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The goal of this research effort has been to perform experiments on and explore the physics associated with a non-reactive, cryogenic, shear coaxial jet interacting with high pressure, high amplitude acoustic waves. These experiments have been conducted in the AFRL cryogenic supercritical laboratory facility at Edwards AFB by a UCLA graduate student Juan Rodriguezas part of his Ph.D. dissertation. The flow configuration, which is similar to that, typically used in cyrogenic liquid rocket systems, allows exploration of the effect of phase and amplitude on chamber acoustic interactions with a shear coaxial jet operating under subcritical, relevance of the observed jet response to phenomena associated with self excitation in liquid rocket combustion instabilities. The effects of magnitude and phase of the acoustic field generated within the chamber on non-reactive coaxial jet dark core lengths and spreading angles have been explored in detail for two alternative injector geometries.

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# FINAL REPORT:
# Shear-Coaxial Jets in a Transverse Acoustic Field at High Pressures

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## Abstract

The goal of this research effort has been to perform experiments on and explore the physics associated with a non-reactive, cryogenic, shear coaxial jet interacting with high pressure, high amplitude acoustic waves. These experiments have been conducted in the AFRL Cryogenic-Supercritical Laboratory facility at Edwards AFB by a UCLA graduate student, Juan Rodriguez, as part of his Ph.D. dissertation[1] research. The studies have been in collaboration with AFRL/RZSA researchers, Drs. Ivett Leyva, Bruce Chehroudi, and Doug Talley. The flow configuration, which is similar to that typically used in cryogenic liquid rocket systems, allows exploration of the effect of phase and amplitude on chamber acoustic interactions with a shear coaxial jet operating under subcritical, critical, and supercritical conditions. It has been of particular interest to understand the relevance of the observed jet response to phenomena associated with self-excitation in liquid rocket combustion instabilities. The effects of magnitude and phase of the acoustic field generated within the chamber on non-reactive coaxial jet dark core lengths and spreading angles have been explored in detail for two alternative injector geometries. Implications for the nature of the coaxial jet under cryogenic conditions in the presence of combustion instabilities, especially with respect to inherent jet instabilities, are also explored and discussed.

## Background and Experimental Configuration

Combustion instabilities in liquid rocket engines (LREs) can have a profound effect on
rocket safety and performance, and the fundamental mechanisms underlying such
instabilities and the means by which they can be controlled
Because supercritical pressures and transcritic
supercritical) temperatures are typically found
fundamental experiments and numerical simul
understand acoustic coupling associated with t
co-workers[2,3,4,5], for example, have explored su
shown that alterations in the behavior of the jet
by acoustic excitation. Since the injectors in L

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effects of acoustic excitation on mixing and transport, which are flow features that are closely related to the reactive phase of the combustion process, of coaxial jets is a relevant topic.

The present study focused on non-reactive coaxial jet behavior in a transverse acoustic field. For these experimental studies, there was only one fluid used to simulate the fuel and oxidizer, nitrogen, $N_2$, which has a critical temperature, $T_{cr}$, of 126.2 K and a critical pressure, $P_{cr}$, of 3.39 MPa. Coaxial nitrogen jets injected into gaseous nitrogen allowed for a clear boundary between the gas, liquid, and supercritical phases of the fluid, avoiding the added complexity introduced when working with mixtures of fluids. Further, having a non-reactive shear coaxial injector flow also allowed the fluid mechanic effects to be isolated from the combustion-related phenomena observed in a reactive combustion chamber. To meet the objective of studying the effects of acoustic forcing in a coaxial jet flow configuration, a transverse acoustic field was generated inside the test chamber. A transverse acoustic field was chosen because transverse acoustic modes lead to more destructive instabilities in LREs than longitudinal ones[6]. Specifically, this work focused on the effects of varying the pressure and velocity perturbations by varying the phase difference between the acoustic sources producing the imposed transverse acoustic field, on the coaxial jet flow.

To accomplish this exposure of the coaxial jet flow to the different conditions found in a transverse acoustic field, two acoustic sources were used in the high pressure chamber. Each source received a signal at the same frequency and very similar amplitude, only varying the phase between the signals to accomplish relative phase differences, or positions of the jet with respect to pressure node and antinode locations. A photograph of the facility is shown in Figure 1 and a schematic of the experiment is shown in Figure 2. The photograph shows the test chamber in the center and the acoustic drivers on each side. The acoustic waves were generated using two piezo-sirens placed at each end of the chamber, custom-designed for the Air Force Research Laboratory by Hersh Acoustical Engineering, Inc.

