2021

Investigation of Various Jet Configurations on Jet-in Crossflow Flame Characteristics at Elevated Pressures

Max K. Fortin
University of Central Florida

INVESTIGATION OF VARIOUS JET CONFIGURATIONS ON JET-IN CROSSFLOW FLAME CHARACTERISTICS AT ELEVATED PRESSURES

by

MAX FORTIN

B.S. Mechanical Engineering 2017

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in the Department of Mechanical and Aerospace Engineering in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

Thesis Chair:

Kareem Ahmed

ABSTRACT

The goal of this study is to investigate how varying the configuration of an axially staged combustion test facility affects the resultant flame and its relevant characteristics. Such relevant characteristics are the jet liftoff and the centerline jet trajectory**.** The configurations that are primarily being investigated are varied jet configuration diameters, 4mm and 12.7mm, preheated and non-preheated air, and different fuels**.** The testing facility is located at the University of Central Florida in the PERL (Propulsion and Energy Research Lab) facility. The facility allows for modeling an industrial, high pressure turbine combustor, specifically axial staged combustor with a Jet-In-Crossflow enabled secondary stage. It also allows for pressurizing the entire facility which keeps the studies performed on the facility consistent with industrial conditions. The facility is running off pressurized methane/other fuels and air. The tests were ran with constant equivalence ratios and momentum flux ratios while varying the above configurations to capture how the relevant characteristics were changed.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1: BACKGROUND

Axially Staged Combustion and Dry-Low NOx Combustors

In recent years, there has been a large increase in reducing emissions in all aspects of industry. As one of the necessary industries that contributes many emissions, large scale energy generation has had a recent focus in reducing emissions which have led to many new developments in chemical combustion systems. The topic of this thesis is such a combustor, an axially staged combustion device.

When running a natural gas/methane turbine at typical high load operating conditions, the required inlet temperature must be high (on the order of 1350°C-2000°C) to maintain a large enough efficiency value to be commercially viable. With these high temperatures comes an overall decrease in CO and CO_2 but an increase in NO_x emissions [1]. Dry-Low NO_x is a technology that combustors utilize that aim to reduce NO_x emissions through the concept of premixed lean combustion, which allows the combustor to run significantly cooler for much longer before achieving the final temperature. This time spent at lower temperatures reduces the total time that NO_x can be emitted from the engine. These engines are also capable of a much higher operational range [2-4].

Staged combustion is a type of combustor that improves upon Dry-Low NO_x through a series of two stages [5]. The first stage serves as a vitiator for the combustor, supplying an incredibly hot crossflow for the secondary stage. The first stage is a lean premixed fuel and air mixture that is ignited and allowed to fully develop through into the secondary section. This secondary section supplies a reacting mixture, which can be premixed, partially premixed, non-premixed, or a diffusion, fuel-only jet, which is lit in the vitiated crossflow. The residence time of this stage is kept relatively short due to its close proximity to the exit of the combustor. This short residence time means the reacting jet is burning for a shorter period of time, thereby producing less NO_x. Staged combustion also improves on the other aspects of Dry-Low NO_x combustors, primarily the operability range.

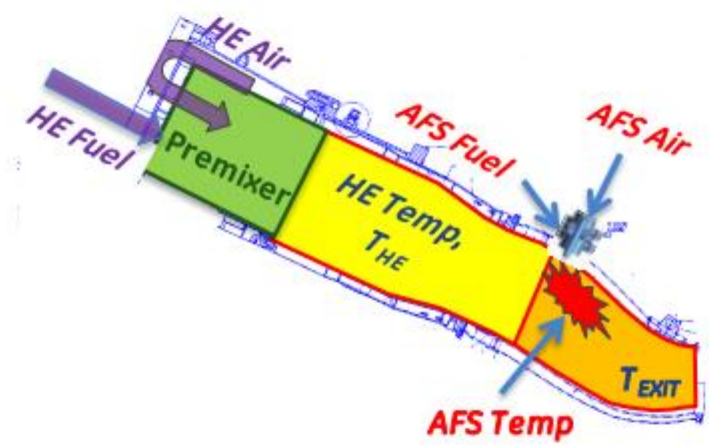

Figure 1: An example of an axial staged combustor from GE Power [5]

Jet-In-Crossflow

The secondary stage of the axial stage combustor requires fuel to be supplied to the vitiated crossflow to complete combustion. The technique most often used is a technique called Jet-In-Crossflow (JICF). This technique involves a crossflow and a jet supplied, at some angle (typically 90 degrees), into said crossflow. When the crossflow and jet react, the technique is said to be Reacting Jet-In-Crossflow (RJICF). This technique, due to the resulting flow structures, allows for efficient mixing and entraining processes [6]. These flow structures and the resulting increased mixing capability has led the technique to be heavily studied in recent years.

