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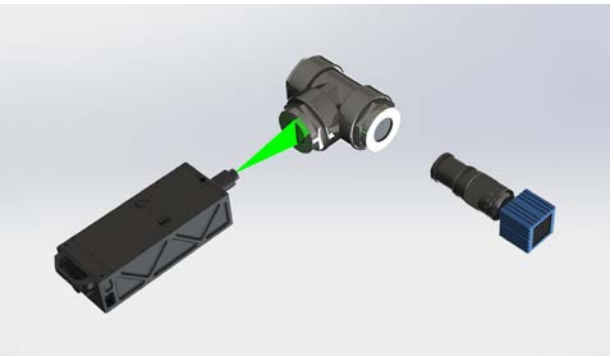
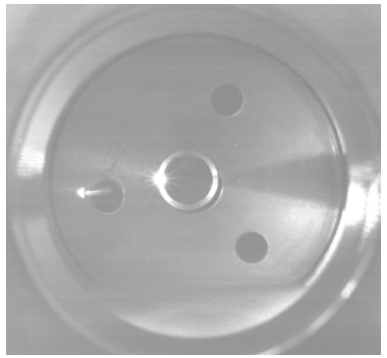
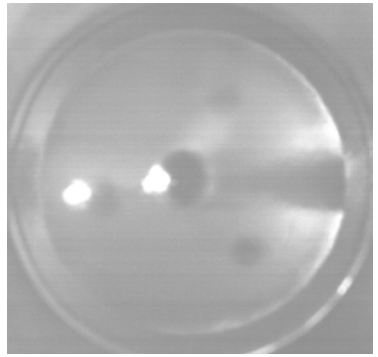
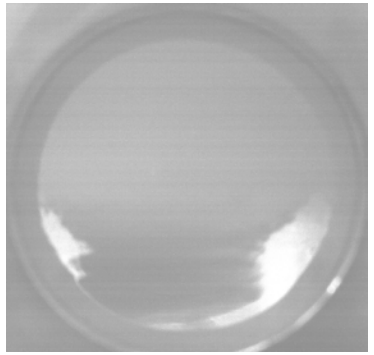
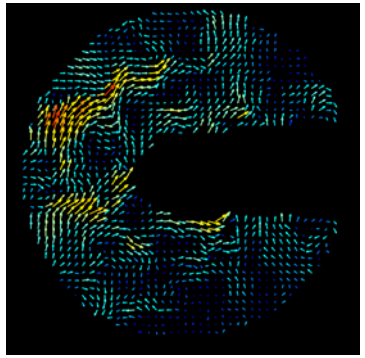
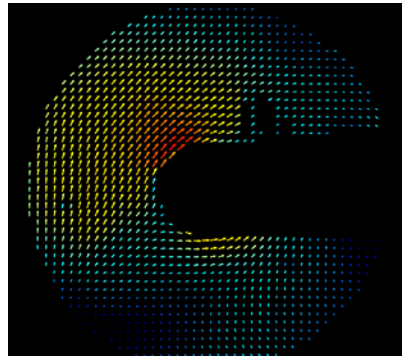







Flow Distribution Measurements in sCO_2

Dr. Blake W. Lance, Sandia National Labs

6^{th} International sCO_2 Power Cycles Symposium

March 27-29, 2018, Pittsburgh, PA

This material was performed under subcontract to Illinois Rocstar LLC and is based upon work supported by the U.S. Department of Energy, Office of Science, Small Business Innovation Research (SBIR) Program under Award Number(s) Grant No. DE-SC0017236.

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

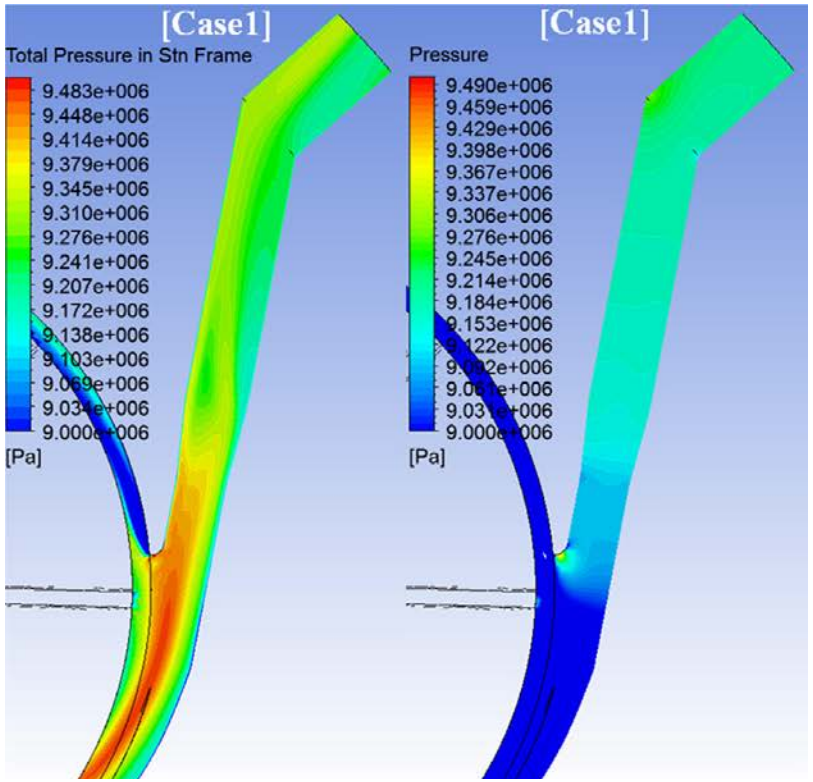
Project Overview

- Illinois Rocstar LLC contracted us to determine the feasibility of doing high fidelity measurements of a sCO_2 flow under a Phase I SBIR award.
- Sandia National Labs' experience with sCO_2 experiments and our Particle Image Velocimetry (PIV) experience and system allowed us to explore this feasibility.
- We were able to show that these measurements are feasible, starting this capability for future projects.
- The experimental budget was $20k

What work have others done in sCO_2 fluid dynamics?

