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# FLOW DISTRIBUTION MEASUREMENT FEASIBILITY IN SUPERCRITICAL CO2

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## ABSTRACT

Supercritical CO2 ($sCO_2$) is a fluid of interest for advanced power cycles that can reach thermal to electric energy conversion efficiencies of 50% or higher. Of particular interest for fossil-fired natural gas is the Allam cycle that captures nearly all $CO_2$ emissions and exports it as a fluid stream where it may be of value. The combustion process conditions are unlike any before realized with 90-95% $CO_2$ concentration, temperatures around 1000°C, and pressures near 300 bar. This work outlines the experimental feasibility of flow measurements to acquire the first known data in pure $sCO_2$ at similar but reduced temperature and pressure conditions.

## INTRODUCTION

Sandia National Laboratories (SNL) has a long history of $sCO_2$ power cycle research including the first lab-scale demonstrations. Currently there are a myriad of active projects that support loop and component testing to obtain experimental data, develop operating procedures, and further enable this technology in a variety of ways. Complementary modeling and simulation efforts improve understanding and support trade studies and design exploration.

Of specific interest to $sCO_2$ oxy-combustion research is the experimental particle image velocimetry (PIV) capability of SNL. The PIV hardware and user experience enable flow distribution measurements with an optical method of velocities in an entire field that does not disturb the flow. The combination of these capabilities with a long history of $sCO_2$ research provided the ideal location to attempt the first known flow measurements in $sCO_2$ in support of combustion model development via validation.

## EXPERIMENT

To test experimental feasibility, a simple $CO_2$ loop was constructed with optical access via sight windows. The loop is outlined in Figure 1 and shows three major components: 1) 4" Tee with sight windows, 2) Haskel gas booster, and 3) Atomizer. Operation began with filling the loop, then closing the valve from the $CO_2$ cylinder and opening the Fill Isolation valve to enable recirculation from the gas booster. Heat was added to the system through a 1000 W maximum cartridge heater inside a thermowell in the center of the 4" Tee. The Atomizer held 50 cSt silicone oil from Sigma-Aldrich that was atomized into small droplets via high velocity $CO_2$ injection about 1 inch under the oil surface. The 4" Tee was the largest volume and was used for imaging the flow. A natural convection plume was expected to rise from the horizontal heating element that could be measured with PIV. The Bypass valve near the Atomizer was used to control the number of particles by controlling the flow.

