Particle Image Velocimetry Analysis of Turbulent Counterflow Flames in High Pressure Extinction Conditions

A Capstone Report
presented to the faculty of the
School of Engineering and Applied Science
University of Virginia

by

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

Signed: ____

Approved: ____________________________________ Date ______________________
Harsha Chelliah, Department of Aerospace Engineering

Introduction

This is an independent research project conducted at the Reacting Flow Laboratory in the Mechanical and Aerospace Engineering Department with the direction from Professor Harsha Chelliah. John Wilder, a University of Virginia alumni, also assisted during the early stages of this research.

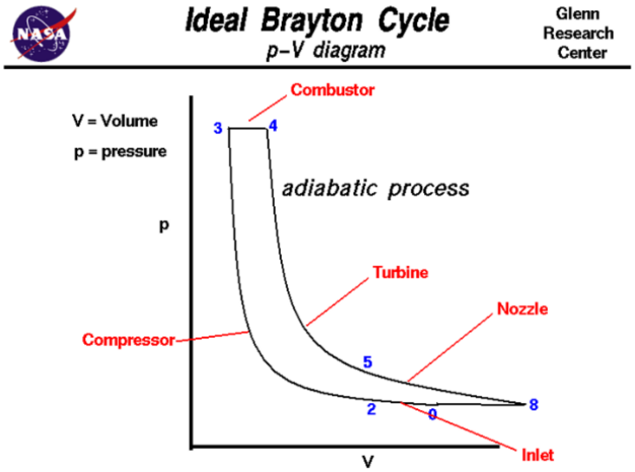

Figure 1: A pressure-volume diagram of the Ideal Brayton Cycle (NASA, 2015).

There is continuing interest within the aerospace community to develop highly efficient gas-turbine or jet engines, with decreased fuel consumption, reduced emissions, and operational cost. As observed by the Brayton Cycle (see Fig. 1), one solution to optimize the thermal cycle efficiency of a gas turbine engine is to increase the pressure differential between the compressor inlet and the combustor outlet (NASA, 2015). While modern gas turbine engines operate at pressures between 45-50 atm, the new generation of engines are expected to reach pressures on the order of 70 atm. This necessitates the fundamental understanding of combustion stability at higher pressure conditions that have never been explored before. New experiments with an expanded range of quantitative data combustion efficiency and emissions are vital to the development of modeling concepts for realistic engine operating conditions.

<u>The objective of this research is the study of transition from laminar to turbulent flames with increasing pressure, in the range of 10-60 atm, with the intent of validating turbulent</u>

combustion models at high pressures. Such validated models can be used in future optimization of the engine design.

Experiments were conducted using a high-pressure counterflow burner available at the University of Virginia's Reacting Flow Laboratory. Due to the closure of the laboratory as a result of the national Covid-19 pandemic, the original goals have yet to be met. Instead, the report reviews in detail (a) work completed and (b) work that remains for others to continue.

Literature Review

Efficient gas turbine engine design typically requires high accuracy computational simulation models before full scale production of engines. Presently, there is limited literature on the high-pressure turbulent combustion conditions for computational model validation. As stated by Geyer, Kempf, Dreizler, and Janicka (2005), there exists a significant need for continued turbulent combustion studies focused on flame characterization. Continued experimentation into near extinction and extinction limits of high-pressure flames will allow for higher accuracy modeling of experimental gas turbine engine combustors. Higher accuracy models will allow for the development of higher efficiency gas turbine engines.

Geyer et al. conducted extinction and near extinction counterflow experimentation at atmospheric pressure. Using 1D Raman/Rayleigh and Laser Doppler Velocimetry (LDV) spectroscopy, time resolved single point scalar quantities and scalar dissipation rates were taken non-intrusively. The collected data were then compared to Large Eddy Simulations (LES) for validation of the model. The spatial resolution of 2D flame structure was approximately 300 µm^2. High resolution measurements are essential for scalar dissipation of flamelets as the dissipation rate is fundamental in characterizing the mixing rate.

