Flow Field Characterization in a Liquid-Spray Swirl Combustor

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Swirl combustors are used extensively in gas turbine engines for power generation and propulsion. The flow field generated by airflow entering the combustor through a swirler plays a central role in influencing the stability of the turbulent flame as well as combustion efficiency and emissions generation. Understanding the flow patterns and velocity distribution of the flow field can provide vital information to optimize combustion performance and stability. This work presents results from experimental approaches to visualize and quantify the swirling flow field using hot-wire anemometry (HWA) and Particle Image Velocimetry (PIV). The relative advantages and drawbacks of each technique are discussed followed by results obtained from each measurement approach. The flow field was visualized to have an inner recirculation zone in the center of the combustor and an outer recirculation zone around the bottom edge of the combustor. Results are presented for cold flow conditions.

I. Introduction

Swirl combustors are used extensively in gas turbine engines for propulsion and power generation, given their high flame stability, minimal emissions, and high combustion efficiency. Within the swirl combustor, air is injected at an angle, called the swirl angle, creating a swirling motion. The swirling flow creates recirculation zones and generates turbulence, which enhances mixing, ensuring stable combustion and reducing the formation of nitrogen oxides (NOx) and carbon monoxide (CO). Their compact design and reliability make them a common choice for aerospace applications where space and weight are critical factors.

There are many ongoing research areas with swirl combustors, such as efforts to reduce emissions, improve combustion efficiency and stability, utilize alternative fuels, and employ advanced manufacturing techniques permitting improved performance through innovative design features. One way to improve efficiency is by visualizing the flow field to identify recirculation zones. Analyzing the flow field can be beneficial, as we can check where the recirculation zones are and optimize the interaction between the flame front and recirculation zones. Recirculation zones help prolong the residence time of the reactants by redirecting them back into the flame, allowing for more thorough mixing and combustion. This information can allow engineers to optimize parameters such as the position of the fuel injectors, or the swirl angle to enhance recirculation and prolong residence time. Identifying recirculation zones also provides insight into the flame behavior, shape, and stability, as recirculating hot gases help stabilize the flame. This information can allow engineers to design a combustor that has flame stabilizing features to prevent flame blowout at lean conditions known as lean blow out (LBO).

This paper will focus on visualizing, analyzing, and comparing the flow field within the combustor using two diagnostic techniques: Hot-Wire Anemometry (HWA) and Particle Image Velocimetry (PIV). Not only will we be comparing the two techniques, but we will also be comparing the data gathered with established observations of the swirling flow field such as those presented by Dinesh, et al. and Ravi. From Fig 1(a), we can see that there will be recirculation zones in the corners of the combustor, as well as the center. We should see similar results from using PIV.

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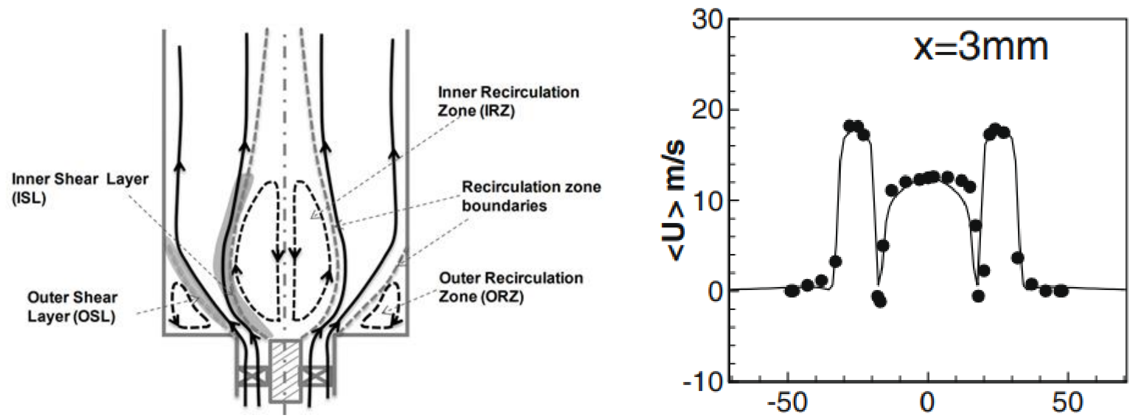
We can also expect to see sharp changes in velocity where the recirculation zone border is located, as shown in Fig. 1(b). Because HWA isn't known to be good at measurements at precise locations, we don't expect to capture the recirculation zone border, but we should see a similar velocity pattern everywhere else.



a) Recirculation zones within swirl combustor [1] b) Velocity pattern vs radial distance from centerline. [2]

Fig 1. Expected results from each flow measurement technique.

