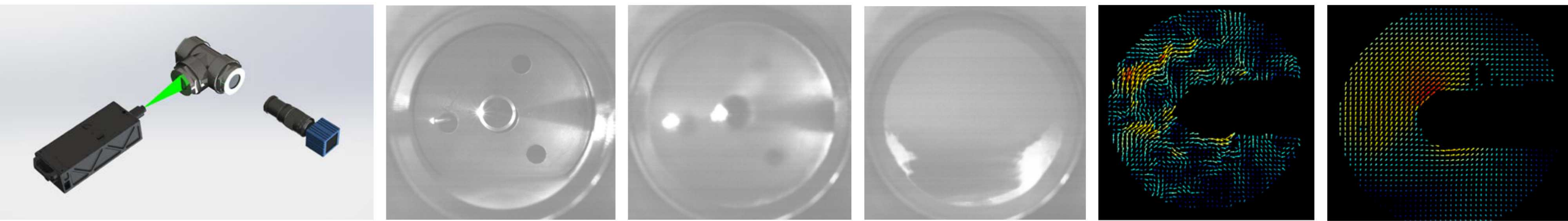


Exceptional service in the national interest



Flow Distribution Measurements in sCO₂

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6th International sCO₂ Power Cycles Symposium

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Project Overview

- Illinois Rocstar LLC contracted us to determine the feasibility of doing high fidelity measurements of a sCO₂ flow under a Phase I SBIR award.
- Sandia National Labs' experience with sCO₂ experiments and our Particle Image Velocimetry (PIV) system and experience allowed us to explore this feasibility.
- We were able to show that these measurements are feasible, starting this capability for future projects.



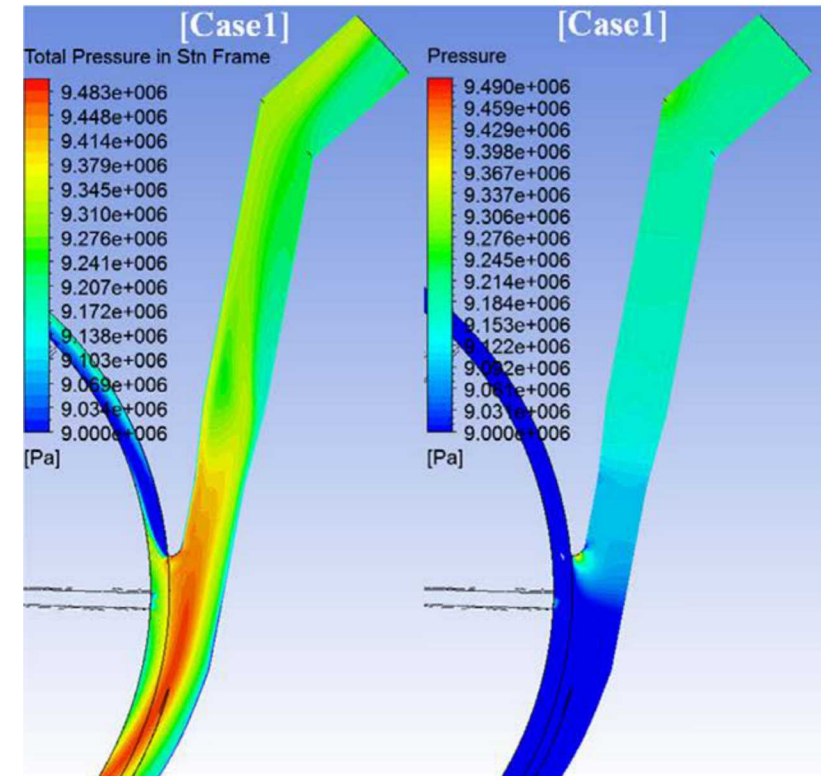
What work have others done in sCO₂ fluid dynamics?

