The 7th International Supercritical CO_2 Power Cycles Symposium
March 31 – April 2, 2020, San Antonio, Texas
Paper # 48

Developing Non-Intrusive Diagnostics for the Characterization of Direct-Fired sCO_2 Flows

Ian P. Bashor
Graduate Research Assistant
University of Texas at San Antonio
San Antonio, TX

Eugene N. A. Hoffman
Graduate Research Assistant
University of Texas at San Antonio
San Antonio, TX

Christopher S. Combs
Dee Howard Endowed Assistant Professor
University of Texas at San Antonio
San Antonio, TX

Jacob Delimont
Senior Research Engineer
Southwest Research Institute
San Antonio, TX

AUTHOR BIOS

Ian P. Bashor received his bachelor’s degrees from the University of Evansville in Mechanical and Electrical Engineering in 2016. He is currently involved with the design and development of the UTSA hypersonic wind tunnel facility. Ian’s research interests lie in experimental supersonic and hypersonic aerodynamics as well as the development and application of non-intrusive diagnostic techniques for compressible flows.

Eugene N. A. Hoffman received his bachelor’s degree in Mechanical Engineering from the University of Evansville in 2016. His past research experience involves the proof of concept and practical applications of a two loop thermosiphon system. His current research interests include experimental supersonic and hypersonic aerodynamics as well as combustion and laser diagnostics.

Christopher S. Combs is the Dee Howard endowed Assistant Professor in Aerodynamics in the UTSA Department of Mechanical Engineering. His primary area of research interest is in the development and application of non-intrusive diagnostic techniques for compressible flows. Dr. Combs is active with AIAA, ASME, and APS and is a current member of the AIAA Aerodynamic Measurement Technology Technical Committee.

Jacob Delimont is the PI of two major efforts, the first is to design and build a direct-fired combustor for sCO_2. The second is a project examining high turn-down combustion in gas turbines. Dr. Delimont’s research interests consist of combustion, heat transfer, fluid mechanics, gas turbine performance, and particulate damage to gas turbines. While at SwRI, Dr. Delimont has been involved in the combustion research portion of the Propulsion and Energy Machinery Section.

ABSTRACT

Direct-fired oxy-fuel combustion as a heat source for sCO_2 power cycles is a promising and innovative method for providing the needed thermal energy input for highly efficient power generation while integrating carbon capture directly into a power cycle, but the lack of experimental data to support existing computational models is currently hampering the development of this technology. These challenges can be mitigated through the development of additional validation data, which will allow trust to be placed in future computational modelling.

The University of Texas at San Antonio (UTSA) and Southwest Research Institute (SwRI) are collaborating to develop non-intrusive diagnostic techniques for the study of supercritical carbon dioxide (sCO_2) power generation systems. SwRI is a leading institution in the research and development of power cycles that employ sCO_2 as the working fluid, and UTSA is currently providing expertise in the application of non-intrusive diagnostic techniques to study this challenging flow environment. The current research project has three primary objectives; develop non-intrusive measurement techniques for direct-fired oxy-fuel combusting in sCO_2 applications, acquire validation data in a simplified combustor geometry, and validate computational fluid dynamic (CFD) models. The work presented in the present manuscript describes research performed using a tabletop supercritical flowing test cell at UTSA that is in direct support of the first objective to develop non-intrusive diagnostic techniques for sCO_2 flows. The design and implementation of the experimental setup along with the results of the measurements are discussed and compared to other work in the field to determine which diagnostic methods are best suited for application in the second phase of the project.

INTRODUCTION

Producing highly efficient power through the use of sCO_2 power cycles is an innovative and novel approach to meeting the growing energy needs [1] [2] [3] [4]. The incorporation of direct oxy-fuel combustion in these cycles is a promising method to attain needed thermal energy input and affords the integration of carbon capture directly into the power cycle. However, direct-fired sCO_2 power cycles pose a number of challenges that are substantially different from a typical combustion process [5] [6] [7]. In a direct-fired combustor, the proportions of CO_2, O_2, and fuel in the primary burning zone can all be controlled independently [8] [9].This adds considerable flexibility to the design process that is not typically found in a combustion system using air as the oxidizer.

Moreover, unlike with traditional gas turbine combustion systems, there is no need to rely on premixed combustion, and diffusion flame combustion will likely dominate [10]. No publicly available data on diffusion flame combustion for the direct-fired sCO_2 application exists. Many chemical kinetic mechanisms available in the literature are not appropriate for such high levels of CO_2 at pressures in the 150 to 300 bar range. These challenges can be mitigated through the development of more validation data which will allow trust to be placed in future computational modelling. However, for progress in computational modelling of these flows to be made, it is critical that synergistic computational and experimental efforts are performed so that there is ample communication and collaboration between researchers performing laboratory testing and researchers performing numerical simulations.

An additional outstanding issue lies in the development of appropriate and accurate experimental measurement techniques for quantifying these complex reacting flow fields. The presence of high-temperature, high-pressure, reacting supercritical mixtures presents many unique challenges to any planned experimental campaign. These extreme conditions render many traditional probe-based measurements useless as the sCO_2 combustion conditions lie outside the operational range of many physical instruments. Non-intrusive optical diagnostic measurement methods are therefore desirable for the interrogation of direct-fired sCO_2 power cycle flow paths.

Compared to many other combustion environments, there are relatively few examples of optical diagnostic techniques employed in sCO_2 flows presented in the open literature. The earliest work, published by Ushifusa, et al. in 2015 [11] at the Tokyo Institute of Technology, observed the dynamic phase transition of sCO_2 as it was heated. The authors used temperature sensors, pressure sensors, and observed the effects of Rayleigh scattering to compare to computational models. They found that the Rayleigh scattering was first observed at the heater and grew with time. At the point when the scattering effects reached the thermocouple and pressure transmitter the properties went beyond critical conditions for CO_2. Large fluctuations in density were observed after supercritical conditions were met. Another study in 2015 by Kazemifar and Kyritsis consisted of visualizing CO_2 flow near the critical point utilizing shadowgraphy. They compared the shadowgraphy results across several different phases of CO_2 and compared how each phase compared with the density gradients identified [12]. In 2018 particle imaging velocimetry (PIV) analysis with sCO_2 as the working fluid was performed at Sandia National Laboratory [13]. It was found that there was high optical clarity in the visible region when the CO_2 was in its liquid, vapor, and supercritical regimes. However, little optical clarity was found at and just above the critical point but was quickly recovered when conditions were pushed further into the supercritical region. The most recent effort was performed by Lim et al. at the Georgia Institute of Technology in 2019 [14]. In this work the authors performed shadowgraph imaging of non-equilibrium flow with sCO_2 through a converging-diverging nozzle. Due to the time-scale of the nucleation they chose a Photron SA-Z high-speed camera and captured images at a frame rate of 40 kHz.