The flow structures of Jet-In-Crossflow are the main reason behind its mixing and entraining ability. There exist many different flow structures downstream of the jet but depend heavily on the geometry of the channel where the flow is present. Near the jet exit is where the most intense and consistent flow structures resulting from JICF reside. They can be broken down into 4 main vortices: jet-shear layer interaction vortices, horseshoe vortices, wake vortices, and counter rotating vortex pair (CVP) [7-9]. Figure 2**,** shown below, shows pictorial representation of a JICF and the resulting flow structures.

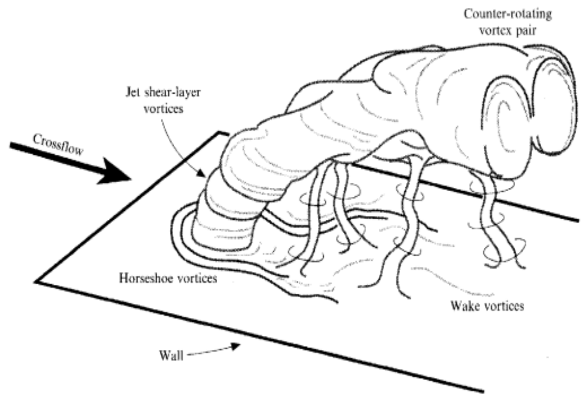

Figure 2: Vortical Structures Created by JICF [7]

The counter vortex pair are typically the dominant structure within a JICF regime. This flow structure is created by the Kelvin-Helmholtz instability that forms when the jet is deflected in the direction of the crossflow. This instability is the result of the shearing created by the differing fluid velocities. This vortical structure is formed very quickly near the jet exit and quickly dominates the rest of the structure as the jet moves downstream, becoming functionally equivalent to it at certain point downstream of the jet exit.

Jet Exit Geometry

The exit of the jet into the vitiated crossflow has been widely studied due to the effect that differing geometry has on the mixing and resulting flame.

For example, Pinchak et al. [10] found that slotted nozzles, when compared to the traditional round jet nozzle, created much larger recirculation zones on the leeward (inside) side of the jet, allowing for far greater mixing and flame stabilization potential. Salewski et al. [11] showed that geometries with high aspect ratios, or the ratio of length and width, showed significantly higher mixing compared to lower aspect ratio geometries such as circles, which have an AR of 1. Ibrahim et al. [12] investigated a wide range of non-circular nozzle geometries compared to a circular nozzle. It was found that jets with slot geometries penetrated much farther into the test section, almost 60% more while triangular geometries penetrated far less. The study also found that the trajectory of the jet was also heavily affected by the geometry. The centerline of slot nozzles was perpendicular up to 2d which was 50% more than any other geometry.

All of these studies reveal important discoveries of how jet geometry can affect the jet and resulting flame. However, none of these studies were performed at industry-relevant pressures. This study attempts to start filling in this gap of knowledge by studying two different nozzle diameters, a half-inch jet, a 4-millimeter jet, and their effect on the resulting flame.

Preheating Inlet Air

In industrial combustors, compressed air is fed directly from the compressor into the combustor. When a fluid, such as air, is compressed from one pressure to another, the fluid will experience an increase in temperature which reduces overall engine efficiency and increases NO_x emissions. The experimental facility in this study utilizes a compressed air source that is stored in high pressure bottles for later use. This storage medium serves to let the air cool over time which an industrial application does not have the luxury of utilizing. The effects of cooling the air have been widely studied to fully understand the benefits of cooling can bring to a combustor. In the case of this experiment, preheating may be used as the air is already cooled as its coming into the facility.

For example, Samuelsen et al. [13] investigated the link between preheating the jet in increments up to the typical operating temperature of a turbine. It was found that preheating the air led to an almost an 2.5x increase in NO_x emissions, meaning that a similar facility in industry may see a significant decrease in NO_x emissions if cooling techniques are used on inlet air. This study will focus expand on these studies by investigating the effect cooling has on the flame lift-off from the jet exit.

Fuel Selection

Fuel selection is an incredibly important aspect to an engine and often determines how the engine will be designed and function.

Pure kerosene was first used to power turbomachinery with new iterations on the fuel being added in subsequent years. JP-1 was one of the first new fuels used in turbomachinery and was made up of kerosene and other additives to fulfill various military needs such as sounds reduction and carbon build-up reduction. Currently, there is a split between military and power generation fuels. Military aircraft typically use JP-8, which is very similar to the civilian Jet-A with other military specific additives. Currently, energy generation fuel sources is dominated by natural gas, which is a primarily methane based gaseous mixture [14].