II. Diagnostic Techniques

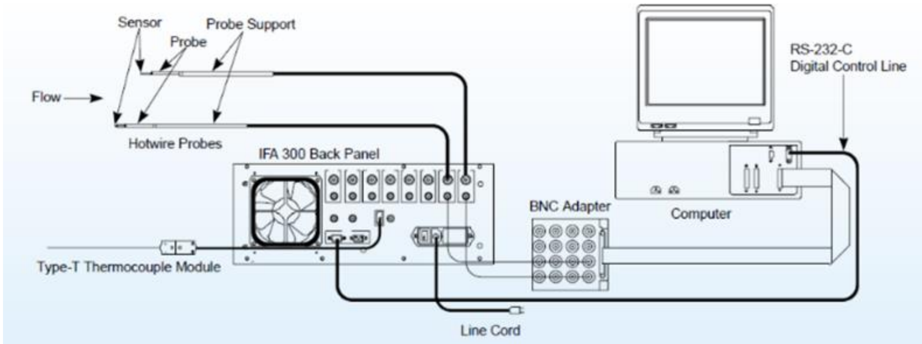
A. Hot-Wire Anemometry

Commonly used in fluid mechanics research and aeronautics, hot-wire anemometry is a diagnostic technique that operates by passing a current through a hot-wire probe, a probe with a thin wire or thin film, placed in a flow field. The anemometer then keeps the wire/film at a constant temperature by automatically increasing or decreasing the current, by changing its voltage output. Fig. 2 shows a schematic of the TSI IFA 300 hot-wire anemometer system used in this work.

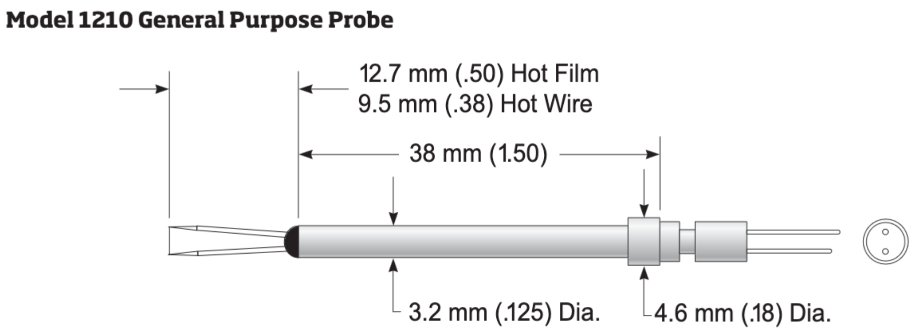
One of the reasons HWA is a popular choice for measuring velocity in a 1-dimensional flow field is because optical access is not necessary for it to work. HWA is also commonly used for measuring turbulence for its high temporal resolution, up to 500 kHz, and ability to capture rapid velocity fluctuations. However, there are also many disadvantages to using HWA, such as it being an intrusive technique. Having to stick a probe into the flow could disrupt the flow field and induce or increase turbulence where there shouldn't be. Positioning the probe in the right place is difficult and doing it by hand is not precise. Because the wire's diameter is in the order of microns, the wire is fragile and is susceptible to breaking if any particulates, such as dust, are present in a high-velocity flow. The wire's fragility is what makes it hard to physically work with, so the user must be very careful. Overall, HWA is best used for 1-dimensional flow applications but requires proper calibration and care for the probe.

Although there are 2-D and 3-D probes, they have some pros and cons that must be weighed to decide whether to use them. Higher dimension probes are often larger and are more intrusive to the flow than 1-D probes. They are also more expensive as they are more difficult to manufacture, making them less cost-effective compared to 1-D probes. The most difficult process of using 2-D and 3-D probes is the alignment of the wires. When aligning the wires on 2-D and 3-D probes, there is usually only one orientation that allows for correct measurements of the flow. In our case, we couldn't use a 2-D probe because of a lack of mounting space within the swirl combustor.