The primary focus of this work is to discuss and assess the experimental set-up constructed by UTSA to perform preliminary sCO_2 optical diagnostics. Upon completion of this system, the team performed flow visualization to confirm that the sCO_2 was optically clear for diagnostics. This work was used as a baseline for future work in the development of more advanced optical diagnostic techniques.

The collimated light technique of shadowgraphy was used to visualize the flow [15]. The concept relies on sending a collimated light source through the test field of interest. An LED (or other source) is to act as a point light source and, although not strictly required, a pinhole is typically used. The light then travels a distance of one focal length to the first mirror. As the light reflects from the first mirror it is naturally collimated. After passing through the test field it will encounter the second mirror which will focus the light back to a point at its focal length. The image is then typically captured by a camera after the second focal point. Figure 1 shows the generic shadowgraphy setup. The mirror configuration is shown in the Z-type optical setup [16] [17].

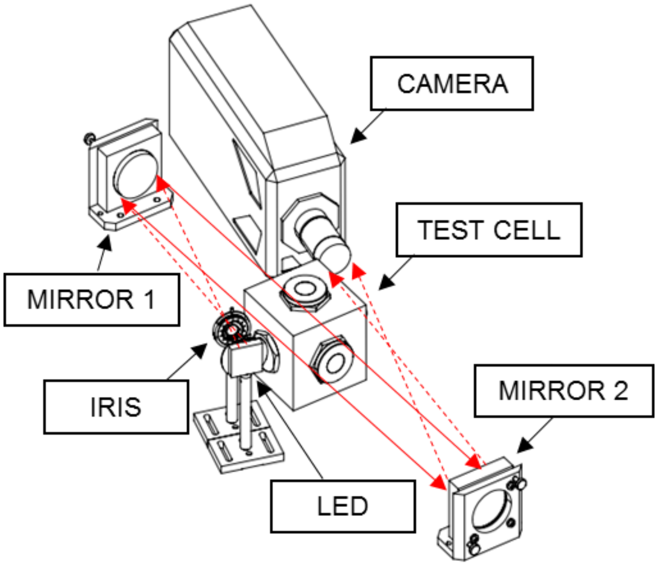


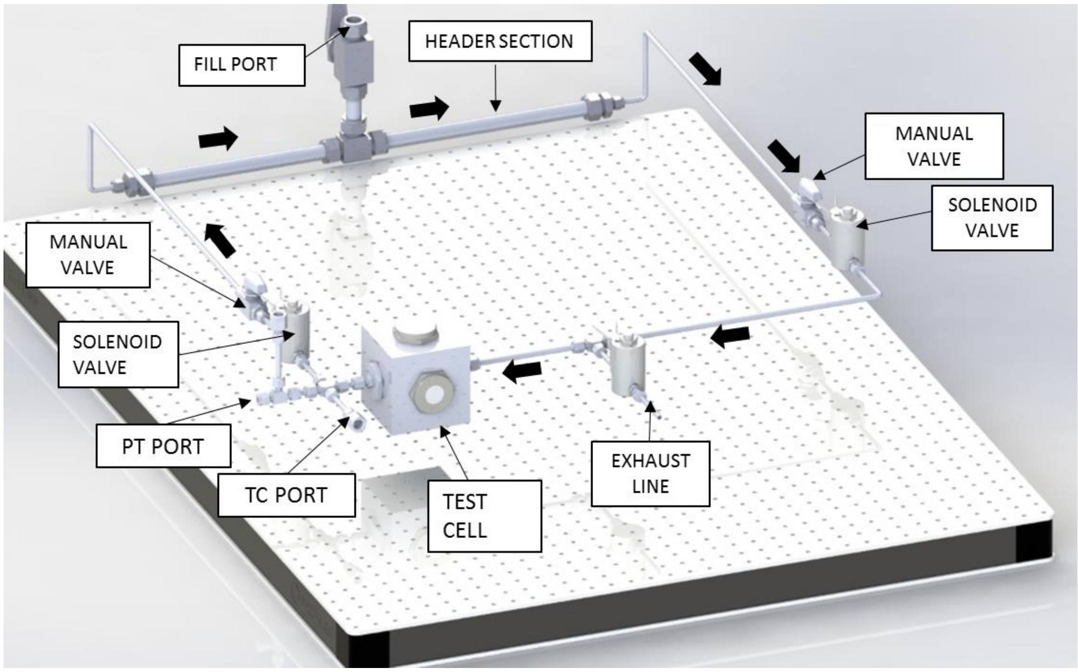
Figure 1 Shadowgraphy Setup

A post processing technique known as Proper Orthogonal Decomposition (POD) extracts meaningful data from a series of still images. POD was first used in the field of fluid dynamics to analyze turbulence. It can broadly be described as a method for decomposing the randomness of the flow field (an infinite sum of continuous dimensions) into a lower set of dimensions that allows for visualization of various kinetic energy structures [18]. Flow structures not otherwise visible by eye, as it would be covered by the higher energy flow, can be extracted and related to the physics of the system. Snapshot POD computes the lower dimensional output as orthogonal in space and independent of time [19] [20].

EXPERIMENTAL METHOD

The experimental studies for this paper were conducted at the University of Texas at San Antonio, on a bench top facility designed and built by student researchers. Various set ups for this facility were employed based on the individual test needs. However, the fundamental principles and geometries governing the functionality of the facility were not changed.

