Regime Classification Methods for a Gas Jet in a Liquid Co-Flow

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Abstract
The present effort evaluates various methods to classify flow regimes from computational fluid dynamics (CFD) simulations of various multiphase flows. The present effort specifically aims to understand a gas jetted into a liquid co-flow, with parametric variations of the freestream liquid velocity and jet mass flow rate. Previous CFD indicated several flow regimes occur in this interaction. However, the method of regime classification relied solely on visual inspection of simulation videos, as well as time-averaged solutions. This work compares several methods to classify gas-liquid interactions, and assesses the regime identification capabilities of each method. The methods evaluated are as follows: Proper Orthogonal Decomposition (POD), Fast Fourier Transformation (FFT), and Mixture of Gaussian (MOG) methods. The results indicate that POD may be the most efficient, effective method to classify the flow regime.

Introduction
The classification of multiphase flows can be a complicated process. Specifically, it relies on qualitative evaluations of the flow that are prone to bias. For this reason, we want to develop quantitative methods for flow regimes specifications. With such methods, we anticipate it will help to develop flow-regime maps based on quantitative descriptions as opposed to an opinion-based assignment.

In this effort, we investigate gas jets in a liquid co-flow in a pipe, which is a flow indicated in Figure 1. Such a flow is being examined to understand gas mixing within a liquid co-flow, which is a process that is dominated by the initial cavity formation and its dynamics. Unlike single-phase jets, such multiphase jets are poorly understood. This is, despite, widespread industrial use for gas jets in a quiescent liquid, such as chemical mixing, nuclear reactor maintenance, and underwater cutting [1-3]; difficulties in experimental visualization cause the full jet formations to be understudied. One factor that makes these jets so interesting is that despite the gas jets having high speeds/momentums, they remain weak with respect to the liquid. Such a feature leads to highly dynamic flow phenomena and multiple flow regimes. CFD is employed to better understand these multiphase jets, which have previously been applied, using two-dimensional, axisymmetric simulations to examine submerged multiphase jets. While varying the freestream velocity (V_∞) and the mass flow rate of the gas jet ($\dot{m}_{jet}$), it became clear that five distinct regimes occur. However, classification of these various regimes has only been conducted through visual inspection, using a combination of videos extracted from the simulations and time-averaged images. The combination of these two visual methods resulted in the classification of five regimes for a gas (air) jet submerged in a liquid (water) co-flow. Therefore, the focus of this paper is to investigate various additional tools to aid in the classification of these multiphase jet regimes.

The following work details the findings of three different methods: POD, FFT, and MOG. The three methods will be compared in their ability to differentiate between the flow regimes, as well as ease of use.

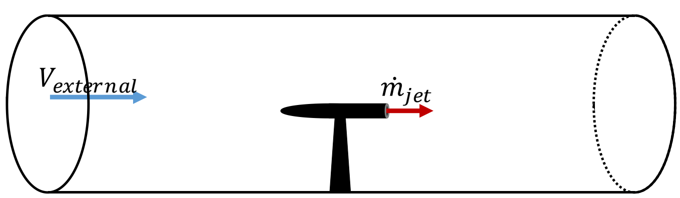

Figure 1: Problem Geometry

Methods
The results discussed in this work focus on different classification methods for multiphase jet flow regimes. The simulations used were conducted using Star-CCM+ [4]. The physics modeling was validated against experimental data from Weiland's PhD dissertation [1], and the validation process is described in the same work which identifies the flow regimes [5,6]. The flow regimes identified in the previous work detail the interactions between the gas jet (using air) and the liquid freestream (using water),a) and are as follows:

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- Shedding Jet: Large bubble ejections; gas is attached to the nozzle
- Toroidal Cavity: Small gaseous cavity; liquid enters cavity in constant stream.
- Pulsating Cavity: Medium gaseous cavity; large interface waves; liquid enters cavity
- Stable Cavity: Large gaseous cavity; little to no liquid enters cavity; small interface waves
- Over-Ventilated Cavity: Small gaseous cavity; large bubble ejections from end of cavity.

