Fuel Sensitivity of Gas Emissions, Lean Blowout and Combustion Dynamics for a 9-point LDI Combustor

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Fuel sensitivity of gaseous emissions, approach to lean blowout and combustion dynamics are evaluated in this study. Experiments were conducted at the NASA Glenn Research Center's CE-5 flame tube test facility with a 9-point Swirl-Venturi Lean Direct Injection (SV-LDI) combustor. A reference jet fuel (A2) and two test fuels (C1 and C3) from were provided by the National Jet Fuels Combustion Program (NJFCP). C1 is essentially a 2-component iso-paraffin test fuel with a low cetane number of 17, and C3 is a high viscosity test fuel. Approach to lean blowout was monitored in terms of the rapid increase in CO emissions index as equivalence ratio decreased, but testing did not proceed all the way to lean blowout (LBO). Burning C1 was found to produce lower NO_x emissions, but C1 flame temperatures were about 25 K higher relative to A2 at near LBO points (where CO emissions increased very rapidly). The NO_x emissions of C3 were similar to A2. At low power conditions where fuel injector performance is not optimized for this 9-point LDI combustor, C3 had higher CO emissions than A2 and C1, likely due to C3's higher viscosity relative to A2 and C1. No discernable difference in combustion dynamics was observed between the three fuels tested in the 9-point LDI combustor. While a systematic ignition test campaign was not conducted, it was observed that C1 required a higher equivalence ratio and inlet air temperature for test rig ignition compared to A2 and C3.

I. Introduction

NASA has been investigating the viability of using synthetic fuel components on newly developed low-emissions combustor designs under the Environmentally Responsible Aviation (ERA) Program and under Advanced Air Transport Technology (AATT) Program. In both programs, capability of burning fuels blended from such blending stocks (up to 50% by volume) was required in the combustor design. Under ERA, both contractors (GE and P&W) had demonstrated their sector combustor designs were able to burn 50/50 (alternative fuel/jet-A volume percentage) blended fuel while having 75% NO_x emissions reductions in relative to ICAO CAEP/6 level [1]. Among the blending stocks tested in NASA's pressurized combustors were narrower-cut mixtures produced from hydrotreated tallow (HRJ), one from direct sugar fermentation (Amyris AMJ-710), and several from Fishcher-Tropsch processes. The blends with these alternative fuels have shown no NO_x emissions and combustor dynamics differences compared to that from distillate Jet A fuel [2].

The National Jet Fuels Combustion Program (NJFCP) is a highly-coordinated effort involving several government agencies, universities, industry partners and international collaborations [3,4]. The NJFCP has focused on looking at the impacts of fuel compositions and physical properties on aviation engine combustors, using models and experiments. These impacts include lean blowout, high altitude ignition, and cold start conditions. The NJFCP fuels are divided into Category A and C test fuels. Category A fuels are petroleum based fuels, such as JP-8 (A1), JP-A (A2), or JP-5 (A3). Category C test fuels are constructed to have distinguishable fuel property and/or composition that could be presented in an alternative fuel source [5].

As a partner in the NJFCP, NASA measured CO and NO_x emissions as well as combustion dynamics data using a 9-point Lean Direct Injection (LDI) combustor with neat fuels. A lean-burn combustor with very short fuel-air mixture preparation time may showcase the differences among feed stock categories.

Three NJFCP test fuels were tested. The C1 test fuel is a high molecular weight duel-component iso-paraffin, to investigate the effect of very narrow-cut heavy-weight fuel on combustion. The C3 fuel is a high viscosity formulation to look at the effect of atomization on combustion. The A2 fuel is an average composition and property

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Jet-A for test control purposes. Among the features investigated were NO_x and CO emissions, approach to lean blowout (LBO), and combustion dynamics.

Carbon monoxide emission at near lean blowout condition could be used as a lean blowout indicator for the 9-point Lean Direct Injection combustor. The 9-point LDI combustor [6] is a lean-front-end concept designed to minimize NO_x and particulates. At low power conditions, the local fuel air equivalence ratios for LDI concept are designed to be less than one throughout the combustor. With low local pilot flame temperature and low inlet air temperature, the flame stabilization may be to be more sensitive to fuel properties than rich-front-end concepts. CO emission increases sharply at near lean blowout fuel air equivalence ratios. For the 9-point configured with all 60 degrees swirlers, this ratio is near 0.25 [6].