Before hot-wire probes can be used for measurement, they must be calibrated at least once a year, as these probes wear out over time due to usage, environmental conditions, and electronic drift. For this experiment, the hot-wire probe was calibrated using an air velocity calibrator, a device that allows us to precisely control the velocity of airflow, as shown in Fig. 3. The probe is inserted at the top hold and oriented so that the probe is lying horizontally to the ground and the wire completely exposed to the airflow. The pressure transducer is also connected to the air velocity calibrator, which measures the pressure in the calibrator and estimates velocity using Bernoulli's equation. The TSI program, ThermalPro, is then used to collect velocity and voltage data to create an equation that relates voltage and velocity. After calibration, the same program can be used for data acquisition.



a) Schematic of hot-wire anemometer system [3]



b) 1-D hot-wire probe [4]

Fig 2. Hot-wire Anemometer System

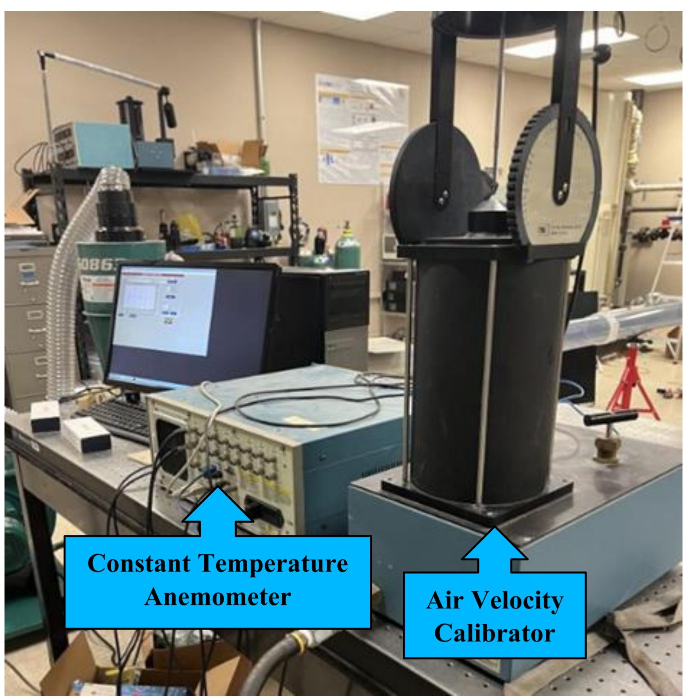


Fig 3. Hot-wire probe calibration setup.

B. Particle Imaging Velocimetry

PIV is another diagnostic technique that operates by introducing seeding particles into the flow. These particles must not alter the flow significantly and must flow seamlessly with the fluid, meaning it must have a Stokes number (Stk) less than 0.1, which results in an error that is less than 1%.

$$Stk = \frac{t_0 u_0}{l_0} \tag{1}$$

$$t_0 = \frac{\rho_p \, d_p^2}{18 \, \mu_g} \tag{2}$$

The Stokes number, defined in Eq. (1) is a dimensionless parameter in fluid mechanics that represents the ratio of a particle's response time to the characteristic time scale of the flow, indicating the particle's ability to follow the fluid motion. The variables for Eq. (1) are t_0, the time constant for the exponential decay of the particle to due drag, u_0, the free stream fluid velocity, and l_0, the characteristic length. The variables for Eq. 2 are ρ_p, density of particle, d_p, particle diameter, and μ_g, fluid dynamic viscosity.

The seeding particles must then be illuminated with a laser sheet, which should only be powerful enough to illuminate a 2-dimensional plane in the fluid. A camera is then used to capture multiple images of the illuminated plane in quick succession, consisting of 2 frames with a time difference of our choosing, typically 10 microseconds, which are then processed by the DaVis program. Using sophisticated algorithms, this program identifies the position of the particles in each image and tracks their movement between each frame. This displacement between each frame is then used to calculate the velocity vectors at each point in the illuminated plane.

The advantage of using PIV is that it's a non-intrusive method that keeps the flow exactly as is. It is also accurate when it comes to visualization of flow structures due to its high spatial resolution. Its large field of view also allows more area to be measured, which allows researchers to study the interactions between different flow regions. Because of its accuracy, PIV is also commonly used to validate and refine theoretical models and computational simulations of fluid flow.

