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I, Arul Kumaran Ramalingam Ammaiayappan, hereby submit this original work as part of the requirements for the degree of Master of Science in Mechanical Engineering.

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Design and Development of a High Swirl Burner with gaseous fuel injection through porous tubes

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Design and Development of a High Swirl Burner with gaseous fuel injection through porous tubes

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ABSTRACT

Lean Premixed combustors reduce NOx emissions by burning fuel at “fuel-lean” conditions. The presence of excess air in the lean mixture reduces the combustion temperature. Since thermal NOx reduces exponentially with temperature, the reduction of temperature brings about a reduction in NOx emissions. The presence of fuel rich zones leads to the formation of prompt NOx. Uniform mixing of fuel and air reduces prompt NOx by eliminating “fuel-rich” pockets in the reaction zone.

In this project, gaseous fuel is injected through eight porous tubes that are aligned parallel to the axis of an axial swirler. The axial swirler differs from other axial swirlers in that it also serves as a transition zone for the fuel-air mixture. While the downstream side of the axial swirler resembles other axial swirlers, the upstream side of the swirler has eight circular holes arranged circumferentially. The circular flow area on the upstream side of the axial swirler transitions into the trapezoidal space between the vanes of on the downstream side. The porous tubes are attached to the holes on the upstream side of the swirler. The diameter of these holes matches the inner diameter of the porous tubes. Air is passed through the porous tubes and gaseous fuel mixes with air from the outside of the porous tube. The swirler helps the flow transition from a circular cross-sectional area (porous tubes) to a trapezoidal cross-sectional area (space between adjacent vanes in an axial swirler is trapezoidal).

The aerodynamics of this swirler is studied using non-reacting flow PIV. PIV measurements are done on the axial plane to study the recirculation zone and on the cross-plane to study the tangential
and radial velocities. A parametric study of centerbodies is conducted using PIV to attempt to narrow down to the centerbody that prevents attachment of recirculation zone to the swirler exit.

Combustion testing is conducted at different preheat temperatures (400°F, 500°F, 600°F) and at different equivalence ratios (0.55, 0.6, 0.65) for flame imaging and emission measurement. The NOx emissions are plotted as a function of the adiabatic flame temperature.
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1. INTRODUCTION

1.1 MOTIVATION

The primary pollutants emitted by gas-turbine engines are NOx, CO and Unburnt Hydrocarbons (UHCs). Gas turbine manufacturers use a variety of techniques to reduce emissions. Some techniques are aimed at modifying the combustion conditions to prevent the formation of NOx while some techniques control NOx emissions after its formation (after treatment).

1.1.1 Pre-formation NOx control

The pre-formation emission control strategies can be further classified into wet control strategies and dry control strategies. Wet controls inject a diluent (water or steam) directly into the combustor to reduce the flame temperature and reduce thermal NOx. Although the lower peak temperature has a beneficial effect on NOx emissions, it can reduce combustion efficiency and prevent complete combustion (*Evolution of best available control technology, Appendix 8.1E*). In addition to this, wet controls need large volumes of purified water. Dry control strategies reduce NOx by using excess of air to reduce the combustion temperature. Some of the popular dry control strategies are Lean Premixed combustion, Lean Premixed Pre-vaporized combustion and two stage combustion. Gas turbine manufacturers use different names to refer to their Lean Premixed Combustion technologies. Dry Low NOx, Dry Low Emissions, SoLo NOx are some of the popular trade names for the Lean Premixed Combustion Technology.

In one of the standards of performance for new stationary combustion turbines (*40 CFR 60, subpart KKKK, dated February 18, 2005*), the Environmental Protection Agency states, “Turbine
manufacturers have significantly reduced CO emissions from combustion turbines by developing lean premix technology. Lean premix combustion design not only produces lower NOx than diffusion flame technology, but also lowers CO and volatile organic compounds (VOC), due to increased combustion efficiency.” It also states, “Stationary combustion turbines do not contribute significantly to ambient CO levels.” Therefore, NOx remains the primary pollutant of concern from gas turbine combustion.

1.2 LITERATURE REVIEW

1.2.1 Dry Low NOx Combustion

In premixed combustion, the fuel and air are mixed at the molecular level prior to burning (RK Cheng et al). The combustion of liquid fuel droplets or solid fuel particles is not premixed and hence premixed combustion is relevant only to gas phase combustion. For practical burners, this primarily means methane or propane burners (RK Cheng et al).

The GE LM 6000 is a popular aero-derivative DLN Combustor.
This combustor uses a configuration of Double Annular Counter Rotating Swirler (DACARS) with a conical centerbody along the centerline of the premixer to supply liquid fuel to an atomizer at its tip. To prevent flashback, this mixer features a reduction in duct diameter towards the premixer exit to create an accelerating flow. The area reduction is about 2:1 (Joshi et al).

The objective of this pre-mixer was to produce a homogeneous mixture of fuel and air at the premixer exit. The LM 6000 pre-mixer shown in the figure has fuel injection holes on the swirl vanes of the outer swirler. Fuel is injected through three holes in the trailing edge of each outer swirl vane and one hole in the outer wall of the mixing duct in between each swirl vane (Joshi et al). To prevent the centerbody from coming in contact with the flame, the centerbody is made shorter than the mixing duct (Joshi et al).
1.2.2 Formation of recirculation zone in swirl stabilized combustion

One of the most effective ways of inducing flow recirculation in the primary zone is to fit a swirler in the dome around the fuel injector (Lefebvre et al). When the amount of rotation imparted to the flow is high, vortex break down happens resulting in flow reversal (Lefebvre et al). This type of recirculation provides better recirculation than is normally obtained by other means such as bluff bodies. The swirler also induces combustion products to flow upstream to meet and merge with the incoming fuel and air (Lefebvre et al).