Listed in Table 1 are some fuel properties for the three NJFCP test fuels used in this investigation. Test fuel C1 is 100% Gevo ATJ fuel, which contains highly branched C12 and C16 paraffins. C3 is made of 64 vol% of high viscosity JP-5 and 36 vol% of farnesane. The heat of combustion of these two alternative fuels is similar to standard jet-A aviation fuel (A2), which ranges from 42.8 to 43.8 MJ/kg. Nevertheless, C1 has low cetane number of 16, while the cetane number of C3 is similar to A2, about 47. The viscosity of C3 is about double of C1 and A2, (8 cSt compares to 4.9 and 4.5 cSt), but C1 has a different distillation curve shape than C3 and A2. Test fuel C1 requires less than 195 ^{o}C to distillate 80% of its components, while other two test fuels require 230 ^{o}C or above.

Table 1: Fuel properties of three test fuels investigated [5].

Properties	A2	C1	C3
Overall composition	Petroleum Jet A (w/ average properties)	Gevo ATJ; C12/C16 highly-branched iso-paraffins	64% A-3; 36% Amyris farnesane (C15 iso-paraffin)
Viscosity, -20 C (cSt)	4.5	4.9	8.0
Cetane number	48.3	16	47
Distillation (^{o}C), 90%	244	228	245
80%	230	195	243
50%	205	182	230

II. Experimental facilities and hardware

Experimental data used in this study were collected on Stand 2 of the CE-5 flame-tube test facility at NASA Glenn Research Center [7]. Figure 1 shows a schematic drawing of the combustion rig. Non-vitiated air was pre-heated to a maximum temperature of 830 K and maximum pressure of 24.13 bar. The fuels listed in Table 1 were used. Fuel flow rates were measured by turbine meters and coriolis flow meters, and the air flow rate was measured by a venturi meter. The fuel-air mixture was injected into a flame-tube with a cast ceramic liner. A gas probe was placed 200 mm downstream of the injector to collect combustion products for analysis. The rest of the combustion products were cooled down to 500 K by mixing with sprayed water before exiting to an altitude exhaust system. The combusted gas samples were analyzed according to the standard gas-analysis procedure, SAE-ARP1256D [8].

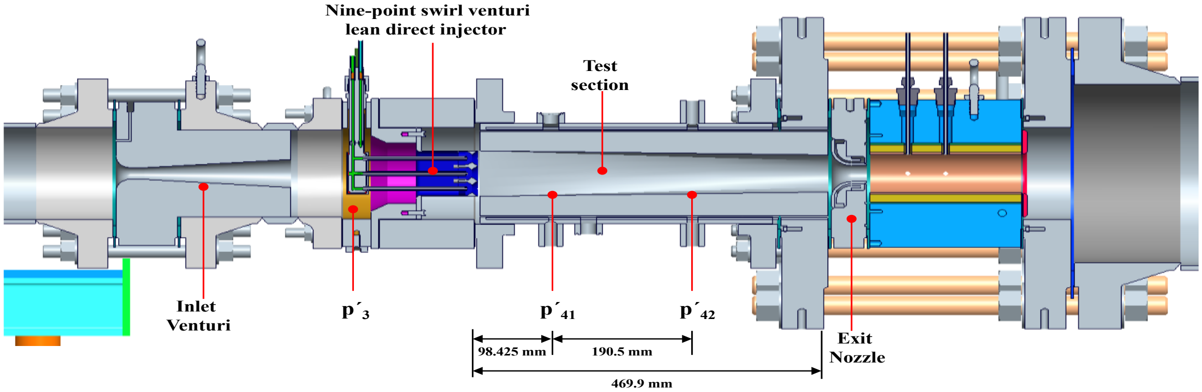
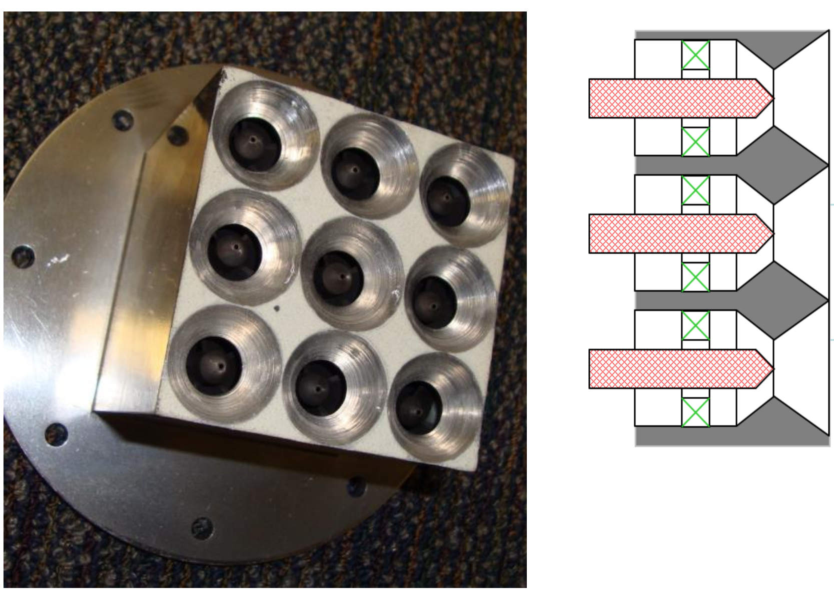