- Many know the well-done YouTube video that shows sCO_2 phase transition and transparency

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

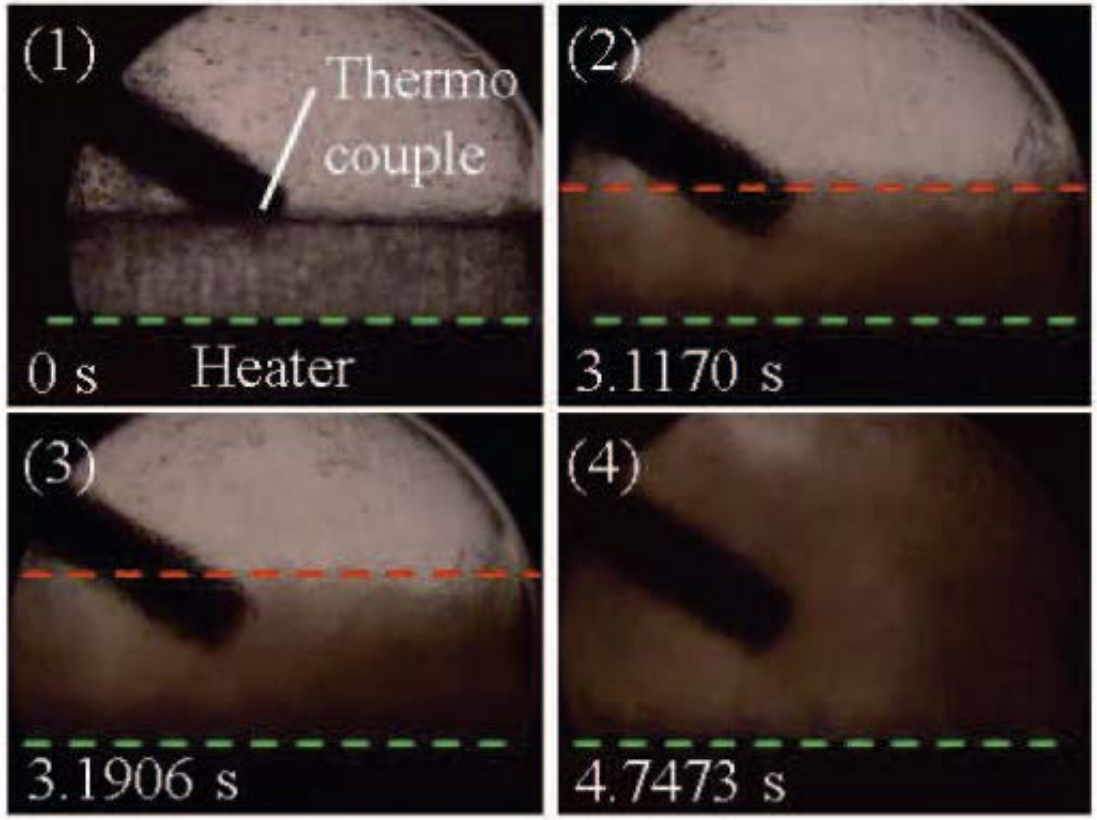


- Several computational fluid dynamics publications exist for geometries such as turbines, compressors, heat exchangers, combustors

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.

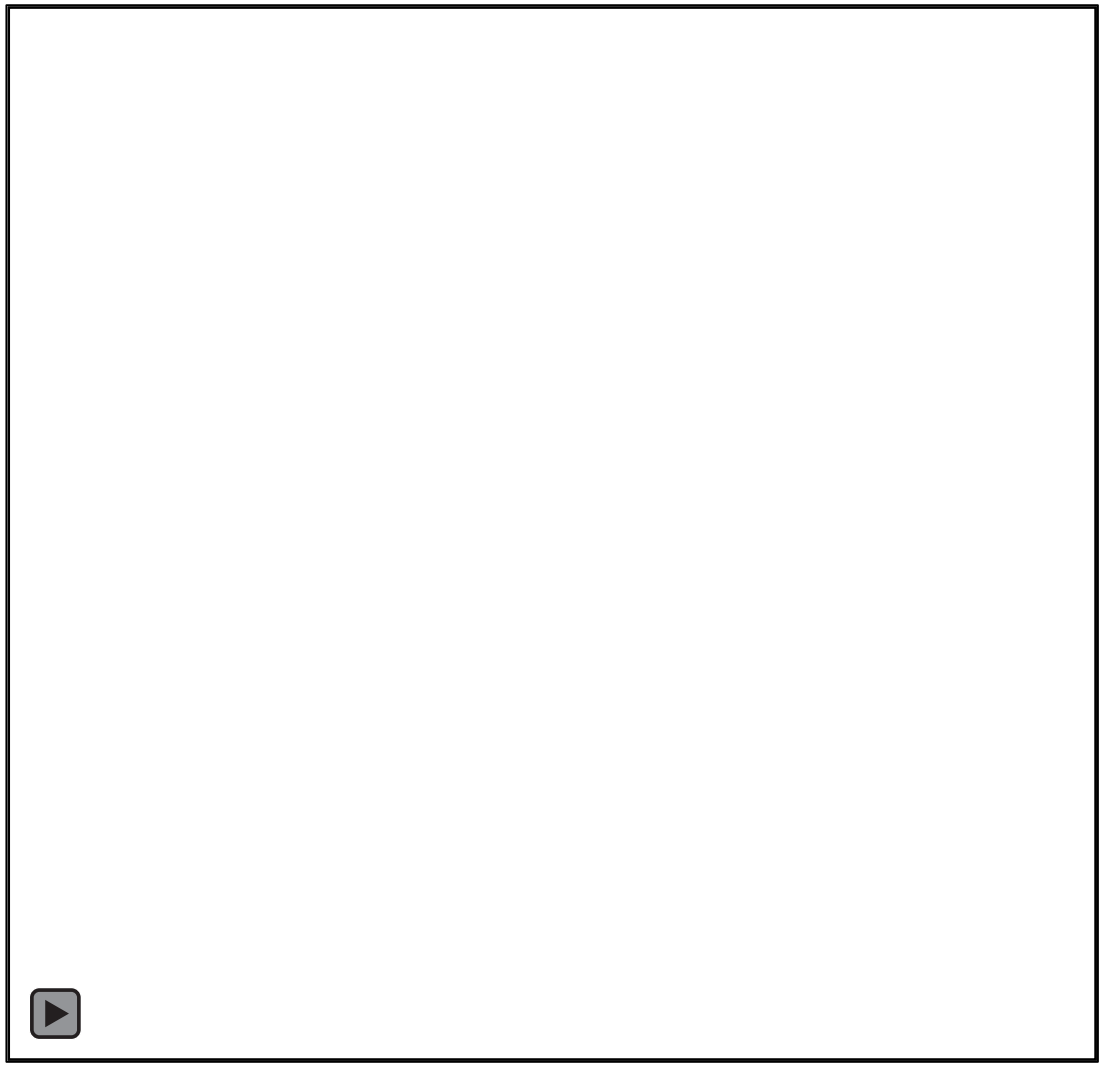
There is one known paper about sCO_2 visualization