- Many know the well-done YouTube video that shows sCO₂ phase transition and transparency



<https://www.youtube.com/watch?v=-gCTKteN5Y4>

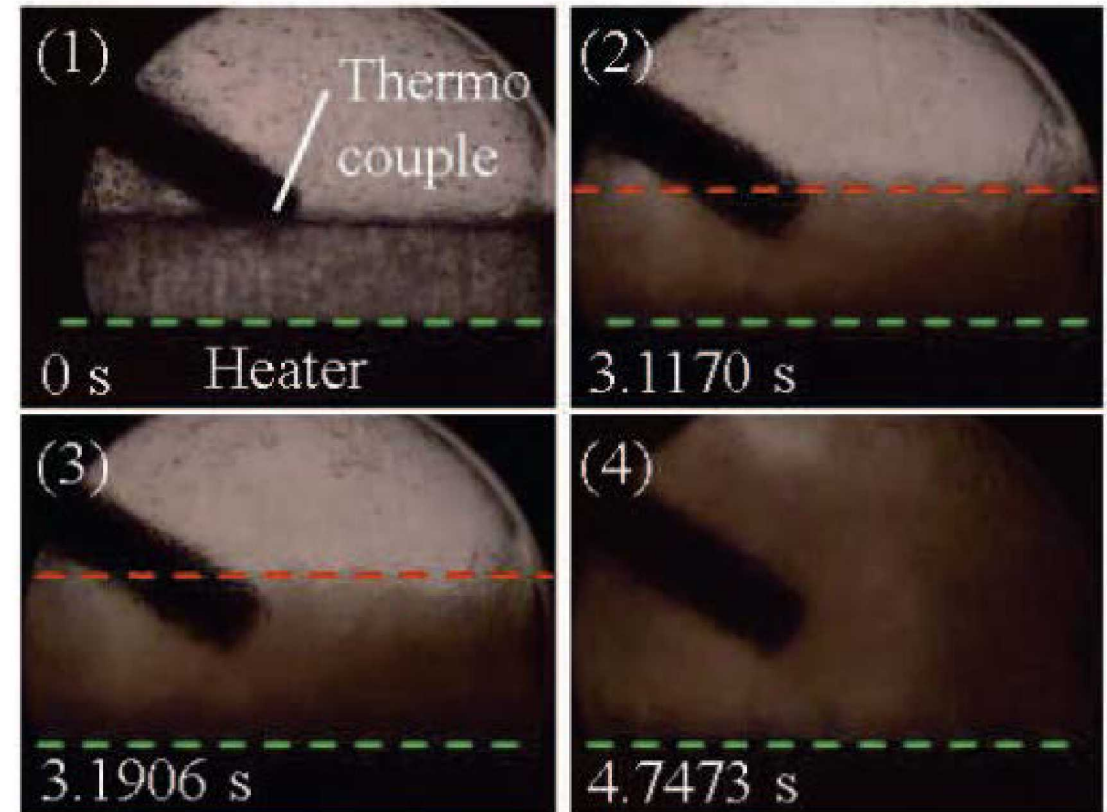
- Several computational fluid dynamics publications exist for geometries such as turbines, compressors, heat exchangers, combustors



Kim, S. G., Lee, J., Ahn, J., Lee, J. I., Addad, Y., Ko, B., "CFD investigation of a centrifugal compressor derived from pump technology for supercritical carbon dioxide as a working fluid", The Journal of Supercritical Fluids, Volume 86, 2014, Pages 160-171, ISSN 0896-8446, <https://doi.org/10.1016/j.supflu.2013.12.017>.