Figure 1: NASA Glenn CE-5 Stand 2 test rig and dynamic instrumentation locations.

The SV-LDI module described here contains 9 identical fuel/air mixers in a 3x3 array as shown in Figure 2 (where air flow is left to right). The 9 fuel/air mixers replace a single conventional fuel injector. Each fuel/air mixer consists of an air passage with a helical axial air swirler followed by a converging-diverging venturi section. A simplex fuel injector is inserted through the center of the air swirler; the fuel injector tip is at the venturi throat. Three fuel circuits are used in this test. One fuel circuit supplies fuel to the center fuel air mixer, which acts as a pilot. The other two fuel circuits each feed four surrounding fuel air mixers: one feeds the corners, and the other feeds the middle mixer on each side.

Combustion chamber geometry was well defined as a rectangular cuboid (7.6 cm X 7.6 cm X 46 cm). Dynamic pressures were sampled from three locations axially. As indicated in Figure 1, the P’3 was located upstream of the fuel injection face, while the P’41 was located 9.8 cm downstream of the injector faceand P’42 was located 29 cm downstream the fuel injector face. Three tubes, 0.46 cm inside diameter, were inserted into the combustor at these three locations to collect combustion dynamic data. The sensors were placed 0.9 m away from the tube inlet, each with a 30m tail to damp out the dynamic signals. A slow nitrogen purge flow at the end of the tail provided positive flow to keep the sensors from the hot combustor gas. The dynamic sensors used were piezoelectric, PCB Piezotronics, model 112A22.



a) Injector hardware **b) Cross-sectional drawing**

Figure 2: 9-point injector configuration a) injector hardware, and b) cross-sectional drawing.

The dynamic pressure signals were transformed to frequency domain with using the Fast Fouier Transform (FFT) function in Matlab. Each dynamic pressure reading is recorded for 60 seconds at 20 or 40 kHz. For spectral processing, each recording was split into segments of 2^{15} points. As a result, each FFT used about 1.1 to 1.5 seconds of dynamic data. After the transformation, the frequency spectrum was corrected for line loss in the sampling line following Samuelson [9]. To reduce noise, the average values of these FFTs are reported in this study. The y-axis of the FFT plot is normalized by the combustor inlet air pressure, which is proportional to the square of the velocity fluctuations inside the combustor.

