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Preliminary Results from a Plasma-Assisted 7-Point Lean Direct Injected Combustor

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Abstract

It has been shown that both Lean Direct Injection and Lean Premixed Pre-vaporized combustion topologies produce well-mixed, lean combustion zones, which allow for significantly reduced NOx emissions over legacy combustor designs. However, stability in these combustor designs can be a challenge. Non-equilibrium plasmas have been shown to stabilize flames with relatively low power input in a variety of configurations. There are very limited studies however demonstrating plasma-assisted combustion (PAC) at relevant jet engine operating conditions. To demonstrate PAC phenomena under realistic conditions, plasma-assisted multipoint lean direct injection (LDI) injector was designed and tested in a single-sector optically accessible combustor rig. With the electrical power disposed in the plasma equal to less than 1% of the thermal power of the flame (50kW), the equivalence ratio at lean blow off was reduced by 24% from. Additionally, the plasma discharge was observed to create a "pre-flame" pilot region which appeared to stabilize the main flame produced by the air blast atomizer. This region persisted well past the extinction limit of the main flame. Further work is needed to better understand plasma-flame interaction under relevant conditions.

1. Introduction

The challenge with implementing lean combustion in continuous combustion systems is that lean flames are prone to instabilities and it is difficult for a single combustor concept to satisfy all design requirements simultaneously through the conventional pathways of aerodynamic stabilization. This necessitates tradeoffs, which balance stability and airworthiness against optimum emissions performance. As an example, the 9-point SV-LDI combustor investigated by Tacina et al exhibited decrease NOx emissions with decreasing swirler vane angle. However, through the same pathway, namely a reduction in the strength of the recirculation zone and a corresponding decrease in the reactant residence time, stability characteristics produced by these designs were compromised [1]. Moreover, the requirement to maintain static stability and the difficulties in predicting lean blow off in flight applications necessitate large margins to the blow off equivalence ratio in order to prevent a possible loss of flame in the combustor. [2] This leads to higher than optimal fuel flow rates at low powers resulting in higher fuel consumption, noise and emissions during aircraft ground movement and decent. The goal of this work was to use non-equilibrium plasma to provide an additional flame stabilization pathway in combustors to liberate designers from some of the aforementioned tradeoffs. This could potentially result in more optimum operation and provide a paradigm-shifting tool in combustor design.

It has long been known that plasma, a quasi-neutral ionized gas composed of high energy particles, has properties that make it useful for enhancing various chemical processes [3] . Of these processes, combustion holds particular promise and plasma assisted combustion is an active research field and has been researched extensively including by the EM2C lab of Ecole Centrale in Paris [4] and at various US institutions primarily funded through the Air Force Office of Scientific Research [5] Most of this research has focused on understanding the phenomenology behind plasma assisted combustion (PAC) but there has been some activity from engine manufacturers conducting exploratory research in this space. In particular GE has looked into this technology both for jet engine and gas turbine applications. The former is disclosed in [6] while the later was carried out through an DOE funded program into fuel flexible combustion systems [7] The authors of ref [8] have also explored PAC at more realistic conditions, although liquid fuels were not used in this work. These technologies have faced several technical hurdles which have prevented their implementation. At a high level, plasma works well with gaseous fuels at atmospheric pressures but as conditions approach those found in an engine (increasing pressure, flow velocities and liquid fuels in some applications) PAC phenomena has either not

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been explored or has not performed well. In particular, Venkatesan et al in [7] found that the plasma discharge itself produced excessive NOx during operation. Other problems including with electrode durability, excessive power consumption from the plasma and practical problems inherent to combining a plasma based system with realistic combustor geometry have also been experienced. Therefore, there still exists a gap in knowledge relating to the application of plasma to enhance stability in realistic combustion systems in order to solve practical problems. A swirl-venturi lean direct injection (SV-LDI) topology has been chosen as the focus of this research. This design presents a unique combination of a simplified geometry which captures the fundamental physics of the problem while still being representative of the state of the art combustor technology which will see service in the next generation of engines. Presented here are preliminary results for the plasma-assisted LDI combustor which was designed to demonstrate stability enhancements to a semi-realistic combustion hardware at conditions representative of idle power, a region where stability has been shown to be problematic [9] [10]