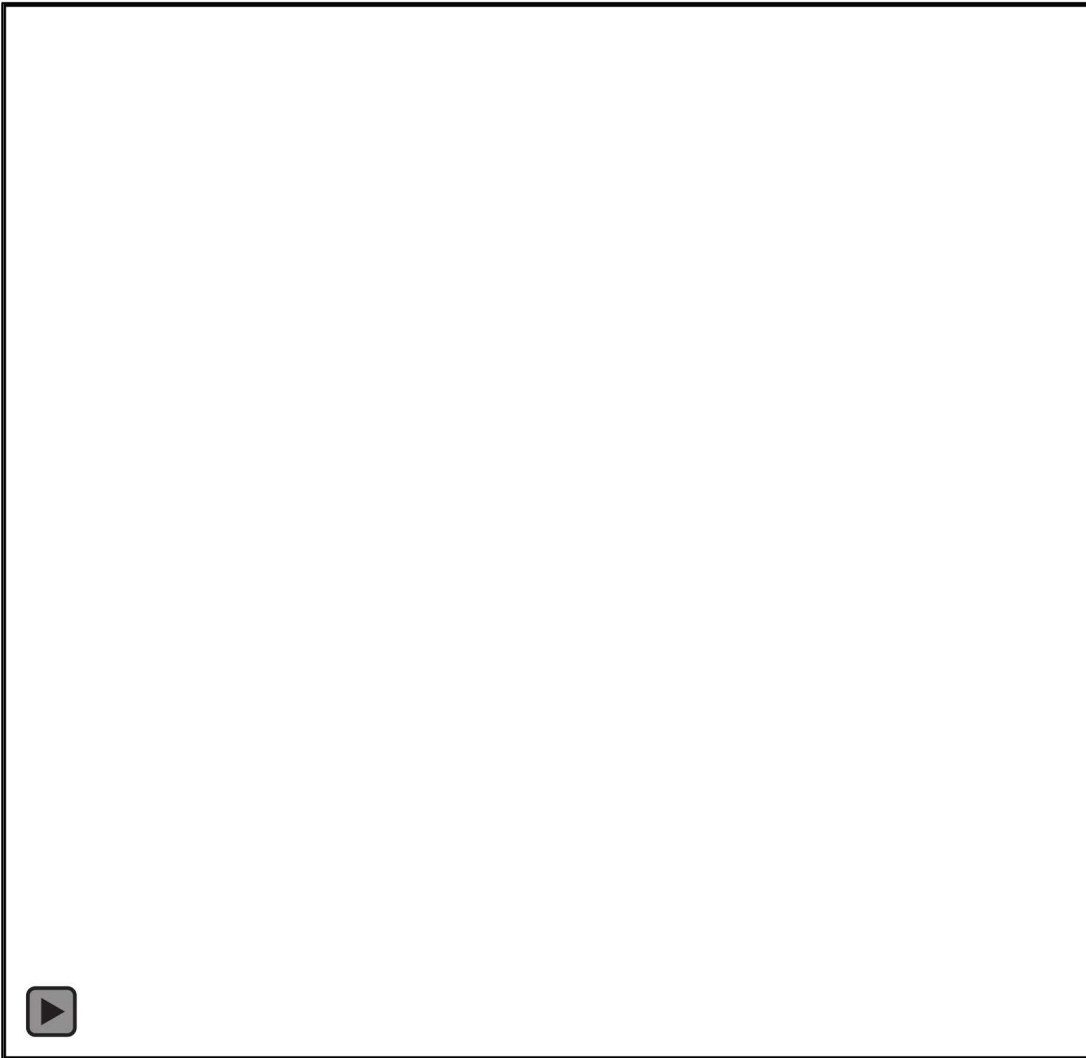
There is one known paper about sCO₂ visualization

- Researchers used Rayleigh scattering to visualize the generation of sCO₂ from heating liquid in a custom pressure vessel
- The image at the right shows the transition from two-phase in (1) to a supercritical mixture as it is heated from the bottom.
- The green line is the heater surface and the red line the approximate phase boundary.



Ushifusa, H., Inaba, K., Sugawara, K., Takahashi, K., Kishimoto, K.,
 "Measurement and visualization of supercritical CO₂ in dynamic phase transition", EPJ Web of Conferences, 92, 02103 (2015).

