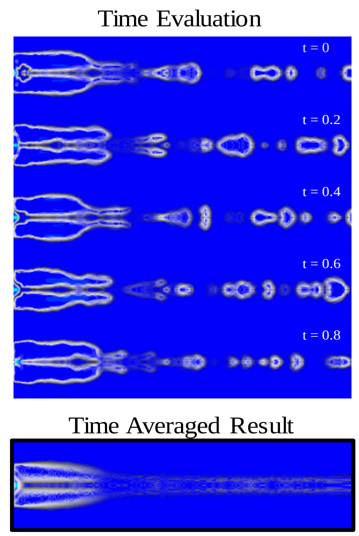


Figure 2: Cartoons of each mode; (a) Toroidal Cavity, (b) Pulsating Cavity, (c) Stable Cavity, (d) Over-Ventilated Cavity, (e) Shedding Jet.

Simulation examples of each of these regimes are shown in Figure 3. In the images, the grayscale lines indicate the volume fraction of the gas (with inside of white being all gas, outside of the black lines being all liquid) and the contours tend to outline the predicted mixture regions of the gaseous cavity. The color contour indicates Mach number, with dark blue being low Mach, and the light blue/cyan color showing the jet (high Mach). The top images are of the time-averaged simulation, while the bottom images are a snapshot of the unsteady simulation.

These regimes were identified using visual inspection; videos of the unsteady simulation, as well as images of the time-averaged solutions were compared for sixty-four separate cases (varied freestream velocity and mass-flow rate of the gas). The following figures show an example of this process, using a toroidal vortex cavity case (Figure 4). The regimes are then assigned an integer value associated with the regime (Figure 5), and then plotted on a grid to indicate the flow-regime map.





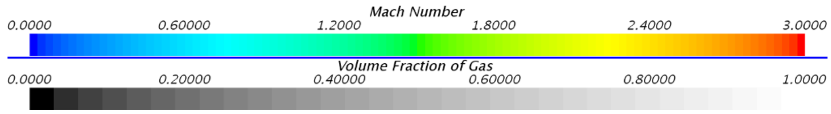
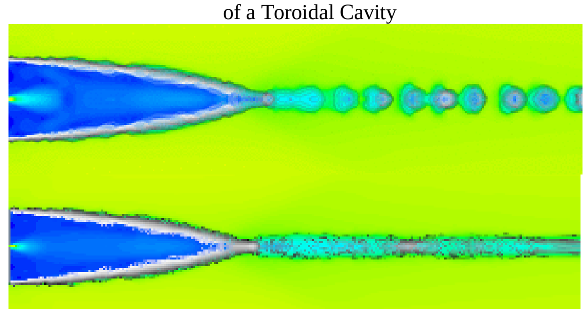


Figure 3: (a) Shedding Jet, (b) Toroidal Cavity, (c) Pulsating Cavity, (d) Stable Cavity, (e) Over-Ventilated Cavity

Figure 4: Time Sequence (top) and time-averaged solution (bottom) of a Toroidal Cavity



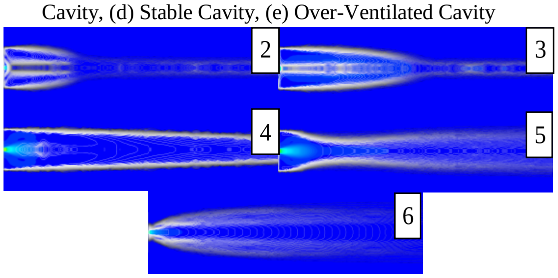


Figure 5: Numeric numbering of regimes

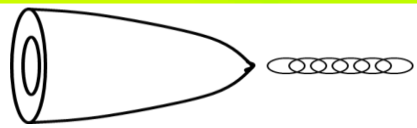


Figure 6: Fast Pulsating

These numeric values are used to create a regime map over a grid of input parameters. Regime maps such as these have been used before to evaluate multiphase flows, such as gas and liquid in a pipe. These maps provide additional insight into controlling parameters between regime, and are a predictive aid in future work [6-7]. The original cases were taken over a sweep of freestream velocity values (1, 5, 10, 15, 25, 30, 40, and 50 m/s), and a sweep of mass-flow rate of the jet values (0.0025, 0.0040, 0.0050, 0.0060, 0.0075, 0.0080, 0.0100, and 0.0125 kg/s). In this work, we expand on the previous wok with additional cases that vary the free-stream volume fraction of air. Hence, the original data set used only water as the freestream liquid. The new data will use a weighted air/water mixture, with volume fractions of air equal to 0.25, 0.50, and 0.75. The same variations of freestream velocity as well as mass-flow rate of the jet are used.