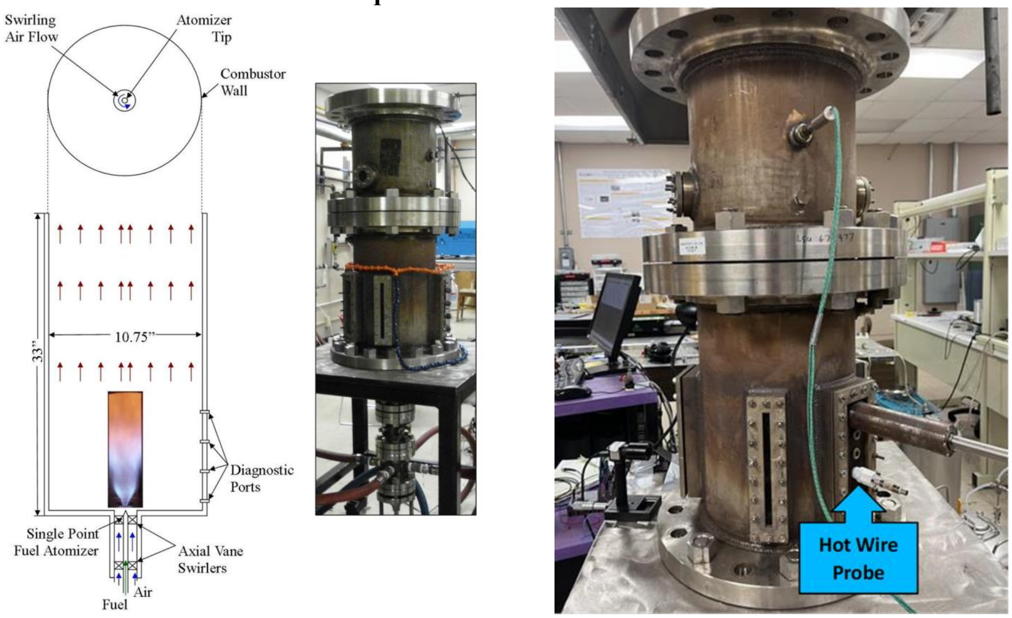
Although PIV is a popular choice in fluid dynamics, it has a few drawbacks. One major issue is the many complexities in particle seeding. To make accurate measurements, you must have the right density of particles to allow the laser to pass through a certain depth. The particles could also clump together if the airflow is not completely dry, which could lead to non-uniform seeding densities. If the particles are too densely packed, the accuracy could drop as the program will have trouble identifying each particle. Some other issues involve laser safety, primarily concerned with damage to the skin and eyes. Before using the laser, users typically must be certified for Class 4 lasers.

The correct choice of seeding particles must also be made. Seeding particles must be able to flow seamlessly with the fluid to ensure accurate readings. For seeding in flames and combustion, the particles must be able to withstand high heat and must not chemically react. The particles must also be smaller than what is used for air, as combustion produces smaller eddies and higher velocities, which requires smaller particles for accurate velocity measurements. Because the flames can be highly luminous, the particles must also have the right light-scattering properties to be visible against the bright flames.

Overall, PIV is very accurate and provides a significant amount of flow information but requires a lot of preparation and consideration from the users to utilize effectively.

III. Experimental Setup

A. Liquid-fueled swirl combustor



a) Liquid-fueled swirl combustor setup [5]   b) Hot-wire probe placement on combustor

Fig 4. Swirl combustor setup.

A single-stage liquid-fuel swirl-stabilized spray combustor was used in the present work. The combustor is currently being used on a project to study combustion stability and emissions while operating on Sustainable Aviation Fuels (SAF). The combustor is supplied with compressed air which passes through a swirler and into which a spray of liquid fuel is injected using a single-point pressure-atomizer. The combustor provides access points for various measurements including temperature and pressure. Fig. 4(b) shows the hot wire probe inserted into one of the access points. The combustor also provides optical access through four windows allowing the use of laser sheets and cameras to image the flow and combustion processes within the combustor.

B. Hot-Wire Setup

The setup for the experiment to use the HWA is like the calibration setup. We have all the hardware from Fig. 3(a) placed nearby, but now we mount the probe into the swirl combustor as shown in Fig. 4(b). The mount allows us to easily slide the hot-wire probe in and out and change the height of the probe. This allows us to probe the air velocity at various radial and axial locations.