1. Methods / Experimental

All experiments were conducted in NASA Glenn Research Center's Combustion Dynamics Facility, in test cell CE-13C. CE-13C is a flametube combustor capable of pressures up to 8 bar and air flows of 0.36 kg/s. The experimental conditions for these tests were chosen on the basis of idle in a 100 kN thrust-class turbofan. The high voltage circuit consisted of the high voltage electrode and the return path to ground which included the test and instrumentation hardware. Parts of the hardware used to modify the facility for these tests limited the combustion chamber upstream temperature (T3) to 500K. As these tests were planned to explore plasma assisted combustion in idle and sub-idle conditions, this was not a major limitation but an alternate strategy may need to be devised for future tests. A test matrix was designed to examine the effect of repetitively pulsed nanosecond discharge (RPNSD) plasma on the stability of a LDI combustor at simulated idle and off-design low-idle conditions. In addition, the failure of a pump in the spray cooling system limited P3 to 330 kPa over concerns of sufficient quenching of the high temperature combusted gasses. Facility time was limited yielding a restricted matrix of only a few test points. Nonetheless, the authors feel that these experiments were adequate to provide a proof of concept.
Temperatures, pressures, and flow rates were recorded at a 10hz sample rate for each point using NASA's ESCORT data acquisition system. The values presented here are arithmetic averages of all of the values obtained per test point. Gas analysis measurements were performed in accordance with SAE ARP-1256 and analyzed according to SAE ARP-1533 but were not available for all test points.

A. Experimental Hardware

A seven point SV-LDI configuration similar to the one disclosed in [11] was developed for these tests. While this configuration typically consists of seven identical pressure atomizer stages, for this work the center element was increased slightly in diameter to accommodate a pre-filming airblast atomizer stage. This geometry allowed the

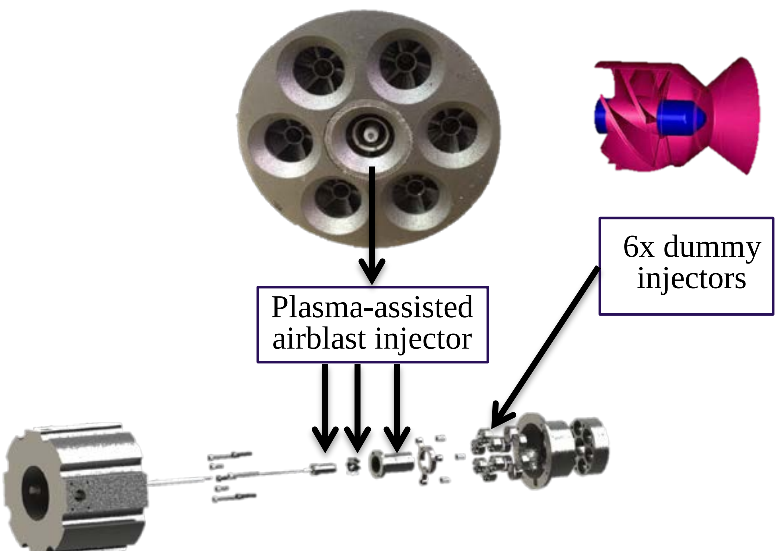

fig-1 plasma-assisted seven point LDI Combustor

insertion of a concentric high voltage electrode within the airblast stage that extended past the throat of the venturi. This design was meant to produce a substantially axisymmetric discharge geometry proximal to the flame front location such that both fuel and air would pass through this plasma zone prior to combustion. The experimental