Particle Image Velocimetry (PIV) allows flow fields to be measured optically

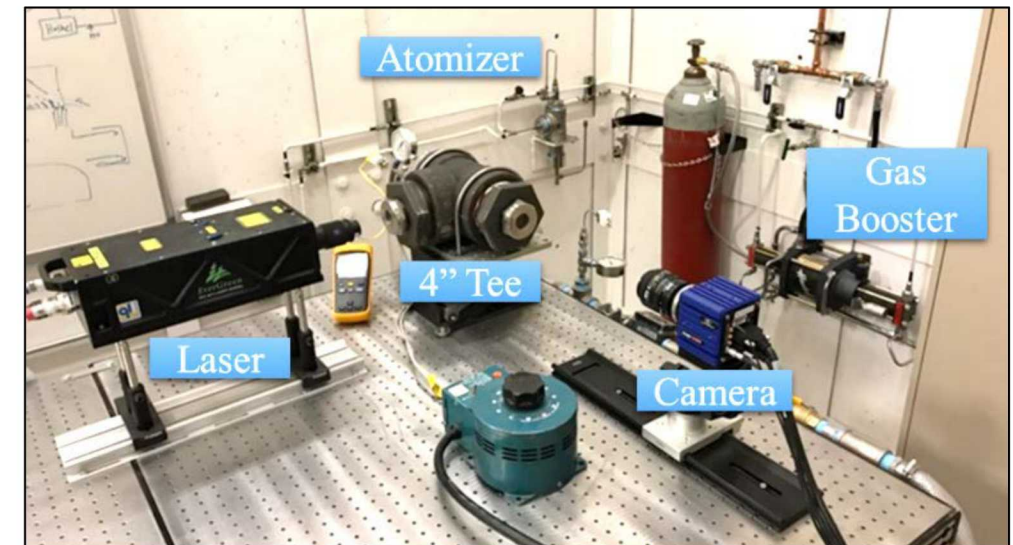
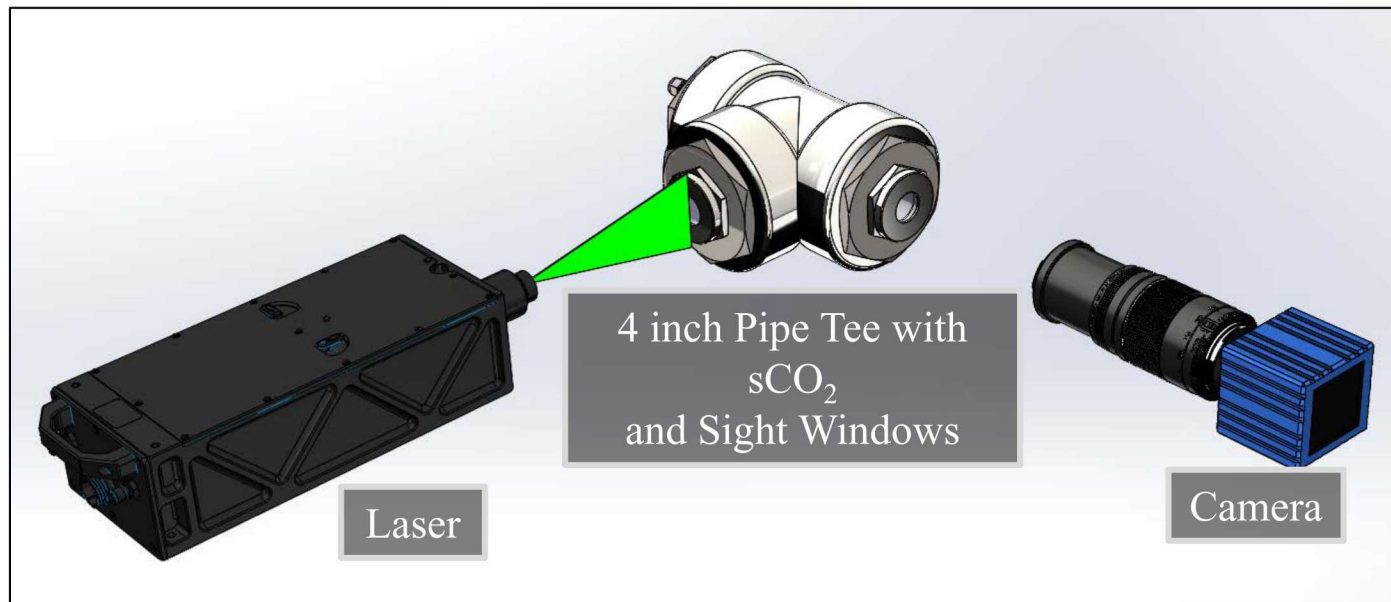


LaVision, <http://www.lavision.de/en/techniques/piv.php>

- PIV requires
 - transparent fluid
 - small seed particles
 - dual-cavity laser (2 lasers in 1)
 - specialized camera for taking two images within $<1\mu\text{s}$
 - programmable timing unit