Erok Kilik studied the influence of swirler design parameters on the aerodynamics of the downstream recirculation region. In his dissertation, he concluded that recirculation region obtained in a swirling flow is an ideal configuration for the primary zone in a combustor; swirlers with curved vanes operate more efficiently than flat vane swirlers as momentum loss is higher in the case of flat vane swirlers; curved vane swirlers lead to better mixing and longer residence times and therefore less pollutant formation.
To characterize the amount of swirl imparted to the flow, Beer and Chigier proposed the non-dimensional swirl number.

\[ S_N = \frac{2 \, G_m}{D_{sw} \, G_t} \]  

(1.1)

If the swirl number is less than 0.4, there is no recirculation and the swirl is weak (Lefebvre). Most swirlers of practical interest operate under conditions of strong swirl (Lefebvre). For an annular swirler with constant vane angle \( \Theta \), the swirl number is given by:

\[ S_N = \frac{2}{3} \left( 1 - \left( \frac{D_{hub}}{D_{sw}} \right)^3 \right) * \tan \Theta \]  

(1.2)

Figure 1.3: Flat vanes vs Curved vanes (Lefebvre)
The recirculation region in a swirling flow is the result of vortex breakdown. Sarpkaya et al reported three types of vortex breakdown namely axisymmetric, spiral and double helix. While the bubble mode happens at high swirl numbers, the spiral mode happens at low swirl numbers. The double helical mode happens only in a diverging tube.

![Image](image.png)

Figure 1.4: Axisymmetric vortex breakdown (Doherty et al, 2001)

Of the three types of vortex breakdown discussed above, the axisymmetric type of vortex breakdown is important for swirl stabilized combustion. In figure, the flow outside $ACB$ is the main flow (positive axial velocity along with swirl). When the swirl number reaches a critical value (>0.4), an adverse axial pressure gradient is formed. This adverse axial pressure gradient brings about reversal of flow and the flow reversal leads to the formation of the Central Toroidal Recirculation Zone (CTRZ). The dotted line AB is the boundary of the CTRZ where the axial velocity is zero. Typical axial and swirl velocity profiles are shown in Figure 1.7. All the velocity components decay in the downstream direction (Lefebvre).
Figure 1.5: A typical swirl flow field (Yang et al, 2009)

Figure 1.6: Main flow and recirculation region (Lefebvre)

Figure 1.7: Typical axial swirl velocity profiles (Lefebvre)
The two main types of swirlers are axial swirlers and radial swirlers.

The design of radial swirlers does not fall within the scope of this thesis. This thesis is confined to the design of axial swirlers and the modifications needed on an axial swirler to adapt it to fuel injection through porous tubes.

An important design requirement is that the swirler should pass the desired airflow rate for a given pressure drop across the swirler. The relation between mass flow rate and the pressure drop is given in equation:

\[
m_{sw} = \left( \frac{2\rho_3 \Delta P_{sw}}{K_{swl} \left( \sec \theta \frac{A_{sw}}{A_{L}} \right)^2 - \frac{1}{A_{L}^2}} \right)^{0.5}
\]  

(1.3)
\[ A_{sw} = \left( \frac{\pi}{4} \right) \times (D_{sw}^2 - D_{hub}^2) - 0.5n_v t_v (D_{sw} - D_{hub}) \] (1.4)

The figure above shows a flat-vaned swirler whose vane angle is constant and equal to \( \theta \). With curved vane swirlers, the inlet blade angle is zero and the outlet angle is \( \theta \).

**Table 1-1: Typical swirler specification values (Lefebvre et al)**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vane angle</td>
<td>30° to 60°</td>
</tr>
<tr>
<td>Vane thickness</td>
<td>0.7 to 1.5 mm</td>
</tr>
<tr>
<td>Number of vanes</td>
<td>8 to 16</td>
</tr>
<tr>
<td>( K_{sw} )</td>
<td>1.3 for flat vanes and 1.15 for curved vanes</td>
</tr>
<tr>
<td>( \Delta P )</td>
<td>4 % of atmospheric pressure</td>
</tr>
</tbody>
</table>
1.2.3 Mixing of Two Jets

Injecting fuel through a slit into a co-flowing air stream is similar to mixing of two streams separated by a shear layer. In this project, gaseous fuel is injected through a porous tube from outside. The gaseous fuel meets the free air stream flowing on the inside of the porous tube. The fuel that is injected through the pores on the porous tube does not have enough momentum to penetrate the air stream. As a result, the fuel grazes the wall and the mixing is controlled by turbulence (Non Mee Boon, 2015).

![Porous tube parallel flow](image)

Figure 1.10: Porous tube parallel flow (Non Mee Boon, 2015)

1.2.4 Fuel injection using Porous tubes

Non-Mee Boon, in his MS thesis, used porous tubes in a swirl injector to inject gaseous fuel. The experimental set-up used in his thesis is shown in Figure 1.11 & 1.12.
Figure 1.11: Experimental set-up for a porous injector (Non Mee Boon, 2015)

Figure 1.12: Sudden flow expansion (Non Mee Boon, 2015)
This porous tube injector uses one porous tube for each swirl vane to inject gaseous fuel. The gaseous fuel from outside meets the air flowing inside the porous tube. In this project, two sets of porous tubes with different porosities are used and it was determined that the porosity size (7 micron and 30 micron) does not influence the fuel air mixing distribution. In this design, the flow suddenly expands as it passes from the porous tube into the swirler leading to a possible recirculation region inside the swirler as shown in Figure 1.12.