- Researchers used Rayleigh scattering to visualize the generation of sCO_2 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., Sugasawa, 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

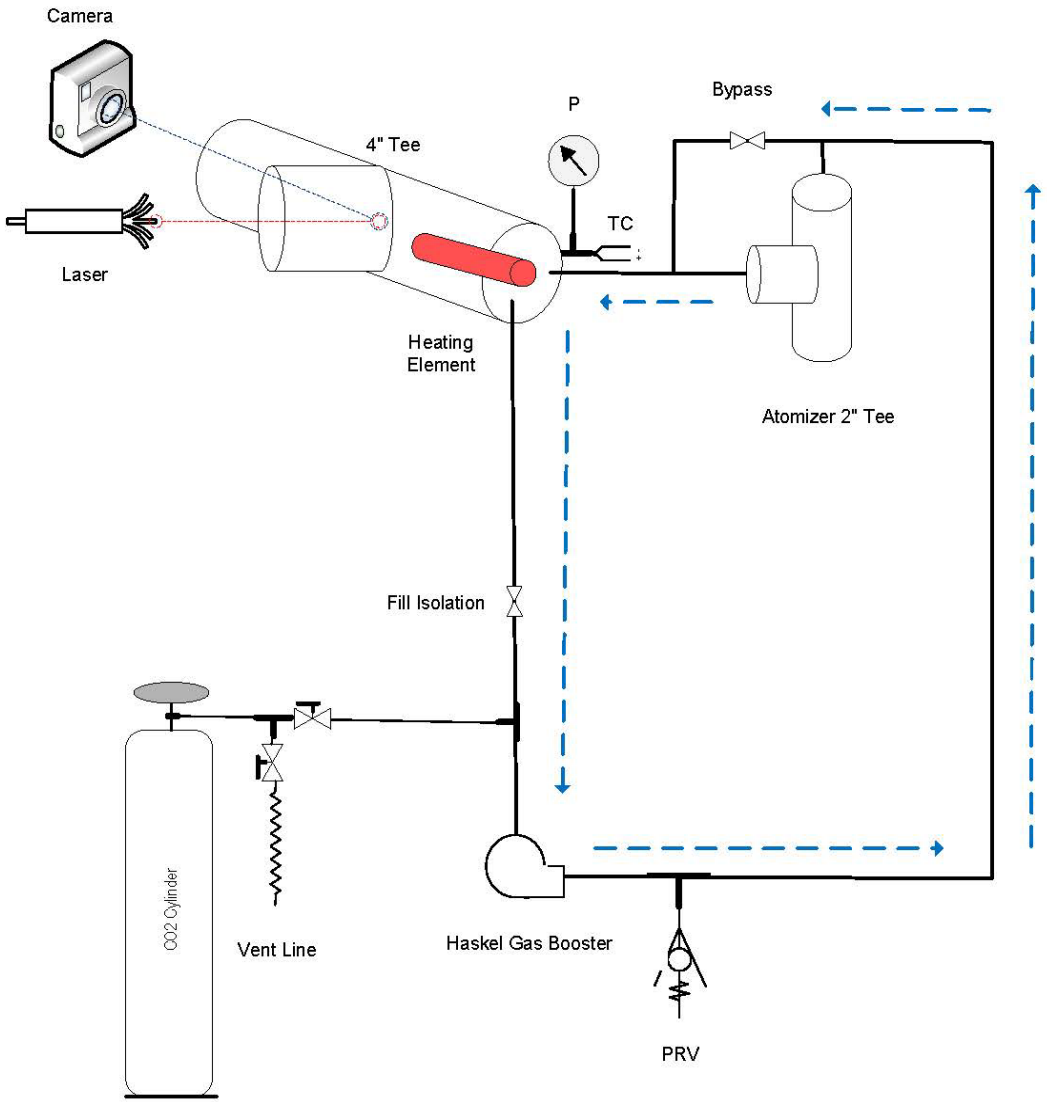


LaVision, http://www.lavision.de/en/techniques/piv.php

- PIV requires
  - transparent fluid
  - small seed particles
  - dual-cavity laser (2 lasers in 1)
  - specialized camera for taking two images within <1µs
  - programmable timing unit