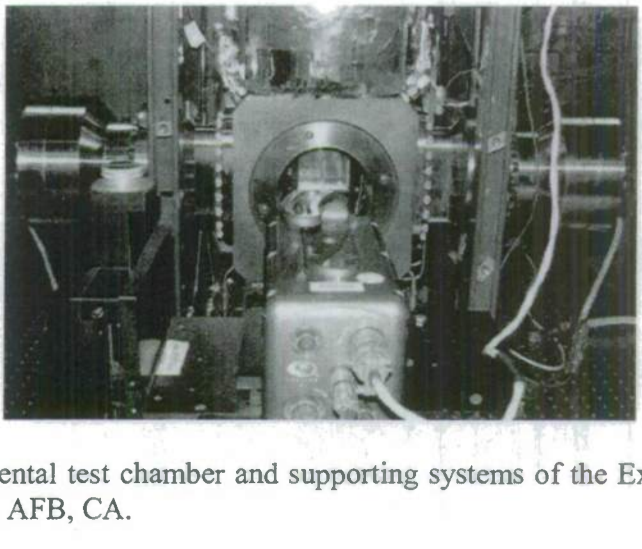

Figure 1. Experimental test chamber and supporting systems of the Experimental Cell 4 at AFRL, Edwards AFB, CA.

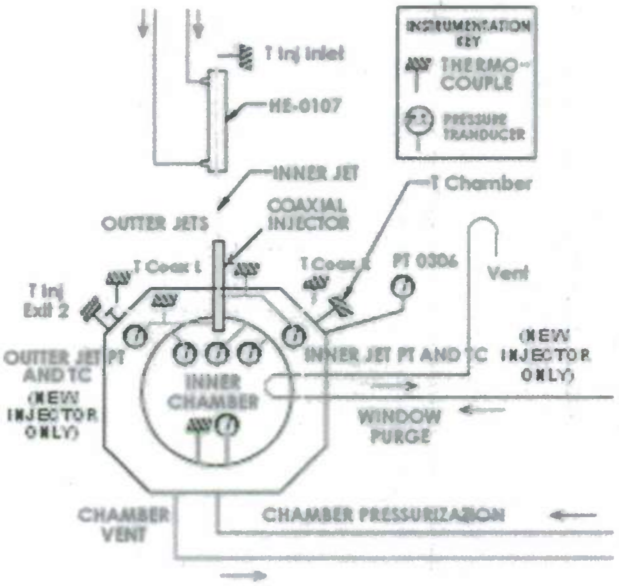

Figure 2. Chamber section view of the flow schematic for Experimental Cell 4 with the upgrades for the new coaxial injector.

An image of the first or "original" coaxial injector used in the majority of these studies is shown in Figure 3a. This injector has a thick inner jet post with a small inner diameter, resulting in a relatively low mass flux. The second or "new" coaxial injector used in these studies is shown in Figure 3b. This injector has a thin inner jet post with a larger inner diameter, resulting in a relatively large mass flux. Unlike the thin post, the thicker post was postulated to delay the formation of a shear layer across the contact between the inner and outer jets, forming instead a recirculation zone with a wake-like region, and thus affecting the mixing between the inner and outer jets. This postulation was found to be correct in the experimental studies, and paves the way for future experiments.