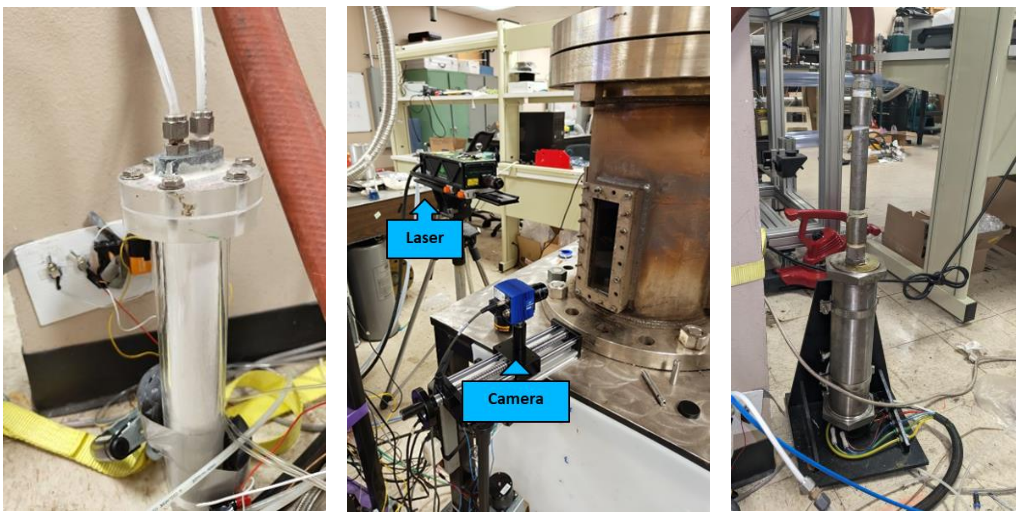
C. Particle Imaging Velocimetry

The PIV setup consists of the pulsed dual-head laser (EverGreen 200, Energy 200 mJ) that illuminates the particles, the particle seeder, as shown in Fig. 5(a), the camera (Imager CX-5, Max. resolution 2440 x2040), as shown in Fig. 5(b), and the computer with the DaVis program. The camera and the laser are pointed toward the swirl combustor where there is optical access and are aimed perpendicular to each other, as shown in Fig. 5(b). The particle seeder is connected to one of the air input lines at the bottom of the swirl combustor. Two particle seeding techniques were investigated in this work, one using liquid oil droplets, and the other utilizing hollow glass spheres. Table 1 provides a comparison of the conditions used for each seeding setup and Fig. 6 shows B&W images of the seeding from each approach as illuminated by the laser sheet. We can see that for liquid particles, it has a higher particle density while having finer particles due to its smaller size. From Table 1, we should expect oil to give a more accurate flow field due to its much smaller Stokes Number compared to hollow glass spheres.

Table 1: Stokes numbers of different particle seeding

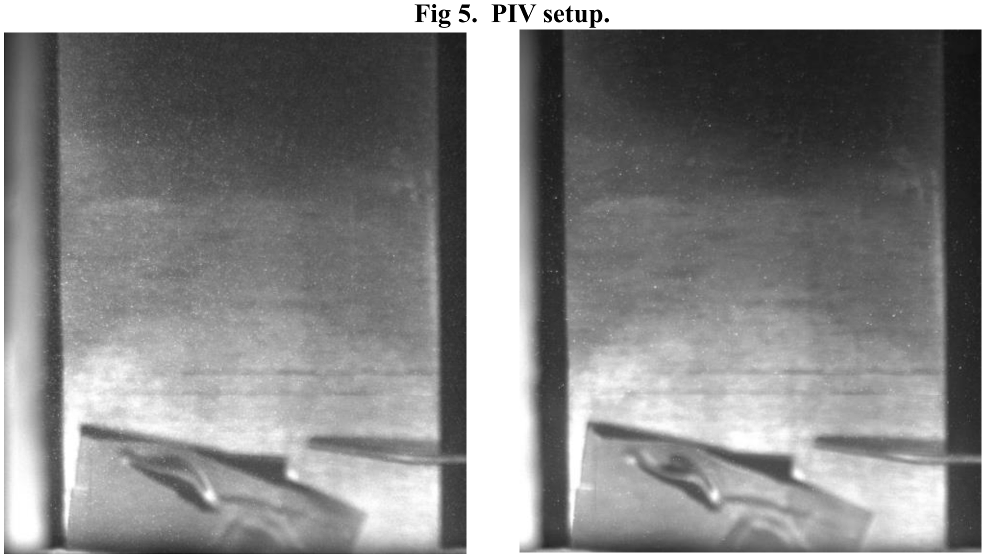
Seeding material	Diameter (μm)	Density (g/cm^3)	Estimated Stk at 20 m/s	Air backpressure (psi)
Oil	0.5 - 5	0.92	0.000047 – 0.0046	20
Hollow glass spheres	9 - 13	1.1	0.018 – 0.037	4