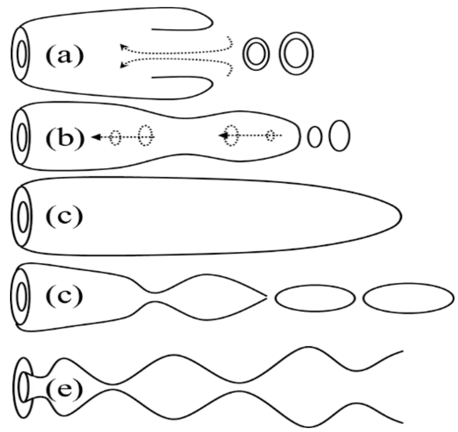

Figure 2: Cartoons of each mode; (a) Toroidal Cavity, (b) Pulsating Cavity, (c) Stable Cavity, (d) Over-Ventilated Cavity, (e) Shedding Jet.

Examples of each of these regimes are shown in Figure 2 (cartoons) and Figure 3 (simulation). The grayscale lines are volume fraction, which outline the gaseous cavity (where regions outside the black are pure liquid and white indicates gas). The color contours are Mach, with dark blue being low Mach, and the brighter blue/cyan colors showing the jet. The top images are of the time-averaged simulation, while the bottom images are a snapshot of the unsteady simulation.

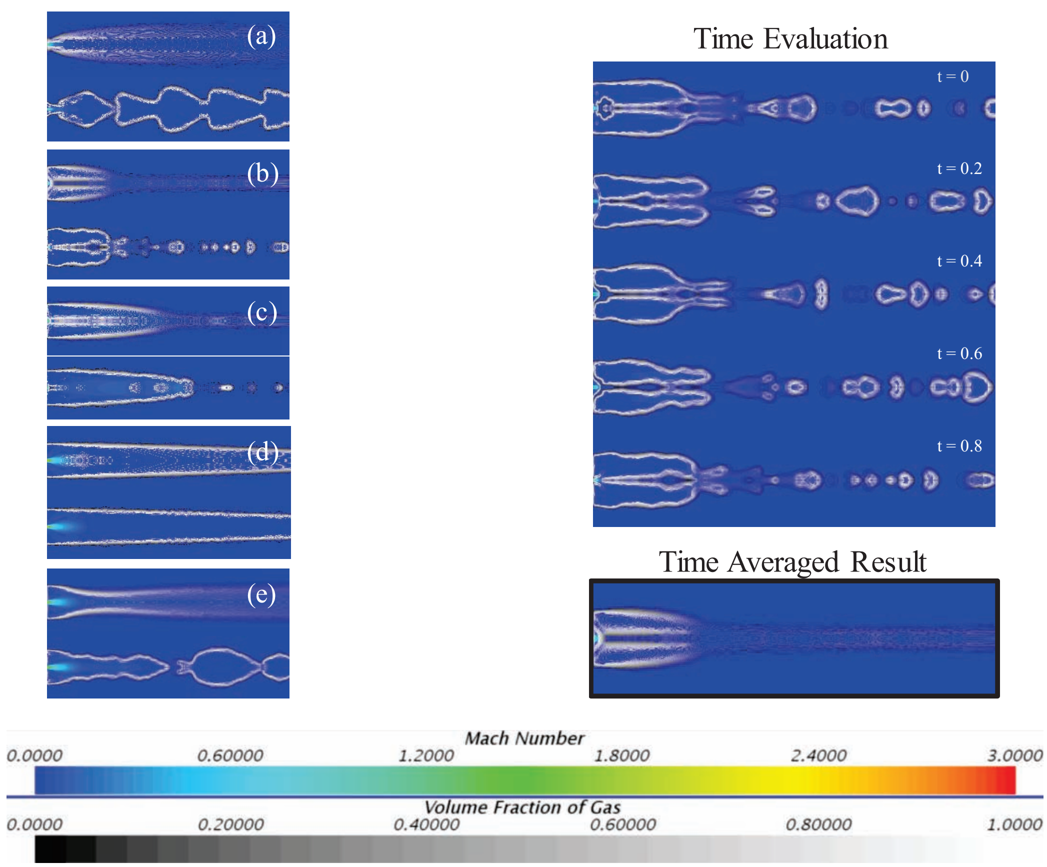

Figure 3: (a) Shedding Jet, (b) Toroidal Cavity, (c) Pulsating Cavity, (d) Stable Cavity, (e) Over-Ventilated Cavity

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

Previously, the regimes were classified through visual inspection, comparing videos created from the unsteady simulations and the time averaged solutions. This provided the insight to pick out the properties described above, and subsequently classify regimes. A sample of this process is provided for a Toroidal Cavity case in Figure 4.