Two test series were conducted. First test series occurred in 2015, with co-rotating pilot configuration and four types of fuel (C1, C3, A2 and a random batch of Jet A). The second test series was performed in 2016, with a counter-rotating pilot configuration and two types of fuel (C1 and A2). The co-rotating pilot configuration had the pilot mixer swirler rotating at the same direction as the main mixers, while the counter-rotating pilot configuration had the pilot mixer swirler rotating in the opposite direction [10]. For these studies, local fuel air equivalence ratios were similar among the nine fuel air mixers, except at one test conditions (inlet air temperature of 575 K and inlet air pressure of 689 kPa) where the pilot ϕ is different from the other two fuel circuits.

III. Results and Discussions

NO_x emissions

Burning the C1 test fuel results in lower NO_x emissions relative to the other fuels tested. Figure 3 shows the NO_x emissions for four fuels as a function of the calculated adiabatic flame temperature (2015 data). The Emission Index (EI) value calculations in this study were corrected for the fuel carbon and hydrogen compositions, and the calculated adiabatic flame temperature was corrected for the heat of combustion of the fuels. The emission results show C1 produces less NO_x emissions than the other three fuels (C3, A2, and a random batch of Jet A fuel) at the same engine operating conditions. The NO_x emissions for the other three fuels are about the same. The NO_x emissions for C1 is about 12% EI lower than A2 at an inlet air temperature of 725 K, and C1 is 5% EI lower than A2 at an inlet air temperature of 825 K. C3 is a high viscosity fuel. The viscosity of C3 is about double of C1 and A2. The NO_x emissions for C3 and A2 are similar, which indicates that the atomization performance of the fuel injectors is not a strong function of fuel viscosity at these engine operating conditions.

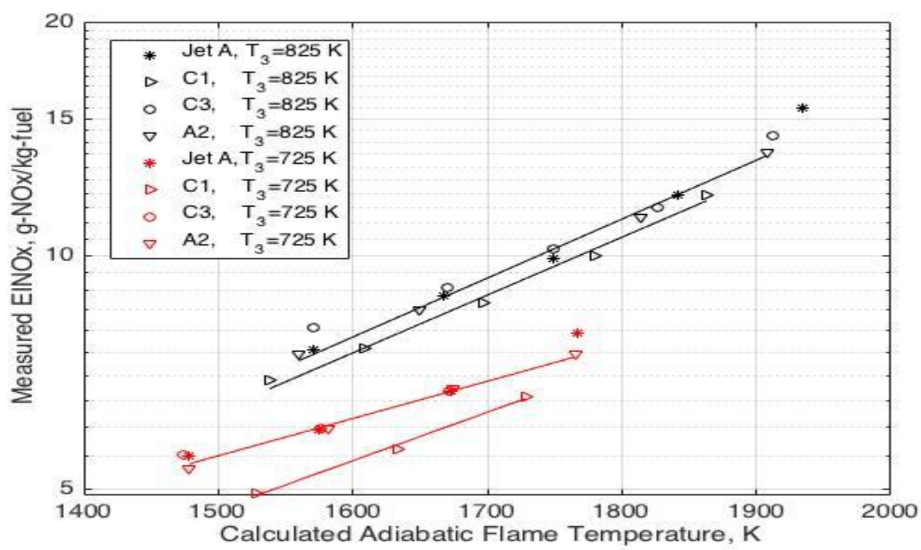


Figure 3: NO_x emissions for four types of fuel, random Batch Jet A, C1, C3, and A2 at 1725 kPa and two different inlet air temperatures.

One possible contribution to the NO_x emissions reduction is the longer ignition delay time for C1 relative to A2 and C3. The autoignition time for C1 is about double that of Jet-A (A2) [11]. This might be because the C1 fuel has a different fuel decomposition pathway. C1 is composed of highly branch iso-paraffins, which results in a low cetane number of 16. An emissions study has found that C1 and the FT-sasol alternative fuels (with high iso-paraffins contents) produce relatively high level of iso-butene but are lower in ethylene emissions than n-paraffins fuels [12]. Also, detailed shock tube experiments and hybrid chemistry modeling [13] has shown that C1 produces mostly iso-butene during fuel decomposition (versus mostly ethylene for A2) with C1 ignition delay times longer than A2 at high temperatures due to the slower chemistry of iso-butene oxidation relative to ethylene oxidation.