While initial tests were carried out with the liquid seeder for proof-of-concept, the solid seeding will be utilized henceforth given the desire to operate at hot flow, combusting conditions which are more compatible with the solid seeding particles with high melting points. After some testing with the laser energy level, the number of images taken, and the gauge pressure for the particle seeder, we decided to use 60% energy on the laser, as any increase afterward makes little difference in the measurements. We also increased the number of images taken to 100, as it gave us the cleanest time-averaged velocity profile, and used a gauge pressure of 4 psi, as it gave us the best particle density.



a) Solid particle seeder b) Laser and camera positioning c) Liquid particle seeder

Fig 5. PIV setup.



a) Liquid particles b) Solid particles

Fig 6. Representative images of the seeding from each approach.

IV. Test Cases

A. Hot-Wire Anemometry

For this test, we used 40 cubic feet per minute of air. When taking measurements, we placed the probe at three different heights, 3.8 cm, 7.6 cm, and 11.4 cm. For radial lengths, we marked the probe with lines that were evenly spaced for 0.16 cm for the first 2 cm and 0.32 cm for the rest of the measurements. The CTA sample rate was set to 1 kHz, and we took measurements for 8 seconds. The probe was then inserted into the swirl combustor so that the wire was at the center. The probe should be parallel with the ground for axial velocities and rotated perpendicularly for tangential velocities. We then collected both axial velocity and radial velocity measurements before moving on with the rest of the heights.

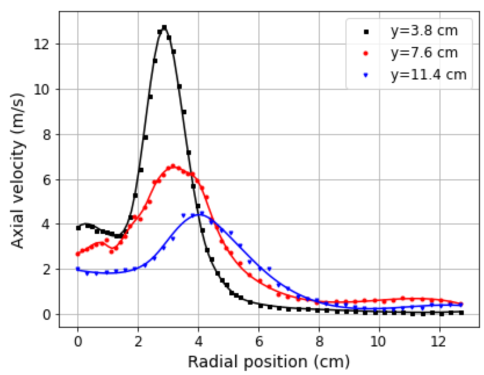
B. Particle Imaging Velocimetry

For the PIV test, we will also be using 40 cfm of air, energy level at 60%, varying number of images, and varying time between frames. The seeding particles will be hollow glass spheres. We will only be testing the case of cold flow and deriving a flow field from it.

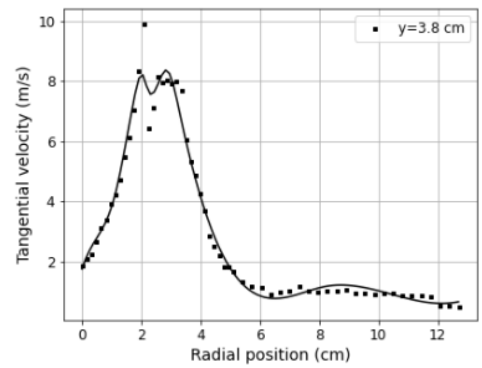
V. Results

A. Hot-Wire Anemometry

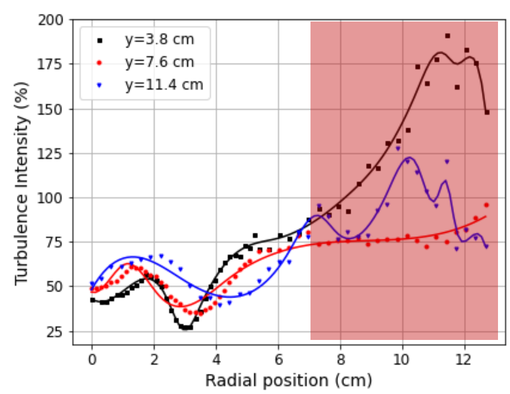
Comparing the axial (streamwise) velocity from Fig. 7(a) and tangential velocity from Fig. 7(b) measurements to Fig. 1(b), we can see that the trend of our velocity profiles shows some similarities. They each have matching spikes in velocity, followed by a sudden drop that plateaus near 0 m/s. As we increase in height, the peak begins to drop and the whole curve begins to flatten out. This is also supported by the works of Dinesh, et al. [3], as their data shows a similar trend. However, we are missing the large drop in velocity near the center. The reason this may have occurred is due to the precision of our measurement. For the first 2 cm, we measure by increments of 0.16 cm. This may not have been enough precision to capture the large drop in velocity.



