Experimental and Numerical Performance Evaluation of a Modified sCO2 Compressor Blade Profile to Reduce Leading Edge Condensation

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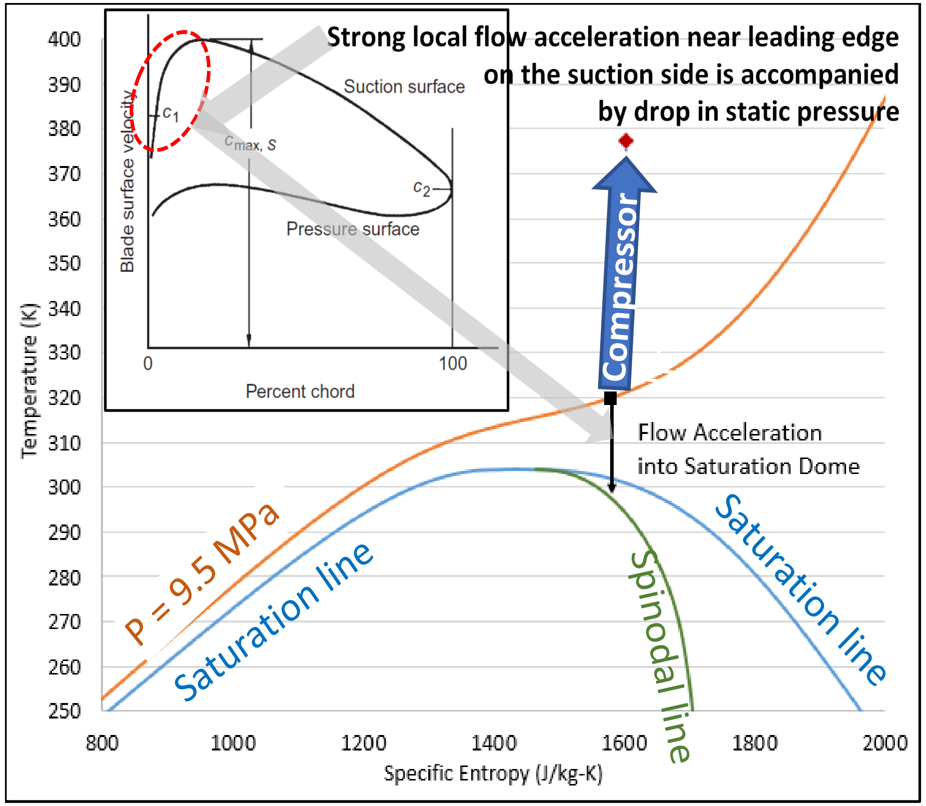
Project Overview

Rapid variations of properties near the critical point and its proximity to the saturation dome makes the compressor susceptible to multi-phase effects

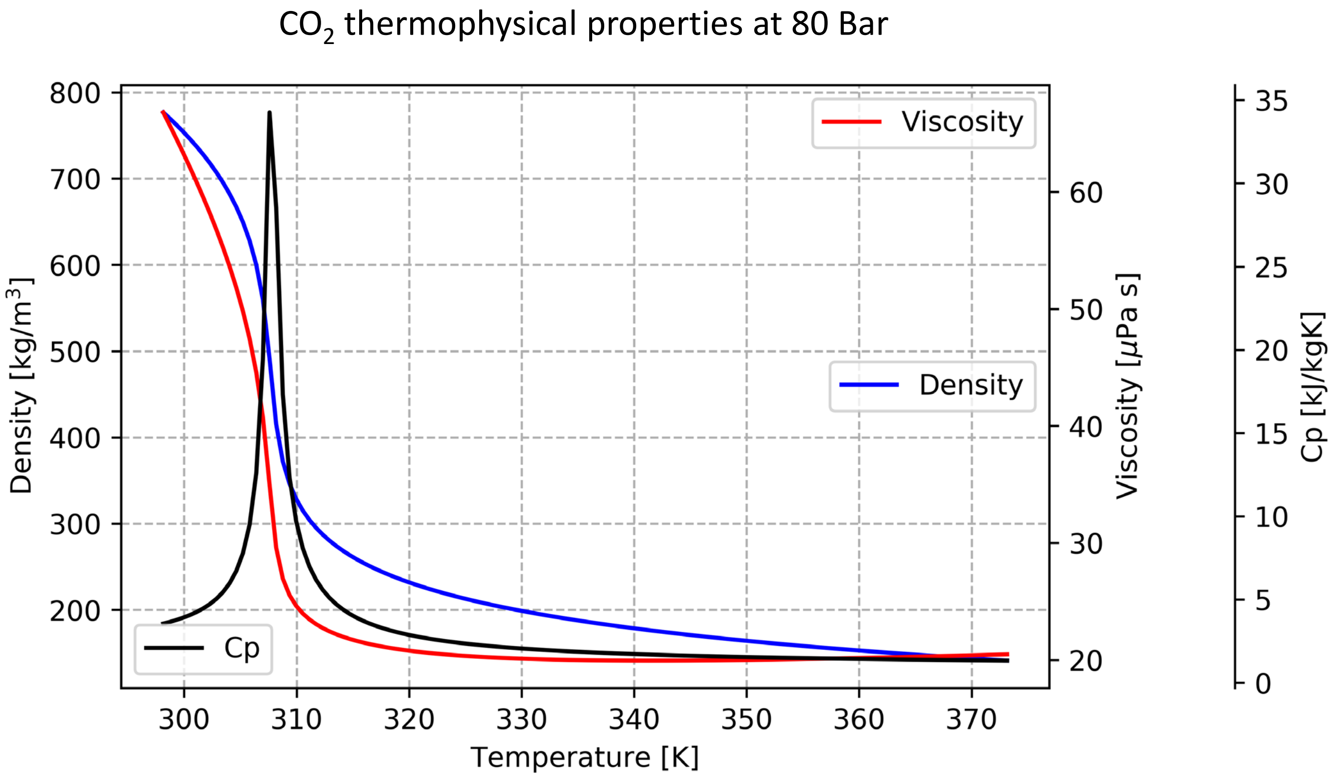


T-s diagram: local flow acceleration [1] (inset: local velocity outside boundary layer around the surface of a compressor airfoil [2].