Longer ignition delay times provide more time for fuel and air to mix before burning, which may lower front-end recirculation zone flame temperature in this 9-point LDI combustor and thus lower the NO_x emissions. NO_x emissions are a function of flame temperature. Even with lean burn, the flame temperature profile for the 9-point LDI combustor is not uniform throughout. Each of the nine fuel air mixers has a 60 degree swirler creating highly swirled air to promote fuel air mixing and a center recirculation zone at the front end of the combustor for flame stabilization. A CFD study on this 9-point combustor has shown the local flame temperature is more than double and the NO_x emissions are more than six to seven times higher near the injector face versus downstream of the reciriulation zone [14]. At the combustor exit, the flame temperature is the same regardless of fuel type when the same amount of energy is input, and combustion reactions have completed. As a result, the long ignition delay time characteristic of C1 should lead to lower the NO_x emissions by lowering the local hot spots temperatures at the front end of the combustor.

An earlier alternative fuel study with this 9-point combustor [3] did not show that NO_x emissions for the HRJ alternative fuel with high cetane number of 69 is different than the regular Jet-A. As a result, no clear trend or correlation is observed between cetane number and NO_x emissions reductions.

The vaporization rate may also play a role in NO_x emissions reductions of C1 relative to A2. According to the distillation curve, 80% of C1 will distill at 180 ºC, while C3 and A2 require 45 ºC and 35 ºC higher, repectively. CFD calculations have found the vaporization rate for the C1 fuel is 16% faster than the A2 fuel [15]. A faster vaporization rate results in smaller fuel drop sizes as the fuel moves into the flame zone, which would lower the local hot spot temperatures and thus provide lower NO_x emissions.

Table 2 compares the percentage NO_x emissions reductions at different inlet air temperature (T_3) and pressure (P_3) conditions between C1 and A2. The percentage NO_x reductions are random, between 5% to 18.7%. The percentage reductions between 2015 and 2016 data are similar, which indicates the center pilot swirler orientation did not have an effect on the C1 fuel NO_x emission reductions. At a high T_3 of 810K, the percentage NOx reduction of C1 fuel relative to A2 is only 5%. The vaporization rate and chemical reaction rate differences between C1 and A2 may be minimized at this high T_3 condition.

Table 2: Percentage NO_x reductions of C1 fuel relative to A2 fuel at various inlet air temperature and pressure conditions.

T_3 (K)	P_3 (kPa)	% reduction (2015 data)	% reduction (2016 data)
810	1723	5.0	*
727	1723	12.0	14.0
644	1034	11.7	18.7
575	1034	16.1	15.5
575	689	13.3	12.5

Ignition

The C1 fuel was harder to ignite than A2 and C3 during standard test rig light-off procedures. Table 3 lists the ignition trials attempted with using C1. An aircraft ignitor was used during the ignition sequence for all the trials. Only one successful ignition at high inlet air temperature of 810K and high overall fuel air equivalence ratio of 0.50. For this 9-point combustor, the autoignition temperature for A2 (without an ignitor) is about 700 K. Studies by UTRC [11] found a strong correlation between the cetane number and autoignition. With low cetane number of 16, the C1 test fuel would need fuel-air equivalence ratios of at least 0.60 for auto-ignition to occur at an inlet air pressure of 55 bar and temperature of 910 K, while A2 requires a fuel-air equivalence ratio less than 0.30. Lower temperature ignition was also attempted using A2 in the pilot fuel air mixer and C1 in the other two fuel circuits. However, no successful ignition was observed. The main fuel mixers' local fuel air ratio (main phi = 0.37) might not be high enough for local ignition. No ignition occurred at conditions with a local pilot ϕ as high as 1.67.

Table 3: C1 fuel ignition trials.