a) Axial velocity measurements with 3 heights



b) Tangential Velocity measurements at 1 height



c) Turbulence Intensity calculated from axial velocities

Fig 7. Results from Hot-Wire Anemometry

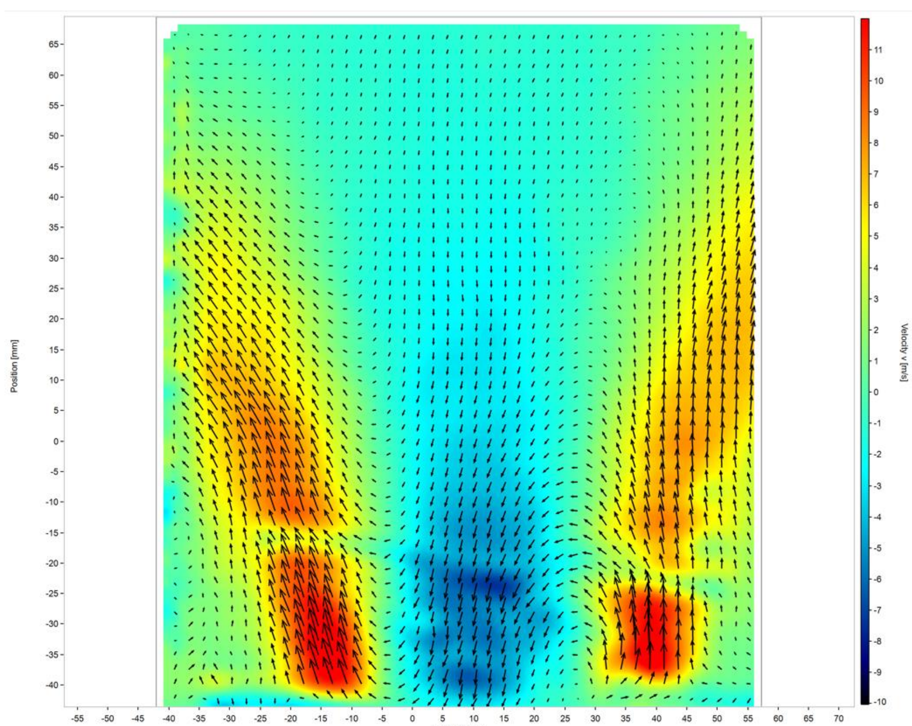
Turbulence intensity is the measure of the fluctuation in velocity compared to the mean velocity. The turbulence intensity graph in Fig. 7(c) was calculated in the ThermalPro program. Wherever turbulence intensity is high, that's where the flame is most stable and where air and fuel are mixed most efficiently. It should be noted that the red highlighted part of the graph can be disregarded as the hot-wire probe has a high error below 1 m/s due to the sensitivity range of the calibration we used. The probe was calibrated from 0 m/s to 50 m/s. However, at velocities below 1 m/s, the signal generated by the hot-wire anemometer may be weak compared to the noise present in the system, leading to high variation in velocity.

When calculating the total cfm with the velocity profile at the height of 3.8 cm using the trapezoidal rule in Python, we calculated 57 cfm when we used 40 cfm of air. This gives us an error of 42.5%. Such a large error could be due to many reasons. One reason, as stated earlier, may be that the probe has a low signal-to-noise ratio below 1 m/s, leading to an inaccurate calculation with the trapezoidal rule. The precision of the marks could have been beyond 0.16 cm but human error when moving the probe to each position would've introduced more error and neglected the improvement in precision.