Project main point/goals:

1. **Creating improved design for compressor airfoils to mitigate the multi-phase effects**
2. **Understanding detailed flow behavior inside a compressor cascade under various compressor inlet conditions**
3. **Experimentally validating the design improvement through testing in a compressor cascade rig with sCO2 as working fluid**
4. **Enhancing understanding and implementation of optical diagnostics implementation in sCO2 applications**

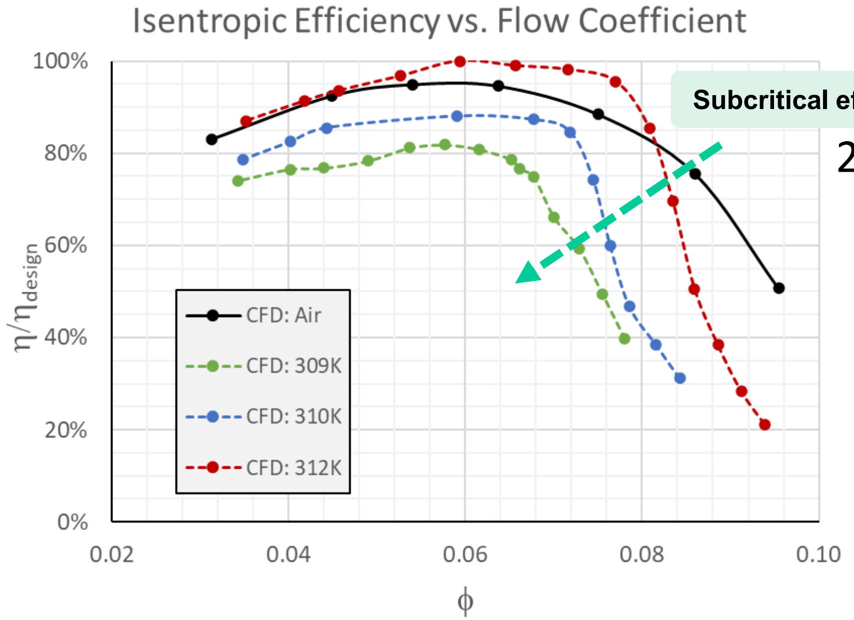
Motivation – sCO_2 Challenges



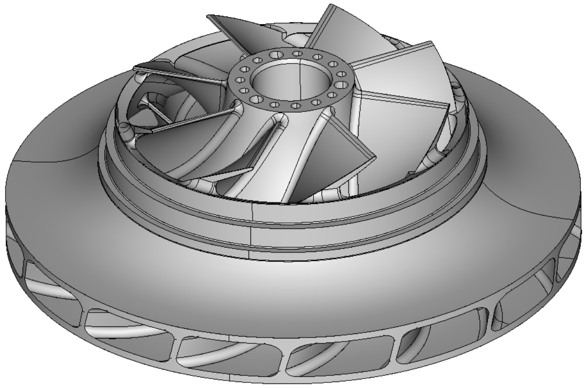
- Overall cycle advantages realized with compressor operation closer to the critical point
- High sensitivity of thermodynamic properties with respect to temperature near the critical point are of concern
- ***Local effects at the compressor inlet can lead to some flow dropping into the saturation dome***

Motivation – sCO2 Performance Sensitivity to Inlet Temperature

Motivating study Results from Hosangadi et al. "Numerical Predictions of Mean Performance and Dynamic Behavior of a 10 MWe sCO2 Compressor with Test Data Validation", GT2022-82017