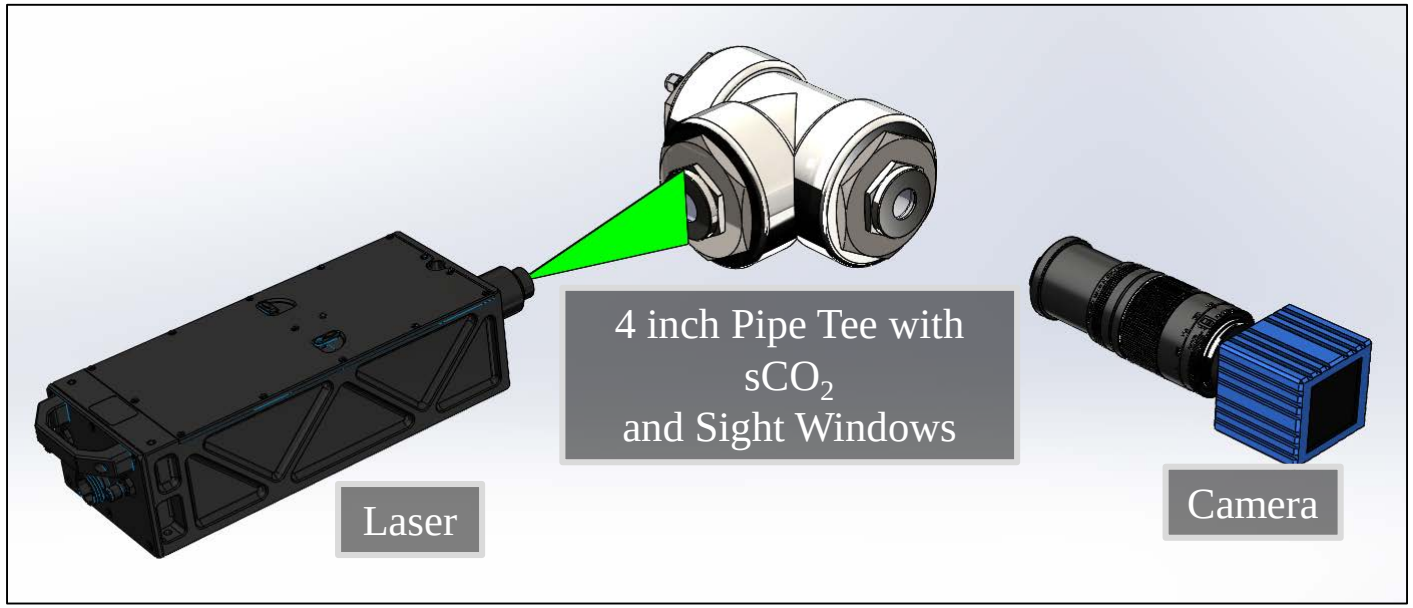
The sCO_2 Visualization Loop was assembled

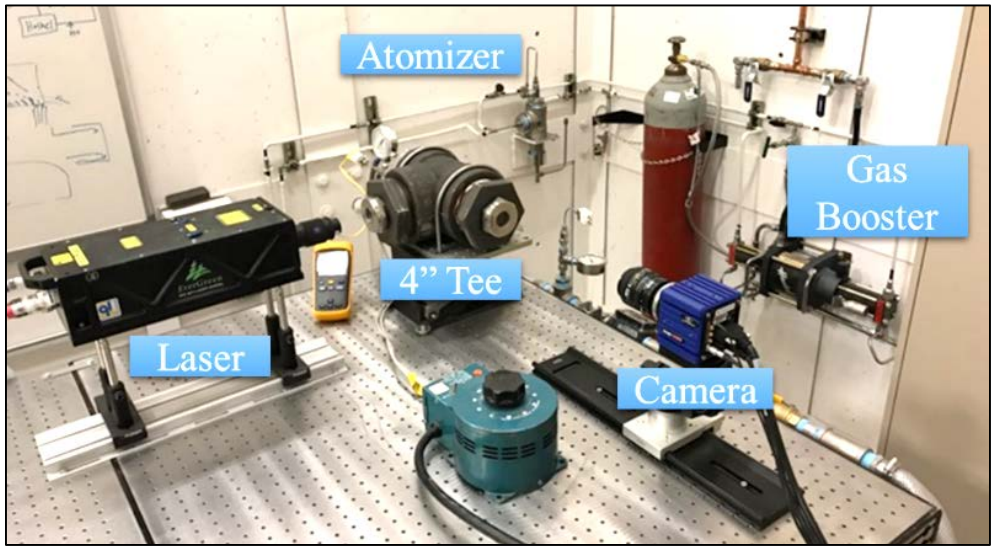
- The 4” pipe tee was used as a test chamber for visualization
- The loop was for filling and recirculating
- An oil atomizer was used to form oil droplets that could be imaged
- A gas booster was used for filling and recirculation



The experiment was basic but allowed for feasibility testing

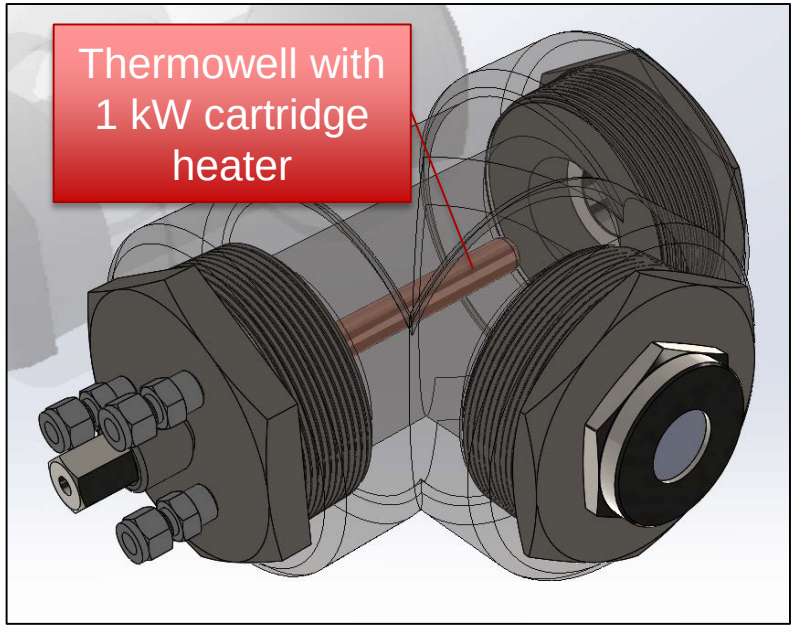
- sCO_2 was imaged in a threaded pipe tee with two optical windows
- Silicone oil particles were generated in an oil atomizer (Laskin nozzle)
- System rating was 2,190 psi and 240 F