However, as the focus of energy generation shifts to reducing emissions, other fuels are being investigated to reduce or completely reduce emissions. The main candidate in this process is hydrogen. It produces no NO_x or CO_2 due to not being a hydrocarbon, with the only potential source of emissions being in the production of hydrogen as the electrolysis process used utilizes electricity. Due to this new interest in hydrogen, studies must be performed to fully understand the dynamics of hydrogen.

This study investigates the effect of fuel selection in a diffusive fuel jet and how it affects flame liftoff from the jet exit. The experiment was performed at two momentum flux ratios.

CHAPTER 2: EXPERIMENTAL METHODS AND SET-UP

Experimental Set-Up

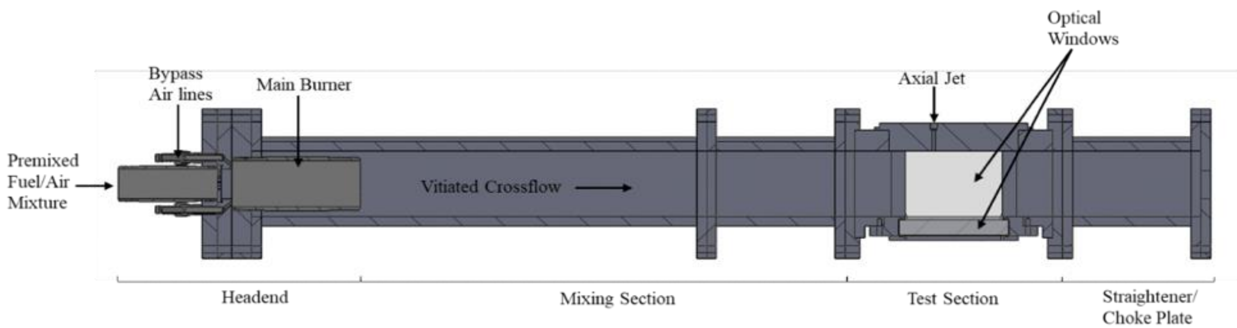

Figure 3: A diagram of the relevant experimental setup

This study was performed at the High Pressure Axially Staged combustion facility at the University of Central Florida. Figure 3 shows the relevant portions of the experimental setup. The setup includes an optical test section that can be used for a number of laser and optical based measurements. These measurements are not present in this study due to time constraints but will be present for future works. Not shown is the fuel and air sources and the requisite piping for delivering said fuel and air.

The first section, known as the headend section, is the source of the vitiated crossflow. A fuel and air mixture is supplied through a pipe into the headend. It is then ignited with a spark wire in the main burner pipe. Air hoses are located circumferentially which are metered by upstream regulators, allow for fine control of the local equivalence ratio in the headend section. There are also multiple hydrogen pilots located around the main burner pipe that serve as pilots which stabilize the flame.

Once the crossflow leaves the headend section, it then enters the secondary section, also known as the mixing section. This section is approximately twenty-six inches long and serves to allow the vitiated crossflow to fully develop its profile and complete mixing. After the twenty-six-inch section, there is a smaller six-inch section that has a perforated screen that induces minor turbulence which promotes more mixing within in the flow.

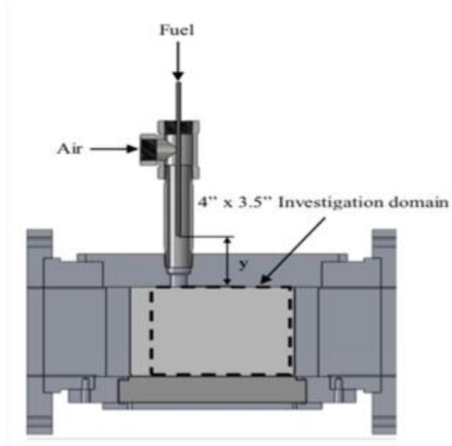

Figure 4: Optical Test Section

After the final mixing section, the flow enters the optical test section, shown in Figure 4. This section is shaped in the 3.5" x 3" profile the rest of the setup utilizes but utilizes quartz glass in 3 out of the 4 sides to allow for optical access for laser and imaging diagnostics. Located at the top of the test section is an interchangeable plate that allows for differing jet geometries. A pipe and a tee are used to introduce fuel and air to each other and allow for enough time to full premix. This fuel and air mixture is then injected normal to the crossflow and ignited where it passes through the last section, the choking plate and nozzle.

The facility is meant to simulate the conditions seen in an industrial turbine combustor which typically have pressures ranging from five atm to 20 atm. This study was performed at 5 atm, which necessitates a choke plate and a nozzle. The choke plate is bolted on to the flanges of the test section where the nozzle is then threaded on to the choke plate to provide back pressure through the system. This nozzle allows for a much smoother transition down to the final area needed to choke the flow. If a simple plate were used instead, the flow would see increased levels of acoustic instability and flame blowout.