Fuel used	***P_3* (kPa)**	***T_3* (K)**	***DP%***	***Φ* (Pilot)**	***Φ* (Main1)**	***Φ* (Main2)**	***Φ* (total)**	***Successful ignition***
C1 only	1723	727	2	0.96	0.37	0.37	0.43	NO
C1 only	1034	727	2	0.96	0.36	0.36	0.42	NO
C1 only	1379	810	3	0.97	0.37	0.37	0.44	NO
C1 only	1379	810	3	0.97	0.43	0.43	0.49	YES
Pilot A2/ Main C1	862	672	2	1.05	0.37	0.37	0.44	NO
Pilot A2/ Main C2	862	672	2	1.67	0.37	0.37	0.51	NO

Near Lean Blowout (LBO)

When the fuel is evenly distributed among the nine fuel air mixers, the CO emissions of this combustor increase sharply (near vertically) at fuel air ratio near lean blowout [6]. With an improved fuel control method and more stable fuel flow rates in the 2016 test, a clear trend is observed between C1 and A2, as shown in Figure 4. The air flow rate was maintained at a constant value as fuel flow rate was decreased. Test procedure stopped the lowering of fuel flow rate when EICO emissions exceeded a preset value or the time rate of change of EICO emissions increase exceeded a preset value. Thus, blowout was not typically achieved, but the the spike in CO emissions as equivalence ratio decrease was typically resolved. Test results using three inlet temperatures and two inlet pressures are shown in Figure 4. The C1 near LBO point (CO spike) occurs at a temperature 25 K higher than the A2 fuel. Large CO fluctuations near LBO might be a result of poor fuel air mixing. This lean blowout adiabatic flame temperature difference is not a function of inlet air temperature, which indicates fuel vaporization rate is not a key factor to determine this temperature. Effect of C3 on this near lean blowout flame temperature is unknown due to large fuel flow fluctuations in the 2015 data.

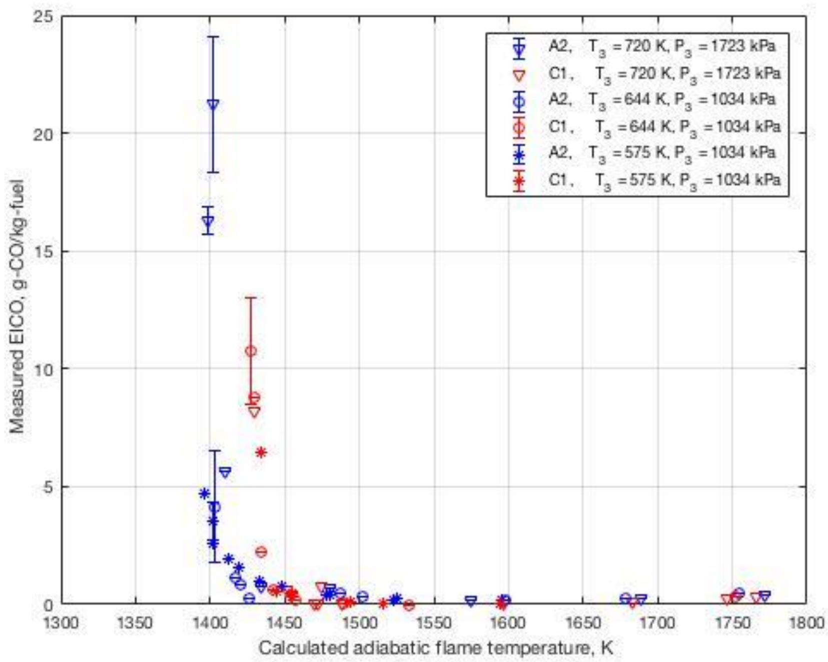


Figure 4: experimental EICO values vs. calculated adiabatic flame temperature for C1 and A2.

The effect of fuels on CO emissions (as shown in figure 4) is not comparable to other combustors. Rich burn combustors are more stable than lean burn combustor. Experiments performed by Air Force Research Laboratory with the "referee" combustor [12], a rich front end combustor, showed the lean blowout fuel air equivalence ratio is much lower (ϕ <0.09) for the "referee" combustor. The CO emissions increase relatively slowly approaching lean blowout, and the flame is not blowing out at high CO emissions conditions (EICO > 250 g/kg). Even for a lean-front-end combustor, the shape of the CO emission curve varies with flame stabilization mechanisms. In the NASA Glenn 9-point LDI tests, 60 degree air swirlers were used in each of the nine fuel air mixers, which promotes fast fuel air mixing and recirculation zone near the front end of the combustor for flame stabilization. The 9-point LDI combustor with 45 degree swirlers does not have recirculation zone (at least in the mean flow) for flame stabilization, and lean blowoff is expected to occur at a higher fuel air equivalence ratio [6].

