I NVESTIGATION OF DROPLET COUPLING IN A THERMOACOUSTIC INSTABILITY

Researcher: Yogesh Aradhey, *Virginia Polytechnic Institute and State University*

Primary Investigator: Dr. Joseph Meadows, Virginia Polytechnic Institute and State University

Abstract:

Lean combustion has proven to be a promising technology for next generation gas turbine engines in terms of efficiency, performance and compliance with target emission standards. Lean direct injection (LDI) is a liquid fuel lean premix injector that has been proposed specifically for commercial aviation vehicles. While there are several challenges that prevent LDI from being implemented in a production system, one formidable challenge is the rampant occurrence of thermoacoustic instabilities. The present investigation extended nonreacting acoustic-spray interaction work to a reacting, self-excited instability. By taking droplet diameter measurements, acoustic pressure measurements and OH* intensity images, the relation between the effects are discussed using a phase averaging algorithm. It is found that droplet diameter couple with the instability which has implications for reduced order modeling of instabilities.

Introduction:

Lean direct injection (LDI) is a fuel-air mixer proposed by NASA for aviation gas turbine engines. LDI was designed for engines that will be required to meet ever more stringent emissions requirements in the future[1-4]. It has several features making it appealing to the aviation industry such a short mixing length to prevent flashback, and compact design which is critical on aircraft. With renewed interest in supersonics transports, engine designers will be faced with great challenges in developing engines that are powerful enough to propel a vehicle at supersonic speeds while still being compliant with environmental regulations.

LDI can be operated in a technically premixed configuration, permitting the full advantages of lean combustion, and while LDI has been shown to reduce emissions beyond the government's targets over the next few decades, there are significant challenges involved in integrating LDI into a production engine[2]. One severe challenge is thermoacoustic instabilities[5, 6].

Thermoacoustic instabilities occur when acoustic pressure fluctuations in a combustor couple with the combustion heat release rate, further driving up the pressure amplitude. The positive feedback loop can lead to extremely high-pressure fluctuations in the burner and can cause failure of engine components. Even if the engine is able to withstand the pressure, the cyclic loading imparted on an engine from operating in an instability reduces the longevity of the device significantly.

All steady-flow combustion devices face thermoacoustic instabilities to some degree, but lean combustion system inherently have much less damping, causing instability to be much more prevalent. In order to design lean combustion systems that avoid thermoacoustic instabilities, a thorough understanding of instabilities is required.

At the current state of technology, there is relatively little physics-based methods to predict instabilities. While the general causes of instabilities are well-recognized, there is no practical method for instability prediction available to the designer on an arbitrary geometry[7]. Instead, industry relies on experimental results from operational engines, and empirically informed reduced order methods of very narrow applicability.

While ground based gas turbine engines have been running on lean premixed burners for several decades, aviation engines require a higher degree of reliability and safety then their ground-based counterparts. Further, they cannot be designed to be heavier and stronger in order to cope with additional loading. Aviation engines also demand liquid fuels, further increased the complexity of instability prediction. Due to these challenges, there are no aviation engines running premixed burners.

Objectives:

The present study is a contemporary effort to better understand the detailed physics of a thermoacoustic instability. Literature on liquid fuel instabilities is limited due to the complex interactions between fuel droplets, turbulent flow, acoustic waves and chemical reactions. While computational tools exist to model each phenomenon separately, we lack the computational power to simulate the coupling between these in a realistic geometry at a relevant Reynolds number.

The present study uses advanced optical diagnostics to investigate the physics of coupling in the instability with the fuel droplet. Fuel droplet coupling has implications for thermoacoustic modeling because fuel droplets drive the heat release rate, which is a coupling mechanism, for instabilities[8]. The present study seeks to understand the dynamics of the heat release, acoustic waves, and droplet.

It is well known that the relative velocity between the droplet and the flow drive the evaporation (and burning) rate of the droplet[9, 10]. Considering that an acoustic wave brings a fluctuating velocity component reveals that there is likely a direct coupling between the acoustic velocity and the droplet heat release rate[9, 11, 12]. It has previously been shown that droplet evaporation and burning rate can be modified significantly by an acoustic field, but this set of experiments is the first data taken in a fully self-excited flow field, or in a swirl stabilized combustor with realistic, aviation fuels. The hypothesis motivating this investigation is that droplet dynamics may serve as a feedback path for instabilities, and is represented schematically in Figure 1.

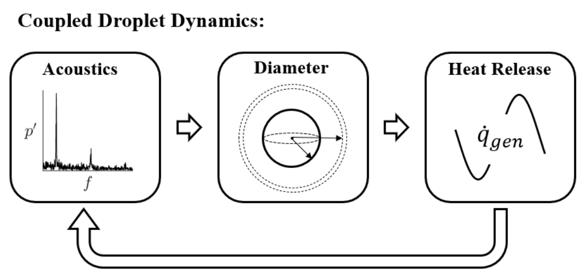

Figure 1: The coupling between acoustic waves, droplet size and heat release provides a potential feedback path for an instability to grow.