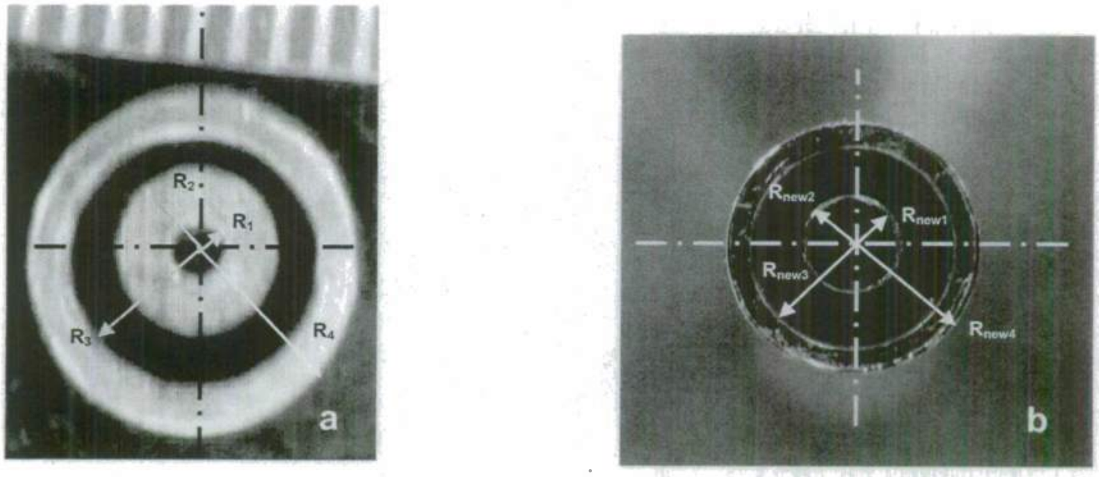

Figure 3 Exit plane views of (a) first ("original") coaxial injector and (b) second coaxial injector used in this study.

## Results

Extensive sets of experimental results for the behavior of the coaxial nitrogen jet during exposure to high pressure acoustic excitation under subcritical, near-critical, and supercritical conditions are documented in the Ph.D. dissertation of Juan Rodriguez[1]. Limited results will be provided here.

The visualization method for the experiments performed for this work consisted of backlit images obtained with a high speed camera. Since the coaxial jet was located between the lens of the camera and the lamp, the denser regions of the inner jet were able to obstruct or deflect the incoming light the most. These denser regions produced dark areas which represented the flow from the inner jet, or the "core" of the coaxial flow. For this study, the dark core is defined as the continuous dark area starting at the exit of the injector and its length was defined as an average of a predetermined number of images obtained with the high speed camera. In this work, the mean dark core length for each particular condition consisted of an average of 998 images. To measure the inner jet spreading angles for a given condition, these same 998 images were again employed, then using the process for quantifying the dark core length, the locations of the left and right core contours were recorded for each image and then averaged. The gaseous outer jet spreading angle was defined to start from the point where the jet started to grow, and to end at a location $10D_1$ downstream of the exit of the injector. A similar procedure was used to measure the outer jet spreading angle. Results were obtained for a range of values of J, the outer jet to inner jet momentum flux ratio.

### *Coaxial Jets in the Absence of Acoustic Excitation*

The images in Figure 4 were obtained for the original jet configuration at subcritical pressures for a range of momentum flux ratios (J) and in the absence of applied acoustic disturbances. These images indicate a significant reduction in the dark core length with increasing J values, suggesting significant increases in mixing with an increase in the momentum mismatch between the inner and outer jets. Similar observations were made for the supercritical jet (shown in Figure 5), although the significant reduction in dark core length was observed at lower values of J than for the subcritical jet. In subcritical jets, surface tension in the liquid prevented the molecules from drifting towards the gaseous outer jet fluid, making the boundary between both phases sharper, thus preventing significant jet mixing. That is a possible explanation for the fact that higher momentum fluxes are needed by the subcritical jet to reach the same dark core lengths and jet spreading angles as in supercritical (and near-critical) conditions. A sample set of results for the differences in dark core length for sub-, near-, and supercritical jets as a function of momentum flux ratio is shown in Figure 6. Consistent with the images, the subcritical jet dark core length is considerably longer than either of the other jets for J values about around 2. These observations have implications for the effects of external acoustic excitation as well.

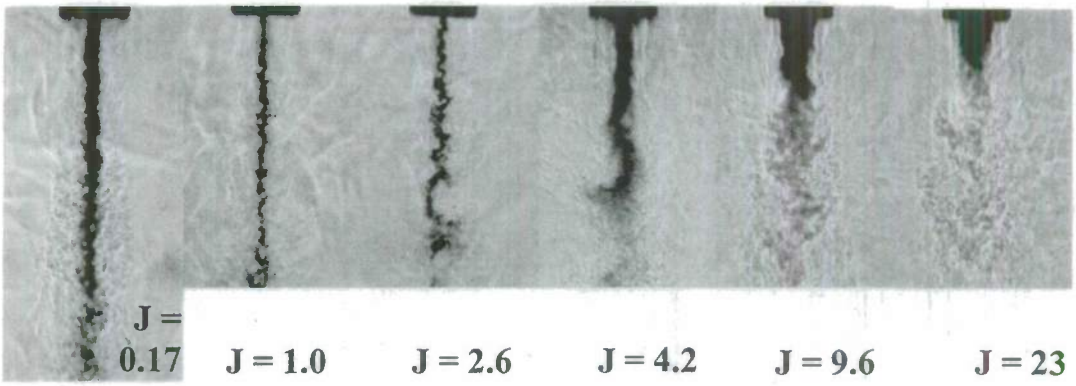

Figure 4. Collection of coaxial jet images without acoustic forcing at subcritical pressure from lowest to highest J. Original injector geometry.