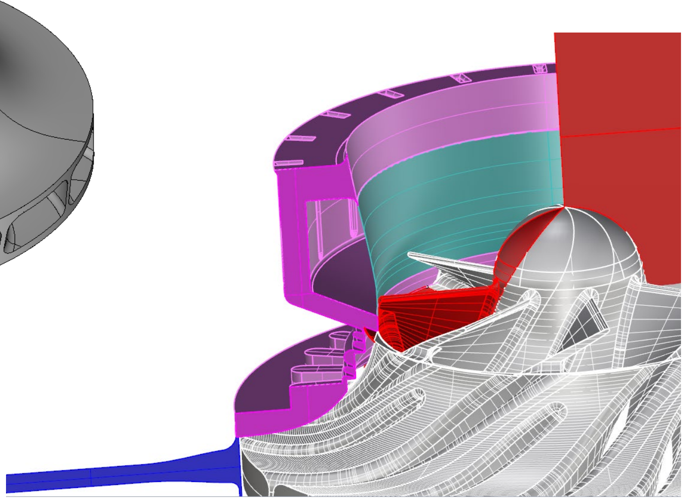


2019 Data



Partially-shrouded impeller with
8 blades and 8 splitters

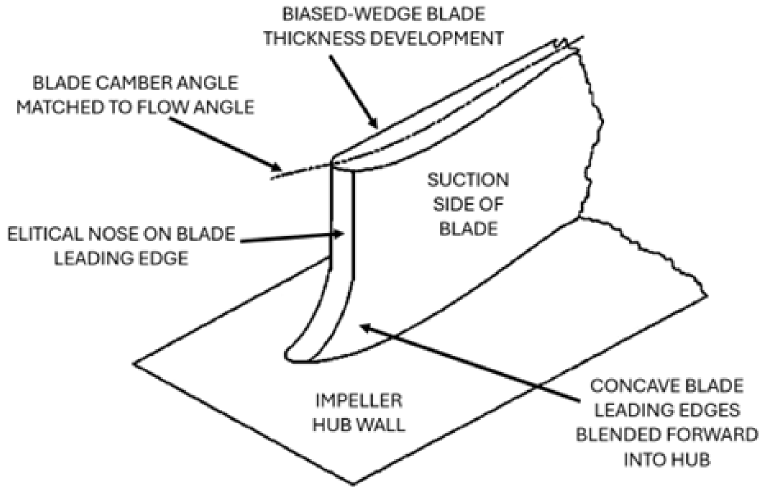
Numerical and Validation Study explored the performance of Hanwha compressor as tested at SwRI as part of the DoE Sunshot program



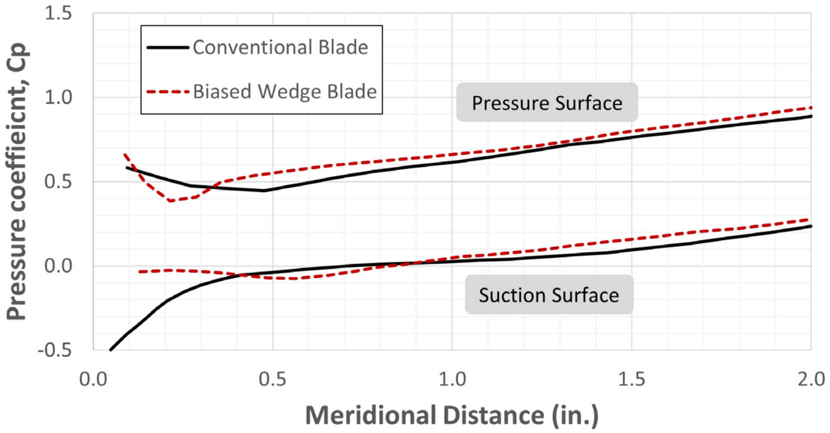
- Two Key Issues:
  1. Peak efficiency values drops substantially as inlet temperature comes closer to critical temperature and the entire efficiency curve is lower
  2. Drop-off at the higher flow rates is steeper and starts at lower flow rates; this substantially reduces the range of the compressor at lower inlet temperatures
- ***Cause for #1 potentially associated with leading blade design that disrupts flow into the splitter blade at lower inlet temperatures causing blockage and mixing losses***
- Cause for #2 is associated with phase change in the inlet "throat" leading to blockage

Leading-Edge Design Considerations

- A new design methodology for leading edge suction surface is proposed based on prior work done in centrifugal pump designs to reduce or eliminate multi-phase effects (i.e. cavitation) at leading edge suction surface
- Conventional blade design philosophy is to have blades of nearly constant thickness with a rounded nose
    - This design leads to larger drop in pressure on suction surface that leads to cavitation in pump
- The new “biased-wedge” design makes a thicker suction surface profile to make the blade shape more like an airfoil and reducing the acceleration on the suction surface
- Goal of present effort is to demonstrate the same concept helps reduce condensation at the sCO_2 compressor leading edge
- Testing performed in cascade with relative velocity settings corresponding to a compressor

