INVESTIGATION OF LEAN DIRECT INJECTION UNDER THERMOACOUSTIC INSTABILITY

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Abstract:

Lean Direct Injection (LDI) is a combustion scheme proposed by NASA to reduce NOx emissions in aerospace gas turbine engines. LDI is susceptible to thermoacoustic instabilities. It is widely known that droplet diameters have an impact on heat release in a spray combustion system such as LDI. Additionally, it is known that acoustic waves have an impact on spray atomization and break-up. The present study shows that during a thermoacoustic instability, droplet diameters couple with the frequency of instability by taking Phase Doppler Particle Analyzer (PDPA) measurements at several locations in the flow of an atmospheric pressure LDI rig.

Motivations:

Modern aircraft engines operate on diffusion-based combustion. Fuel is sprayed directly into the incoming air, and the reactants burn as they mix. Another type of combustor can be designed such that the fuel and air mixes thoroughly before combustion. Such combustors, known as "lean premixed" combustors have been shown to significantly reduce emissions, and run more efficiently than diffusion burners[1-4]. While premixed combustion is already prevalent in gaseous fueled ground-based gas turbine application, it is not yet, common in aviation engines. One of the reasons for this, is that lean premixed engines are more susceptible to thermoacoustic instabilities [5, 6]. A thermoacoustics instability is a combustion instability where unsteady flame fluctuations couple with an acoustic mode of the combustor which causes pressure fluctuations to grow to violent amplitudes, potentially damaging hardware, and reducing service life. Thermoacoustic instabilities occur when the phase of unsteady heat release coincides with that of pressure fluctuations, and when coupling occurs, the pressure fluctuations grow until a limit cycle is reached[7]. Instabilities occur in a complex environment, where unsteady combustion, turbulence, chemical kinetics, and acoustics all play significant rolls. Accurate modeling of such an environment is too computationally demanding to be practical[8], and the high temperature environment makes detailed flow measurements more challenging.

Lean Direct Injection (LDI) is a lean premixed combustion scheme proposed by NASA which targets the aerospace gas turbine industry[9-14]. Several features of LDI make it appealing to the aero industry such as a short mixing length to reduce the risk of flashback. While LDI has shown NOx reductions up to 70%, the combustors face the same challenges as any other lean premixed system; they are prone to instabilities[13].

The purpose of this investigation is to help build a fundamental understanding of the interaction between the instability and the LDI fuel / air mixer. Spray dynamics are known to be an important parameter in liquid fuel combustion, and typically, spray combustion is evaporation limited[15], thus it is natural to investigate the droplet dynamics of an injector to help understand the nature of the heat release during the instability.

Previous work in the literature has focused on the time averaged droplet characteristics[16-18]. Spray measurements have been taken in a combustor during stable and unstable operation, and while this approach proves that once a combustion instability has manifested, the fuel spray is altered, the time averaging inherently removes any temporal response characteristics which may help explain how the instability was formed to begin with.

It is well known that acoustics also directly impact nozzle sprays and atomization, especially though secondary break up, and even moderate SPL waves can alter LDI spray dynamics[18]. In a combustion environment, assuming the system is evaporation limited, increased atomization will clearly lead to increased heat release. During a combustion process, some of the acoustic waves are propagating at a burner resonance frequency, and since incident acoustic waves on a spray may cause periodic fluctuations in heat release rates, this interaction may provide a feedback path for a combustion instability to occur. The hypothesis to be tested in the present study is that during a thermoacoustic instability, droplet dynamics will couple with the frequency of the combustion instability.

Experimental Setup:

The experimental rig that was designed for this investigation operates at atmospheric pressure conditions. Optical access for the PDPA was accomplished by using a single piece clear fused quartz flame tube. The flat windows provide easy optical access at the expense of a truly axisymmetric flow field. The rig is fueled on low-volatility liquid-hydrocarbon fuel such as kerosene.

A Swirl Venturi - LDI (SV-LDI) combustor was designed based on the original NASA geometry provided by Tacina[10]. The geometry was scaled to maintain velocity through the swirler at a relevant test condition.

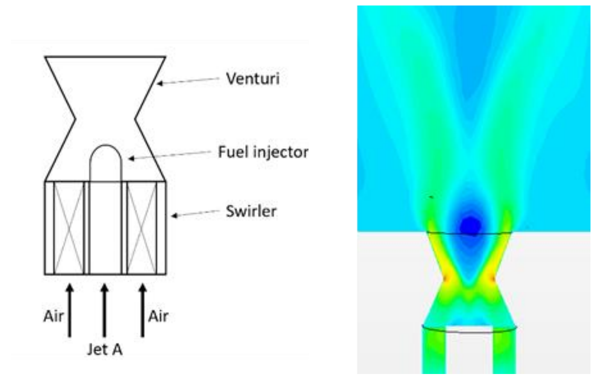

Figure 1: (Left) The sketch of the LDI injector illustrates key components of the system such as short mixing length. (Right) The axial velocity contour shows the recirculation region anchored to the outlet. This recirculation zone provides the rapid fuel / air mixing which is desirable in lean combustion systems.