Two critical criteria governing the design of this test facility were optical accessibility and the ability of the system to withstand the pressure and temperature constraints at supercritical operating conditions. The facility setup adopted by the researchers at UTSA was made up of three main components; the test cube, the header section, and the controls. A general layout diagram of this can be seen in the figure below.



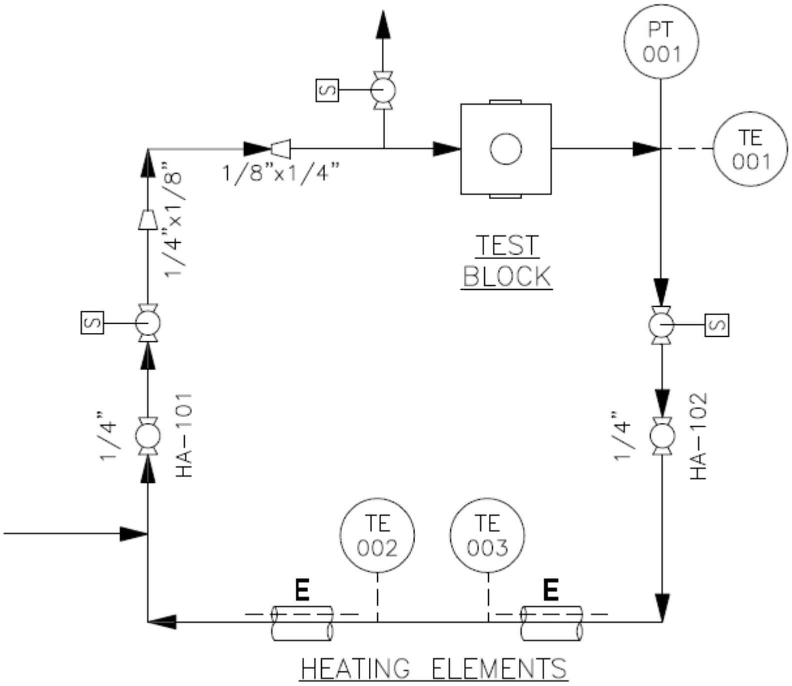


Figure 2 3D rendering and block diagram of Optical Diagnosis Facility at UTSA

The test cube was machined from a 4" x 4" block of 304 stainless steel with five through holes machined on adjacent faces, which converge at the center. These holes were tapped to a 1-1/4" NPT thread size. Three of the five holes were fitted with 1-1/4" NPT sight windows from RAYOTEK providing an approximate 1" field of view for flow visualization and laser transmission. The other two openings had bushings connecting the test cube to the rest of the system. The interconnected tubing and header were made from ¼" and ¾" 316 stainless steel tubing respectively with Swagelok fittings connecting the various components. The test system was designed to withstand pressures up to 3000 psi at 220°F. To ensure safety while using this facility, both active and passive safety systems were employed. A safety relief valve set for 2050 psi was incorporated into the system as a passive failsafe in collaboration with three solenoid valves granting researchers the ability to drain the system remotely if needed.

The system was designed to be filled with dry ice pellets introduced through the ¾" ball valve on the header section. Dry ice introduced into the system was allowed to sublimate and come to an equilibrium temperature with the room, at which point heat could be added with the use of an Omega FGH102-100 heat strip, with the goal of increasing the system's pressure and temperature into the supercritical domain. Owing to natural convection, it was then possible to generate a nozzle flow with the use of two control valves and a section of 1/8" tubing inside the test cell that served as the jet exit. Images of the resulting flow and a further discussion can be found in the results section. A picture showing the final layout of the test system after construction can be found in the figure below, as well.

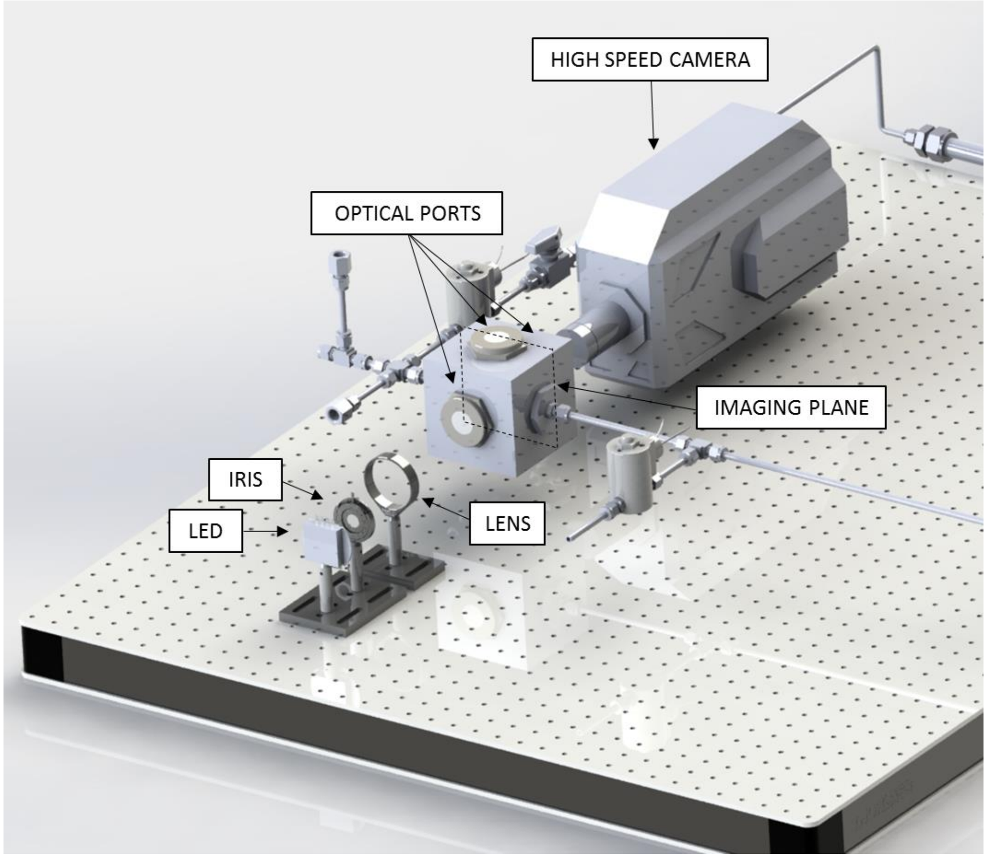


Figure 3: Diagnostic setup for sCO2

The test facility employed traditional probe-based intrusive measurement devices to monitor the state of the process fluid. A high-pressure Omega PX319-3KGI transducer, capable of accurately measuring pressures between 0 and 3000 psi was installed close to the test cell to measure fluid pressure. Surface-mounted thermocouples (Type K) were used to monitor the temperature at the heated section. An additional thermocouple (Type K) with a 1/8” sheath was inserted into the flow downstream of the pressure vessel to obtain accurate working fluid measurements. Information from these measurement devices as well as controls for the various solenoid valves were routed to a National Instruments cDAQ-9172 unit which was interfaced with NI’s LabVIEW software.