1.2.5 Particle Image Velocimetry

PIV is an experimental technique that uses a sheet of laser to illuminate a plane in a flow field for a short duration (of the order of micro-seconds). The flow is seeded with tiny alumina particles. When the laser sheet illuminates a plane in the flow field, a digital camera captures a frame of the flow field and saves it. After a specified time duration (usually a couple of micro-seconds), the laser pulses again and the camera captures another frame of the flow field. The PIV software compares the two frames taken in quick succession to calculate the movement of the tiny alumina particles that were illuminated by the laser pulse. The software uses the displacement of the particles in a given direction and the time duration between the laser pulses to calculate the velocity of the particles in that direction. Since the particles are small enough to faithfully follow the flow, the velocity of the particles at a location is the velocity of the fluid at that location.

The laser pulse acts as a photographic flash for the digital camera. The laser light serves two purposes. It avoids blurred images and helps focus the laser beam into a thin light sheet. A thin light sheet is essential in PIV to illuminate the seeder particles in a plane. To obtain high light
energy within a short duration, a pulsed laser is used in PIV (LaVision website/Velocimetry website). A New Wave Research Solo 120 XT PIV laser is used for this project.

The number of pulses that a laser can deliver per second is the Pulse Repetition Rate of the laser. The Solo 120 XT laser has a repetition rate of 15 Hz. A cylindrical lens generates the thin sheet of laser light from a laser beam to illuminate a plane of the flow field.

Figure 1.13: Particle Image Velocimetry – Concept (Dantec Dynamics)

The number of pulses that a laser can deliver per second is the Pulse Repetition Rate of the laser. The Solo 120 XT laser has a repetition rate of 15 Hz. A cylindrical lens generates the thin sheet of laser light from a laser beam to illuminate a plane of the flow field.
For PIV, a special CCD camera that can transfer the first frame fast enough to be ready to capture the second frame is used. The LaVision Imager Intense PIV camera used for this project has a frame rate of 10 Hz and a resolution of 1376 X 1040 pixels.

The tracer particles chosen for PIV should be small enough to faithfully follow the flow but large enough to scatter the laser beam. The ability of a particle to faithfully follow a flow is given by the Stokes number. In this project, alumina particles are used as tracers.

Measurement volume refers to the area of interest in the flow field. The velocity vectors are obtained only for this area in the flow field.

For vector calculation, the PIV software divides the image into a number of interrogation windows. The default interrogation window is square. The size of the interrogation window is determined such that all particles within this area have moved homogeneously in the same direction and the same distance. For good results, the number of particles within one interrogation window should be at least ten (LaVision). 32 X 32 and 64 X 64 are some of the common interrogation window sizes.

Figure 1.14: Interrogation window (LaVision)
The evaluation of the particle images can be done by ‘Auto correlation’ or ‘Cross correlation’ depending on the way these images were recorded by the PIV camera (LaVision).

If the scattered light of both exposures are recorded in one frame, it is called “Single-frame, Double exposure” and this data is evaluated by auto correlation. The auto correlation function is characterized by two identical correlation peaks rotationally symmetrical about the highest central peak indicating zero displacement. The sign of the displacement cannot be detected in auto correlation as it is not possible to determine which particle is illuminated by the first pulse. The information from the auto-correlation is ambiguous if we do not have prior information about the flow. The detection of very small displacements is a problem as the correlation peaks are very close to the central peak.

![Auto correlation diagram](image)

**Figure 1.15: Auto correlation (LaVision)**

In “cross correlation”, the scattered light from the first and second exposure is recorded in two different frames. The frame is then divided into interrogation windows and each window is evaluated by cross correlation (LaVision). For cross correlation, a double shuttered CCD camera
records images with “double frame, double exposure”. The frame rate of the CCD camera determines the time delay between the laser pulses. Since the second frame cannot be shuttered, the two images have different background intensities and a suitable filter is used along with the camera lens. In comparison with auto correlation, the correlation peak in this method is unambiguous (LaVision).

Figure 1.16: Cross correlation (LaVision DaVis 8.0 Manual, 2011)

Overlap size defines the percentage of overlap (intrusion) between neighboring interrogation windows. The bigger the overlap, the closer the grid of the computed velocity vectors (LaVision). A zero percent overlap means that the interrogation windows do not overlap at all.

A window size of $32 \times 32$ pixel and an overlap of 0% will give a grid size of 32 pixels. In contrast, a window size of $32 \times 32$ pixel and an overlap of 50% will give a grid size of 16 pixels. The position of the first vector at the top left corner of a vector field is determined by the grid size. The convention is that the pixel position ($x/y$) is determined by half the grid size, i.e. if the grid size is 32 pixel, the top left vector is located at the position $(16/16)$ (LaVision). This convention allows
vector arithmetic on vector fields that have been calculated using different interrogation window sizes and same grid size (LaVision).

![Diagram showing vector position depending on overlap size and interrogation window size](LaVision)

Figure 1.17: Vector position depending on overlap size and interrogation window size (LaVision)

The LaVision PIV software allows us to decide whether the vector calculation is done in a “single pass” with constant window size or “multi pass” (with constant or decreasing window sizes). If the vector calculation is done only once, then the operation is said to be “single pass”. The interrogation window size and overlap are user-specified and constant for the single pass operation.