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hardware was manufactured via a direct laser sintering process from 17-4H stainless steel with the exception of the high voltage electrode which consisted of a Thoriated tungsten welding electrode with a 20 degree cone half angle at the tip. The overall effective area of the experimental hardware was determined to be 600mm^2 while the Center Injector ACd was determined to be 81 mm^2. This yielded a flow split with reference to the center injector of 15.8%. This value was used to determine the local equivalence ratios stated in proceeding sections of this paper. The six surrounding SV-LDI modules surrounding the central airblast pilot stage were unfueled but were used to create a realistic flow field and replicate the confinement of the comparable SV-LDI designs. On the recommendations of the authors of [1] the outer swirlers were flipped relative to the central injector such that all six outer swirlers imparted a counterclockwise rotation to the air while the central injector had a clockwise orientation, thus minimizing the fluid shear experienced by the central element and increasing the strength of the CRZ.

2. Results and Discussion

One of the goals of this work was to demonstrate that plasma could be effective in extending the lean stability limit of a combustor from an aeronautical engine. This stability criterion has important practical implications as currently, due to the stochastic nature of LBO, a wide margin lean blow off equivalence ratio is used in engines[2] . To this end,

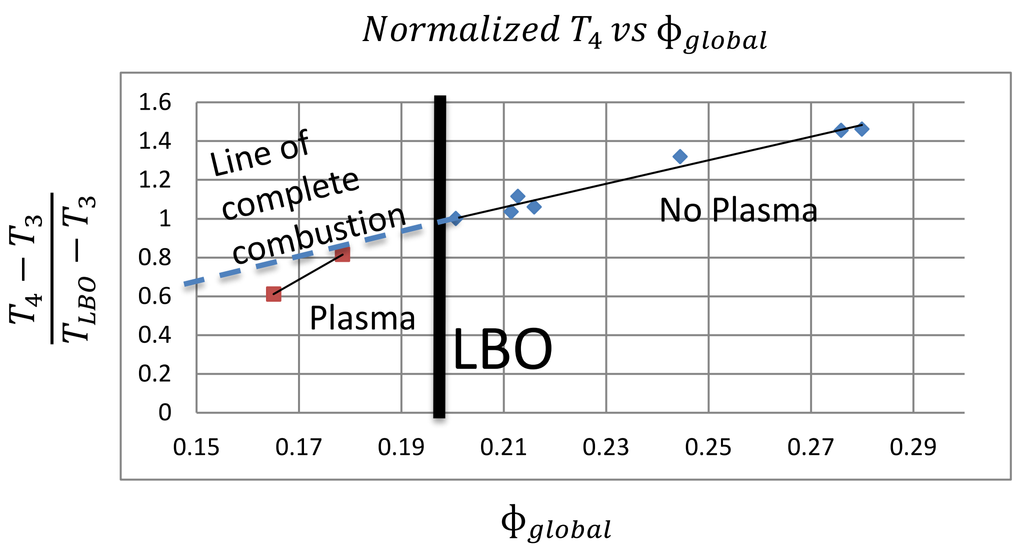

fig-2 Plot of reduced temperature vs equivalence ratio to show lean limit extension

Table I. Nominal Range of CE-13 Opperating Conditions

Pressure drop	1.75-2.10%
P3 (kPa)	324-330
Air Mass Flow Rate (kg/s)	0.1-0.99
Global Equivilance Ratio	0.12-0.28
T3 (K)	470-477

the test facility was used to simulate idle and sub-idle conditions as shown in *table 1*. Plasma-based technologies could allow for increased turndown which could potentially lead to a decrease in fuel consumption at idle and more optimum emissions performance. It is also of value to industry to demonstrate enhanced authority in protecting against LBO to satisfy airworthiness considerations. In order to explore LBO with and without plasma, the combustor was ignited with the aid of a plasma discharge and

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the discharge was then turned off allowing the combustor to stabilize. The fuel flow rate was gradually decreased via the electromechanical adjustment of a throttle valve.
This process was repeated at different pressure drops across the injector which were controlled by varying the chamber pressure and mass flow rates. At higher pressure drops, which promoted increased atomization, the flame stand-off