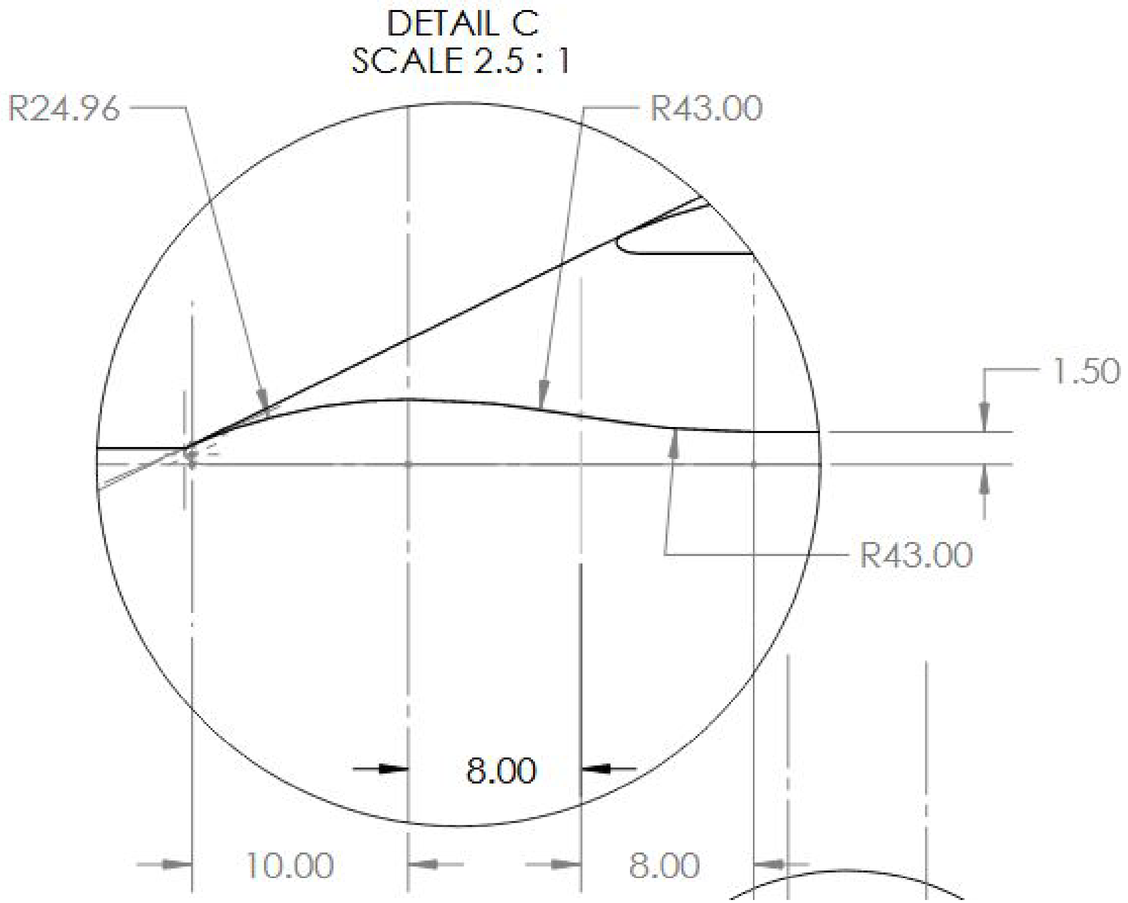


Biased Wedge impeller blade to reduce pressure drop on suction surface

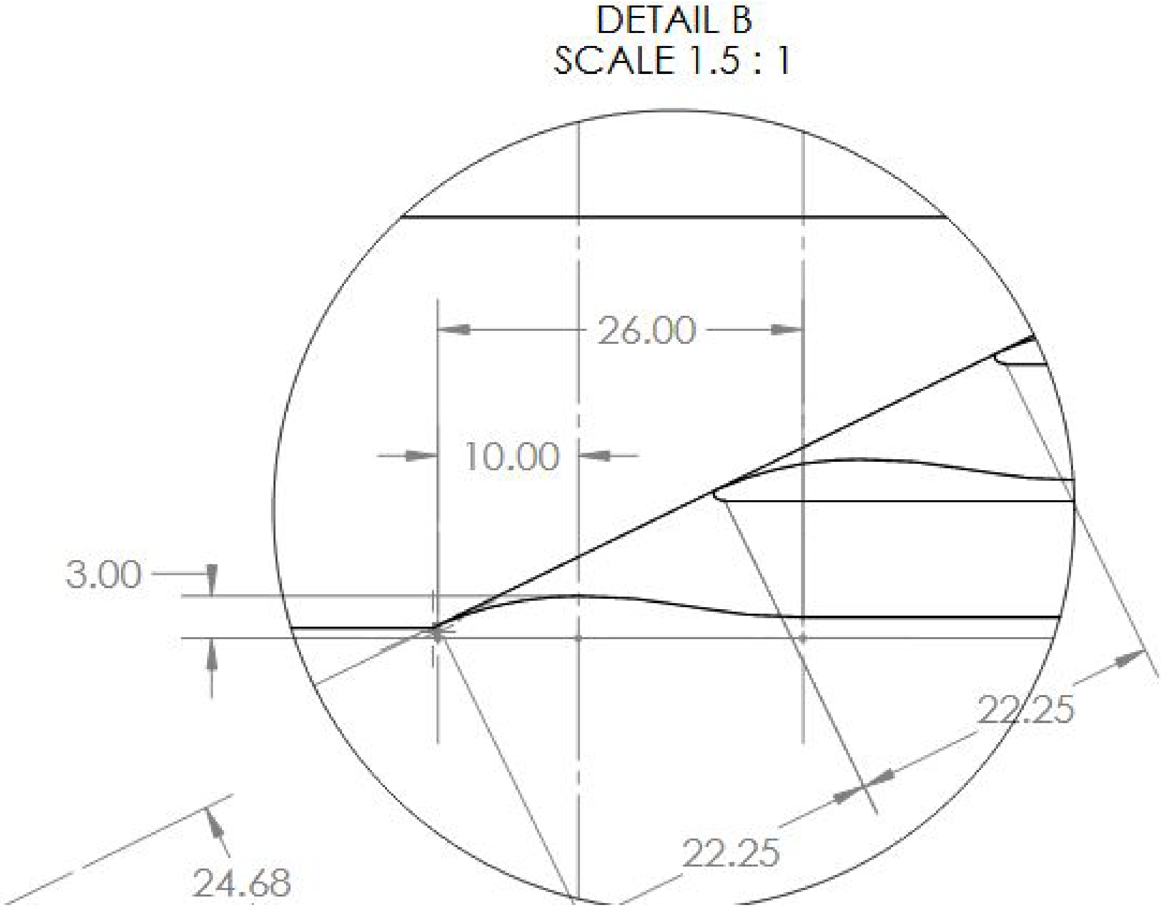


Pressure distribution on conventional blade and “biased wedge” for a high energy centrifugal pump (Ref 3)