Experimental Procedure

The High-Pressure facility is a complex facility that necessitates a lengthy setup process. Before the facility is setup, a testing matrix has to be determined based on what test points are needed. Based on the test matrix, mass flows of the main air and fuel, bypass air, hydrogen, and the secondary stage's fuel and air must be determined. Once those mass flows are determined, a calculator is used to determine what restricted orifices are needed to choke at those mass flows and their subsequent pressure range. Once the pre-setup is complete, the air, fuel, and hydrogen pressure is setup for the test case being ran.

Once the facility is started, the main air and fuel mixture enters the main burner pipe and is ignited by the spark wire. A hydrogen pilot is used to keep the crossflow burning while the bypass air keeps the local equivalence ratio where the test matrix requires. The vitiated crossflow flows through the twenty-six-inch mixing plenum which allows the flow to fully develop. Passing through the perforated screen in the six-inch section induces more mixing within the flow. While the crossflow is moving towards the test section inlet, the air and fuel mixture for the jet is injected into the test section. Once the vitiated crossflow reaches the jet, ignition occurs and exits out the choke plate and nozzle, pressurizing the system. Figure 5 shows a typical reacting JICF reaction.

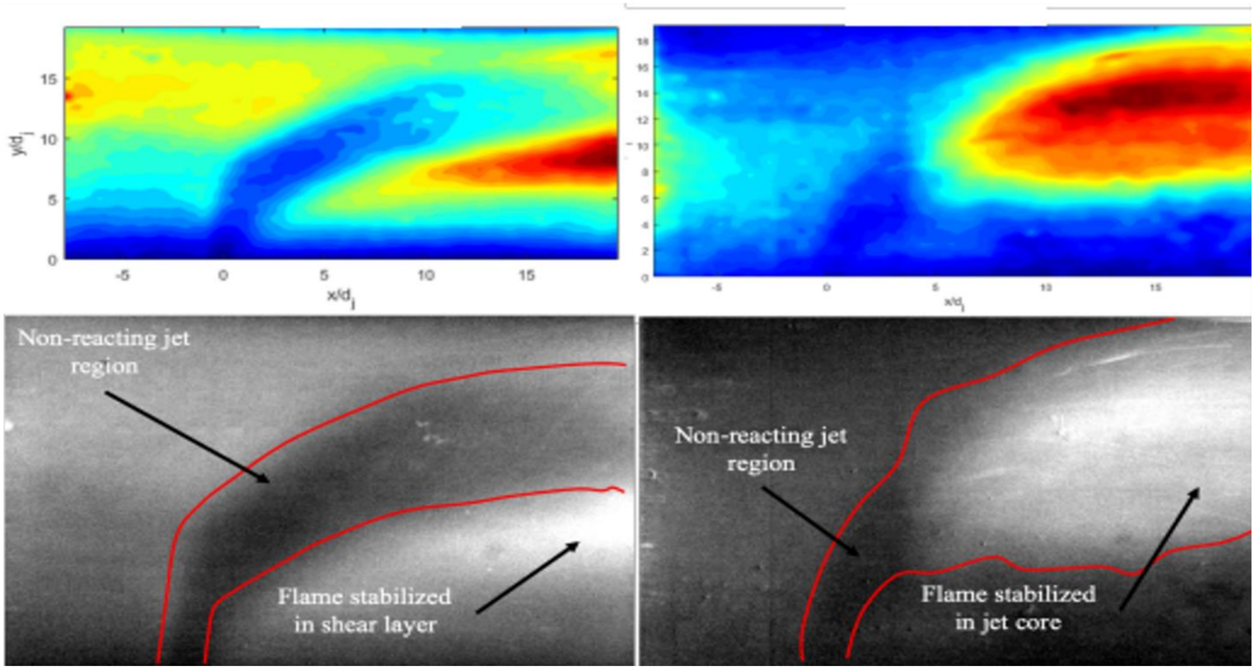

Figure 5: Different Examples of a Reacting JICF

CHAPTER 3: RESULTS

Jet Geometry and Effects on Resulting Flame

As previously discussed, the test section utilizes an interchangeable top plate. The facility has two such plates with two different diameter holes: a half inch jet diameter exit and a 4-millimeter diameter jet exit. As shown in Figure 4, the fuel and air are injected into a pipe independently and are given time, through the length of the pipe, to fully premix. The cases related to jet diameter were run with two different sets of conditions. A constant momentum flux ratio (J), shown in equation 1, and a constant equivalence ratio (φ), shown in equation 2, were used to investigate jet centerline. A constant momentum flux and variable equivalence ratio was used to investigate flame liftoff from the jet exit.