The new methods of regime analysis to be investigated (POD, FFT, and MOG) all require the full simulation data. The POD and FFT methods require a video, or series of snapshots, extracted from the simulation while it was running. MOG can be conducted on mean data collected at the end of the simulation.

The first tool of interest is the use of POD. The POD approach offers several advantages(1) it is statistically based, (2) it has clear analytical foundations for understanding its limitations and capabilities, and (3) it allows for the extraction of spatial and temporal structures from a turbulent field (Berkooz, Holmes, and Lumley) [7]. Applying POD to a set of multiphase jet cases, simulated through CFD, isolates large-scale structures within the regimes, such as waves on the interface. The exact method that will be applied in this paper is a singular value decomposition (SVD). The approach uses a series of images, with a known time delay between images, and computes the spatial eigenmodes, or POD modes. The number of modes is dependent on the number of images input into the code. Each mode has a given amount of energy, with lower number modes being the most energetic, and thus they cause the more pronounced interfacial motion on the jet regimes. The original images can then be reconstructed using a set energy cut off, which allows one to determine the dominant modes and large scale motions in the overall movement. This in turn aids in the identification of regimes based on significant interfacial characteristics. In regards to this method, the input parameters, such as initial image quality and the number of input images, must also be investigated. Using very large or high-quality images can become computationally expensive, with large amounts of computer memory required to process the data. This method provides additional visual information for study in the spatial modes, and the amount of energy required to reconstruct an image provides some quantitative data.

The second method is employing an FFT of the temporal behavior linked to the POD modes. Thus, this FFT data is collected and output within the same code as the POD analysis. This gives the frequency characteristics of the corresponding POD modes from the latter analysis. However, this is highly dependent on the number of images input, as well as their temporal spacing, as the method is incapable of extracting frequency data below the temporal cutoff. However, it is worthwhile to investigate the frequency peaks which correspond to the different spatial POD modes, looking for a method of classification

The final method investigated with respect regime classification is the MOG method [8]. This method takes a histogram of the resulting field within each condition and using the distribution to map to a specific regime. More specifically, the resultant peaks in data (such as internal pressure, volume fraction of gas in a defined region, internal velocity, or turbulent kinetic energy within the system) can then be compared from regime to regime, to see if they have any discerning power in regime classification. These peaks can be statistically analyzed, and the overall system of peaks can be reconstructed using a number of Gaussian peaks. This method has previously been applied to cavitation and supercavitation to identify regions and physical phenomenon, and it will be interesting to apply the method to regime classification.

Results

This section details some of the results of each method, along with a description of the regime discerning power with regards to the original visual method.

POD is similar to the time-averaged solution images, but the coherent structures of the waves are easier to identify. Such a process allows for better discriminatory power of the flow regimes, though it still requires visual inspection and comparison. A case for each regime (classified by the original visual method) is shown below (Figure 5) The bottom half of each image is the 1st spatial eigenmode, which is the mode with the largest energy. The black and white patches distinguish wave formations, giving an idea of frequency and distance over which they occur. The modes have been placed under a slice of the original simulation (converted to black and white to highlight the gas-liquid interface), at a single time step.

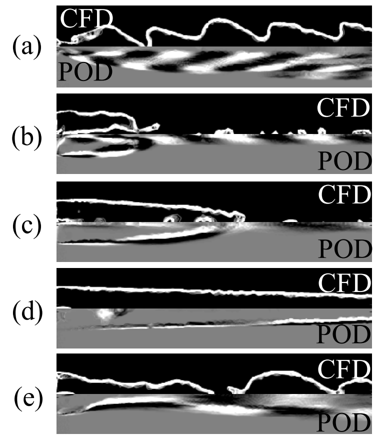

Figure 5: POD of Shedding Jet (a), Toroidal Cavity (b), Pulsating Cavity (c), Stable Cavity (d) and Over-Ventilated Cavity (e)