Biased Wedge Leading Edge Design



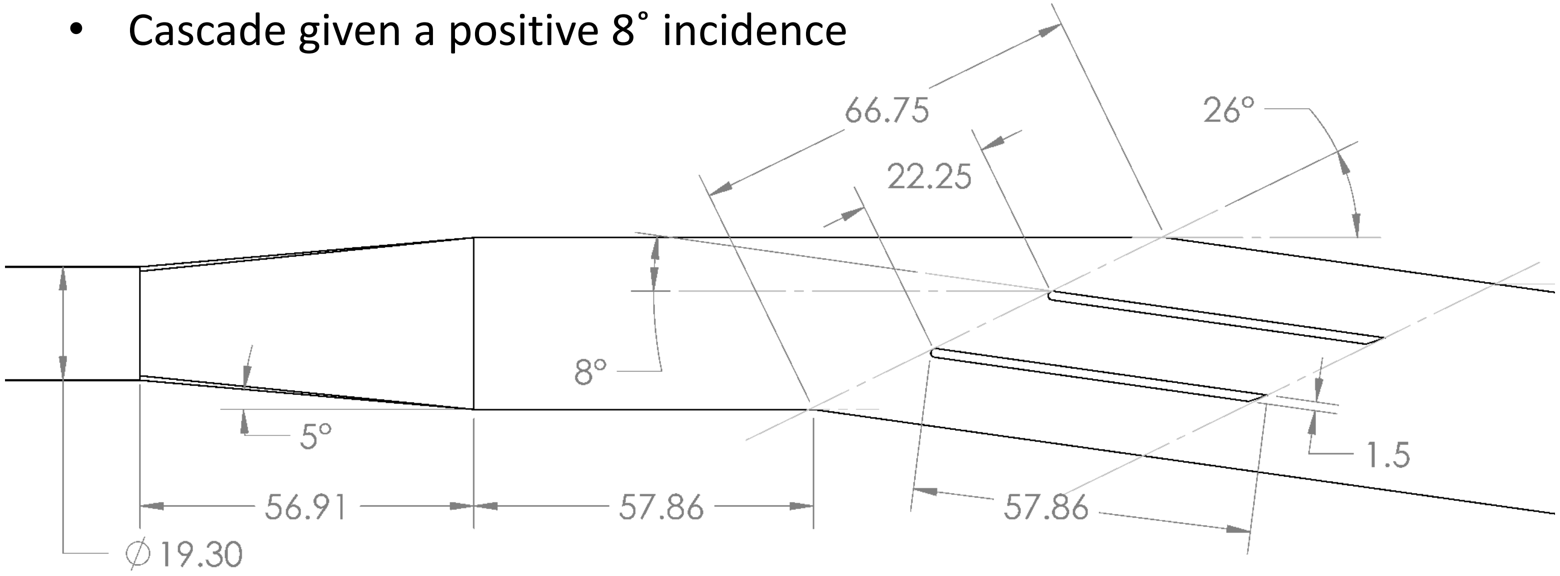
“Biased Wedge”
Blade Design



Cascade Stagger

Geometry – Cascade Parameters

- Designed with an inlet flow angle of 26˚ wrt to vertical
- Constant blade height of 10mm
- Solidity of 2.6
- Blade to blade spacing = 22.25mm
- Chord = 57.86mm
- Constant blade thickness of 1.5mm for baseline blade
- Two blades fully immersed
- Cascade given a positive 8˚ incidence