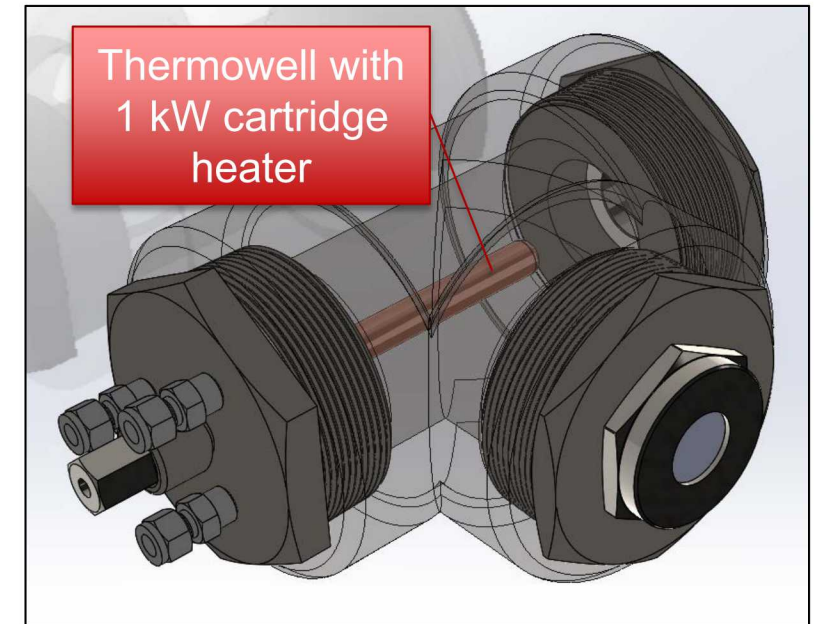
The experiment was basic but allowed for feasibility testing

- sCO₂ would be imaged in a threaded pipe tee with two optical windows
- Silicone oil particles were generated in an oil atomizer (Laskin nozzle)



The 4" pipe tee was used for visualization

- The tee had two sight windows and a custom plug with four smaller ports for CO2 injection/extraction, instrumentation, and insertion of a thermowell.
- Sight windows used 2" NPT thread as the 4" version was not in stock in time for ordering.
 - This proved to be a blessing since 4" threads required >1000 ft-lb of torque to seal at 3,250 psi and the windows were not rated for this torque