If the vector calculation is done more than once, then the operation is multi-pass. The number of iterations is specified by the user. Multi-pass operations can have a constant or a decreasing interrogation window size. If the interrogation window size is constant, the vector calculation operation is repeated with the same interrogation window size but the vector field information from the previous iteration is used as a reference for the next iteration. The multi-pass operation with constant window size is shown in Figure 1.18. If the interrogation window size is decreasing,
the interrogation window size is halved after each iteration until the final interrogation window size is reached.

Figure 1.18: Multi-pass PIV operation - constant interrogation window size (LaVision)

1.2.6 Formation of NOx

Most of the nitric oxide (NO) formed in combustion subsequently oxidizes to NO₂ (Lefebvre). As a result, NO and NO₂ are combined together and expressed as NOx. The four mechanisms that produce NOx are: thermal NO, nitrous oxide mechanism, prompt NO and fuel NO. Thermal NOx and prompt NOx are of interest in gas turbine combustion and are discussed in this chapter. Thermal NOx is produced by the oxidation of atmospheric nitrogen in high-temperature regions of the flame and in the post-flame gases (Lefebvre). The process is endothermic and it proceeds at
a significant rate only at temperatures above around 1850 K (Lefebvre). Thermal NOx is produced by the extended Zeldovich mechanism which is given below.

\[ \text{O}_2 = 2\text{O} \]  
\[ \text{O} + \text{N}_2 \leftrightarrow \text{NO} + \text{N} \]  
\[ \text{N} + \text{O}_2 \leftrightarrow \text{NO} + \text{O} \]  
\[ \text{N} + \text{OH} \leftrightarrow \text{NO} + \text{H} \]

Thermal NOx increases exponentially with flame temperature and the dependence is shown in the figure. Inlet air temperature and residence time also influence NOx formation.

![Figure 1.19: NOx vs Time (Lefebvre)](image)

Prompt NOx is prevalent in rich flames. Under certain conditions, NO is found very early in the flame region (Lefebvre).


\[ \text{N}_2 + \text{CH} = \text{HCN} + \text{N} \]  \quad (1.9)

Under lean-premixed conditions, the HCN oxidizes to NO mainly by a sequence of reactions involving HCN → CN → NCO → NO (Lefebvre)

The *California Analytical Instruments 600 CLD* emission analyzer is used for the measurement (dry analysis) of NO and NO\textsubscript{2}. The analyzer uses the principle of chemiluminescence for analyzing the NO or NO\textsubscript{x} concentration of a gaseous sample. In the NO mode, the chemiluminescent reaction between ozone and NO produces NO\textsubscript{2} and oxygen. The intensity of the light produced by this reaction is proportional to the mass flow rate of the NO\textsubscript{2} into the reaction chamber and is measured by a photodiode and amplification electronics. In the NO\textsubscript{x} mode, an internal NO\textsubscript{2} to NO convertor converts the NO\textsubscript{2} in the sample to NO and then the NO concentration is measured like it is done in the NO mode.

The *California Analytical Instruments 600 NDIR* emission analyzer is used for the analysis of CO and CO\textsubscript{2}. The method of operation is based on the infrared absorption characteristics of the gas. The analyzer uses a single infrared beam to measure the gas concentration. The beam is modulated by a chopper system and is passed through a sample cell of predetermined length containing the gas sample (CO/CO\textsubscript{2}). As the beam passes through the cell, the sample gas absorbs some of the energy of the beam. The attenuated beam is then introduced into the front chamber of a two-chamber infra-red microflow detector filled with the sample gas. As a result, the beam experience further absorption of energy and the pressure increases in both the chambers. The differential pressure between the front and rear chambers triggers a gas flow between the chambers. A mass flow sensor detects this gas flow and converts it into an output signal.
1.3 SCOPE OF THE THESIS

The objective of this thesis is to design and test the performance an axial swirler that makes use of porous tube fuel injection. The swirler differs from conventional axial swirlers in the method of fuel injection. The swirler designed in this thesis incorporates a passage that facilitates a smooth transition of flow from the porous tube to the swirler. It is this transition region that differentiates this swirler from conventional axial swirlers.

In Chapter II, the design of the swirler and the experimental set-up are discussed. The PIV set-up that is used to study the pre-mixer aerodynamics is discussed along with the set-up used for combustion testing.

In Chapter III, the results of the PIV, flame imaging and emission results are discussed. 2D PIV is used to characterize the axial, radial and tangential velocities. To measure the radial and tangential velocities, horizontal plane PIV is done. Axial velocity data and Horizontal plane PIV results are discussed. A parametric study of center-bodies is conducted to attempt to prevent the recirculation zone from coming in contact with the injector tip. Combustion testing is done for flame characterization and NOx emission measurements. The flame images are shown and the NOx emission results are discussed.

In Chapter IV, future work and recommendations are discussed. A CFD model is attempted using ANSYS Fluent and the scope for future CFD work is discussed.
2. EXPERIMENTAL SET-UP

2.1 SUMMARY

The design and testing of this pre-mixer was done at the Combustion and Fire Research Laboratory (CFRL) located at the off-campus research facility in Center Hill. The CFRL has eight test cells. The aerodynamics and combustion testing of this injector was done at Cells 1 & 2 respectively. CFRL has a main compressor that supplies air at a pressure of 150 psi with a maximum flow rate of 2 lb/s. The compressor has a de-moisturizing system and a reservoir. The air enters the test cells through a 4” pipe. A pressure regulator is used at the entrance of the test cell to control the mass flow rate. The test cells have an exhaust blower to prevent inhalation of any hazardous smoke resulting from combustion. The design and assembly of the pre-mixer is also discussed in this section. The pre-mixer is an assembly of five components and eight porous tubes.