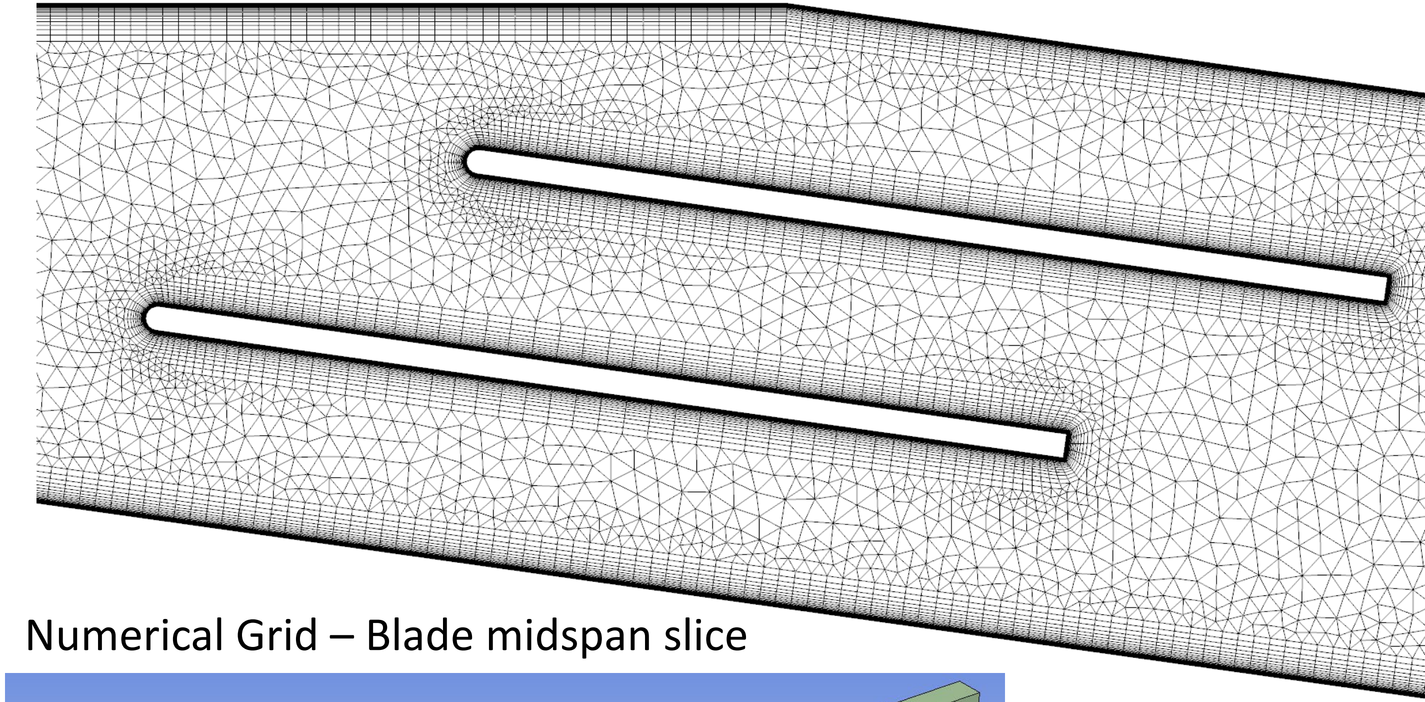


Constant thickness baseline blade shown

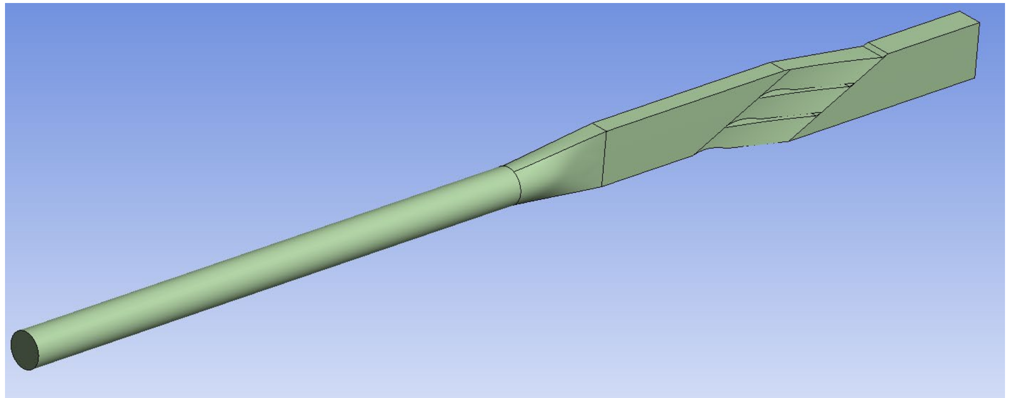
Final layout cascade as tested

Methodology – Numerical Model Details

- Run using CRAFT's CRUNCH CFD®
- NIST tables used for Thermophysical properties
- Simulations run across flow regimes to overlap with experimental conditions, and application conditions
- Run in full 3d to duplicate experimental test section
- Average wall y+~5 for highest flow rate cases
- Turbulence modeled by Standard two-equation k-ε model
- Inlet condition ranges from 80 to 90 Bar, and 306K to 310K (for validation cases).



Numerical Grid – Blade midspan slice



Numerical domain

Hosangadi et al. "Modeling Multiphase Effects in CO_2 Compressors at Subcritical Inlet Conditions", Journal of Engineering for Gas Turbines and Power, Vol. 141, 2019.

Overview of CFD Simulations

- Initial Simulations performed at conditions that UCF pump can support, for validation.

- Parametric study with varying velocity conducted at reduced inlet temperature of 306 K (32.85 C)

- Parametric study in velocity also conducted at conditions relevant to Hanwha compressor in Sunshot program
  - Inlet temperature of 310 K and velocity approaching relative velocity at inlet tip

Experimental Setup and Methodology for Numerical Validation

Experimental Effort Objectives

- Design linear compressor cascade rig capable of accommodating optical based diagnostics