The experimental setup to perform the flow visualization involved the use of standard equipment such as a camera, an LED light source, and a power supply. A Luminus CBT-140 LED was used as a light source to provide illumination (up to 5000 Lumens) to the optical system. This LED was connected to an Allegiant E3631A power supply that provided variable control of the intensity of emitted light. Changes in light resulting from density gradients in the test area were then captured by a camera. Data acquisition for this experimentation initially involved the use of a Lavision Imager ProX camera which is capable of capturing images at a rate of up to 20 Hz at a resolution of 1024x1024 pixels with 944 pixel per inch pixel density. Post processing and interfacing for this was completed within the Lavision Davis software package. A Photron Fastcam SA-Z camera, capable of capturing images at a rate of up to 2.1 MHz was then utilized to obtain time resolved data at a rate of 2kHz with a 1024 x 1024 pixel resolution.

RESULTS AND DISCUSSION

Experiments in this system were centered on the use of optical diagnostic equipment to gain useful information about the sCO_2 flow field. During testing, the changes in density witnessed were strong enough that the flow from the nozzle could be visually observed. Figure 4 shows the experimental setup discussed with the LED, corrective optic, and camera.

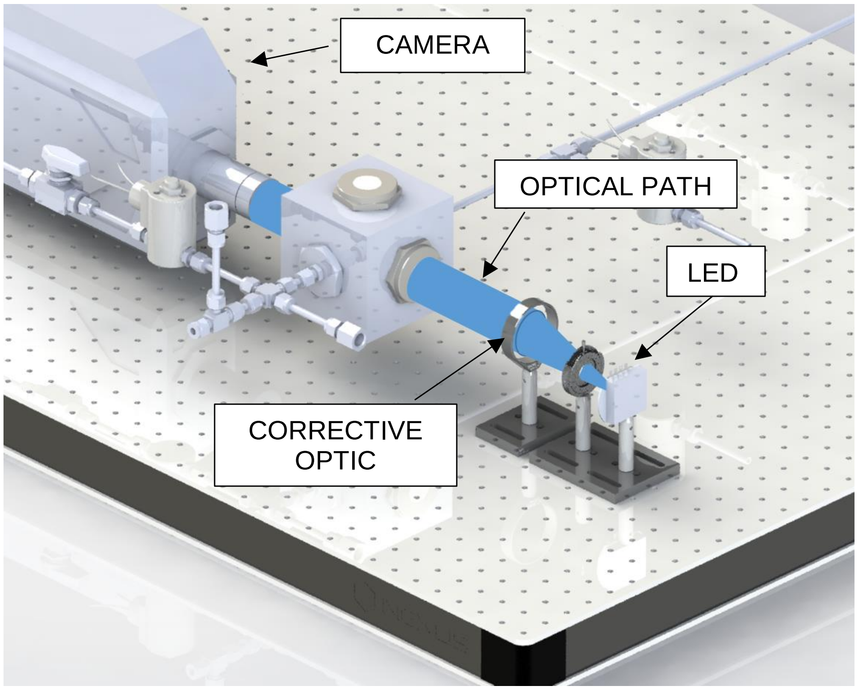
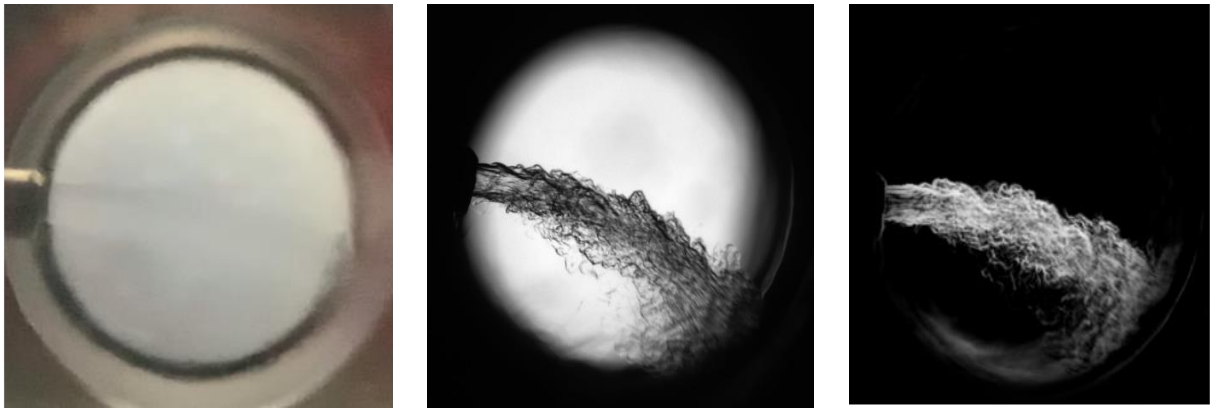


Figure 4: Experimental Setup for General Image Capturing

Figure 6 shows an example of the flow visible by eye in the test block during operation, raw, and adjusted images captured during nozzle flow, and serves as proof of concept for the current test loop as an optical diagnostic platform.



a) b) c)

Figure 5: a) Visible Jet Flow Image b) Raw Image Captured c) Image after cropping, contrast adjustment, and background subtraction at a fluid temperature of 43 Celsius and pressure of 86 bar.