In a similar study, Kitagawa et al. (2008) measured counterflow turbulent burning velocities at 1, 2.5, and 5 atm for varying equivalence ratios. Hydrogen flame propagation was observed with Schlieren imaging and velocity measurements were taken using Particle Image Velocimetry (PIV). This study compared laminar and turbulent flame measurements at an expanded pressure range.

Sarnacki, Esposito, Krauss, and Chelliah (2011) emphasized the importance of accurate description of local flow strain rates at extinction and the onset or transition to turbulent flow based on velocity fluctuations (rms velocity). These values can be determined from measurements of the velocity profile of the flow structure across the flame (Boldman & Brinich, 1977). Sarnacki, Esposito, Krauss, and Chelliah utilized a PIV system to analyze the velocity profile of the flow structure across a flame using a atmospheric pressure counterflow burner. Their experiments characterized the laminar flame extinction conditions of ethane, ethylene, propane, and n-butane flames.

Method of Experimentation

A complimentary numerical simulation of experimental conditions is essential to the mitigation of experimental error. The numerical model allows the experimentalists to explore critical parametric conditions before beginning the study and provides a basis for experimental expectations. Several numerical codes are available for simulation of pressurized non-premixed counterflow flames, including the Open Source Cantera software package (Cantera, 2019). Figure 2 displays a typical solution of the counterflow flame structure (velocity Fig. 2 (left) and temperature Fig. 2 (right)) at a pressure of 1 atm, with a maximum local strain rate of 843.5 1/s. From the simulated velocity profile, local extinction strain rates vs pressure can be readily

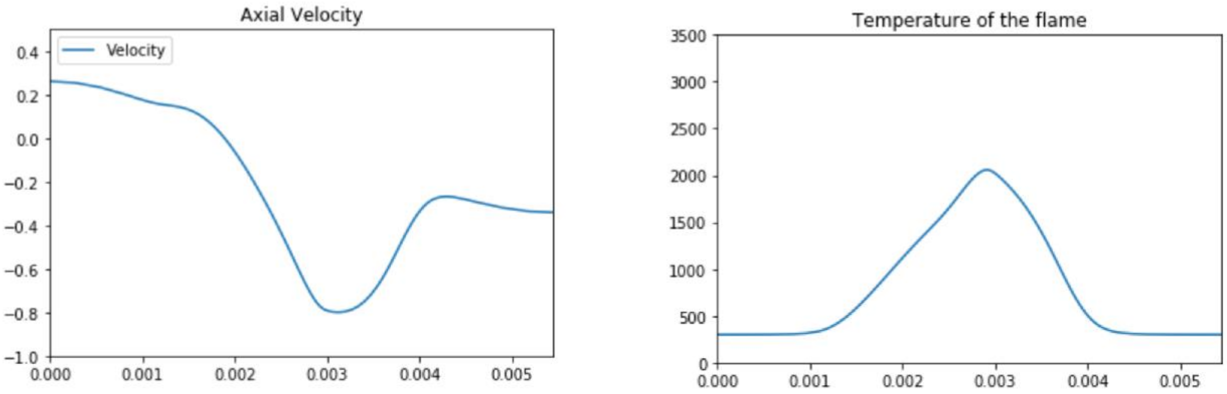

Figure 2: Left: Axial flow velocity as a function of vertical position. Right: Temperature as a function of vertical position. (Wilder, 2019).

iterated to pressures well beyond the pressure limits of the UVA counterflow burner, provided all the submodels are accurate.