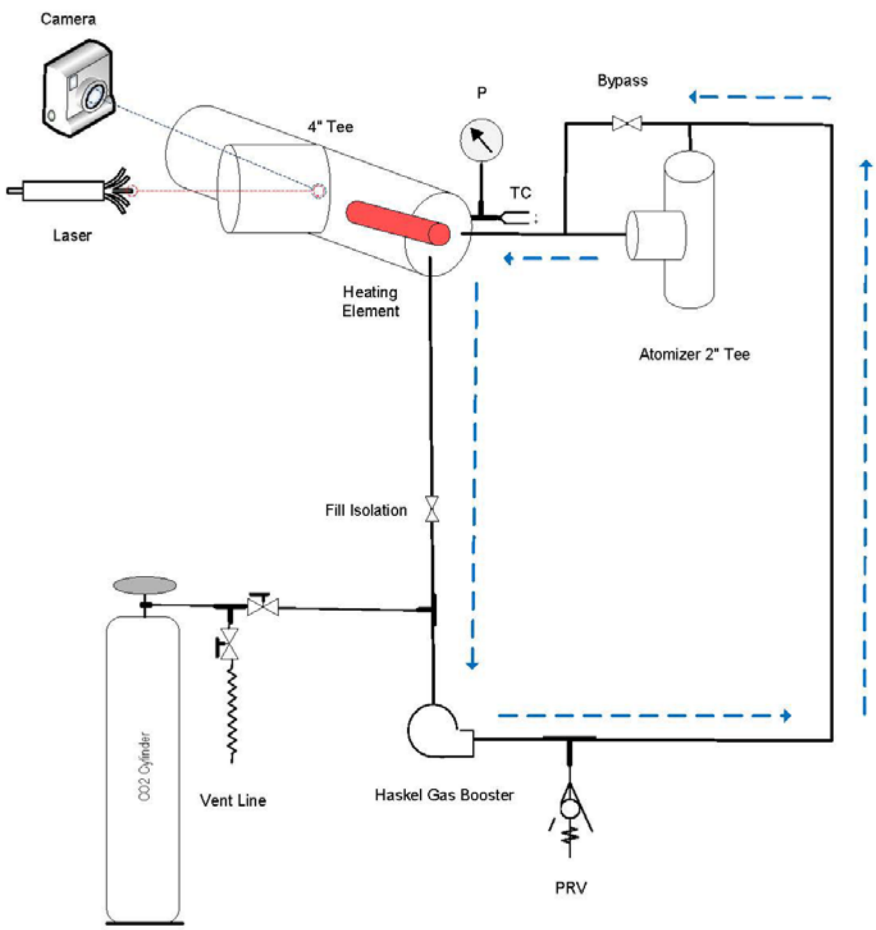


*Figure 1. $sCO_2$ Visualization Loop Schematic*

The experiment is pictured in Figure 2 and shows the physical layout of the loop and associated instruments. The 4" Tee and PIV system were mounted to an optical table for consistent alignment. Most of the supporting loop components were mounted along a wall for an organized and distributed layout. In general, ¼" stainless tubing was used. The temperature and pressure in the 4" Tee were measured with a type K thermocouple connected to a Fluke handheld meter and 3,000 psi pressure gauge, respectively. The sight windows were from Rayotek with a 2" NPTM connection, aperture of 1.22", and ratings of 4,000 psi and 392°F.

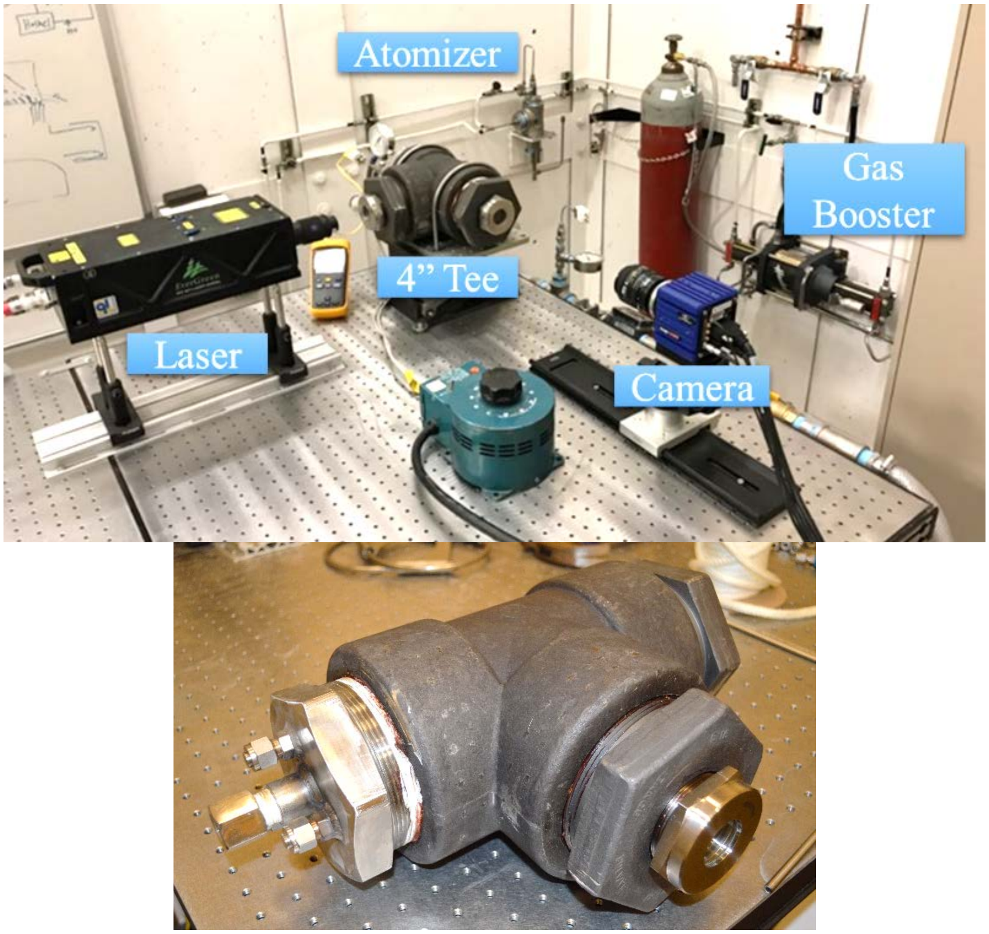


*Figure 2. $sCO_2$ Visualization Loop photo with labels (top) and 4" Tee with custom plug on left and sight window on right (bottom)*

The loop maximum operating pressure was 2,000 psi and temperature was 230°F, allowing testing comfortably into the supercritical regime (CO2 has a critical pressure of 1,070 psi and temperature of 88°F). The loop ratings were based mainly on the gas booster maximum pressure of 2,500 psi and steep temperature de-rating of the fastest component which was aluminum. Other components could be operated near 2,800 psi at 230°F.