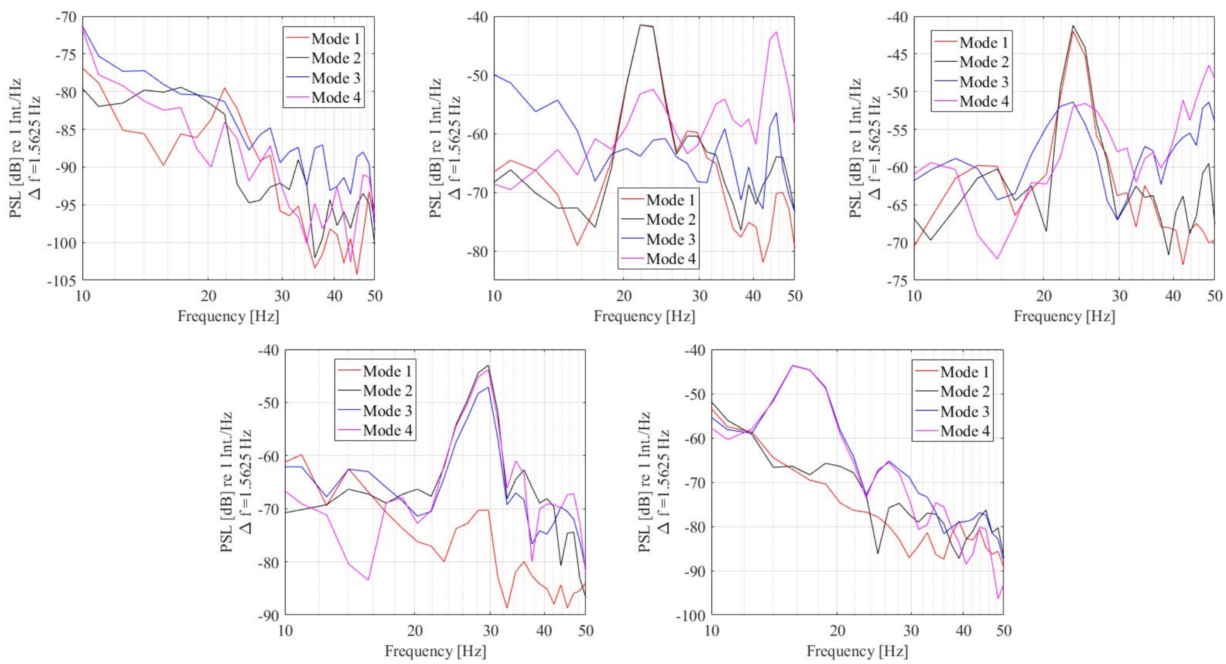

Figure 6: FFT of Shedding Jet (top left), Toroidal Cavity (top middle), Pulsating Cavity (top right), Stable Cavity (bottom left) and Over-Ventilated Cavity (bottom right)