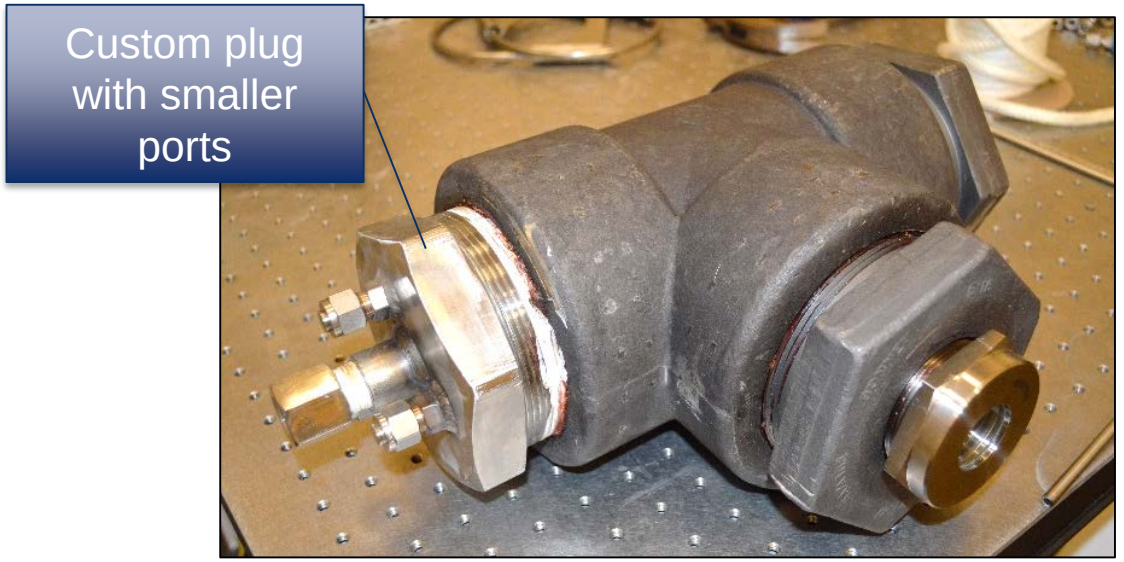




The 4” pipe tee was used for visualization

- 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 and were rated to 4000 psi and 200 C
- Pipe tee rating was 3000 psi





CO_2 is transparent except for conditions around the critical point

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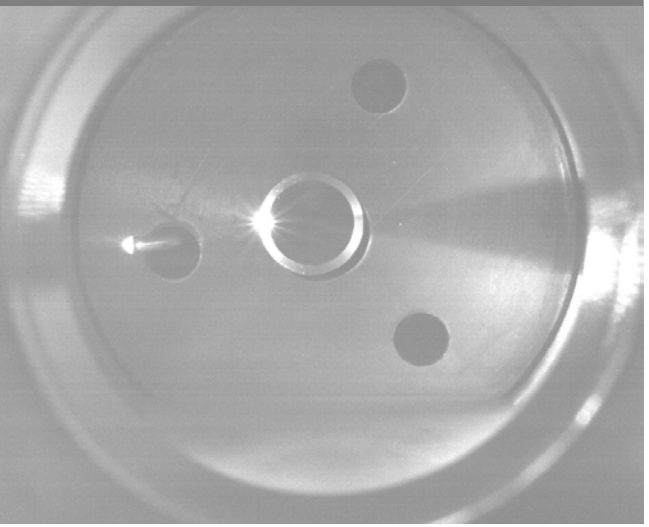
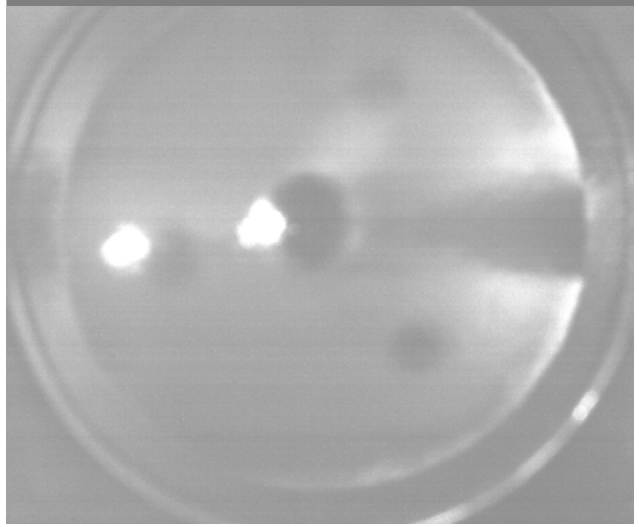
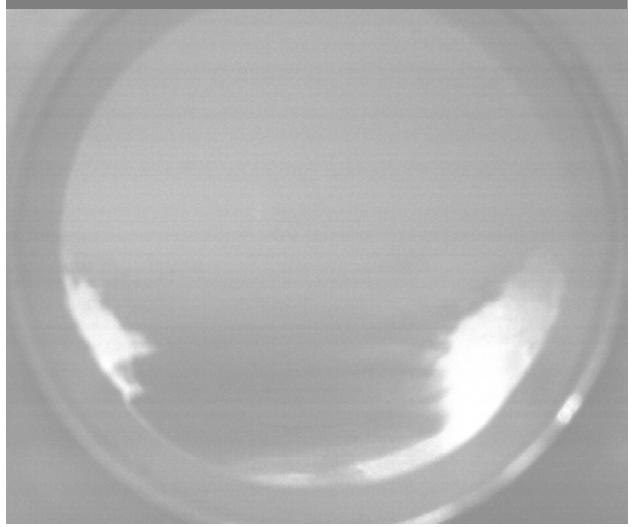
T = 84°F, P = 1000 psi