The loop consisted of off-the-shelf parts where possible. There were two custom parts required to add extra feed-throughs into standard pipe fittings. The main one was a 4" NPTM plug that had a ½" NPTF fitting and three 3/8" Swagelok tube adapters for inlet flow, outlet flow, and sensor ports. The second fitting was a 2" NPTF cap with an added 3/8" Swagelok tube adapter at the bottom of the Atomizer for oil draining. These custom fittings required hydrostatic testing for pressure certification and performed without issue.

The original Gas Booster was a Haskel AGT-7/30 pneumatically-driven, reciprocating gas booster with two stages. It was found after it failed to cycle that it may be suffering from inter-state stall from the inlet pressure being too high. A single stage Haskel AGD-5 was then installed in parallel for circulation purposes since it does not have an inter-stage. It performed just as expected, even with high inlet pressures.

The $sCO_2$ Visualization Loop had optical access that enabled PIV measurements. PIV involves a dual-cavity laser, specialty camera, and high accuracy timing unit and is depicted in Figure 3. The flow of interest is seeded with small particles that follow the flow, are illuminated by the laser sheet, and imaged by the camera. Two images are acquired close in time. The images are divided into regions and a cross-correlation performed in each region between the two images to determine the most likely displacement direction and magnitude of the particles in that region. The displacement, scaled from pixels to physical length and divided by the elapsed time between laser pulses, provides the measurement of velocity.

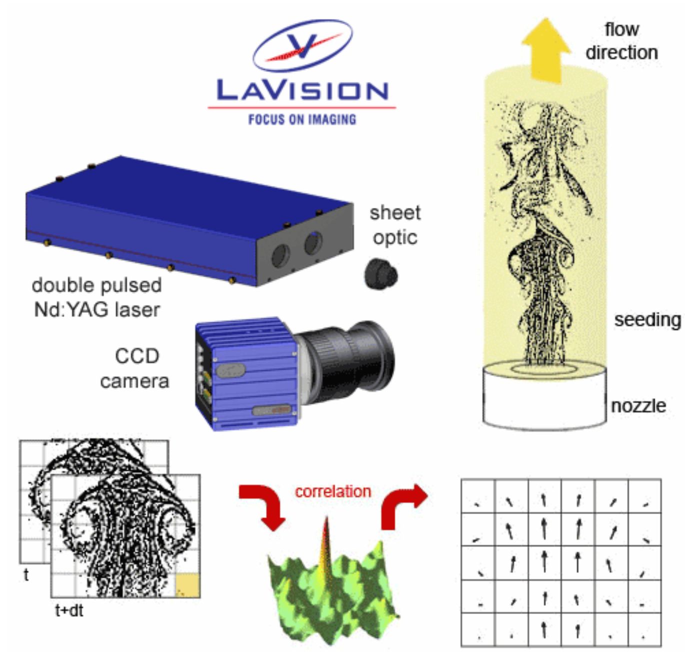


*Figure 3. Particle image velocimetry method [http://www.lavision.de/en/techniques/piv-ptv/index.php]*

The PIV system was made by LaVision, Inc. It had a Quantel Evergreen dual-cavity laser that produces green light at 532 nm at up to 15 Hz and 200 mJ per pulse. The camera was a LaVision Imager sCMOS with 16 bits of intensity resolution and about 5.5 MP. The lens was a Nikon 28 mm, f/2.8D. The timing unit was an external PTU X. The software used for acquisition and processing was DaVis 8.4.0.