Results

As the volume fraction of air in the freestream is increased, the first major change is the appearance of a new regime. When air is mixed into the water, the higher freestream velocity cases begin to form the regime shown in Figure 6. This regime, which will be called the Fast Pulsating Cavity, is characterized by a small cavity with no visible waves on the interface, but a constant stream of small gaseous ejections from the cavity tip. Comparing over a reduced sets of data for the volume fractions of 0.25, 0.50, and 0.75, it appears that this regime would fit into the numeric value of 1, for plotting and transitional purposes. Reduced data sets (only 16 cases; 4 mass-flow rates and 4 freestream velocities) are shown in Figure 7, Figure 8, and Figure 9.

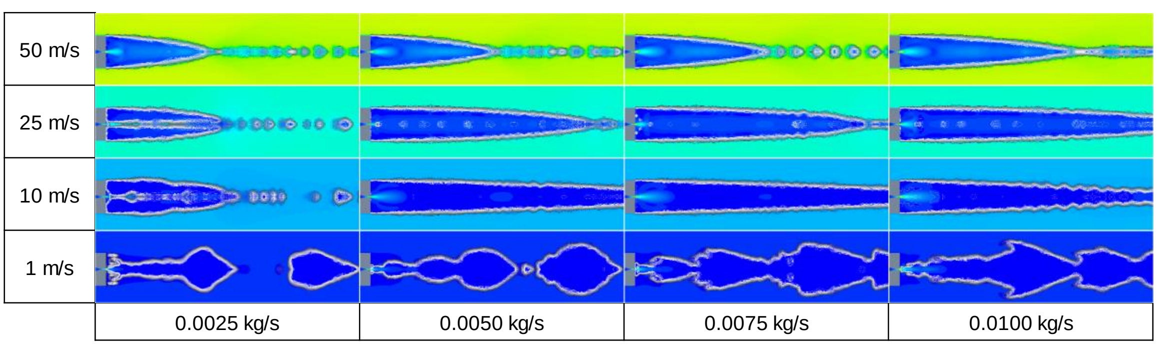


Figure 7: Reduced Data Set, Volume Fraction of Air = 0.25

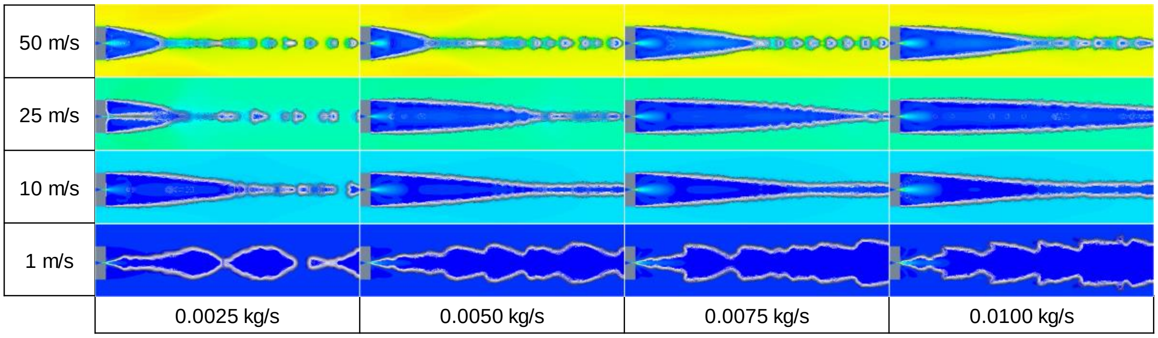


Figure 8: Reduced Data Set, Volume Fraction of Air = 0.50

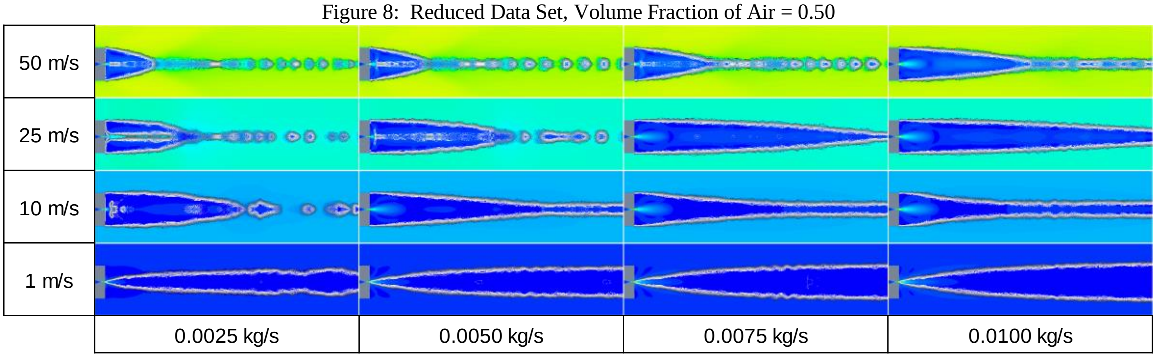


Figure 9: Reduced Data Set, Volume Fraction of Air = 0.75