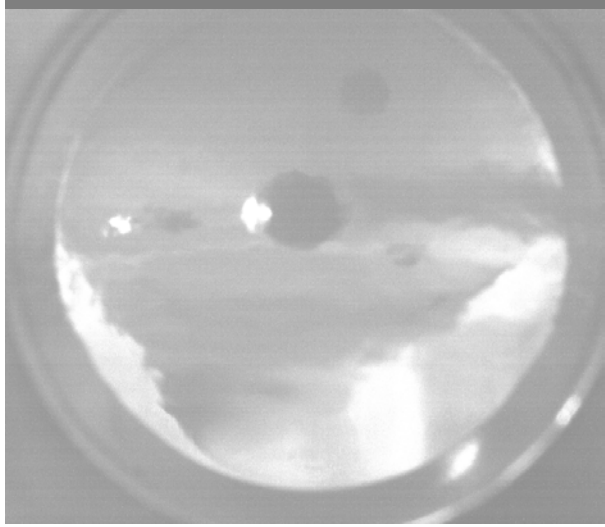
T = 88°F, P = 1070 psi



T = 93°F, P = 1080 psi

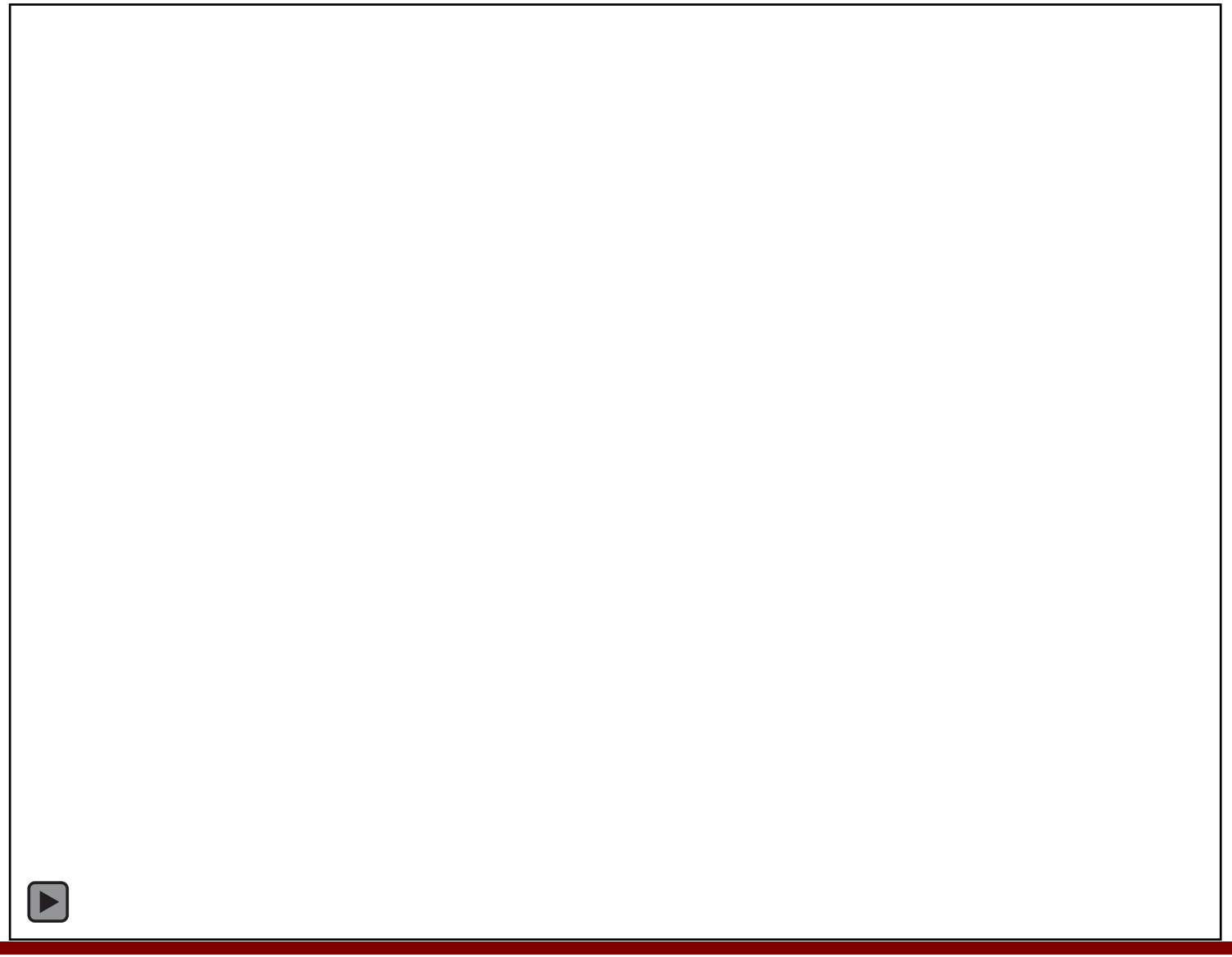


T = 106°F, P = 1100 psi

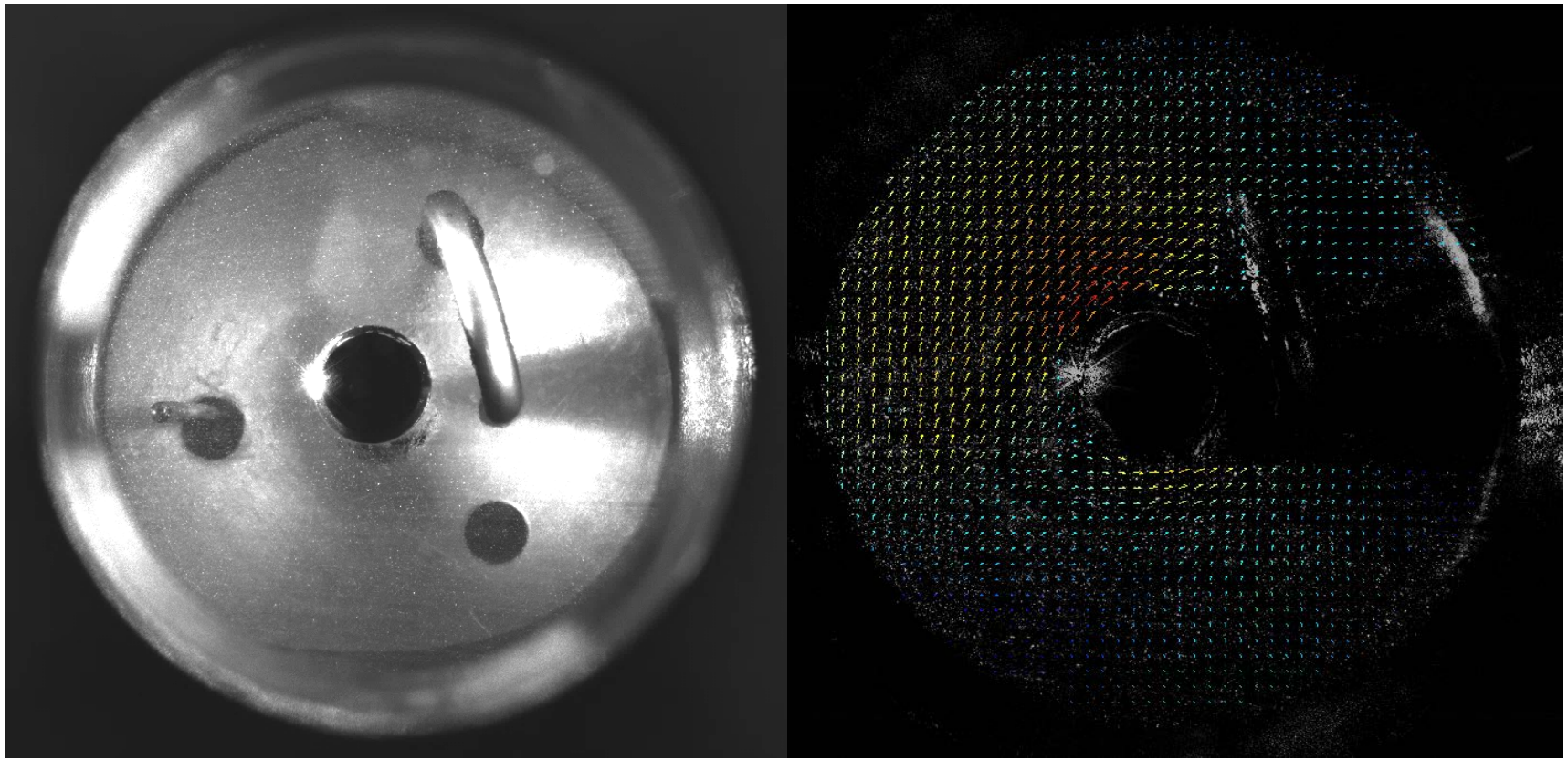


Stratification was observed over a large range of pressures and temperatures