A schematic of the LDI injector shows the three distinct parts: The fuel / air swirler, the fuel injector and the nozzle. The recirculation which can be seen situated at the venturi exit is one of the important features of LDI which promotes rapid fuel / air mixing (at the cost of combustor pressure).

A square shaped flame tube made from clear, fused silica quartz glass allows clear line of sight for optical diagnostics. The internal side length of the flame tube is about 62mm.

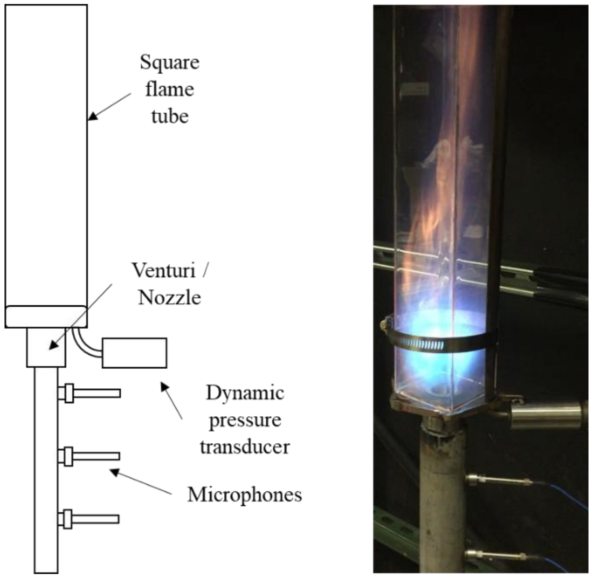

Figure 2: LDI Combustion rig running in a stable mode of operation.

Sound Pressure Levels (SPL's) up to 166dB ($20\mu Pa$ reference) have been observed which is equivalent to 3.9% of the combustor static pressure.

Test logic:

Combustor operability limits were defined in order to select test conditions. The goal of combustor mapping was to identify robustly stable and unstable operating locations for the respective PDPA measurements. For the purposes of this study, dump plane acoustic intensities below 140dB (at the frequency of instability) were considered stable while intensities above 152dB (at the frequency of instability) were considered unstable. All combustion instabilities observed seem to have coupled with the first longitudinal (1L) mode of the burner at a frequency of approximately 400Hz. The conditions at which data is presented are as follows.

Table 1: Test conditions used in the procedure.

Condition:	Air flow rate (SLPM):	ER:	400Hz Sound Pressure Level (dB):
Stable	400	0.9 - 1.0	139
Unstable	500	1.0 - 1.05	157

ER's presented are approximate, but the instability was not sensitive to ER. Fuel nozzle delivery pressure was changed in order to meet the fueling needs for each condition, and the manufacturer flow curve indicates and expected change in SMD was about $3\mu m$ smaller for the unstable case than the stable case. Still, it should be noted that some change is spray between the cases may be attributed to the change in air and fuel flow rate, and not to the presence of an instability.

Future work will aim to conduct these experiments at exactly the same air flow rate and ER, but the present study is conducted with the operability parameters presented. Thermoacoustic instabilities are highly sensitive to geometry and are also affected by wall heat transfer, and, while beyond the scope of the current project, small geometric changes such as flame tube length could be used to allow stable operation at the conditions that cause an instability in the current configuration.

A total of 35 axial and radial locations were chosen for PDPA measurement with an axial spacing of 6.5mm and a radial spacing of 5.5mm as seen in Figure 3. The right-most measurement location was limited to about 4mm.

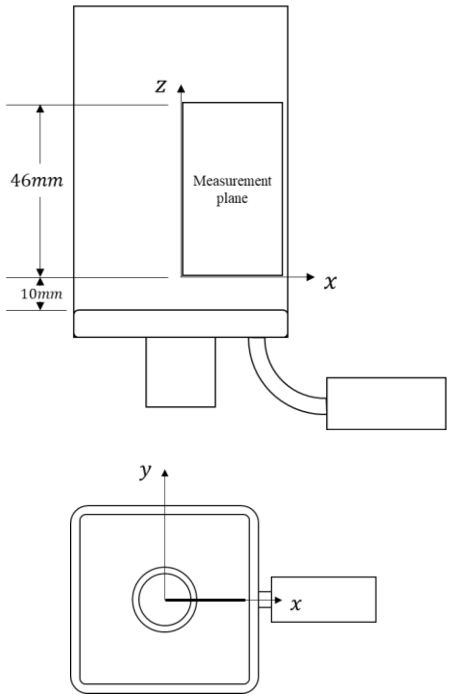

Figure 3: Schematic of the measurement locations. A total of 35 points were targeted.