Burning hotter or at a higher fuel air ratio locally (usually at the pilot fuel air mixer) in the combustor is a common practice to stablize the flame at low engine power conditions, where inlet air tempeature and overall fuel air ratio are low. Under such conditions, the EICO emissions curve approaching lean blowout is not nearly vertical but has finite slope. Figure 5 shows the test data for the 9-point LDI taken at inlet air temperature of 575 K and pressure of 689 kPa (2015 data), with a center pilot at ϕ ~ 0.66. The combustor did not blowout even at high EICO values. Similar EICO emissions trends occurred in another lean burn combustor, the P&W N+2 ACS combustor, for which the pilot fuel air equivalence ratio was maintained at 0.40 or 0.50 [16]. The data in Figure 5 shows C3 has higher CO emissions than C1 and A2 at low (calculated) adiabatic flame temperatures. This might be due to the high viscosity property of C3 that causes the fuel injector to produce relatively larger fuel drop sizes at low fuel flow rate conditions relative to the other two fuels and thus produces higher CO emissions. Chemical reaction rates, such as for CO to CO_2 conversion, are also slower at low inlet air temperature (T_3) conditions. Due to fluctuation in fuel flow control in the 2015 test, this result might not be accurate. More data for A2 and C1 fuels are needed to show a clearer trend.

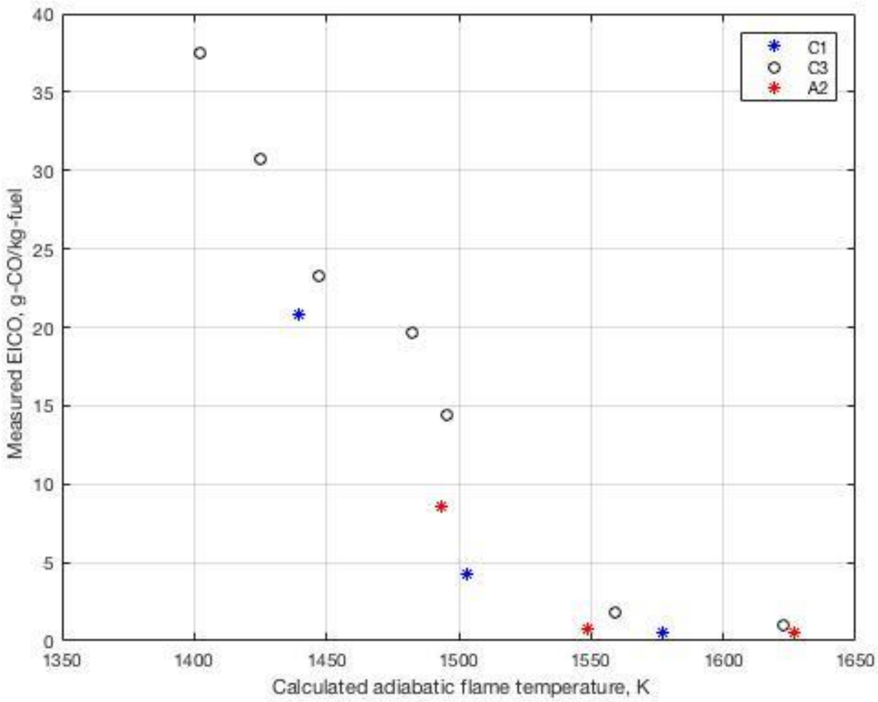
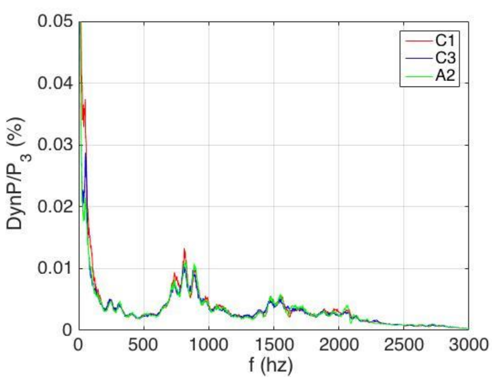