Figure 6b shows the raw data captured. The sCO_2 flows into the test cell from left to right. Images obtained from the applied flow visualization technique were then subtracted from the background, scaled to the region of interest, and enhanced in contrast to aid in visualization and post processing. It is possible to see the turbulence and smaller structures associated with the flow after the image processing.

In order to observe the transient startup of the jet, a Photron FASTCAM SA-Z was utilized at 2000 frames per second (fps) to gather time resolved images.

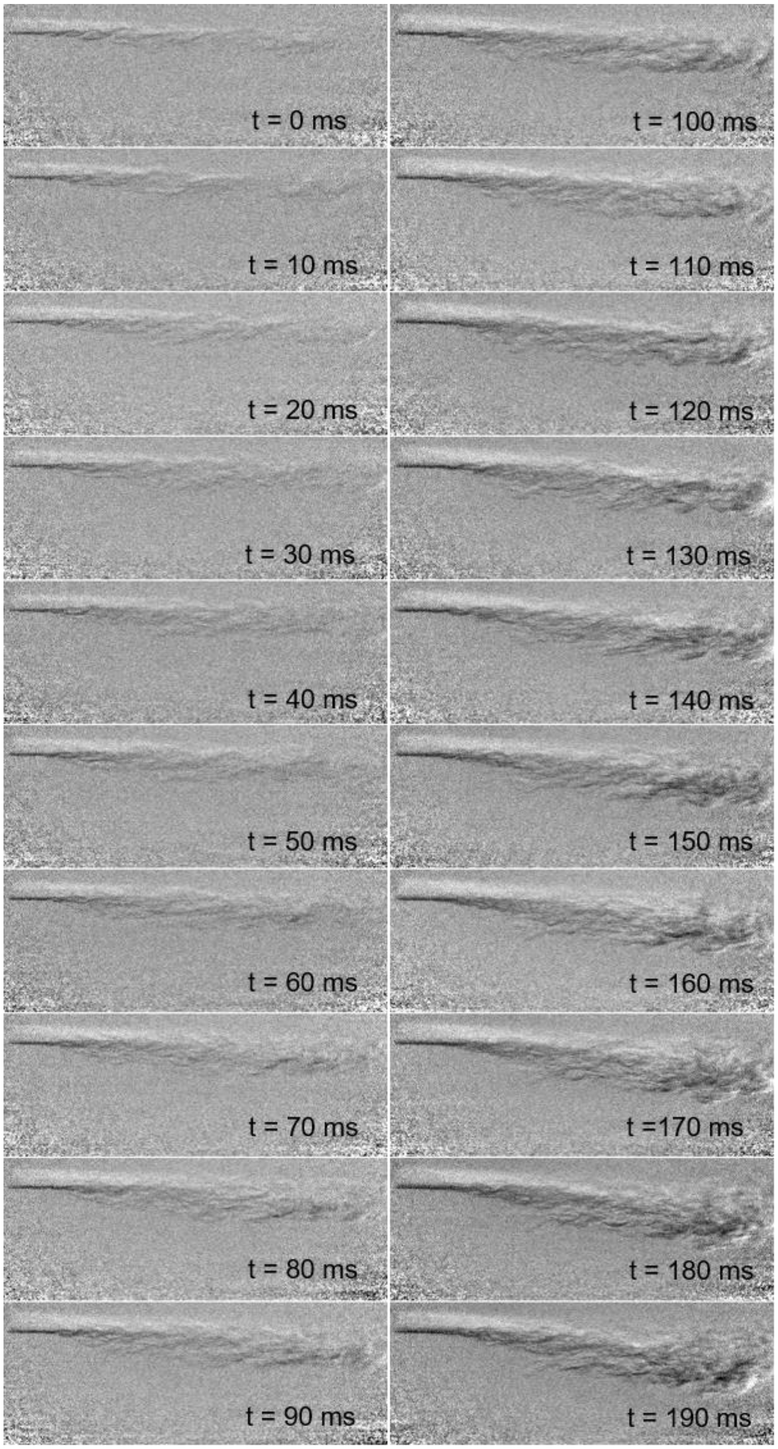


Figure 6: Photron Imaging of Nozzle Startup

The flow is from left to right in Figure 6. The solenoid controlling flow into the jet is opened and the natural buoyancy from the heated supercritical fluid at the lower portion of the test loop begins driving the sCO_2 through the nozzle and into the test cell. This methodology for creating flow without any moving parts was inspired from a thermosiphon loop configuration. After the first 100ms of image capturing, the flow structure begins to become visible and then develops into its full structure approximately 500ms after the solenoid is opened. At 2000 fps it is possible to get time resolved information from the nozzle flow and validate the use of the nozzle control.

To understand the complex flow structures that were visualized, a basic understanding of the mean flow was necessary to serve as a foundation for understanding the turbulent characteristics. The mean image of the flow was calculated using 3200 acquired images. A picture presenting the comparison between the mean, standard deviation, and instantaneous flow structures is shown below in Figures 8a, 8b and 8c.

a) b) c)

Figure 7 a) Mean image of jet flow b) standard deviation image c) Instantaneous image of jet flow

To further expand the knowledge about the turbulent structures visualized, POD analysis was performed on an acquired data set. POD gives spatial information about the kinetic energy contribution of the flow field by present turbulent structures. The chart below shows the modes that were generated in the analysis alongside the cumulative and individual energies of the modes.