<u>Results:</u>

<u>Time averaged results:</u>

The plot of time averaged data (Figure 5) suggests that the instability had an impact on Sauter Mean Diameter (SMD). All but two points showed a statistically relevant change in SMD based on a 95% confidence interval of random uncertainty. The effect of the instability on the droplet size was spatially varying in the sense that it caused droplets in some regions to grow and others to shrink. In general, droplets in the corner recirculation tended to be bigger during the instability. The instability most notably increased the standard deviation of the spatial SMD distribution from $7.6\mu m$ to $23.3\mu m$.

The frequency of instability was confirmed to be 400 Hz by plotting the FFT of the dynamic pressure transducer signal. Figure 4 shows that during unstable operation there is significant pressure fluctuations in the burner, presumably the 1L mode.

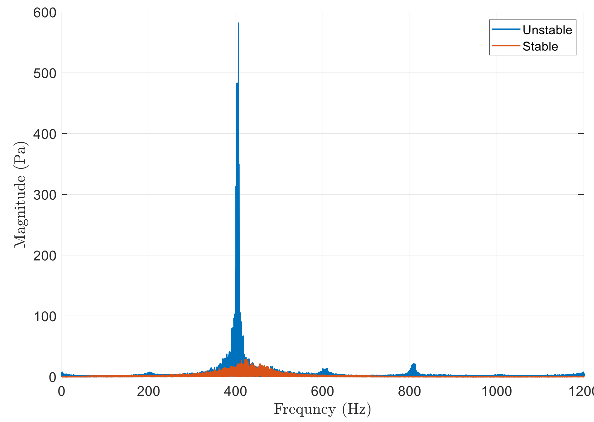

Figure 4: FFT of the dynamic pressure transducer signal in the combustor during the instability in comparison to a stable case. While some 400 Hz excitation was observed, it was far less than during stable operation.

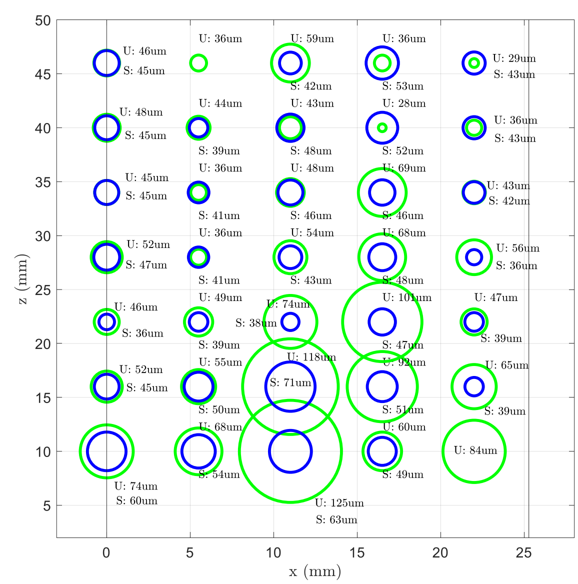

Figure 5: Spatial distribution of SMD. Blue markers correspond to stable operation and green markers correspond to unstable

operation. The labels marked as "U" correspond with the green, unstable markers, and the "S" labels correspond to the blue, stable cases.

<u>Periodic results:</u>

To understand the time resolved response of the droplets in the instability, the power spectrum of the diameter signal was compared between the stable and unstable cases as seen in Figure 6. Clearly, there is a fluctuation occurring in the unstable case which is not present in the stable case. Further, the fluctuation occurs at the frequency of instability. One way to quantify the size of the fluctuating component is to take the ratio of the mean squared value (MSV) of the fluctuation to the MSV of the steady component. Such a parameter is a percent fluctuation and ensures that fluctuations are normalized by the arithmetic mean at that particular, spatial location. The MSV was taken from the power spectrum. A graphic interpretation seen in Figure 6 is the ratio of the height of the arrow marking the peak of the FFT, to the height of the stable component at $0Hz$. It should be noted that the diameter data is non-uniformly spaced in time, and appropriate signal processing tools were used to produce the specrtum.