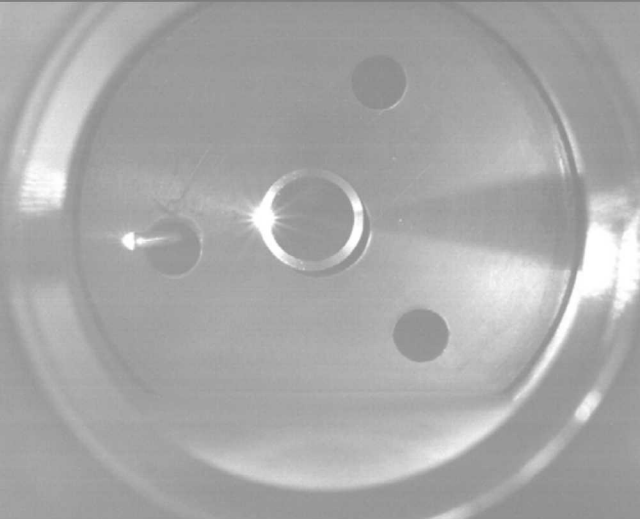


Custom plug with smaller ports

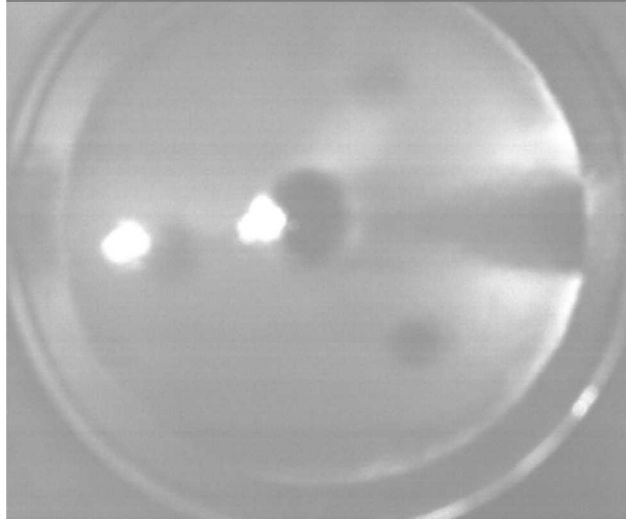


CO₂ is transparent except for conditions around the critical point

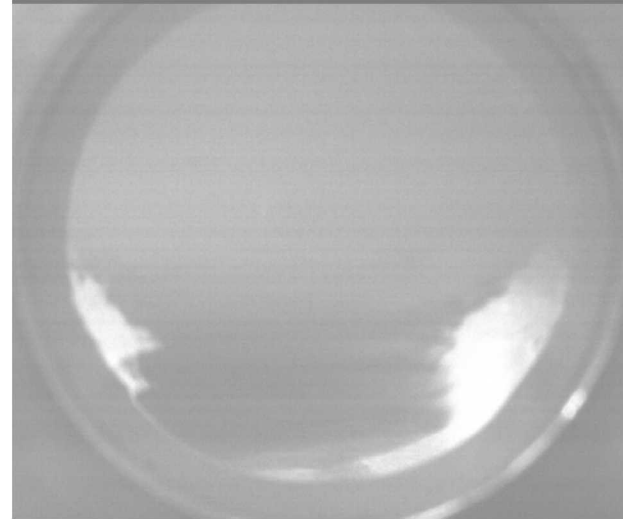
T = 84°F, P = 1000 psi



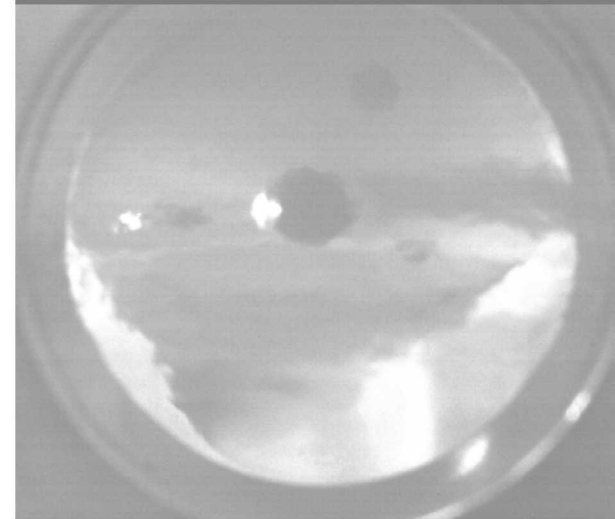
T = 88°F, P = 1070 psi



T = 93°F, P = 1080 psi



T = 106°F, P = 1100 psi

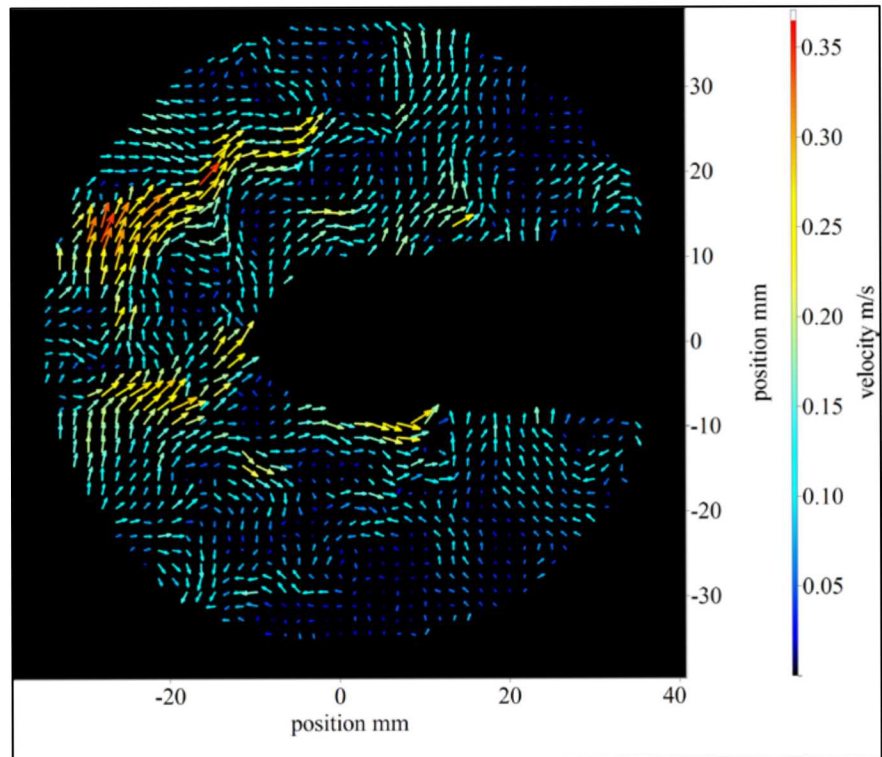


Stratification was observed over a large range of pressures and temperatures