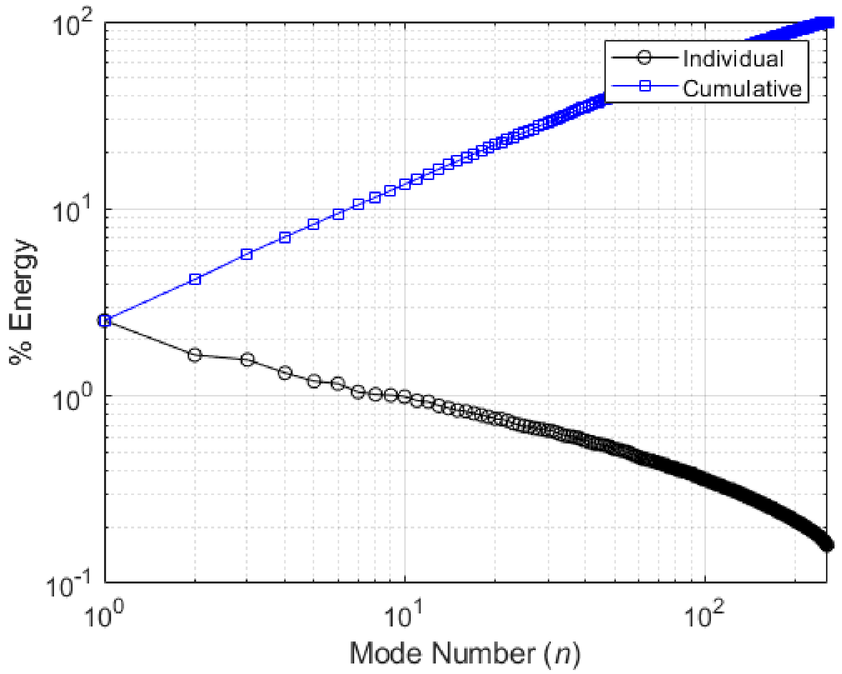


Figure 8: Mode Number vs. Energy contribution

As can be seen, the lower order mode numbers contribute the most significant portion of the total energy percentage of the flow visualized and have the largest physical structures. As the mode number increases the total energy shrinks as well as the physical size of the structure. Because of the turbulent flow, larger mode numbers generally correspond to smaller turbulent structures.

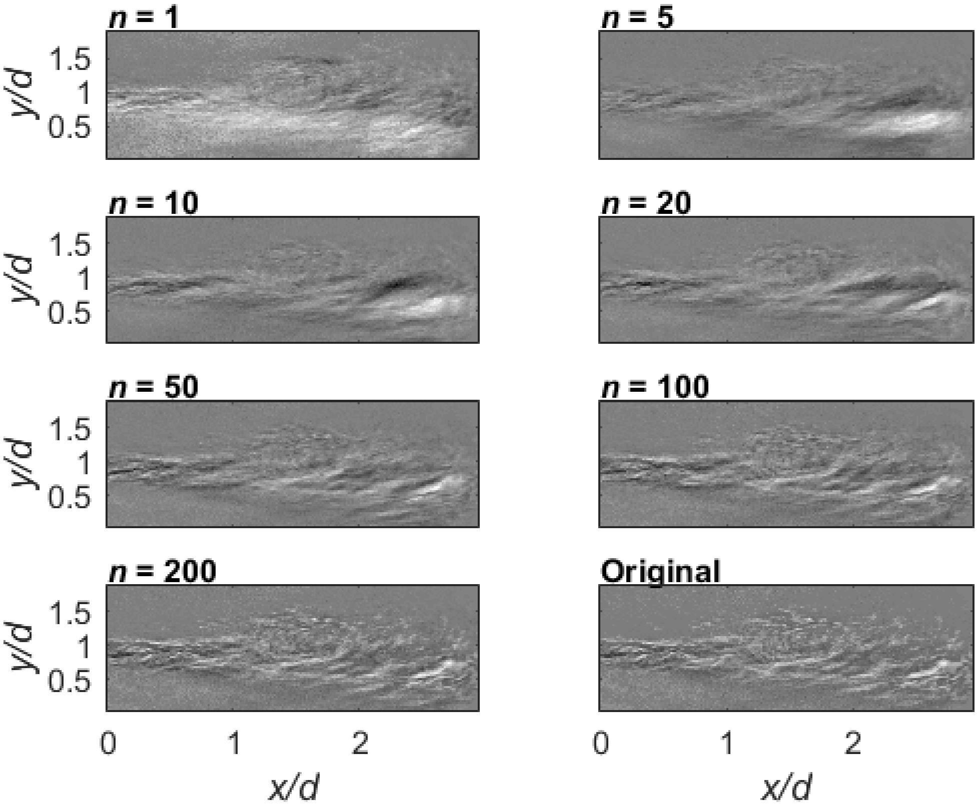


Figure 9: Cumulative Mode Contribution vs. Original Flow

Shown in Figure 9 are the cumulative modes of the flow. The x and y axis have been normalized to the jet diameter. As discussed in Figure 8, the lower modes correspond to the larger flow structures and the larger mode numbers correspond to the smaller scale structures. As they are superimposed on top of each other, the original flow structure is recovered. As shown in mode 1, the largest structures are at the nozzle outlet as the flow flows from right to left with the nozzle tip just out of frame at the middle of the right side. The x and y spatial dimension have been made non dimensional.