The resulting regime maps were created by plotting the associated integer for reach regime values over a two-dimensional grid of freestream velocity and mass-flow rate for each volume fraction, interpolating between given values. The limits between each regime (and intermediate zones) are then smoothed by applying curve fits. An interpolated and smoothed plot are shown in Figure 10, with the rest of the smoothed plots shown in Figure 11. Displaying the information in this map format shows how flow is affected by increasing the volume fraction of air in the freestream. When the volume fraction is increased from 0.00 to 0.25, the fast pulsating regime appears. Similar to the shedding jet, it appears to be almost completely controlled by freestream velocity, creating an upper cap on the freestream velocity values. In addition, the over-ventilated and stable regimes expand. When the volume fraction is raised to 0.50, the fast pulsating regime appears at lower freestream velocities, and the over-ventilated and stable cavity regimes expand further, showing that the intermediate regime bands become compressed (fewer instances of Toroidal and Pulsating cavities). These changes are depicted in Figure 11.

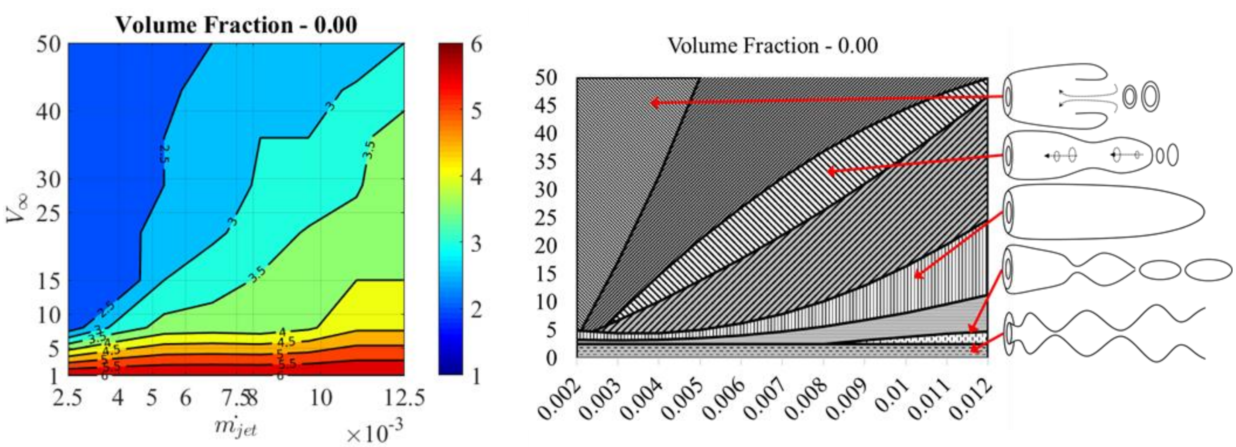


Figure 10: Original regime map (left) and smoothed regime map (right).