$$J = \frac{\rho_j U_j^2}{\rho_\infty u_\infty^2} \qquad (1)$$

$$\varphi = \frac{\text{fuel-to-oxidizer-ratio}}{(\text{fuel-to-oxidizer-ratio})_{st}} \qquad (2)$$

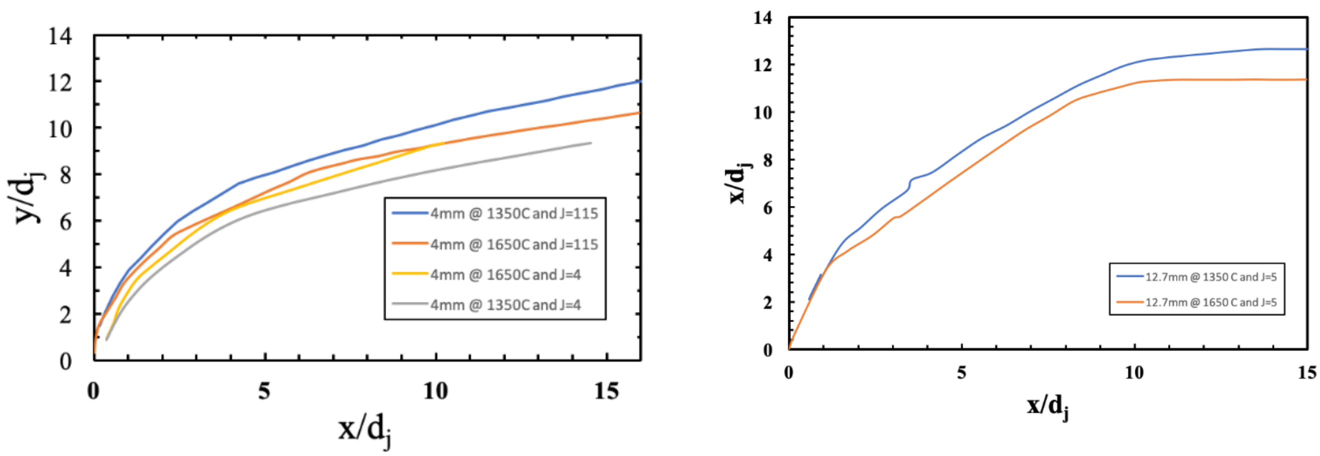

Figure 6: 4mm and 12.7 mm Jet Centerline

As shown in Figure 6, there are 4 cases present for the 4 millimeters at 2 different momentum flux ratios. The half-inch jet, referred to as the 12.7mm jet, has 2 cases present at constant momentum flux ratios. As seen in the graphs, the 4mm jet and the 12.7mm jet have a remarkably similar jet penetration profile. However, the 12.7mm jet penetrates slightly slower when compared to the 4mm jet.

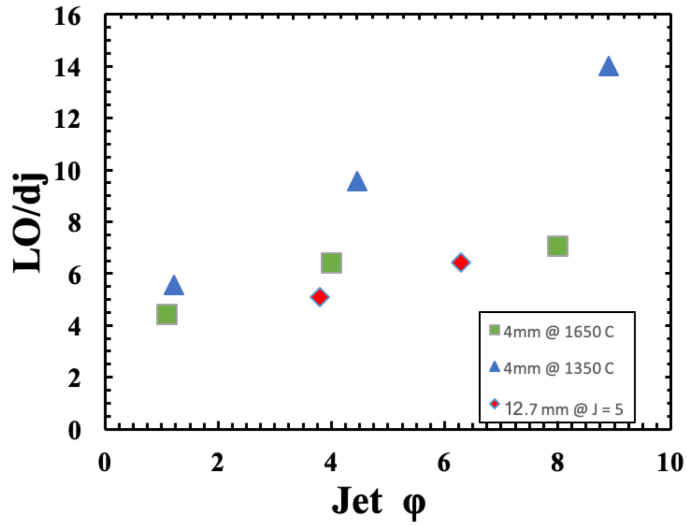

Figure 7: Flame Lift-Off Related to Equivalence Ratio

Figure 7 shows flame lift-off from the jet exit related to jet equivalence ratio. As seen in the figure, at every equivalence ratio the 4mm flame lifted of the jet exit more than the equivalent 12.7mm jet, especially as the 4mm jet experiences a hotter flame. It is worth mentioning that recent research has shown that an increase in flame liftoff can lead to a decrease in NO_x emissions, which is a major design requirement for this combustor.