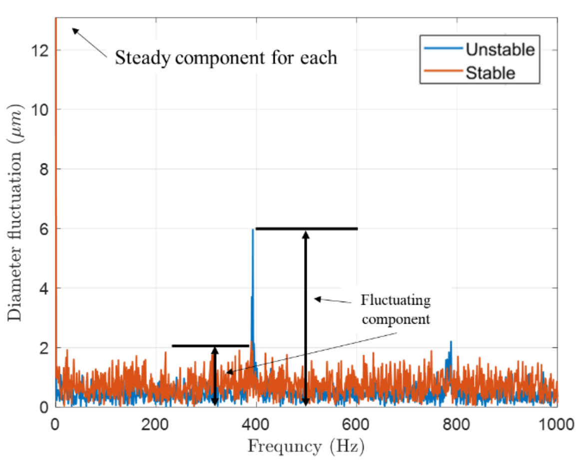

Figure 6: Spectral plot of the diameter signal measured above the dump plane. Definitive evidence of coupling was seen. This particular FFT is from the point 10mm above the venturi, on the longitudinal axis.

The percent fluctuation was found be spatially varying in the region measured. As expected, all the stable cases (except for one location) had a higher percent fluctuation than the corresponding stable measurement at the same location. The single exception was at a location in where the floor noise of the stable spectrum was greater than the peak of the unstable case.

The presence of definitive coupling is remarkable because it can now be shown that during an instability, the droplet diameters couple with the pressure fluctuations, thus providing a path of feedback from the pressure waves to heat release. Further, the fluctuations are seen at the frequency of instability meaning that they are either a driving or damping the instability.

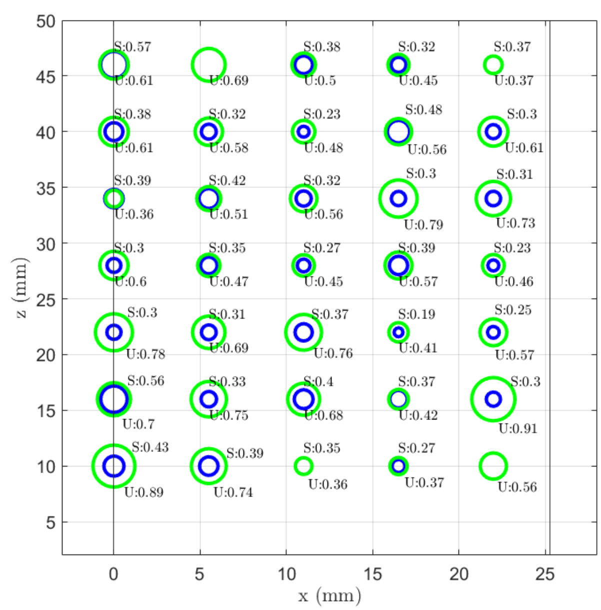

Figure 7: Comparison of the size of the fluctuating component relative of the steady component. In all but one case, the unstable

case's 400Hz fluctuation percentage was higher than during stable operation. The significant increase in fluctuation indicates coupling across the entire flow field.

The average percent fluctuation for stable cases was 34.7% whereas the unstable cases had a value of 58.7%, a significant change. The existence of finite fluctuations at 400 Hz during stable operation was attributed to the noise floor as seen previously (in Figure 6). It should be noted that reference of Figure 4 confirms that minor pressure fluctuations exist even during the stable operation which may potentially be contributing to physical diameter fluctuations even during stable operation.

Limitations:

Limitations which were identified in this procedure have inspired future work. In the current configuration, the combustor operating point must be changed in order to move from stable to unstable operation. Changing operating condition inherently alters the fuel spray regardless of the presence of an instability. It would be more desirable to conduct experiments such that the stable and unstable PDPA measurements are taken at the same flow conditions.

Future work:

The present work has prompted further investigation into the coupling phenomena. The stable and unstable operation needs to be conducted at the same combustor operating conditions in order to have a truly one-to-one comparison. Once a better data set is collected, the phase relation between the diameter fluctuation and the pressure waves can be studies. The phase relation is significant to this combustion application because, in accordance with the Rayleigh criteria, the phase relation of pressure and heat release dictate whether the pressure wave will be amplified into and instability or damped out of the system.

Conclusions:

The present work has proven that droplet diameters can couple with the instability frequency in liquid fuel combustion systems, by taking measurement in an LDI combustor at two operating conditions. A lean direct injection combustor was design with optical access for PDPA measurements, and was equipped with dynamics pressure transducers to capture the acoustic phenomenon. Spray measurements were taken as several axial and transverse locations. In addition to the time averaged spray being affected by the instability, droplet diameter fluctuations were also observed by performing a FFT of the spray measurements. The coupling of diameters with pressure fluctuations from the instability is significant due to the impact of droplet sizes on heat release rates, and thus instability formation. Experimentally verifying that droplet diameters are coupled with the combustion instability is the first step towards modeling the unsteady heat release in a reduced order combustion model such as a flame transfer function.

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