2.1.1 Pre-mixer design

Three pre-mixers are designed as part of this project. Each pre-mixer is an assembly of an axial swirler, a centerbody and shroud. A plastic pre-mixer (Pre-mixer I) is designed based on 1-D calculations and rapid proto-typed in ABS. In this pre-mixer, the design feasibility to achieve a smooth transition from the circular cross sectional area to the trapezoidal inter-vanal space is checked. Cold flow PIV is conducted for this plastic pre-mixer and the results are used to optimize the design of the swirler. Based on the PIV results, the design of the swirler and mixing length are optimized. The redesigned pre-mixer (named pre-mixer II) is rapid proto-typed in plastic. Pre-mixer II has a different vane profile, centerbody and shroud when compared to Pre-mixer I. The comparison between Pre-mixer I and Pre-mixer II is shown in the Figure 2.2. Cold flow PIV is
conducted for this swirler (pre-mixer II). After studying the cold flow PIV results of the plastic pre-mixer (Pre-mixer II), it is rapid proto-typed in metal (316L Stainless Steel). There is no difference in terms of geometry between pre-mixer II and pre-mixer III. The geometry of the swirler, centerbody and shroud are the same for pre-mixer II and pre-mixer III. Since Pre-mixer II is used only for cold-flow measurements, it does not have the set-up for porous tubes that is present in Pre-mixer III. Pre-mixer III assembly is shown in Figure 2.4.

The metal pre-mixer (Pre-mixer III) is used only for combustion testing. For cold flow PIV, the plastic swirlers are used without the porous tubes as there is no fuel-air mixing (no combustion) in a non-reacting case PIV. The axial swirlers designed in this thesis differs from conventional axial swirlers in the method of fuel injection. This is shown in Figure 2.5 & 2.6. The number of vanes in these axial swirlers are the same as the design done by Non-Mee Boon to facilitate carry over of some auxiliary parts. In conventional axial swirlers, there are holes on the vanes that serve the purpose of fuel injection (refer GE DLN combustors). In the axial swirlers used in this project, gaseous fuel is injected through porous tubes (made of sintered stainless steel) aligned in the axial direction. The porous tubes are directly connected to the space between the vanes. Since the porous tubes are circular in cross section and the inter-vane space is trapezoidal, the flow needs to transition from a circular cross section to a trapezoidal cross section. This is achieved by incorporating a passage that helps the flow transition from a circular cross sectional area to a trapezoidal cross sectional area as shown in Figures 2.5 & 2.6.
The plastic pre-mixer I is shown in the Figure 2.3. Pre-mixer I is a prototype built for this project and the PIV results of this pre-mixer were used to optimize the design of the pre-mixer. The feasibility of providing a circular to trapezoidal transition was checked using pre-mixer I.

![Pre-mixer I mounted for cold-flow PIV](image1.jpg)

**Figure 2.1:** Pre-mixer I mounted for cold-flow PIV

![Comparison between a configuration of Pre-mixer I and Pre-mixer II](image2.jpg)

**Figure 2.2:** Comparison between a configuration of Pre-mixer I and Pre-mixer II (right)
Upstream and downstream side of the axial swirler

Axial swirler modified for porous tube fuel injection

Figure: A cross section of the pre-mixer assembly

Centerbody
Shroud
Axial Swirler
Air
Air
Air

Figure 2.3: Plastic Pre-mixer II used for cold flow PIV

Figure 2.4: Metal Pre-mixer III design (for combustion testing)
Figure 2.5: Axial swirler design used in Pre-mixers II & III (downstream and upstream views)

Figure 2.6: Circular to trapezoidal transition of the swirler in Pre-mixers II & III
2.1.2 Challenges in using porous tubes for fuel injection

A conventional axial swirler is designed to pass the desired mass flow rate at a given pressure drop. The diameter of the swirler is varied to achieve the desired mass flow rate at a given pressure drop. In this swirler, an increase in the diameter of the swirler will not lead to an increase in mass flow rate because the effective area of this swirler is determined by the diameter of the porous tubes that are used for fuel injection. In addition to this, the additional length of the premixer needed to accommodate the porous tube leads to an increase in resistance to air flow.

Since the objective of this project is to offer a proof of concept for porous tube fuel injection, the diameter of the swirler and the hub were adjusted to match the cross sectional area of the porous tube with the area of the space between two swirl vanes. This was done to make sure the velocity
of the fuel-air mixture does not decrease as it moves from the porous tube to the swirl vanes. The calculations done to determine the dimensions of the swirler, centerbody and shroud are shown in the Appendix section.

Figure 2.8 (left): Metal swirler (Pre-mixer III) with the centerbody

Figure 2.9 (right): A picture of all the pre-mixer III components before assembly

Figure 2.10: The plastic swirler (Pre-mixer II), centerbody and shroud used for cold flow PIV
2.1.3 Specifications of the axial swirler

The axial swirler has eight curved vanes with a vane outlet angle of 60° and a vane incidence angle of 0°. The stagger angle for the vane is 30°. The curved vane follows a circular arc of radius 17.3 mm. The swirler has central blading and the vanes do not have any holes for fuel injection. The vanes have a constant thickness of 1.5 mm. The trailing edges of the vanes have fillets and the vane outlet angle was measured before the fillets were given.