This research uses the University of Virginia's high-pressure counterflow burner, mass flow controllers, and the LaVision PIV system. The same PIV system and burner system developed by Sarnacki, Esposito, Krauss, and Chelliah are used for this project. The counterflow burner, designed by Hazelgrove, Le, and Levick (2010) (see Fig. 3), is designed to simulate fundamental aspects of high-pressure laminar and turbulent flame conditions found within a gas turbine engine. The burner chamber has been hydrotested up to 200 atm with aluminum blanks and up to 150 atm with 25 mm quartz windows for optical access

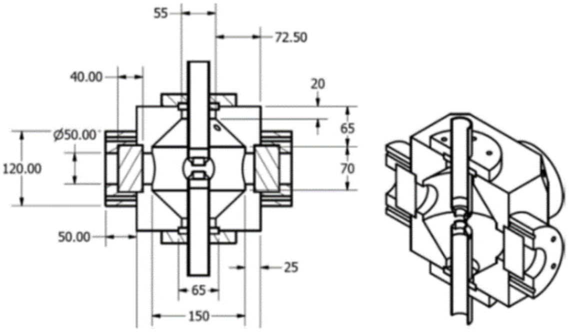

Figure 3: Cross-sectional and iso-metric views of the high-pressure chamber, with key dimensions, in mm (Sarnacki & Chelliah, 2018).

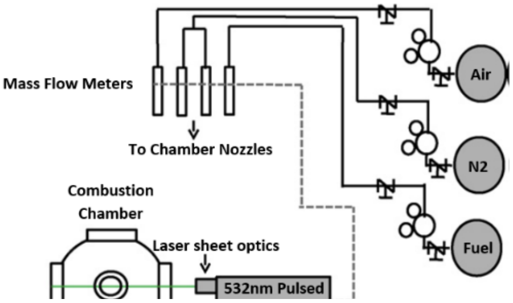

Figure 4: Top view of the counterflow setup for the particle image velocimetry (PIV) (Sarnacki et al., 2012).

(Hazelgrove, et al., 2010). At high pressures, owing to high ratio of momentum to viscous dissipation effects (i.e. large Reynolds numbers), the flame becomes self-turbularized with increasing flow velocities. While such transition from laminar (planar) to turbulent flame can be observed by the naked eye or simple flame imaging, quantitative data on mean and fluctuating flow velocities via Particle Image Velocimetry (PIV) is much more valuable for ongoing model development efforts. In addition, volume or mass flow rate of fuel and air provides information about the transition from laminar to turbulent flame as well as the stability (or extinction) limits of the flame (Sarnacki et al., 2012).

Shown in Fig. 3 are two cross-sectional views of the counterflow burner (left figure provides the key dimensions in mm and right figure provides an isometric view). The two vertical co-annular tubes provide the reacting fuel and air streams, with annular tubes providing diluent gas to eliminate any secondary flames in the chamber (Sarnacki & Chelliah, 2018). Figure 4 provides a schematic of the gas supply system and the PIV layout (top view). The pressures from the compressed air, nitrogen and fuel tanks are controlled using pressure regulators before feeding into the mass flow controllers and to the chamber nozzles. The chamber pressure is controlled via a back-pressure regulator. The oxidizer and fuel streams are often diluted with nitrogen before feeding to the top and bottom nozzles. The momenta of two opposed streams are balanced such that a stagnation plane sits near the center of the domain where the axial velocity approaches zero. When ignited with a spark, a stationary flame disk, approximately the size of a dollar coin, is formed between the two opposed nozzles. The exact flame location depends on the stoichiometric ratio of the fuel to air (Sarnacki, 2014). At high pressure the flow is naturally turbulent.

The high-pressure counterflow burner and the gas supply system (air, nitrogen, and methane tanks) as well as the computer for measurement and control are separated by a barrier consisting of a quarter inch aluminum shield and three-quarter inch thick bulletproof glass (Hazelgrove, et al., 2010). From behind this shielding, the ignition, supply tank regulators, flow controllers, camera, PIV laser system, backpressure regulator, and recording functions can be safely monitored and controlled. In the case of an uncontrolled combustion in the chamber, the flame can be safely extinguished by closing the fuel line. Within the Labview data acquisition system, there is also an emergency shutoff which will shut all of the mass flow meters and; should the backpressure regulators fail, there are two pressure relief systems which will safely vent the gases and depressurizing the chamber (Sarnacki, 2014). Additionally, a laser safety curtain is secured around the experiment setup to prevent stray reflections from possibly injuring others. Laser goggles are used at all times while operating all laser equipment. Additional laser operation safety training and necessary laser lab preparations have been met as well.