Preheating Air and Effects on Resulting Flame

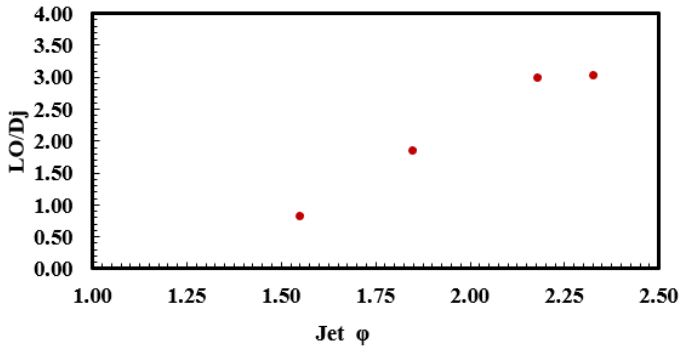

Figure 8: 300C Preheated Air

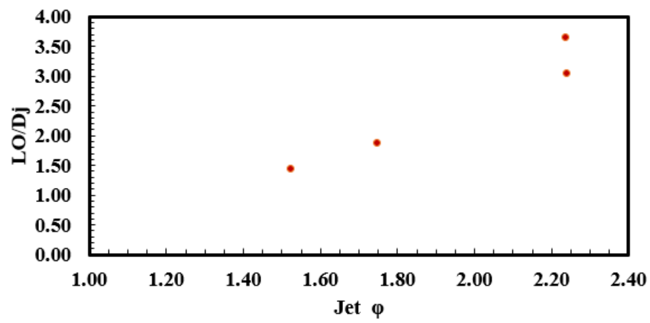

Figure 9: 150C Preheated Air

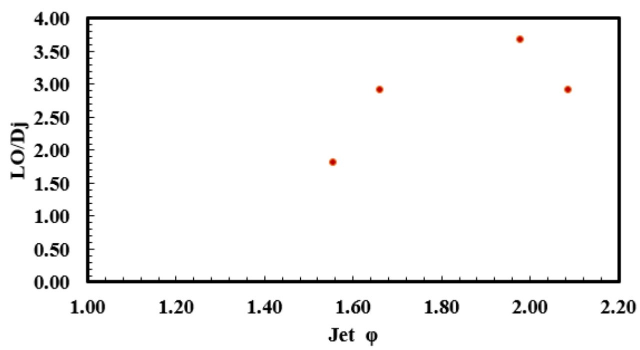

Figure 10: 25C Preheated Air

As previously discussed, industrial combustors utilize compressed air pulled directly from the compressor. This causes the air to be heating beyond the ambient temperature when it reaches the inlet of the combustor. This “preheating” of the air has led industry to investigate what effects cooling has on the resulting flame. This facility utilizes a pressure source that allows the air to cool before use, so the air was preheated to an industrial relevant temperature and then lowered to simulate cooling.

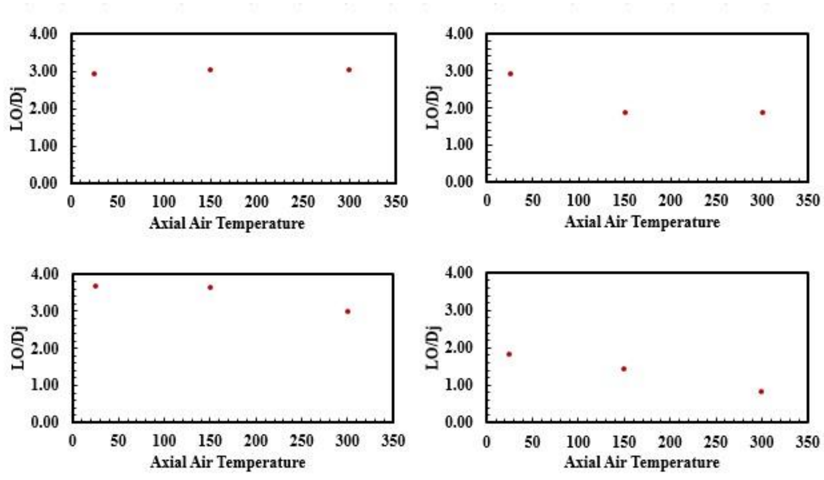

Figure 11: Independent Test Runs

Figures 8,9, and 10 all show cases taken at a range of jet equivalence ratios compared to their subsequent flame lift-off from the jet exit. The experiments were ran at multiple temperatures, 300C, 150C and 25C. Figure 11 shows a different perspective of the data by plotting each temperature measurement in each respective test matrix. As seen in all four figures, at any given jet equivalence ratio, a hotter inlet air temperature resulted in lower lift-off when compared to colder cases. The effect becomes much less noticeable when the equivalence ratio moves beyond 2.0. Further testing would address whether another mechanism is dominating in this regime.