Figure 2.11: Vane profile showing vane outlet angle of 60° and stagger angle of 30°
Figure 2.12: Premixer III CAD assembly showing the mounting plate and confinement

2.2 PIV EXPERIMENTAL SET-UP

LaVision DaVis 8 PIV system is used for cold-flow velocity measurements. Alumina is used as the seeder for the PIV measurements. The particle seeder is connected to the air line and the alumina particles mix with the air from the compressor upstream of the pre-mixer. The air line is connected to the air plenum on top of which the pre-mixer is mounted. A New Wave Research Solo 120XT PIV laser is used for illuminating the seeder particles and a LaVision Imager Intense CCD camera is used for capturing the images. PIV is conducted with and without a combustion chamber. The back-side of the combustion chamber that faces the camera is coated with black paint to reduce reflections that affect the quality of the PIV measurements. Similarly, for horizontal
plane PIV, the pre-mixer itself is coated with black paint to avoid reflections. Before recording, the camera lens is focused on the seeder particles using the “live mode” and calibration is performed by using the PIV calibration plate. Lights are switched off before recording. The PIV laser is adjusted to a high power mode that delivers 48 mJ per pulse at 532 nm. 200 images are taken for the case without combustion chamber. For the case with combustion chamber, the number of images is reduced as the seeder particles soil the glass combustion chamber. The cross correlation method is used to process PIV data. A constant interrogation window size of 32 X 32 with an overlap of 50% and a two-pass processing is used for the processing of images.

2.3 COMBUSTION EXPERIMENTAL SET-UP

Flame imaging and emission measurement are done at cell 2 of CFRL. The flame images are captured using the PIV camera. The test rig has a 24 kW heater that can preheat air upto 850°F. For measuring the dry NOx values, an oil cooled emission testing probe is placed 6 inches above the exit of the pre-mixer. The temperature of the probe is maintained at 230 °F to avoid water condensation. The sample is passed through a filter that is maintained at 350 °F and then through a chiller. The probe is used to measure the emissions at three locations, one inch apart, along a straight line in the middle of the combustion chamber. The emission values were then averaged and the average was used for the plots between NOx and Adiabatic flame temperature.
Figure 2.13: PIV Experimental set-up
3. RESULTS AND DISCUSSION

3.1 PRE-MIXER AERODYNAMICS

The aerodynamics of this pre-mixer was studied using non-reacting flow Particle Image Velocimetry (PIV). A plastic pre-mixer was rapid prototyped using ABS (Acrylonitrile-Butadiene-Styrene) material. Since no fuel is needed for non-reacting flow PIV, the porous tubes were not needed for studying pre-mixer aerodynamics. PIV was conducted using the swirler-centerbody-shroud assembly without the set-up needed for porous tubes.

3.1.1 PIV results

PIV measurements were conducted along the middle axial plane to measure the axial velocity. The velocities were measured with a confinement (a glass chamber) and without confinement.

Figure 3.1: Unconfined case PIV with the alumina seeding particles
The maximum axial velocity is around 55 m/s for the unconfined case. The pre-mixer exhibits a strong recirculation zone with reversed axial velocities reaching 5 m/s. The axial velocity decreases as the axial distance from the pre-mixer exit increases. As un-swirled air is injected through the centerbody, the axial velocity near the centerbody is positive and is about 20 m/s. It is evident from the contour plot that air injection through centerbody does not fully prevent the recirculation zone from coming in contact with the centerbody. It is likely that a part of the centerbody is in contact with recirculation zone.

Figure 3.2: Time averaged Axial velocity at 4% pressure drop - Unconfined case

The maximum axial velocity is around 55 m/s for the unconfined case. The pre-mixer exhibits a strong recirculation zone with reversed axial velocities reaching 5 m/s. The axial velocity decreases as the axial distance from the pre-mixer exit increases. As un-swirled air is injected through the centerbody, the axial velocity near the centerbody is positive and is about 20 m/s. It is evident from the contour plot that air injection through centerbody does not fully prevent the recirculation zone from coming in contact with the centerbody. It is likely that a part of the centerbody is in contact with recirculation zone.
For the confined case, the flow gets attached to the wall of the confinement at about 20 mm from the pre-mixer exit. The maximum velocity is seen at the exit of the swirler (main flow) and it is close to 60 m/s. The maximum reversed velocity is -13 m/s. The confined case has a much wider recirculation zone and the recirculation zone reversed velocities are stronger compared to the unconfined case. The confined case too has a positive axial velocity at the center because of axial air injection through the center body. In the confined case too, the recirculation zone appears to come in contact with the exit of the burner.
For both confined and unconfined cases, axial velocity data along the diameter of the pre-mixer was extracted from the PIV data taken 3.5 mm above the exit of the pre-mixer. The axial velocity was plotted against the radial distance. This graph verifies that the maximum axial velocity is 60 m/s for the confined case. The graph for the confined case also shows a dip in axial velocity (reversed velocities) at a radial distance of 5 mm from the center of the pre-mixer. This indicates that there is reversed flow near the centerbody. Because of axial air injection, velocities at the center of the pre-mixer are around 20 m/s for the confined case.

At a distance of 23.5 mm above the pre-mixer exit, the peak axial velocity is around 35 m/s and a strong recirculation zone about 20 mm in width is present with reversed axial velocities exceeding 10 m/s.