- The movie is for T=145F (62.8C), P=1120 psi (7.72 MPa), and Q_{heater}=500 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.

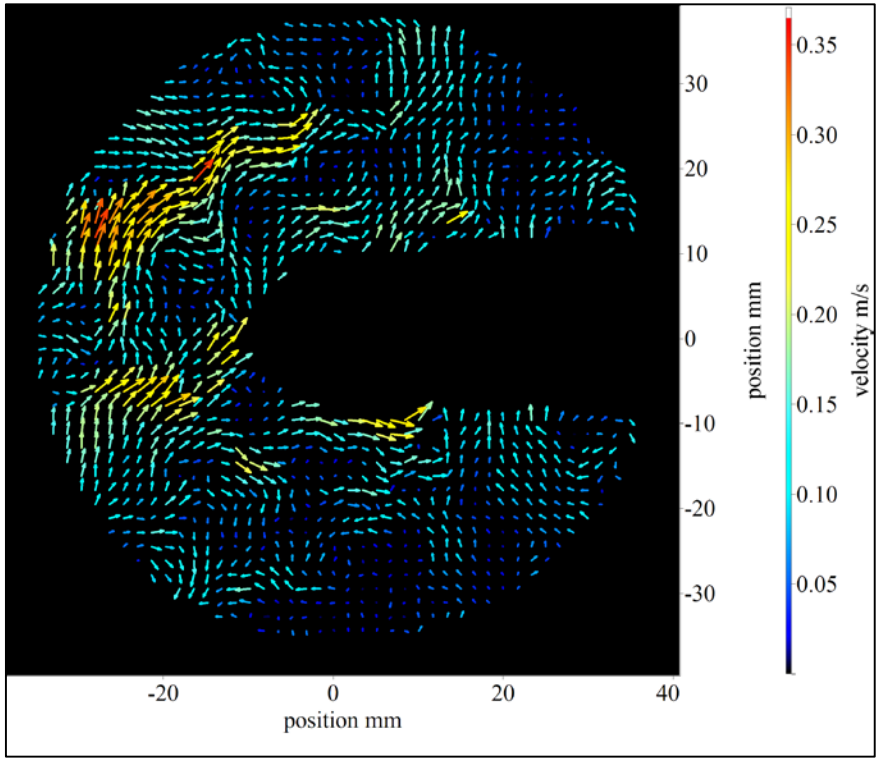


Particles were added for PIV

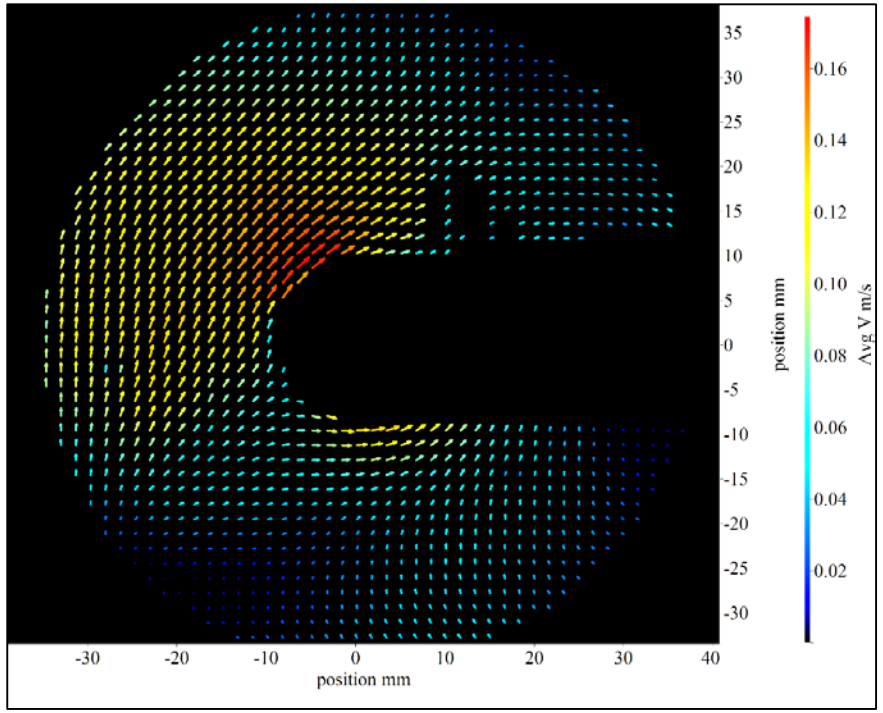


- Raw particle image
- Particle image with background removed and velocity vectors superimposed