## FEASIBILITY RESULTS

The s$CO_2$ Visualization experiment allowed us to show that PIV measurements in s$CO_2$ are feasible. Previous to this work, little was known about the optical clarity of $CO_2$ near the critical point. The clarity was found to be high in the liquid, vapor, and supercritical regimes in the visible spectrum. Optical opacity was found for conditions near the critical point, but this cleared as the temperature and pressure were increased only slightly. This effect is shown in Figure 4 as imaged from the camera. The image shows the heating element near the center, the thermocouple probe on the left, and the inlet and outlet ports on the right. A two-phase fluid is observed on the left with a very clear gas phase on top. Both temperature and pressure increase as heat was added to the system. The conditions passed right through the critical point at 88°F and 1070 psi. Conditions just above the critical point are very opaque. Adding heat further begins to clear the opacity. It is interesting to note the density stratification observed in the right-most image for supercritical conditions. This phenomenon was observed under a large range of pressure and temperature conditions when the $CO_2$ was stationary but disappeared immediately with circulation. Supercritical $CO_2$ is known for its rapid density change with temperature which is likely the cause of this stratification.

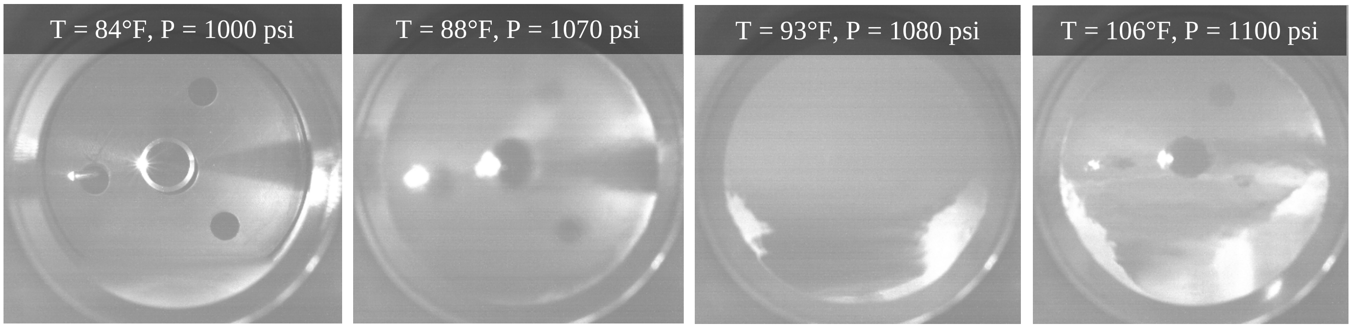


*Figure 4. Images of CO2 under increasing temperature and pressure conditions near the critical point*

The images in Figure 4 were for visualization purposes. Images for PIV were very similar but had the addition of laser illumination of oil particles for seeding. An example PIV image is shown in Figure 5 and has similar background with many small particles that are similar in intensity. Because of this, the average background of the 500 images was subtracted from each to highlight the particles and improve accuracy. One added feature was the inlet tube that extends into the Tee and curves around, guiding the inlet flow to imping on the far wall. This was done to reduce the amount of oil that was initially impinging on the sight window. Another change was that the heater and thermocouple were painted flat black to reduce laser reflections.

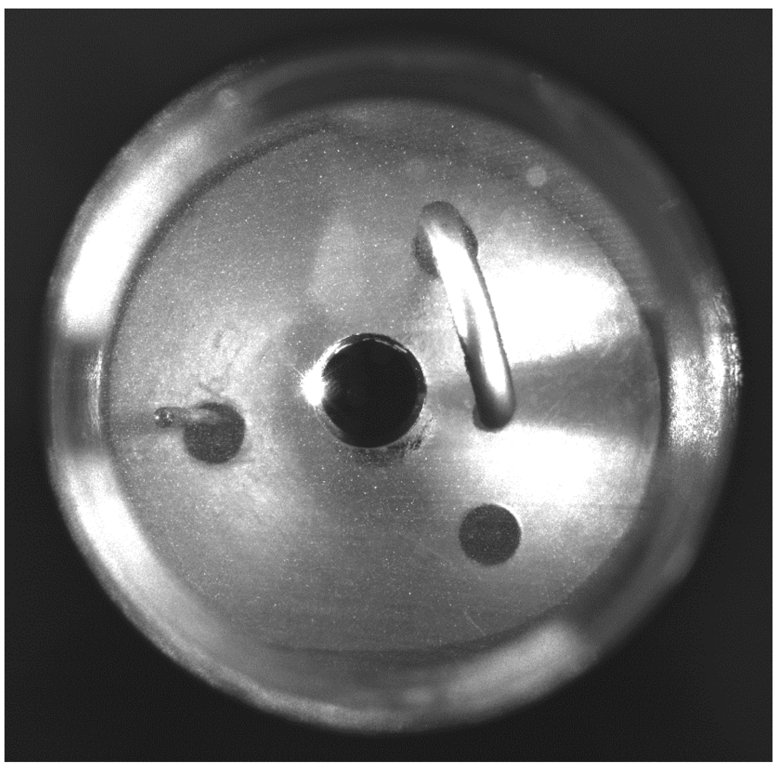

*Figure 5. Particle image for a case at T=132°F, P=1130 psi, and heat power at 500 W*