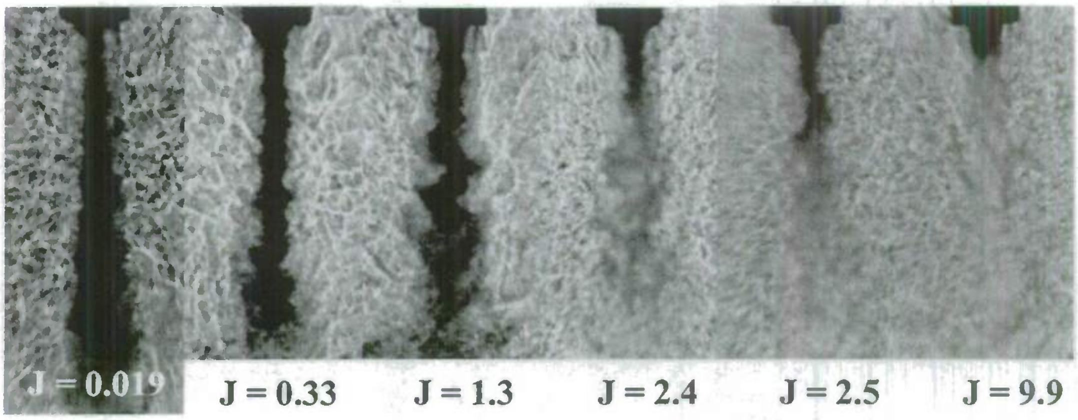

Figure 5. Collection of coaxial jet images without acoustic forcing at supercritical pressure from lowest to highest J. Original injector geometry.

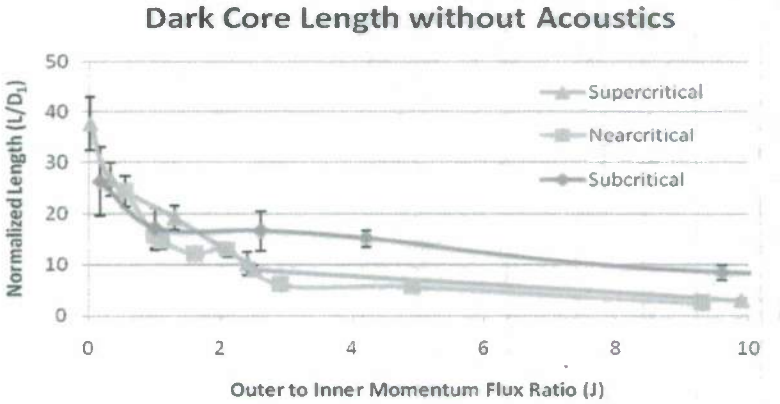

Figure 6. Dark core length normalized by the inner jet post inner diameter, $L/D_1$ for all pressure regimes using the original injector geometry in the absence of acoustic excitation. Results are shown in the $0.02 < J < 10$ range.

### *Coaxial Jets in the Presence of Acoustic Excitation*

In the presence of acoustic excitation, the coaxial jets displayed different types of responses, depending on the injection conditions (J values and sub-, near-, and supercritical injection). For example, when the "baseline" jet behavior in the absence of acoustic excitation suggested a longer dark core length and a lesser degree of mixing, acoustic excitation tended to produce significant jet distortion, increased mixing, and a reduction in the overall jet length. An example of this behavior for the subcritical jet at a moderate value of J is shown in Figure 7. The jet under these conditions responded significantly to such excitation, with specially enhanced mixing in the regime where the phase angle between the speakers lay between 45 and 215 degrees. In contrast, when the unforced coaxial jet was already well mixed due to the significant mis-match in momentum fluxes between inner and outer jets, as for the supercritical condition at a high value of J (shown in Figure 8), there was no substantial alteration of jet structure nor dark core length with acoustic excitation. These observations were similar to those for near-critical jets at relatively high values of J (above about 6). But even at very high values of J for the subcritical jet, there was an observed change in the jet structure, dark core length, and jet spread.

A quantification of changes in the average dark core length of the jets due to acoustic excitation, for all conditions explored and for a range of momentum flux ratios, is shown by the solid lines in Figure 9, for example. While there was virtually no change in dark core length for either near- or supercritical jets at J > 10, there were still changes taking place for the subcritical jet at J = 23.