Experimental setup:

The experiments were performed on a single point LDI element at a realistic flow velocity. The rig is seen in Figure 1. The rig operates at atmospheric pressure with ambient temperature inlet conditions. Liquid kerosene

(Jet A) is delivered through a hollow cone pressure atomizing nozzle and a square cross sectioned flame tube made of quartz glass provided optical access.

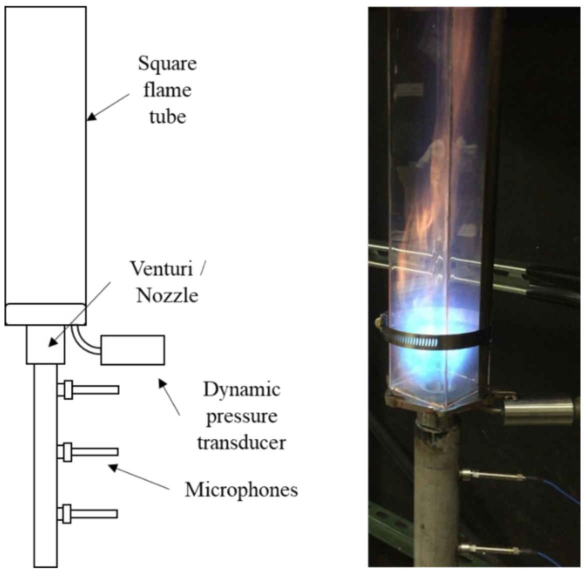

Figure 2: Schematic and image of the experimental facility.

Phase Doppler Particle Analyzer (PDPA) measurements were taken of the droplets at several locations in the flow. PDPA uses two laser beams to take droplet diameter and velocity measurements non-intrusively. The optical setup was optimized based on the refractive index of Jet A.

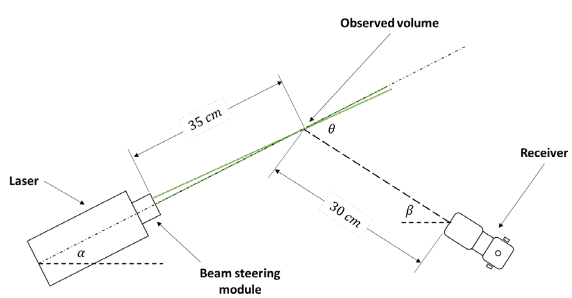

Figure 3: Optical layout of a PDPA system.

A timing signal allows accurate time stamps to be places on each droplet measurement. To characterize the acoustic field, a high sample rate dynamic pressure transducer (DPT) was installed on the dump plane to measure the acoustic pressure in the burner. Samples were taken at 100 kilo-samples per second, and the acoustic data acquisition was synchronized with the PDPA measurements.

<u>Results:</u>

The instability was presumed to be the first longitudinal mode of the combustor. While the instability frequency was approximately constant once the rig reached a quasi-steady state, some fluctuations around the mean were noticed as seen in Figure 4. The distribution appears to be roughly normally distributed.

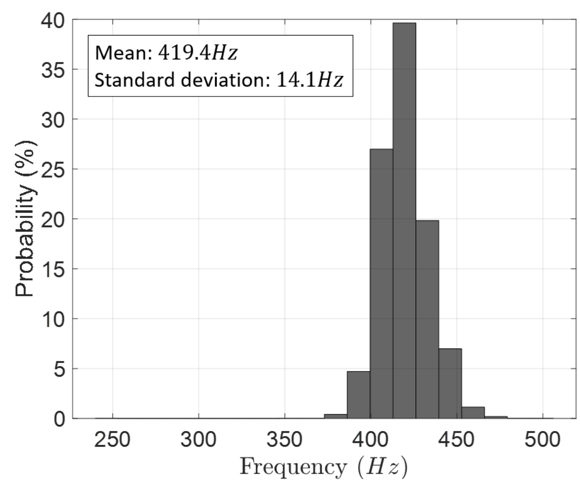

Figure 4: The distribution of instability frequency during a single run show that the instability frequency fluctuated at the quasi-steady state.

Time average droplet diameter taken during the instability are shown in Figure 4. The Sauter mean diameter (SMD) of the distribution was 15.4 μm.

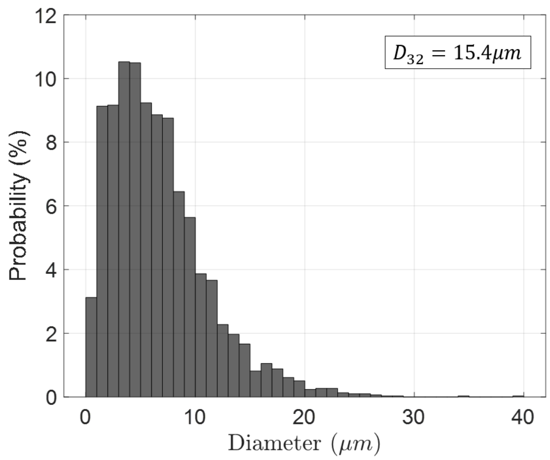

Figure 5: The droplet distribution collected by the PDPA showed a typical distribution for a pressure atomizing nozzle.