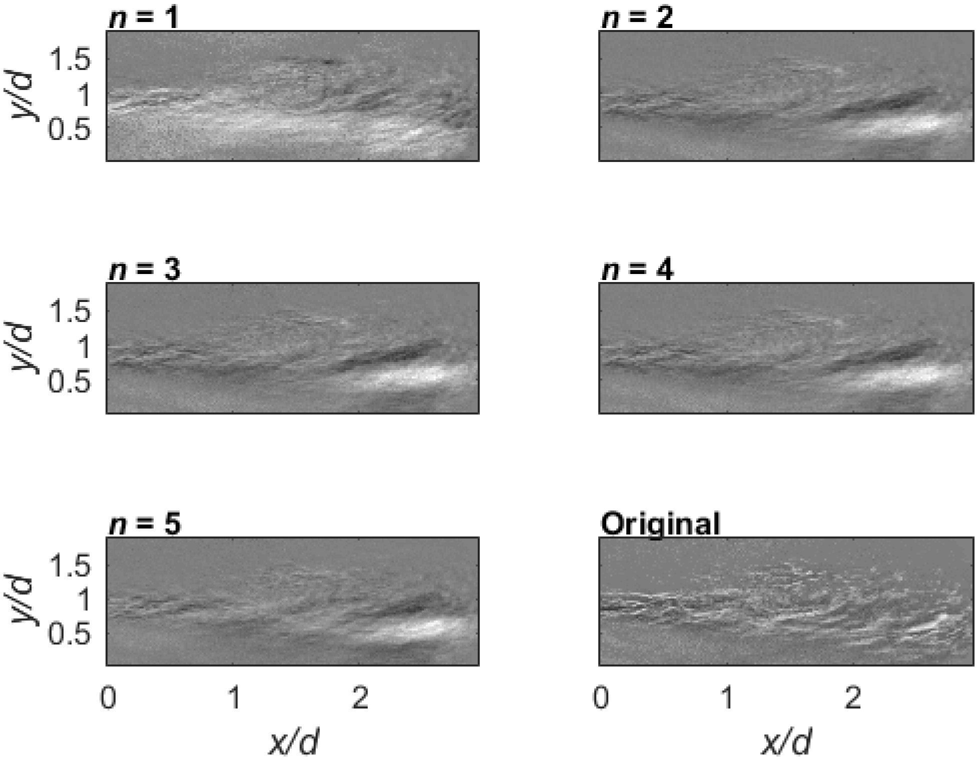


Figure 10: Cumulative Mode Contribution at Lower Modes vs. Original Flow

Figure 10 shows the accumulative modes at lower mode numbers. Because the lower modal numbers correspond to the largest energy contribution they are the dominate flow structures in the total flow. By mode 5 it is possible to see the smaller eddies at the outer region are beginning to form although they are not as clear as accumulating 200 modes as shown in Figure 10.

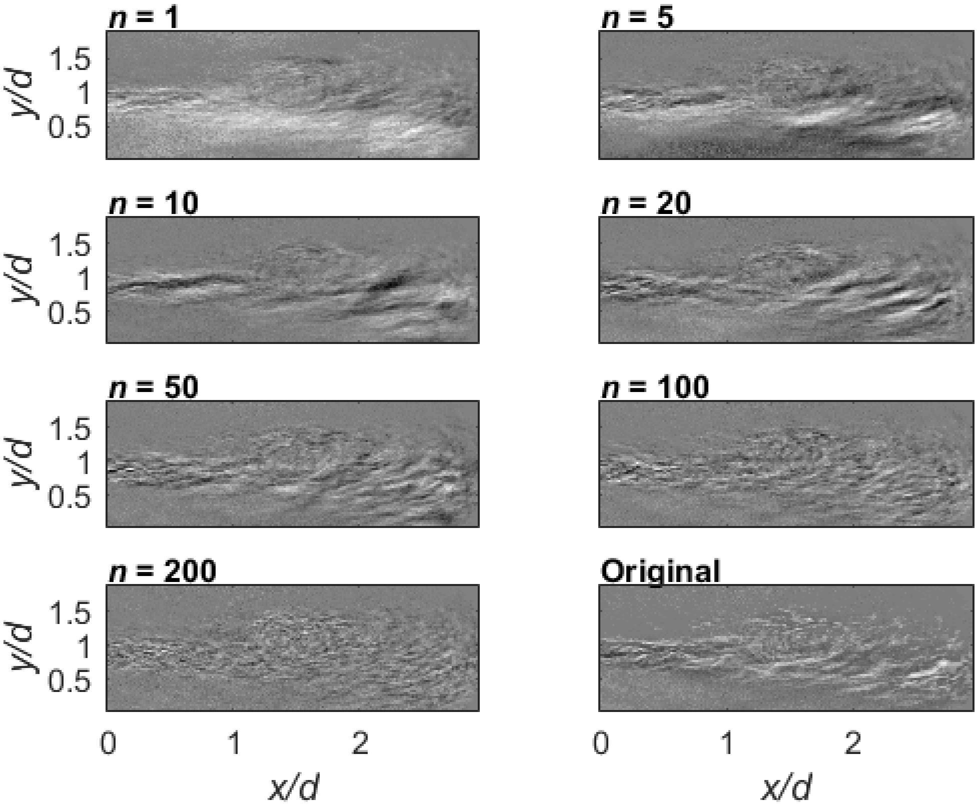


Figure 11: Individual modes for the sCO_2 jet.

Figure 11 shows the individual mode contribution to the mean flow as opposed to cumulated modes shown in Figure 9. This is done to show the special location of modal contribution. As anticipated, mode 200 only contains the smallest scale structures and the lowest energy content. Again, the first five modes were plotted to understand where the most energetic flow was distributed at each individual mode.

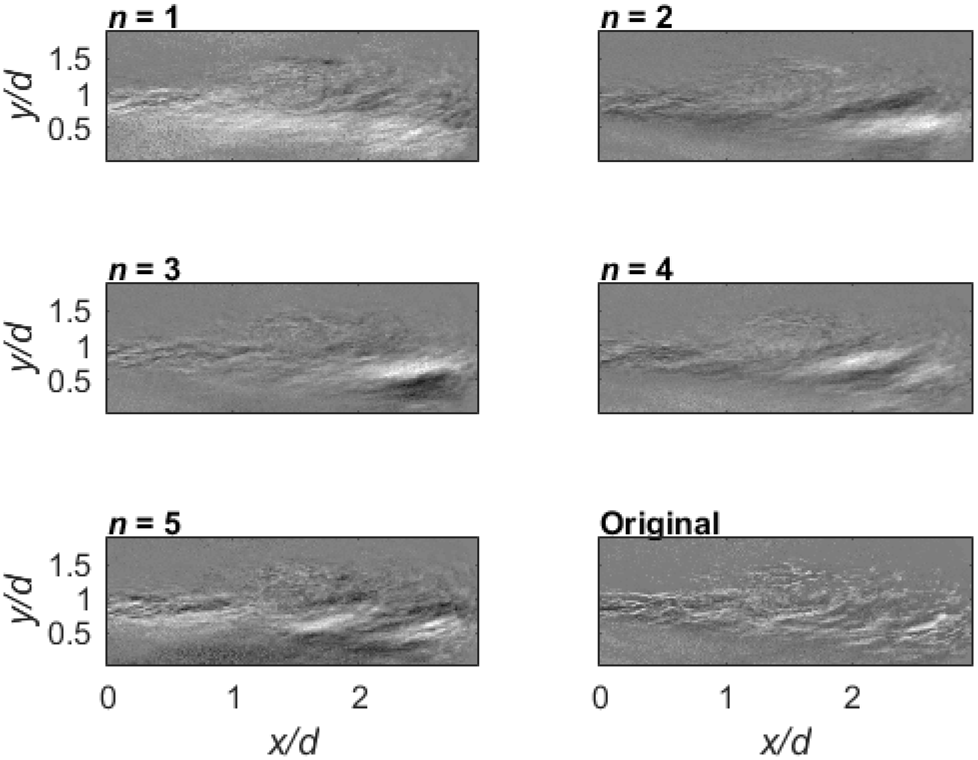


Figure 12: Individual Mode Contribution at Lower Modes

As anticipated, the higher energy content in mode one is located along the centerline of the jet. As the modes grow in number the structure begins to shift from the centerline to the outer regions of the flow as the smaller energy structures begin to show.