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

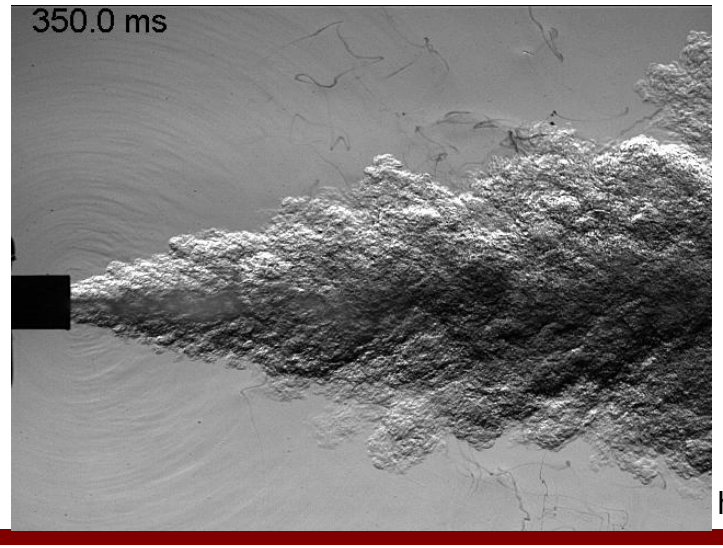


- Time-average velocity field shows smoother profile with recirculation causing a swirling effect

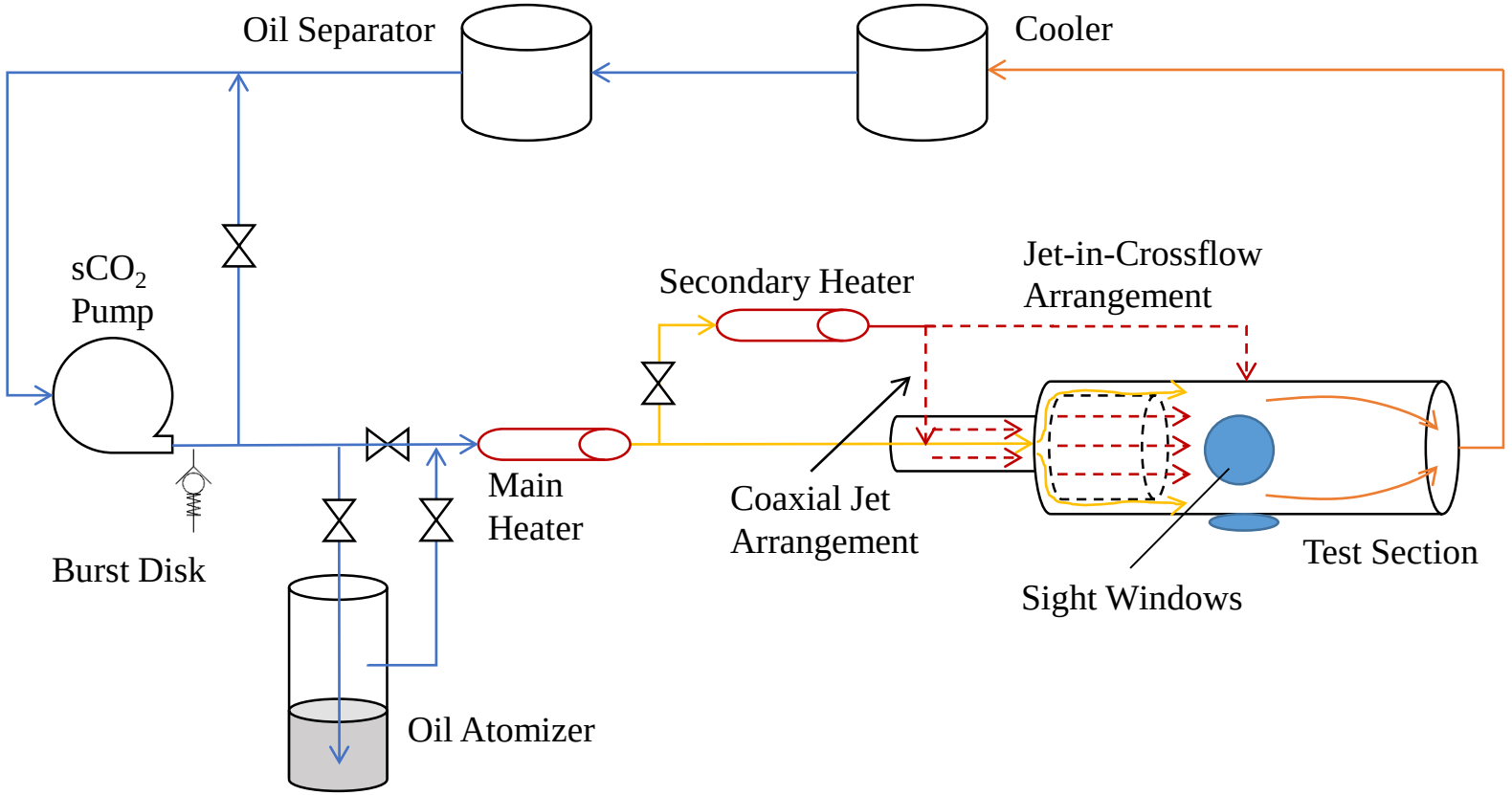
- Quantities that are measured
  - $u(t), v(t)$
  - $\bar{u}, \bar{v}$
  - $\overline{u'u'}, \overline{v'v'}, \overline{u'v'},$
- Uncertainties that are calculated
  - $U_{u(t)}, U_{v(t)}$
  - $U_{\bar{u}}, U_{\bar{v}}$
  - $U_{\overline{u'u'}}, U_{\overline{v'v}}, U_{\overline{u'v'}}$

This flow measurement feasibility opens the door for future work

- Potential Phase II SBIR with Illinois Rocstar, providing validation data
- Compressor inlet conditions (density field measurements with Schlieren)
- Pipe tee and elbow flow measurements



http://www.hpcl.psu.edu/Diagnostics%20-%20Schlieren.html



Backup

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