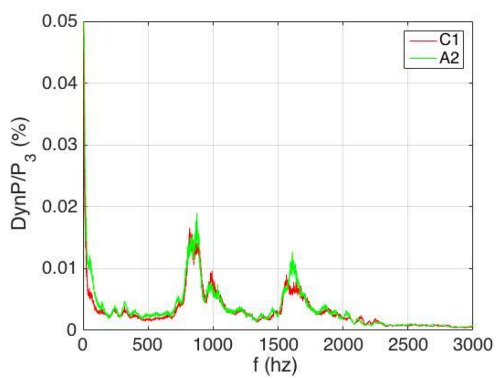
Figure 5: EICO curves with pilot ϕ =0.68 at 689 kPa and 575 K (2015 test data) for 9-point LDI.

Combustion dynamics

Both 2015 and 2016 data show alternative fuels do not cause a significant difference in the combustion dynamic spectrum. No high-magnitude combustion instability is observed in these two tests. Figure 6 shows the frequency spectrums that obtained with the three fuels (A2, C1, C2) at near lean blowout test conditions. Figure 6a is the 2015 data, and Figure 6b is the 2016 data. Under similar test conditions, the frequency spectrums obtained with several types of fuels essentially overlap with each other.



a) 2015 data



a) 2016 data

Figure 6: frequency spectrum at near lean blowout P_3= 1034 kPa, T_3=644 K, ϕ = 0.35, at P'41 location.

Two broadband noise features are present in the spectrum at around 900 hz and 1700 hz. These two broadband features look slightly different between the 2015 and 2016 data. This might be caused by the differences in the pilot swirler rotational direction. The 2015 test is used the counter-rotating pilot configuration, and the 2016 test used co-rotating pilot configuration [10]. Changing the pilot fuel air mixer swirler rotation direction changes the shear layers interactions between the pilot and the main mixers. Studies on a 7-point LDI configuration show a more contiguous boundary around the center swirler for the counter-rotating pilot configuration than the co-rotating pilot configuration [17]. These results might indicate the shear layers interactions between the pilot and main fuel air mixers is acting as a damper to combustion dynamic noises. With weaker shear layer interactions (2016 data on Figure 6b), the two broadband noise features are narrower but the amplitudes are higher for the counter-rotating pilot configurations.

IV. Conclusions

Two tests were done with the 9-point LDI combustor to identify fuel effects on gaseous emissions, approach to lean blowout and combustion dynamics. A reference jet fuel (A2) and two test fuels (C1 and C3) from were provided by the National Jet Fuels Combustion Program (NJFCP). Test fuel C1 has a low cetane number and longer ignition delay time (at high temperatures) relative to the NJFCP reference jet fuel A2, and a faster vaporization rate reatlive to A2. The C3 fuel is high in viscosity but otherwise fairly similar to A2. The C1 fuel characteristics promote better fuel air mixing that may produce lower flame temperatures in the recirculation zone downstream of each of the nine LDI mixer elements and thus produce lower overall NO_x emissions. Test data showed 5-18% reductions in NOx for C1 relative to A2. While C1 did results in lower NOx emissions, the approach to lean blow data indicates that C1 is likely to blowout at higher flame temperature (25 K) relative to A2. The high viscosity C3 test fuel would theoretically give larger size fuel droplets and slower overall vaporization rate, and thus, higher NO_x emissions compared to A2. However, no such a difference is found in this study. At low power, with pilot ϕ maintained at 0.68 (P_3=689 kPa and T_3=575 K), the C3 fuel produces higher CO emissions that the other two fuels, likely due to its high viscosity relative to A2 and C1. No difference in combustion dynamics was observed between the three fuels for the 9-point LDI combustor and condition considered in this study.

Acknowledgments

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