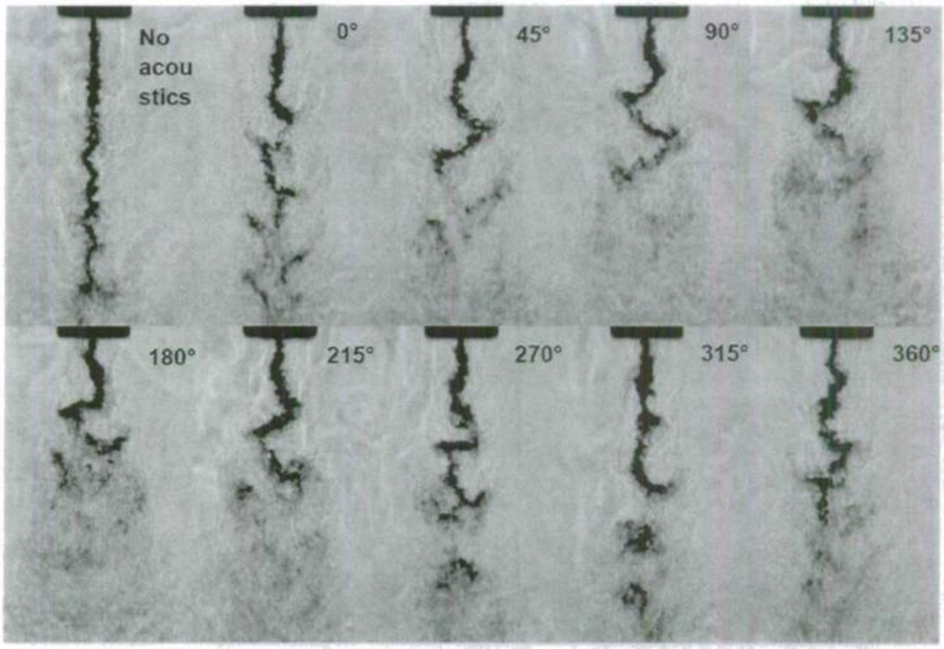

Figure 7. Collection of subcritical coaxial jet images at different phase angles of excitation with $P_{chamber}$ = 1.45 MPa, J = 2.6. Original injector geometry.

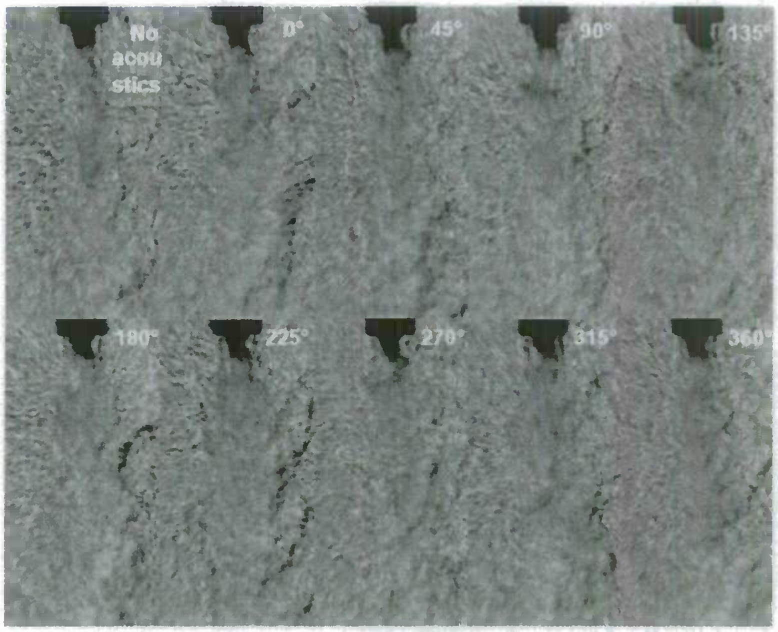

Figure 8. Collection of supercritical coaxial jet images at $P_{chamber} = 4.96$ MPa, J = 9.9. Original injector geometry.