The PIV laser sheet (at 532 nm wave length with two pulses 10 ns apart) with particle seeding will facilitate measurement of the two-dimensional flow field between the opposed jets. In previous work, the same laser system without seeding particles, but with an intensifier and optical filters was used to quantify the amount of soot generated by the flame (see Fig. 5), which is not the focus of this work. In this work, the necessary particle seeding system has been introduced, though there remains more to be done in seed distribution improvement. Typically,

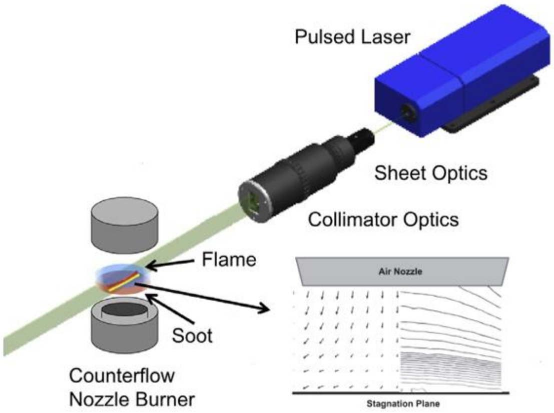

Figure 5: Schematic and general layout of the PIV with a secondary diagram PIV imaging for the velocity (left) and pressure (right) fields (Sarnacki et al., 2012).

50 velocity images are used to obtain the mean velocity field for laminar case; but for turbulent flames, a much higher number of velocity images are needed to quantify the mean and fluctuating velocity components. The mean velocity gradient in the axial direction can be used to quantify the local flow strain rate across the flame (Sarnacki & Chelliah, 2018). This can be used to quantify the pressure effect on flame extinction or stability limits. Figure 4 shows the process of data collection from the PIV as well as a sample flow field with pressure density. Such data allows for direct comparisons of the flow between pressures within individual tests as well as between tests for future model validation.

Results and Recommendations

At pressures greater than 5 atm, a “self-turbulerization” regime is achieved without the introduction of a turbulence generating grid. Oxidizer and fuel flow not diluted with low density inert gas can be elevated to certain global strain conditions increasing the Reynold number to the turbulent regime. The current work explores methane/air diffusion flames at high pressure using opposed-flow jets within the high-pressure chamber. Turbulent conditions were achieved by varying the bulk flow strain rate and gas density at pressures up to 10 atm. Kolmogorov length scales in the turbulent eddies are approximately 15-20 microns. The current 2D PIV vector spacing allows resolving of 50 microns turbulent eddies. Future work, including extending the measurement to include three-component velocity fields using stereoscopic PIV, is needed for full resolution and comparison with planned DNS simulations. The experimental pressure regime can then be expanded to the 30-60 atm objective range. Planar laser induced fluorescence (PLIF) of the OH radical can additionally be employed for visualization of the reaction zone. The flame surface density and local curvature can be investigated through fluorescence images. These results can then be compared to the turbulent velocity fluctuations acquired.

Conclusion

Demand for more efficient and cost-effective forms of commercial and public transportation continues to grow. One approach is to increase the operational pressure of the gas turbine thermal cycle in airliners. However, if the flow path inside the engine is not optimized, higher pressure can lead to higher amounts of soot particle emission, which can affect the air quality as well as global energy balance due to contrail formation. Thus, it is imperative that the simulation tools used in developing new engines are based on high quality data. In addition, the turbulent flame extinction limit data offers invaluable insights into other propulsion systems such as supersonic combustion ramjet engines.

Resources

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