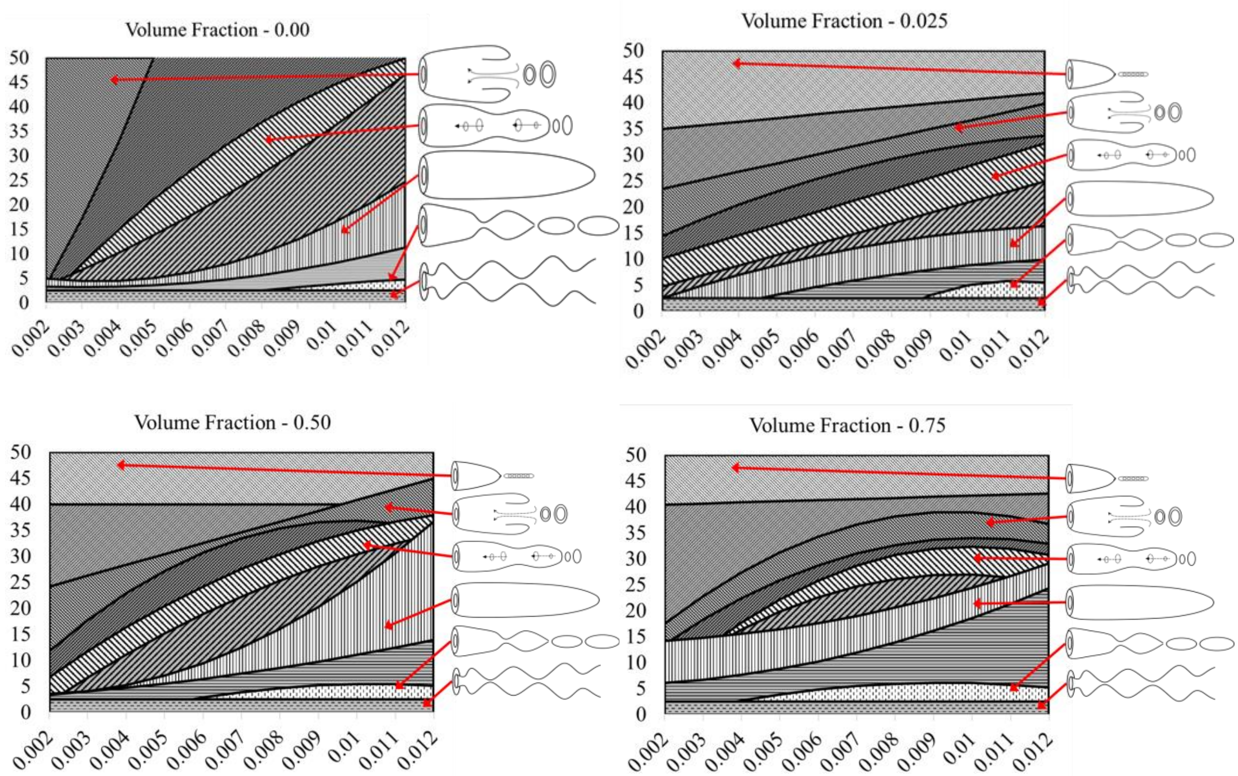


Figure 11: Smoothed regime maps of volume fractions 0.00 (top left) 0.25 (top right), 0.50 (bottom left), and 0.75 (bottom right).

Conclusion

The present simulations evaluated the initial breakup mechanisms for a gas jet vented into a liquid pipe flow with parametric variations in the free-stream gaseous air content, the freestream velocity, and the gaseous mass-flow rate. The overall results indicate a rather complicated regime map that is still presently being evaluated. When the new simulations are compared to an only water co-flow, it is found that an additional regime occurs which seems to dominate when the free stream is high, appearing as the gas content of the freestream is increased. These datasets can be further analyzed to in the hopes of identifying two non-dimensional parameters which can collapse the all of the data to a single map. This can better generalize the dynamics found in high speed multiphase mixing of a gas into a freestream liquid, or a liquid/gas mixture.

References

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