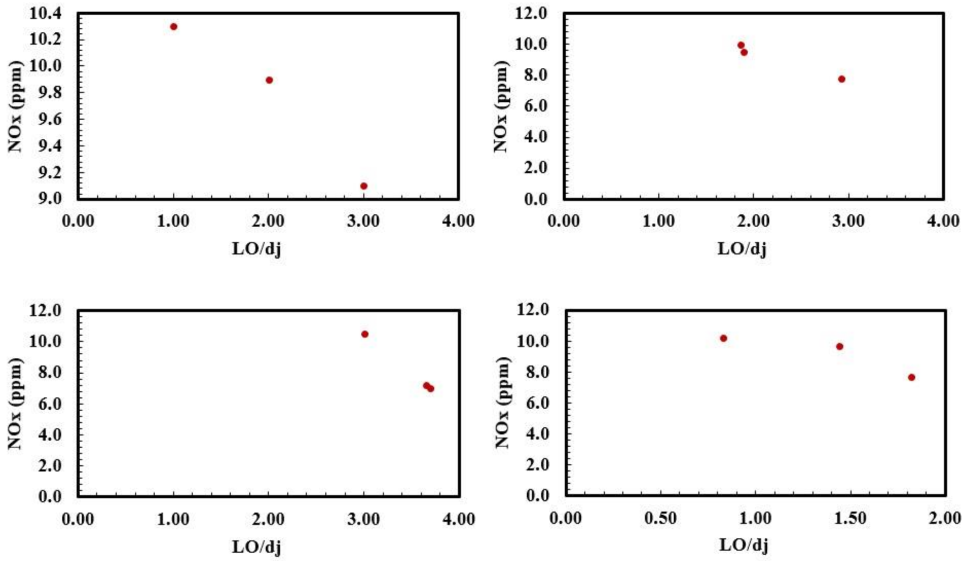

Figure 12: NOx emissions vs Flame Liftoff

Figure 12 shows the NOx emissions plotted against the flame liftoff for each test matrix. As shown in the figures, as the lift-off increases, NOx emissions trend downward in every test. This correlates with recent research that has shown that higher flame liftoff tends to lead to a decrease in overall emissions [15].

Differing Fuels in Axial Stage and Effects on Resulting Flame

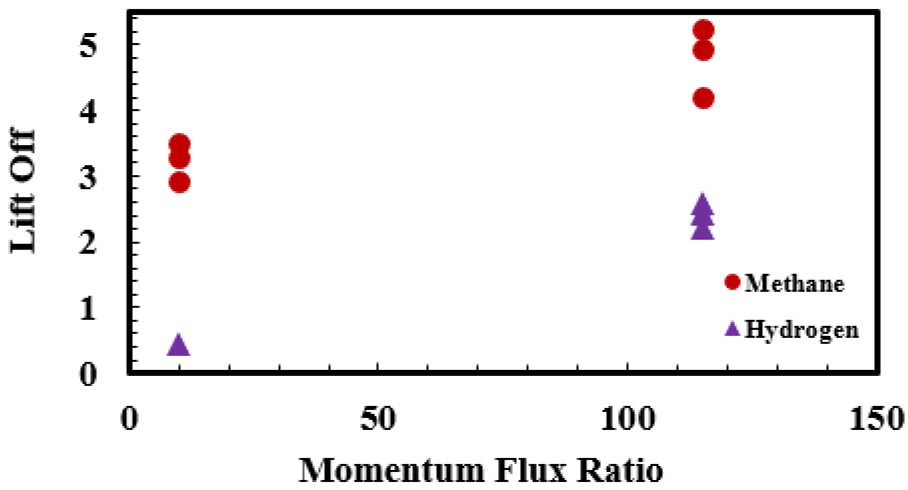

Figure 13: Flame Lift-Off from Methane and Hydrogen

Figure 13 shows two fuel choices utilized in the axial stage of the facility. These tests were ran in a diffusive configuration with no air added to the jet. Two momentum flux ratios were chosen, 50 and 115. As seen in the figure, at every momentum flux ratio, the methane jet has much higher lift-off when compared the respective hydrogen jet.

Previously lift-off height has been mentioned in terms of emissions data but is irrelevant in this case as hydrogen inherently releases no emissions. Flame liftoff also brings mixing benefits that allow for more stable flames, increased operational range, and more efficient combustion.

CHAPTER 4: CONCLUSIONS

A high-pressure, axially staged combustion facility was ran with multiple jet configuration experiments that simulate industrial combustor inlet and outlet conditions.