CONCLUSION

In the current work, a supercritical carbon dioxide loop was designed, built, and commissioned for optical diagnostics and flow visualization. With the relevance of sCO_2 as a working fluid in power generation, valid diagnostic techniques are relevant for flow characterization in direct-fired combustion application. Optical diagnostics are an ideal choice for validating data as it can be used to extract planar data instead of limited point information. The work performed provided validation for the working platform to visualize supercritical sCO_2 and established preliminary data to be built upon as the diagnostic techniques are refined.

Based on results and observations made during testing, the high density gradients witnessed from sCO_2 in regions well into the supercritical regime make it well suited for optical techniques involving background illumination. Validation data as well as flow visualization images can be generated through the use of these techniques. It was also observed that at the critical point, these techniques were rendered inefficient due to the opaque nature of the fluid. Future work will consist of more advanced diagnostic techniques such as Rayleigh Scattering and Laser Induced Florescence.

REFERENCES

[1] Dostal, Vaclav, Pavel Hejzlar, and Michael J. Driscoll. "The supercritical carbon dioxide power cycle: comparison to other advanced power cycles." Nuclear technology 154, no. 3 (2006): 283-301.

[2] Dostal, Vaclav, Pavel Hejzlar, and Michael J. Driscoll. "High-performance supercritical carbon dioxide cycle for next-generation nuclear reactors." Nuclear Technology 154, no. 3 (2006): 265-282.

[3] Dostal, Vaclav, Michael J. Driscoll, and Pavel Hejzlar. "A supercritical carbon dioxide cycle for next generation nuclear reactors." PhD diss., Massachusetts Institute of Technology, Department of Nuclear Engineering, 2004.

[4] Brun, Klaus, Peter Friedman, and Richard Dennis, eds. Fundamentals and applications of supercritical carbon dioxide (sCO2) based power cycles. Woodhead publishing, 2017.

[5] Delimont, Jacob, Nathan Andrews, and Lalit Chordia. "Exploration of Combustor Design for Direct Fired Oxy-Fuel Application in a sCO2 Power Cycle." Global Power and Propulsion Society, Proceedins Montreal,, Montreal.

[6] McClung, Aaron. "Oxy-Combustion Integration for Direct Fired sCO2 Cycles." In Fifth International Symposium—Supercritical CO2 Power Cycles, San Antonio, TX, Mar, pp. 28-31. 2016.

[7] Strakey, Peter A. Oxy-Combustion Flame Fundamentals for Supercritical CO2 Power Cycles. No. NETL-PUB-21467. NETL, 2017.

[8] Manikantachari, K. R. V., Scott Martin, Ladislav Vesely, Jose O. Bobren-Diaz, Subith Vasu, and Jayanta Kapat. "A Strategy of Mixture Preparation for Methane Direct-Fired sCO2 Combustors." In ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition. American Society of Mechanical Engineers Digital Collection, 2018.

[9] Delimont, Jacob, Aaron McClung, and Marc Portnoff. "Direct Fired Oxy-Fuel Combustor for sCO2 Power Cycles: 1MW Scale Design and Preliminary Bench Top Testing." In ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition. American Society of Mechanical Engineers Digital Collection, 2017.

[10] Mortazavi, Halleh, Yiran Wang, Zhen Ma, and Yang Zhang. "The investigation of CO2 effect on the characteristics of a methane diffusion flame." Experimental Thermal and Fluid Science 92 (2018): 97-102.

[11] Ushifusa, Hiroyuki, Konosuke Sugasawa, and Kazuaki Inaba. "Rayleigh Scattering of Supercritical Carbon Dioxide in Dynamic Phase Transition." In ASME 2015 Pressure Vessels and Piping Conference. American Society of Mechanical Engineers Digital Collection, 2015.

[12] Kazemifar, Farzan, and Dimitrios C. Kyritsis. "Near-critical CO2 flow measurement and visualization." Journal of Energy Resources Technology 137, no. 1 (2015).

[13] Lance, Blake. Flow Distribution Measurement Feasibility in Supercritical CO2. No. SAND2017-13152R. Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2017.

[14] Lim, Chang Hyeon, Dorrin Jarrahbashi, Sandeep R. Pidaparti, and Devesh Ranjan. "Flow of Supercritical Carbon Dioxide through a converging-diverging nozzle." The 6th International Supercritical CO2 Power Cycles Symposium, 2018.

[15] De Izarra, Grégoire, and Charles De Izarra. "Quantitative shadowgraphy made easy." European journal of physics 33, no. 6 (2012): 1821.

[16] Settles, Gary S. Schlieren and shadowgraph techniques: visualizing phenomena in transparent media. Springer Science & Business Media, 2012.

[17] Merzkirch, Wolgang. Flow visualization. Elsevier, 2012.

[18] Weiss, Julien. "A Tutorial on the Proper Orthogonal Decomposition." In AIAA Aviation 2019 Forum, p. 3333. 2019.
[19] Rowley, Clarence W., Tim Colonius, and Richard M. Murray. "Model reduction for compressible flows using POD and Galerkin projection." Physica D: Nonlinear Phenomena 189, no. 1-2 (2004): 115-129.
[20] Rowley, Clarence W., and Scott TM Dawson. "Model reduction for flow analysis and control." Annual Review of Fluid Mechanics 49 (2017): 387-417.