For the unconfined case, the maximum axial velocity along the diameter (3.5 mm above pre-mixer exit) is 55 m/s. Velocities at the center of the pre-mixer are around 35 m/s - much higher than the velocities of the confined case. At a radial distance of 5 mm from the center of the pre-mixer, reversed flow is present.
Figure 3.4: Confined case - Axial velocity variation with radial distance at 3.5 mm above premixer exit

Figure 3.5: Unconfined case - Axial velocity variation with radial distance at 3.5 mm above premixer exit
3.1.2 Horizontal plane PIV results

Horizontal plane PIV was conducted by putting the PIV camera on top of the pre-mixer and using the PIV laser to illuminate the horizontal plane. A set of measurements was taken 5 mm above the pre-mixer exit and another set was taken 15 mm above the pre-mixer exit.
Figure 3.7: Horizontal plane PIV showing the PIV camera mounted on top

Figure 3.8: Horizontal plane PIV showing the illuminated seeder particles on the horizontal plane
Figure 3.9: Horizontal plane PIV - Tangential velocity profile
The tangential and radial velocities were measured at two locations i.e 5 mm above pre-mixer exit and 15 mm above pre-mixer exit. 2D PIV measures the components of velocities along the X and Y axis. The PIV software does not directly give the tangential and radial velocities. To extract the tangential velocity from the velocity components along the X and Y axes, a MATLAB code was used and the data was post-processed using the visualization software Tecplot. However, along the diameter of the swirler, the X-velocities and Y-velocities directly give the tangential and radial velocities. If the diameter coincides with or is parallel to the X-axis, the Y-component of the velocity is the same as the tangential component of velocity and the X-velocity component gives the radial component of velocity along the diameter. If the diameter coincides with or is parallel to Y-axis, the X-component of velocity is the same as the tangential velocity and the Y-component of velocity gives the radial velocity. This is illustrated in the figure below. Line plots were drawn by extracting the X velocity and Y velocity components along the two diameters of the pre-mixer exit parallel to X and Y axes. These line plots were used to get a sense of the tangential and radial velocities along the diameter.
A line-scan along the diameter parallel to Y-axis tells us that the maximum tangential velocity is close to 40 m/s and the distribution is nearly symmetric. The radial velocity shows a somewhat asymmetric distribution with the maximum radial velocity being 20m/s.

Figure 3.10: Radial and tangential velocity along the diameter of the pre-mixer
Figure 3.11: Tangential velocity along the diameter on Y-axis – 5mm above pre-mixer exit

Figure 3.12: Radial velocity distribution along the diameter on Y-axis – 5mm above pre-mixer exit
Figure 3.13: Tangential velocity distribution along the diameter on X-axis

Figure 3.14: Radial velocity distribution along the diameter on X-axis
3.1.3 Parametric study of centerbodies

Since the axial velocity profile at the exit of the pre-mixer suggests that some part of reversed flow is coming in contact with the exit of the pre-mixer, four configurations of centerbody were rapid-prototyped in plastic and cold-flow PIV was conducted to study the velocity distribution and the recirculation zone. The goal of this parametric study was to find out if there is a centerbody configuration that pushes the recirculation zone away from the exit of the injector. This study was done with the combustion chamber (with confinement).

The recess distance which is the distance by which the centerbody is “recessed” into the outercone is varied along with the shape of the hole in the centerbody that is used for axial air injection. The recess distance was changed by changing the height of the centerbody.

Table 3-1: Parametric study of bluff bodies

<table>
<thead>
<tr>
<th>Configuration Name</th>
<th>Centerbody hole</th>
<th>Recess distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>S4</td>
<td>Straight</td>
<td>4 mm</td>
</tr>
<tr>
<td>S2</td>
<td>Straight</td>
<td>2 mm</td>
</tr>
<tr>
<td>D4</td>
<td>Diverging</td>
<td>4 mm</td>
</tr>
<tr>
<td>D2</td>
<td>Diverging</td>
<td>2 mm</td>
</tr>
</tbody>
</table>
Figure 3.15: Parametric study of center-bodies

Figure 3.16: Comparison between Straight hole and Diverging hole center-bodies
Figure 3.17: S2 configuration axial velocity profile (time averaged)

Figure 3.18: D4 configuration axial velocity profile (time averaged)
Figure 3.19: S4 configuration axial velocity profile (time averaged)

Figure 3.20: D2 configuration axial velocity profile (time averaged)
Figure 3.21: S4 configuration - Axial velocity vs Radial distance

Figure 3.22: S2 configuration - Axial velocity variation with radial distance
From the axial velocity profile of the four configurations, it is evident that S4 comes the closest to pushing the recirculation away from the exit of the injector. S4 centerbody pushes the recirculation zone away on one side but the recirculation zone still remains attached to the burner on the other side. The variation of axial velocity profile 5 mm above the exit of the injector with respect to radial distance was plotted for two configurations S4 and S2. The peak axial velocity through the S2 centerbody was around 65 m/s. On the other hand, the axial velocity through the S4 centerbody is 55 m/s. Since the S4 configuration has a recess distance of 4 mm, the axial flow through the centerbody starts interacting with the swirl flow earlier than the S2 configuration which has a recess distance of 2 mm. As the flow starts to interact with the swirl flow earlier than S2 configuration, the axial velocity slows down by 10 m/s for the S4 configuration. The flow from the S4 centerbody also diverges and this is the reason why the recirculation zone is pushed farther from the exit of the injector on one side. For the D2 and D4 configurations, the axial velocity is low and the recirculation zone remains fully attached to the exit of the injector on both sides.
3.2 COMBUSTION TESTING