First, different jet exit diameters, 4mm and 12.7mm, were tested and their effects on flame lift-off from the jet exit and the centerline of the path of the resulting flame. The 4mm jet exit was found to lift further off the outlet when compared to the 12.7mm jet exit. However, the profiles created by either jet centerline was found to be similar with the only exception being the 12.7mm jet penetrating slightly slower than the 4mm.

Second, jet inlet air preheat was tested. This process involved studying how preheating the jet inlet air to industry relevant conditions and subsequent cooling down affects the flame lift-off from the jet exit and emissions. It was found that as the air was cooled down from 300C to 150C to finally 25C, lift-off from the jet exit was found to increase. As mentioned previously, typically flame lift-off predicts a decrease in NO_x emissions which is confirmed by the study.

Third, differing the fuel used in the diffusive axial stage was also studied. Methane and hydrogen were tested at two momentum flux ratios and flame lift-off was recorded for a number of cases for both fuels. It was found that methane produced a much more lifted flame when compared to hydrogen jets.

Future study will include a deeper investigation on how differing fuels will affect the flame including using multiple imaging techniques such PIV (Particle Image Velocimetry) and PLIF (Planar Induced Fluorescence).

REFERENCES

[1] Seinfeld, John H., and Spyros N. Pandis. Atmospheric Chemistry and Physics: from Air Pollution to Climate Change. Wiley, 2016.

[2] Myers, G., Tegel, D., Feigl, M., Setzer, F., and Tuthill, R., 2003, "Dry Low Emissions for the 'H' Heavy-Duty Industrial Gas Turbines: Full Scale Combustion System Rig Test Results', Proceedings of ASME Turbo Expo 2003,

Atlanta, Georgia, USA, Paper NO. GT2003-38193

[3] Dusing, K., Ciani, A., Benz, U., Eroglu, A., Knapp, K., 2013, "Development of GT24 and GT26 (Upgrades

2011) Reheat Combustors Achieving Reduced Emission & Increased Fuel Flexibility", Proceeding of ASME Turbo Expo 2013, San Antonio, Texas, USA, Paper No GT2013-95437

[4] Vandervort, C., 2000, "9 ppm NOx/CO[5] Combustion System for "F" Class

[5] Karim, Hasan, et al. "Staged Combustion System for Improved Emissions Operability and Flexibility for 7HA Class Heavy Duty Gas Turbine Engine." Volume 4A: Combustion, Fuels and Emissions, 2017, doi:10.1115/gt2017-63998.

[6] MUPPIDI, SUMAN, and KRISHNAN MAHESH. "Direct Numerical Simulation of Round Turbulent Jets in Crossflow." Journal of Fluid Mechanics, vol. 574, 2007, pp. 59–84., doi:10.1017/s0022112006004034.

[7] Fric, T. F., and A. Roshko. "Vortical Structure in the Wake of a Transverse Jet." Journal of Fluid Mechanics, vol. 279, 1994, pp. 1–47., doi:10.1017/s0022112094003800.

[8] SMITH, S. H., and M. G. MUNGAL. "Mixing, Structure and Scaling of the Jet in Crossflow." Journal of Fluid Mechanics, vol. 357, 1998, pp. 83–122., doi:10.1017/s0022112097007891.

[9] Brede, M., et al. "On Secondary Vortices in the Cylinder Wake." Physics of Fluids, vol. 8, no. 8, 1996, pp. 2117–2124., doi:10.1063/1.868986.

[10] Pinchak, M. D., Shaw, V. G., & Gutmark, E. J. (2018). The effects of nozzle geometry and equivalence ratio on a premixed reacting jet in vitiated crossflow. Combustion and Flame, 191, 353-367.

[11]] Salewski, M., Stankovic, D., & Fuchs, L. (2007). Mixing in Circular and Non-circular Jets in Crossflow. Flow, Turbulence and Combustion, 80(2), 255-283

[12] Ibrahim, I., Murugappan, S., & Gutmark, E. (2005). Penetration, Mixing and Turbulent Structures of Circular and Non-Circular Jets in Cross Flow. 43rd AIAA Aerospace Sciences Meeting and Exhibit.

[13] Samuelsen, G. S., et al. "Experimental and Modeling Investigation of the Effect of Air Preheat on the Formation of NOx in an RQL Combustor." Heat and Mass Transfer, vol. 49, no. 2, 2012, pp. 219–231., doi:10.1007/s00231-012-1080-0.

[14] "Jet Fuel." *Jet Fuel - Engineering and Technology History Wiki*, ethw.org/Jet_Fuel.

[15] Kolb, Michael, et al. "A Model for Predicting the Lift-Off Height of Premixed Jets in Vitiated Cross Flow." *Volume 4A: Combustion, Fuels and Emissions*, 2015, doi:10.1115/gt2015-42225.