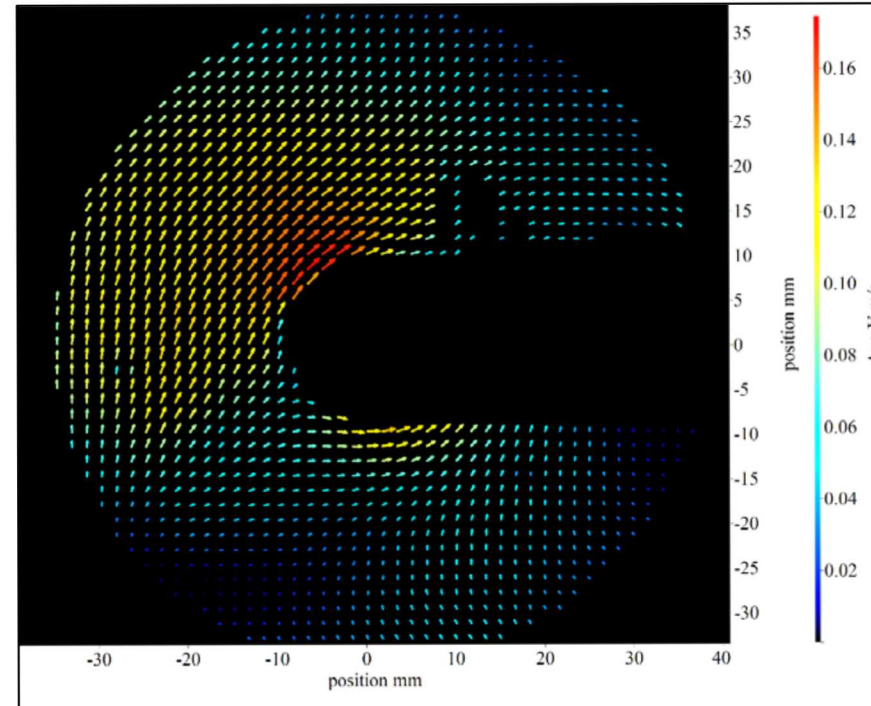
- The movie is for $T=145\text{F}$ (62.8C), $P=1120\text{ psi}$ (7.72 MPa), and $Q_{\text{heater}}=500\text{ W}$
- The density appears uniform while the recirculation gas booster is injecting and extracting CO_2 from the tee.
- But when the recirculation is stopped, the CO_2 quickly stratifies.



You can view both instantaneous and time-average velocity fields



- Instantaneous vector fields show eddies
- Note that the vectors are sub-sampled in this image for clarity