3.2.1 Flame characterization

The PIV camera is used to take images of the flame at different equivalence ratios and pre-heat temperatures. The flame images are shown in Figure 3.23. At an equivalence ratio of 0.55, the flame is present in the recirculation zone and regions with low positive axial velocities because of the lower turbulent flame speed. As the equivalence ratio is increased, the flame becomes brighter because of higher heat release. The reaction zone is approximately 75 mm in length for the cases where the equivalence ratio is 0.65.
3.2.2 NOx emission measurement

The NOx emissions are measured at three different air pre-heat temperatures namely 400 °F, 500 °F and 600 °F. For each pre-heat temperature the emissions are measured at three different equivalence ratios namely 0.55, 0.6 and 0.65. The emission is measured at three locations along a

Figure 3.23: Flame imaging
straight line inside the combustor and the emissions are averaged. The measurements are done at a pressure drop of 4%. The air flow rate is calculated at different pre-heat temperatures and the corresponding fuel-flow rate is calculated for a given equivalence ratio. The air flow rates and fuel flow rates at different pre-heat temperatures and equivalence ratios are given in the table below.

Table 3-2: Air flow rate and Fuel flow rate at different pre-heat temperatures

<table>
<thead>
<tr>
<th>Air pre-heat Temperature</th>
<th>Air flow rate (lb/hr)</th>
<th>Fuel flow rate (lb/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>°F</td>
<td>K</td>
<td>Φ0.55</td>
</tr>
<tr>
<td>400</td>
<td>477.59</td>
<td>141.95</td>
</tr>
<tr>
<td>500</td>
<td>533.15</td>
<td>134.35</td>
</tr>
<tr>
<td>600</td>
<td>588.71</td>
<td>127.86</td>
</tr>
</tbody>
</table>

The adiabatic flame temperature is calculated for a given temperature and equivalence ratio using an online tool ([Adiabatic Flame temperature calculator, CERFACS website](http://cerfacs.toulouse.fr)) and the NOx values are plotted as a function of the Adiabatic Flame Temperature. The NOx values (dry) are corrected to 15% O2 based on Equation 2.0 and both the values are shown in the plot in Figure 3.24. For an Adiabatic Flame Temperature of 2900 °F, the NOx emissions are around 2.5 ppm.

\[
X_{NOx,dry\ (15\%\ O2)} = (X_{NO(dry)} + X_{NO2(dry)}) \cdot \frac{20.9 - 15}{20.9 - X_{O2,\%\ dry}}
\]  

(2.0)
Figure 3.24: NOx vs Adiabatic Flame Temperature
CFD simulations can be used to identify a center-body configuration that pushes the recirculation zone fully away from the pre-mixer exit. Initial simulations were run for this purpose using ANSYS FLUENT. The flow domain is shown in the figure below.

The CFD model needs further refinement to be able to predict the center-body configuration that prevents the recirculation zone from attaching to the pre-mixer exit.

Figure 4.1: CFD flow domain for the pre-mixer
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APPENDIX

Cross sectional Area of the eight porous tubes

Radius of the porous tube = 4.5 mm

Cross sectional Area $A = \pi r^2$

$A = \pi \times 4.5 \times 4.5 = 63.585 \, mm^2$

Area of the eight porous tubes $= 63.585 \times 8 = 508.68 \, mm^2$

Area of the trapezoidal space between the vanes

The area of the trapezoidal space between the vanes can be directly measured by Solidworks

Area of the trapezoidal space between two vanes $= 78 \, mm^2$

Area of the trapezoidal space between the vanes for the swirler $= 78 \times 8 = 624 \, mm^2$

Increase in Area as the circular hole transitions into a trapezoidal space

$= \frac{624}{508.68} = 1.226 = 22.6\%$.

As the air-fuel mixture moves from the circular hole to the trapezoidal space, the velocity comes down by 22.6\%

Area of the annulus between the shroud and centerbody

Both the centerbody and the shroud resemble the frustum of a right circular cone. The annulus area is the area between the centerbody and the shroud at the top surface of the centerbody. To prevent a reduction of velocity as the air-fuel mixture moves downstream from the trapezoidal space between the vanes, the desired annulus area is $624 \, mm^2$. 
The base diameter of the centerbody is decided by the inner diameter (hub diameter) of the swirler and is 31 \( mm \). The top circle diameter \( D_2 \) of the centerbody is 7 mm (hole diameter of 5 mm and 1 mm thickness for rapid prototyping). The Area of the shroud at the top surface of the centerbody is \( A_1 \).

The circular area at the top of the centerbody = \( A_2 = \pi \times 3.5 \times 3.5 = 38.46 \, mm^2 \)

The annulus area is given by \( A_1 - A_2 = 624 \, mm^2 \)

The desired area of the shroud at the top surface of the centerbody is \( A_1 = 624 + 38.46 = 662.46 \, mm^2 \).

Radius of the shroud at the top surface of the centerbody = \( \sqrt{\frac{662.46}{\pi}} = 14.52 \, mm \)

From the radii of the centerbody and shroud, the cone angles are calculated. The centerbody cone angle and the shroud cone angle are 62.45 ° and 74.97 ° respectively.

**Mass flow rate calculation for a given pressure drop**

The mass flow rate at a given pressure drop is given by \( Q_m = \rho \times C_d \times A \times \sqrt{\frac{2\Delta P}{\rho}} \)
Figure 4.2: Centerbody
Figure 4.3: Mounting plate
Figure 4.4: Shroud
Figure 4.5: Ring
Figure 4.6: Bottom plate