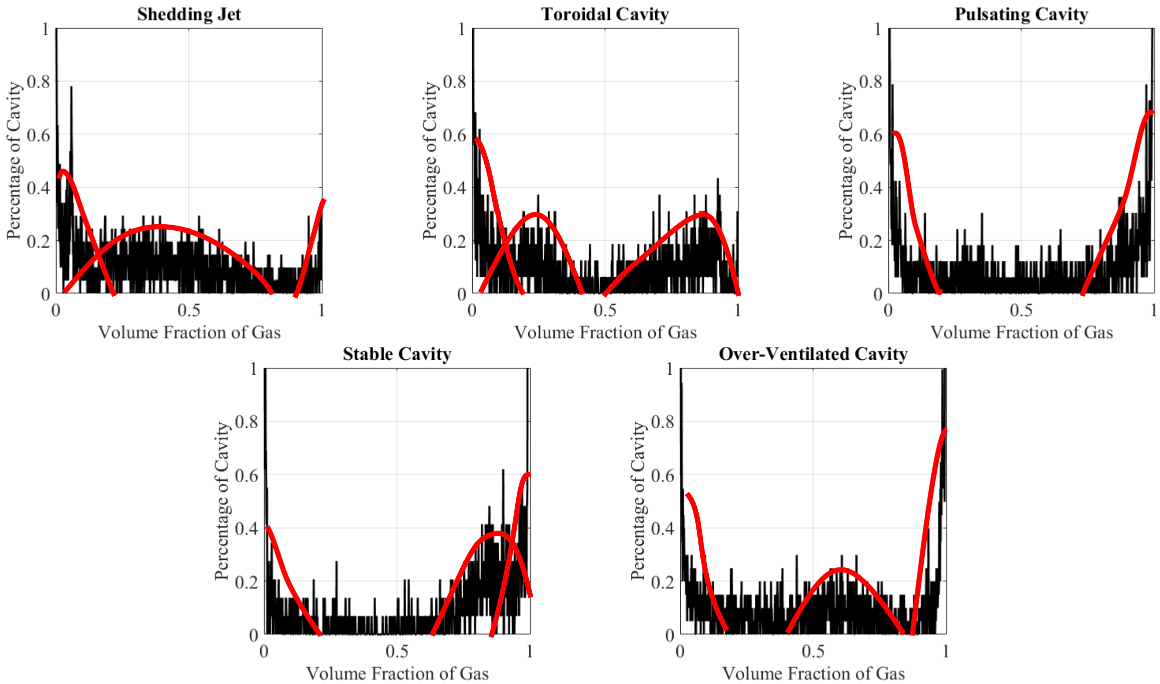

Figure 7: Volume Fraction PDFs of a Shedding Jet (left) and Pulsating Cavity (right)

FFTs are limited by image quality and number of images that can be processed at once, which is overall limited by processing power. The number of images input in these cases limits the overall frequency that can be extracted from the simulations. Due to this, only the lower frequency waves on the gas-liquid interface can be expressed as peaks. This is apparent in the toroidal and pulsating cavities (Figure 6), where the 1^{st} and 2^{nd} modes result in lower frequency peaks. However, there is no discriminatory power, currently limited by computational inputs, for the higher frequency regimes such as the shedding jet, stable cavity, and over-ventilated cavity.

Initial data from the MOG method (currently displayed using thee mean volume fraction of gas as the underlying PDFs) indicates there is some discerning capability to this method. The plots are displayed in Figure 7. Through comparison of plots for multiple cases from each regime, there are several trends that stand out. The shedding jet regime typically has the majority of the cavity at lower volume fractions of gas (0-0.2), and can typically be identified by this trait. Similarly, the stable cavity regime is heavily weighted towards high volume fractions of gas (0.7-1.0). The over-ventilated case has roughly three peaks (towards 0, 1.0, and one in the 0.4-0.8 range). The toroidal and pulsating cavities are the hardest cases to distinguish using this method, both being weighted at the 0 and 1.0 ends of volume fraction of gas. The possible difference may be that the center area (0.4-0.6) of the toroidal cases is very low (less than 0.2%), but more cases may need to be evaluated.

Conclusion

All three methods (POD, FFT, and MOG) still rely on some form of visual inspection. However, POD does provide more information than the original two methods (video and time average images). The ability of FFT to distinguish regimes is highly dependent time step and number of images fed through the process. The MOG method has some discerning ability, though many cases must be compared to classify the unique differences between each regime from the PDF plots. It seems that it is not necessarily peak location/size, but more statistical ranges in the jet's downstream volume fraction of gas. Additional methods of regime classification will still be of assistance in better differentiating intermediate regimes, or regimes that are not easily distinguished from only video and time averaged solutions.

References

[1] Weiland, C. J., 2009, "Characteristics of the high speed gas-liquid interface," Ph.D. thesis, Virginia Tech, Blacksburg

[2] Shi, H., Wang, B., and Dai, Z., 2010, "Research on the mechanics of underwater supersonic gas jets," Sci. China. Ser. G: Phys. Mech. Astron., **53**(3), pp. 527–535.

[3] Shi, H.-H., Guo, Q., Wang, C., Dong, R.-L., Zhang, L.-T., Jia, H.-X., Wang, X.-G., and Wang, B.-Y., 2010, “Oscillation flow induced by underwater supersonic gas jets,” Shock Waves, **20**(4), pp. 347–352.

[4] Siemens, "StarCCM+," 2017.

[5] Fronzeo, Melissa, Michael Kinzel, and Jules Lindau "A Flow Regime Map for Gas Jets in a Bubbly Flow" Proceedings of the 91st Fluid Engineering Division Summer Meeting FEDSM July 2017.

[6] Fronzeo, M. A., 2017, “A Computational Study of Gaseous Jets Submerged in a Liquid Co-Flow”, M.S. thesis, The Pennsylvania State Univeristy, State College

[7] Berkooz, Gal, Philip Holmes, and John L. Lumley. "The proper orthogonal decomposition in the analysis of turbulent flows." *Annual review of fluid mechanics* 25.1 (1993): 539-575.

[7] Esplin, J. J., Kim, B. J., Kinzel, M. P., and Culver, R. L., 2016, “Bulk cavitation extent modeling: An energy-based approach,” J. Acoust. Soc. Am., 140(4), pp. 3121–3121.