The particle images were processed with the cross-correlation algorithm in DaVis. An example instantaneous vector field is shown in Figure 6 and shows areas of relatively high and low velocity as well as several eddies of differing size. Note that this case was with gas booster circulation, so natural convection from the heated cylinder is not apparent. The laser was blocked by the heater in the center and right sides of the image, so no data could be measured in these areas. The original data spatial resolution is 0.83 mm and field of view is an approximate circle with diameter of 72 mm. The cross-correlation algorithm used the adaptive region method to use the most appropriate region shape, size, and angle for the measured displacements. Since the observed particle density was low, limiting the minimum region size, only 64x64 pixel window sizes were used, but with four passes for robustness. Results with peak ratios under two or overly-large differences to neighbors were removed during post-processing.

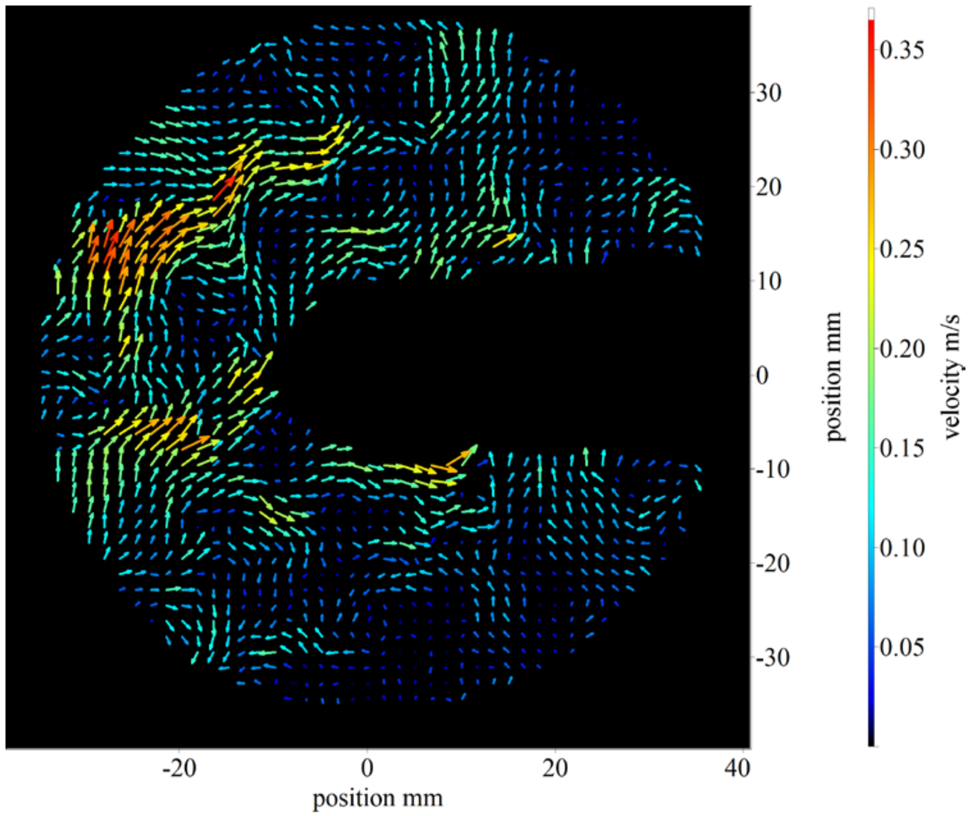


*Figure 6. Instantaneous vector field showing eddies*

Time-mean velocities are shown in Figure 7 and has a much smoother vector field. There is a relatively high velocity area moving to the upper right as a consequence of the reflected impinging jet on the far wall. In both velocity figures, only every other vector is displayed for clarity, but the set has approximately four times the number of vectors. With further oil particle system improvement, a further increase in four times the number of vectors is possible.