Given the acoustic pressure and the PDPA data, a phase locking algorithm was used to phase average the droplet diameters. A MATALB code was used to identify the peaks and troughs of the acoustic signal. Due to shifts in the instability frequency, each period was not exactly the same length, but it was split into the same number of bins. Figure 6 shows the algorithm being used to reconstruct the pressure signal.

The phase locking procedure was then used to exclusively average the droplets that were measured during a particular phase. The acoustic period was discretized into ten bins for this procedure. Once the diameters were sorted into the bin during which they were collected, the diameters were averaged.

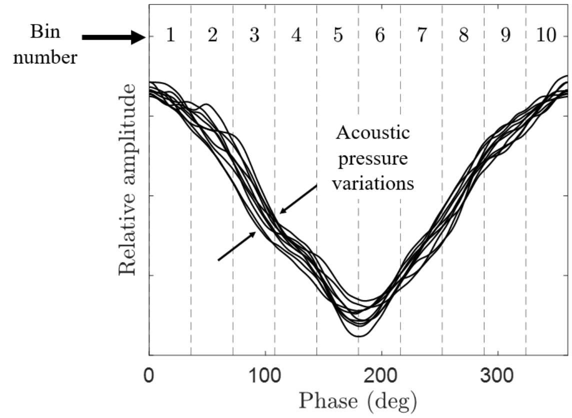

Figure 6: Sample reconstruction of the acoustic wave using the phase locking algorithm.

When the diameters were phase locked, there was a clear coupling between the instability and the diameters and seen in Figure 7. The magnitude of fluctuation is a significant fraction of the mean value. The phase difference between the two signals was found to be 72°, which, interestingly, is comparable to non-reacting spray literature[13].

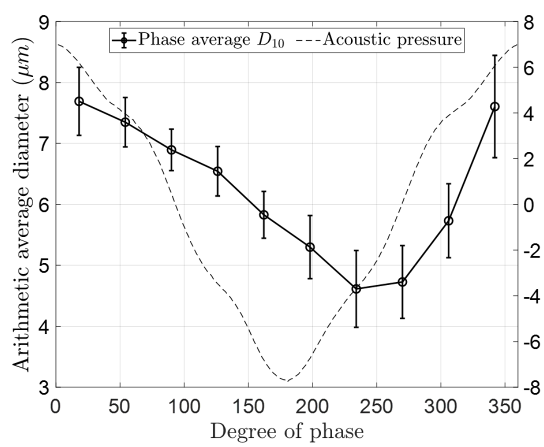

Figure 7: Phase locked droplet diameters show a clear and significant coupling.

In addition to PDPA measurement, OH* intensity was phase locked with the acoustic wave. OH* is a frequency of light that is known to be produced in regions of high heat release, near the fame front. A small region of the OH* images surrounding the PDPA measurement location was isolated, and the OH* intensity was, unsurprisingly, cyclic in nature. While the oscillations of the intensity are not very insightful, the phase of these oscillations in comparison to the density of droplets is more interesting. As seen in Figure 8, there is an inverse relation between the OH* emission and the number of data points collected in a given bin. This relationship indicates that the flame-spray response is also a possible contributor to the diameter coupling or that the flame is moving locations and evaporating the droplet, thus reducing their size.

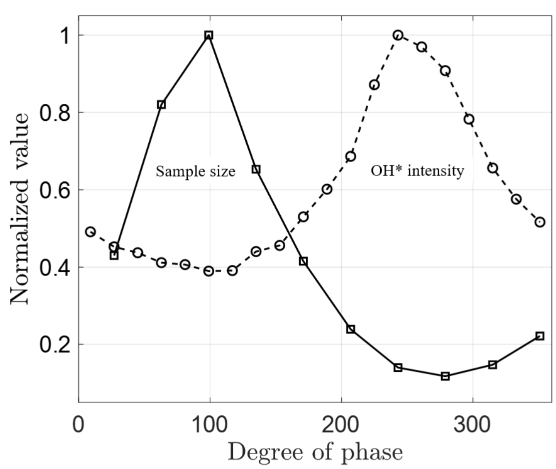

Figure 8: Sample size was found to be out of phase with the OH intensity.*

Additional experiment will be needed to separate the effects of the flame-spray interaction and the acoustic-spray interaction as the two are tightly coupled.

The dynamics observed are significant since reduced order models must account for these phenomenon. Further, CFD models that are used to simulate thermoacoustic instabilities may be improved if the droplet breakup and evaporation models are tuned in order to resolve droplet fluctuations.

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