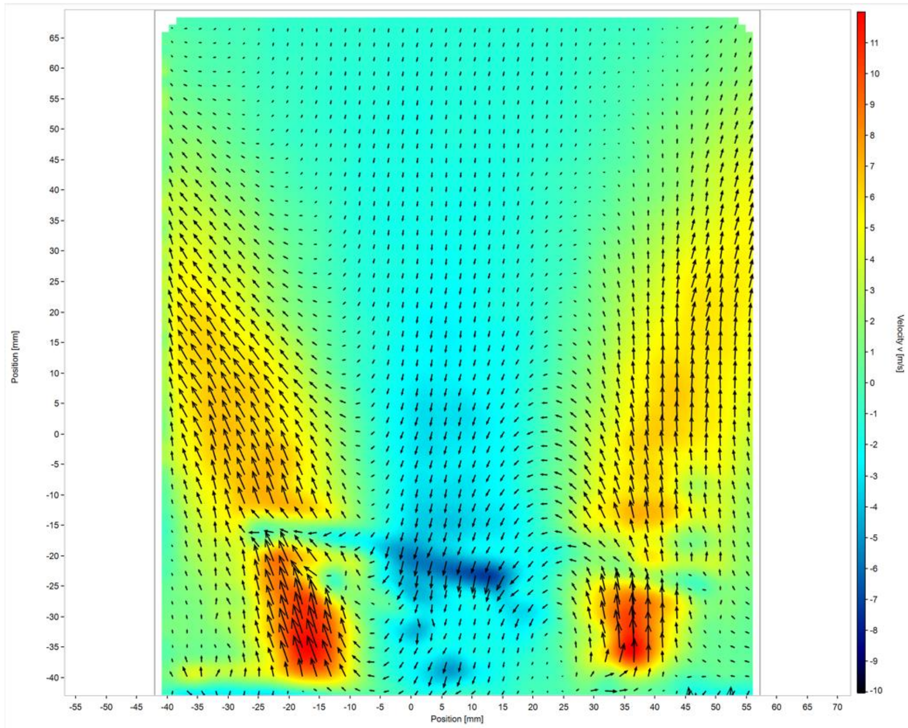
B. Particle Imaging Velocimetry

Comparing our results shown in Fig. 8 obtained with solid seeding with the diagram from Fig. 1(a), we can see that we have captured the inner recirculation zone, as well as the upward flow between the outer and inner recirculation zone. The outer recirculation zones were not able to be seen because of the lack of field of view due to the window being too narrow and protruding out of the swirl combustor. Because of the similarities in the flow field patterns, we can say that our results match the trend of the diagram from Fig. 1(a). When comparing Fig. 8(a) and Fig. 8 (b), we can see that liquid particle seeding has captured higher velocities in the recirculation zone and forward flow field near the nozzle.

When comparing our own PIV results with our HWA results, we see similar results. The figures in Fig. 8 have the time between frames set to 10 microseconds, which gives us the values that match our results from HWA. We now have about 12 m/s at 38 mm high at a radial distance of about 30 mm. It should be noted that the height values on the y-axis are incorrect, as we set the reference point at an offset of 40 mm. These results are promising and suggest the potential suitability of the 1-D probe for assessing 2-D flows.



a) Averaged velocity field of liquid particle seeding



b) Averaged velocity field of solid particle seeding

Fig 8. Results from PIV

VI. Conclusion

Because of the similarities in the trends of our graphs compared to known flow fields, we can say that HWA can be used to identify changes in patterns of velocities, but due to the 42.5% error when calculating the cfm of air, we can say that a 1-D probe for HWA is not accurate for 2-dimensional flows. Some improvements for this experiment are to accurately calibrate the hot-wire probes for velocities below 1 m/s with the right nozzles for the air velocity calibrator. We could also use a different method for implementing the hot-wire probe into the swirl combustor that allows for more precise movement and accurate movement.

Because of the matching peak velocities from HWA and PIV, we can say that HWA isn't completely inaccurate, but lacks good results due to radial precision. However, PIV is very good for characterizing the flow field within the swirl combustor as it matches the known swirl combustor flow field. There could be a lot of improvements to our measurements, such as removing as many reflections as possible. This will allow us to possibly remove the cover, which will let us capture the flow field much closer to the nozzle. We could also adjust a lot of our settings to reduce any unnecessary computational time from post-processing the data.

For future experiments, we will be testing reacting flows, but that requires a lot more preparation than cold flow. With the presence of reflections and lack of data near the nozzle, we need to first find a way to deal with the reflections. One idea we have is the use of high-temperature, black paint, as it will absorb more light than the metal combustor. The position of the camera might be changed to account for the reflections from the nozzle.

Acknowledgments

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