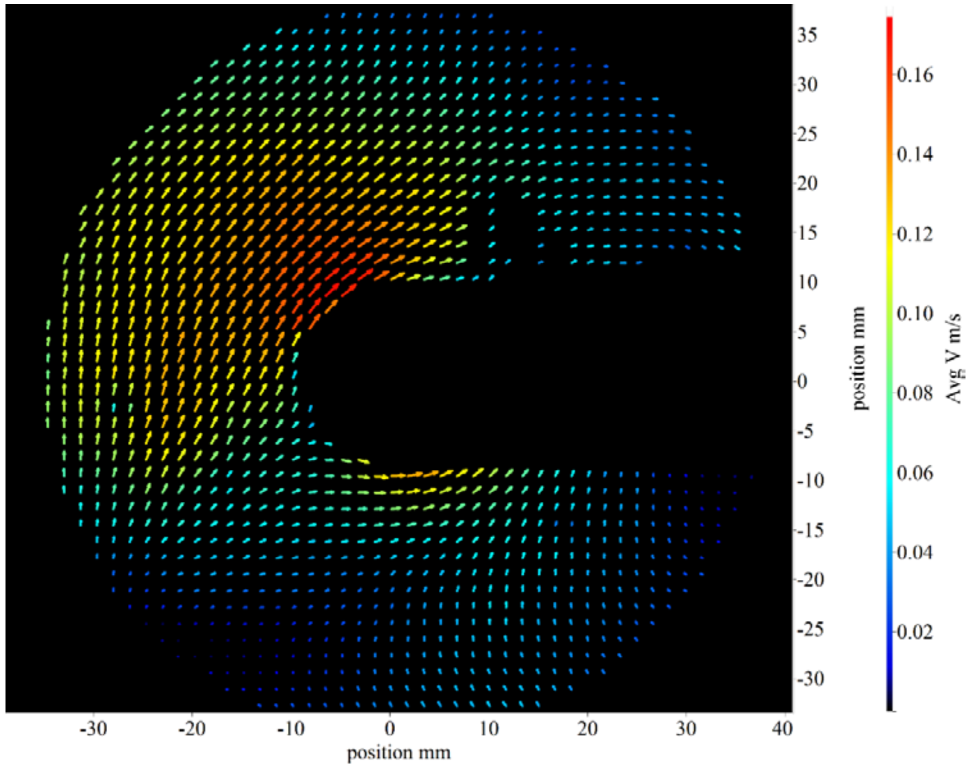


*Figure 7. Time-mean vector field result*

Several challenges were discovered while performing these experiments. The first was bright laser reflections inside the 4" Tee, even for apparently dull, grey surfaces. This was remedied by painting these parts black. The heated cylinder and thermocouple were easily removed, cleaned, and painted with a high temperature, flat black paint. The inside surface of the Tee was challenging to reach, so a thin piece of sheet metal was painted and inserted into the cavity to reduce reflections.

The second challenge was oil transport inside the loop that coated the inside and impaired optical access through the sight windows. Attempts to remedy this effect were to increase the height between the oil surface and the main CO2 flow in the atomizer and to add a series of deflectors in this area to remove large particles and suppress any potential foam. These efforts were moderately successful, but further improvements to keep larger drops in the atomizer should be explored for reliable measurements. One area of potential improvement is to apply the design principles for Laskin Nozzles for atomization to high density $CO_2$. Laskin Nozzle design has been studied previously for low density air, but no known works describe design principles when the working fluid has a density similar to the oil. In our experiments, the highest density possible was for liquid $CO_2$ when filling the loop at approximately 60°F and 1000 psi and was about 850 kg/m^3, similar to the 950 kg/m^3 of oil. One theory that could be tested is to heat during the fill process, keeping the high pressure $CO_2$ in a gas/supercritical state with densities on the order of 250 kg/m^3 that should help the oil to remain at the bottom of the atomizer.

## CONCLUSIONS

The work described herein outlines the experimental design, testing, and results that confirm that distributed velocity measurements are feasible in $sCO_2$ with PIV. Though this test was for a benchtop scale, one of the benefits of PIV is that it scales very well from the mm scale to multiple-meter scale. Measuring a more prototypical flow to the direct-fired sCO2 combustor is possible with increased flow rates as well as pressure and temperature increases and improvements to geometry.

**ACKNOWLEDGEMENT**

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