$\phi_{global} = 0.178$ $\quad$ $\phi_{global} = 0.147$ $\quad$ $\phi_{global} = 0.120$

$$P_3 = 334\ kPa \qquad T_3 = 494\ K \qquad \frac{\Delta P_3}{P_3} = 1.75\%$$

fig-3 Sequential images of plasma-assisted flame at decreasing equivalence ratio

distance decreased and the effectiveness of plasma in improving stability as measured by change in the lean blow off limit with and without plasma increased. It is hypothesized that this effect is due to a shorter time of flight for radicals and active species generated by the plasma reduced the quenching of these species prior to their interaction with the

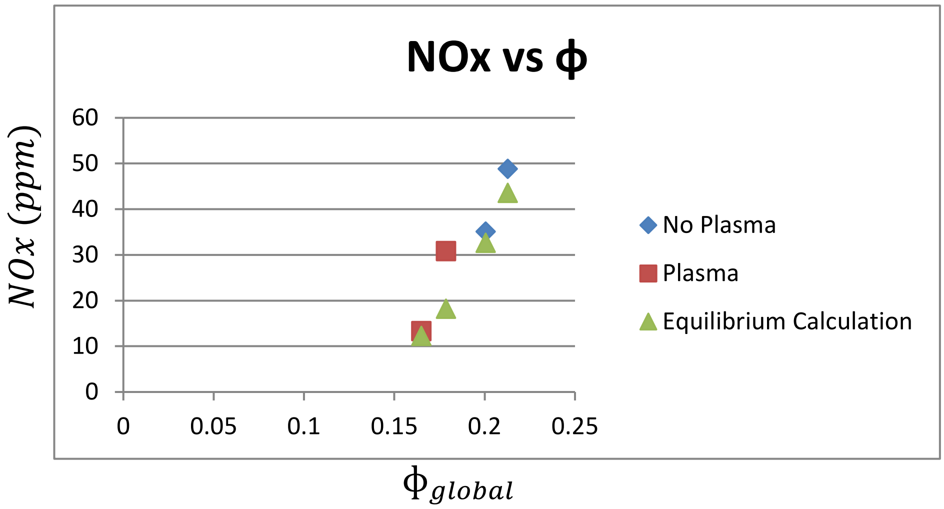

fig-4 Plot of NOx emissions as a function of global equivalence ratio

reaction zone. It is of note however that changing the pressure drop also alters local flow patterns so more work is necessary to further understand this phenomenon. The effect of plasma on CO and NOx emissions was also examined. Due to test matrix restrictions, emissions data was available only for five test points (one non-reacting and four reacting.) The non-reacting case demonstrated an increase of 0.16ppm in the NOx reading. While emissions readings

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with and without plasma for the same test conditions were not available, the increase in NOx from the presence of plasma appears to be of a similar magnitude as that obtained in the non-reacting case, stated another way, the NOx readings obtained when plasma was present in the combustor are not out of the ordinary for an air blast LDI atomizer at those conditions. Further work is needed to understand NOx formation in spray combustion at realistic conditions.

3. Conclusions

With the electrical power disposed in the plasma equal ~1% of the thermal power of the flame (50kW,) the equivalence ratio at lean blow off was reduced from $\phi_{\text{global}} = 0.21$ to ϕ_{global}=0.16. Additionally, it was observed that the plasma discharge created a “pre-flame” pilot region which appeared to stabilize the main flame produced by the air blast atomizer. Luminosity in this region persisted well past the extinction limit of the main flame. It is hypothesized that plasma may promote the formation of a cool flame as observed in methane by Kim et al in [12] and [13]where in-situ fuel reformation and partial oxidation takes place. Future work with OH and Formaldehyde PLIF will help to determine the character of this region.

4. Acknowledgements

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