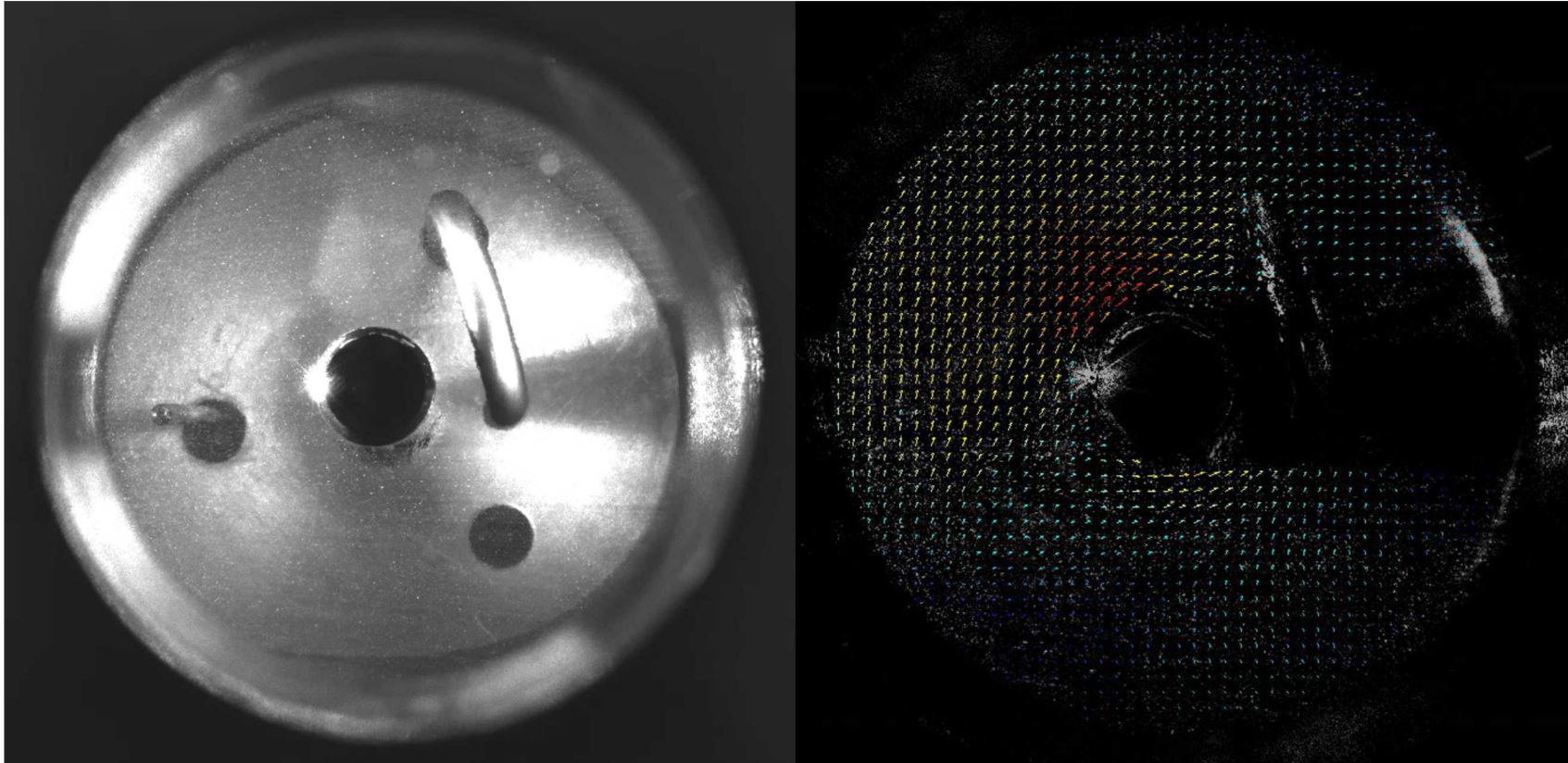


- Time-average velocity field shows smoother profile with recirculation causing a swirling effect

- Quantities that are measured
 - $u(t), v(t)$
 - \bar{u}, \bar{v}
 - $\overline{u'u'}, \overline{v'v'}, \overline{u'v'}$
- Uncertainties that are calculated
 - $U_{u(t)}, U_{v(t)}$
 - $U_{\bar{u}}, U_{\bar{v}}$
 - $U_{\overline{u'u'}}, U_{\overline{v'v'}}, U_{\overline{u'v'}}$

Backup

Particles were added for PIV



- Raw particle image
- Particle image with background removed and velocity vectors superimposed

Oil Atomizer

- The oil atomizer was modeled after a low pressure version that it commonly use to atomize oil for PIV experiments in air.
- CO_2 is injected in the top, forced through small holes under the oil, and the atomized oil and CO_2 mixture exits the side