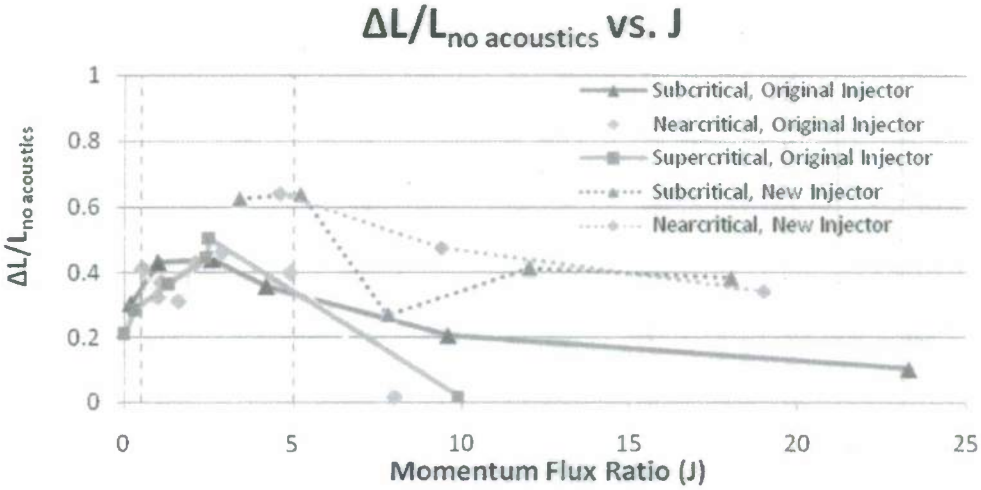

Figure 9. Comparison of the maximum dark core length reduction as a function of momentum flux ratio between the original injector geometry and the new injector geometry.

All of the images shown above pertain to the "original" injector with the relatively thick lip separating inner and outer jets (Figure 3a). Rodriguez' dissertation[1] also contains numerous datasets for the new injector configuration as well (Figure 3b). Relevant changes in the dark core length for sub- and near-critical coaxial jets with this new configuration, at different values of J, are shown by the dashed lines in Figure 9. The thinner lip between the jets and the lack of a recirculation zone separating the jets appeared to diminish the degree of jet mixing at higher momentum flux ratios, thus increasing the influence of acoustic excitation at these higher J values (in contrast to the same conditions for the original injector).

### *Conclusions and Implications for Future Research*

The extensive sets of experiments in these studies clearly quantified the influence of strong acoustic excitation on coaxial jets under sub-, near-, and supercritical conditions and for a range of momentum flux ratios. The unusual behavior whereby the jets responded to excitation under certain operating conditions and not at all under other conditions is quite intriguing. The fact that the coaxial jets were already well mixed under certain operating conditions and did not respond to external excitation is actually consistent with the jets' being globally unstable, where a disturbance at the jet's initiation is propagated to the entire flowfield and creates a large-scale disturbance, rather than having the disturbance evolve in space along the jet flow after initiation (which is known as convective instability).

While it has not been conclusively proven, the data for both injectors suggest that the coaxial jet can be made absolutely unstable, and hence unresponsive to moderate to high levels of excitation, at relatively high momentum flux ratios. If this is indeed the case, the findings have important implications for combustion instabilities in LREs. If injection conditions are employed whereby the fuel-oxidizer mixing is already enhanced in the absence of combustion instabilities, the presence of acoustic disturbances may not have an influence on the mixing (and potentially, the reaction) process. Future studies of this phenomenon, with additional injector geometries and, more importantly, in the presence of a reactive environment, will elucidate these mechanisms.

## References

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[1] Rodriguez, J. I., "Acoustic Excitation of Liquid Fuel Droplets and Coaxial Jets", Ph.D. dissertation, UCLA Department of Mechanical and Aerospace Engineering, June, 2009.
[2] Davis, D. W. and Chehroudi, B., "The Effects of Pressure and Acoustic Field on a Cryogenic Coaxial Jet," *42nd AIAA Aerospace Sciences Meeting & Exhibit*, 5-8 Jan. 2004.
[3] Chehroudi, B., Talley, D. G., and Coy, E. B., "Fractal Geometry and Growth Rate Changes of Cryogenic Jets near the Critical Point," *35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, AIAA, Washington, DC, 20-24 Jun. 1999.
[4] Chehroudi, B., Cohn, R., and Talley, D. G., "Cryogenic Shear Layers: Experiments and Initial Growth Rates of Round Cryogenic Jets at Subcritical and Supercritical Pressures," **International Journal of Heat and Fluid Flow**, Vol. 23, 2002, pp. 554-563.
[5] Davis, D. W. and Chehroudi, B., "Measurements in an Acoustically Driven Coaxial Jet under Sub-, Near-, and Supercritical Conditions", **Journal of Propulsion and Power**, Vol. 23, No. 2, 2007, pp. 364-374.
[6] Sutton, G. P., **Rocket Propulsion Elements**, 6th Ed., John Wiley & Sons, Inc., New York, 1992.