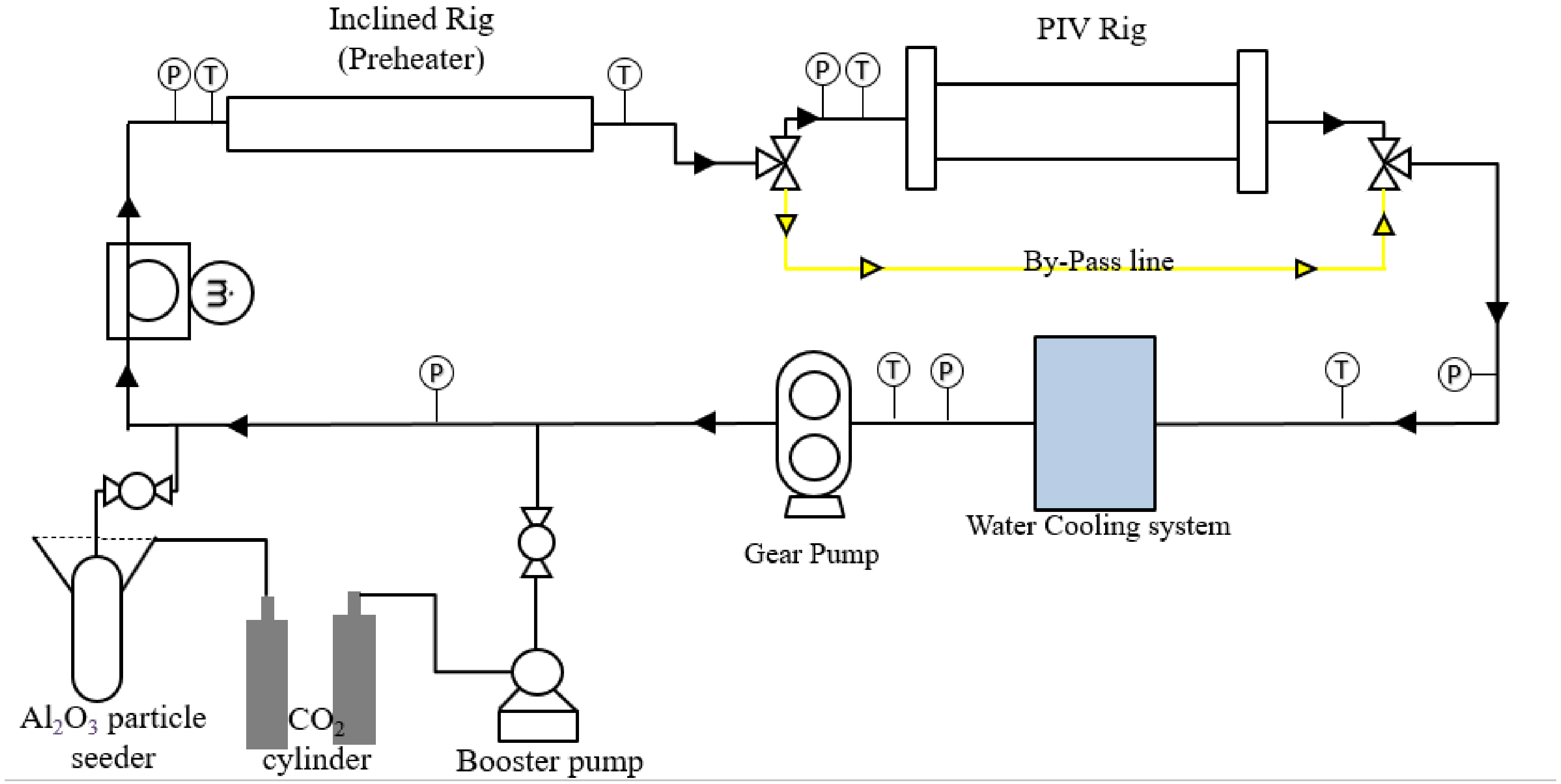
- Application of Particle Image Velocimetry for quantitative velocity field measurements in sCO2

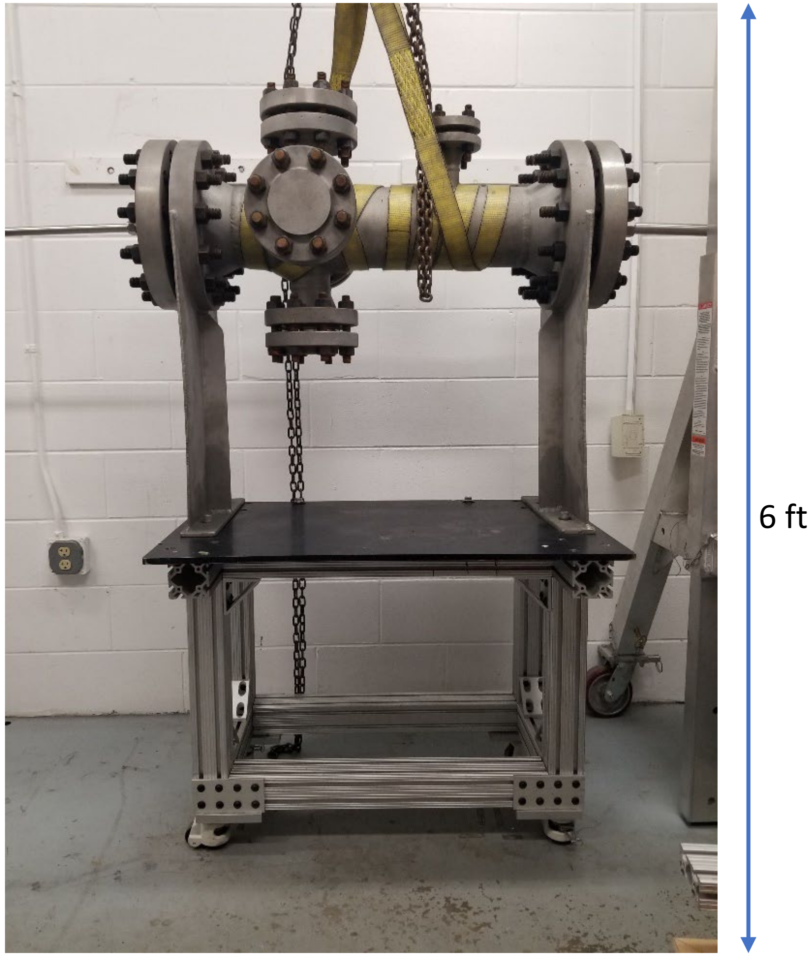
- Validate numerical results with experimental data

- Evaluate feasibility of laser-based diagnostics for liquid phase detection

sCO_2 Loop for Cascade Testing

Experimental sCO2 rig:





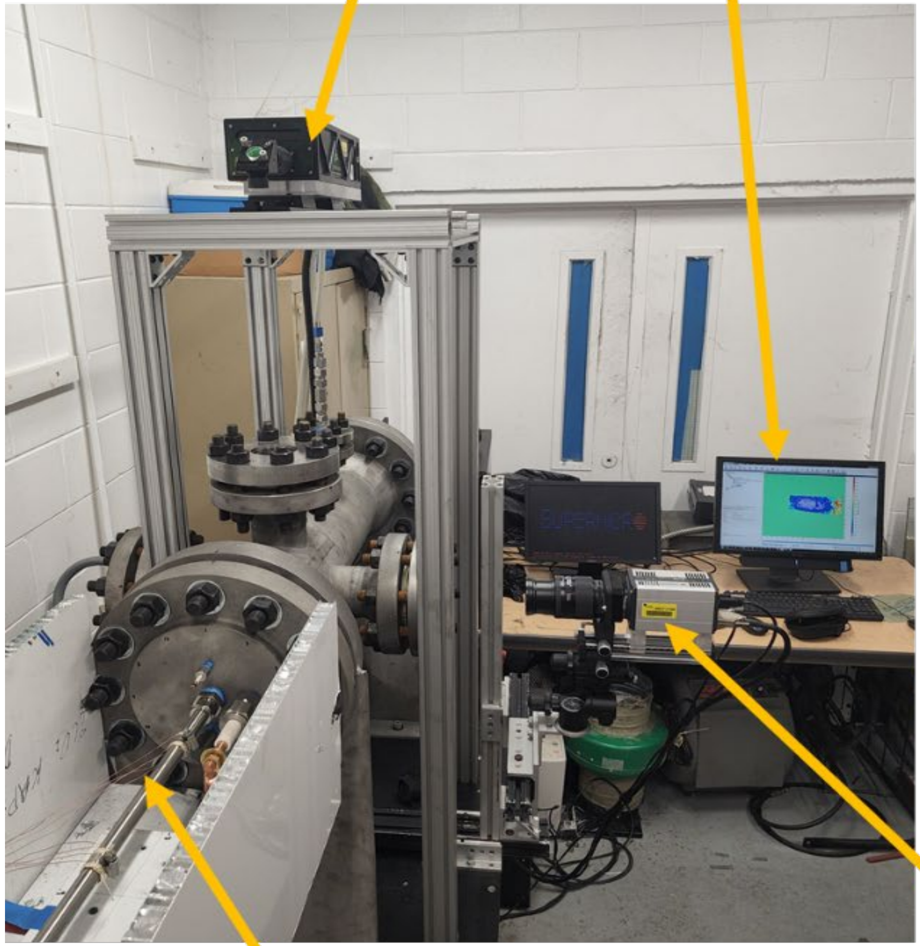
- Non-Recuperated
- Operating Pressure: 70 – 100 Bar
- Operating Temperatures: 20C – 100C (293K – 373K) (Optical Diagnostics Test Section Vessel Limitation)
- Mass flow rates up to 3.6 kg/min @90Bar

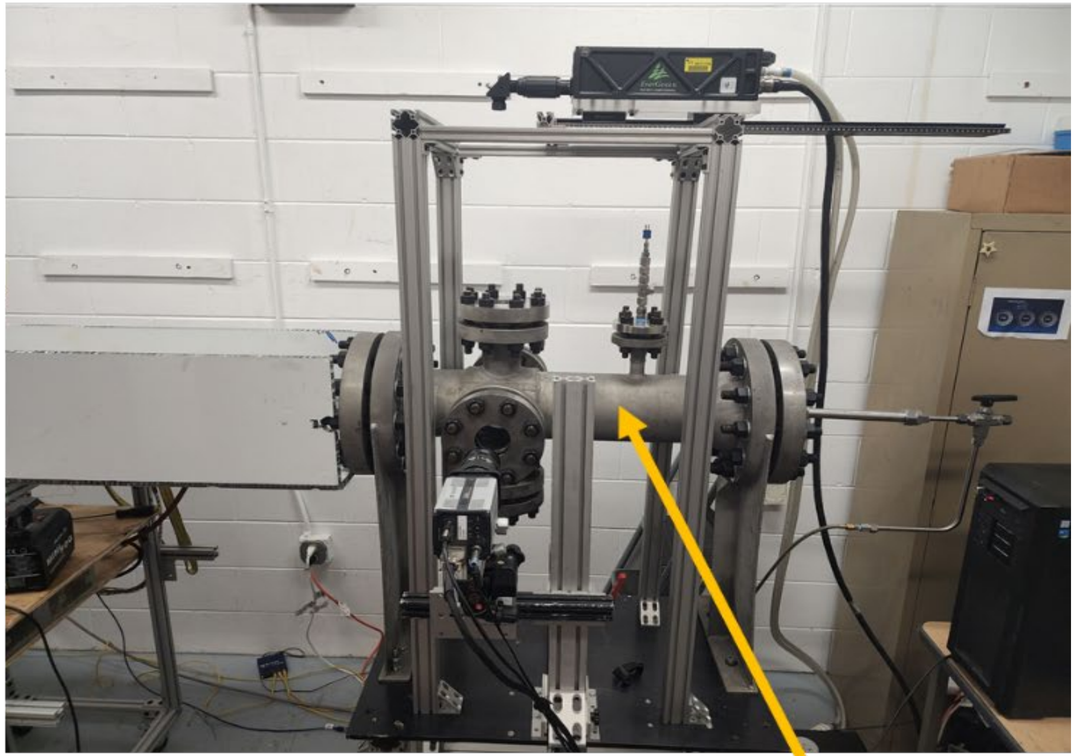
The operating pump was changed from the gear pump to the sigma pump (piston type) due to higher flow rate capability

Test Facility with Current Experimental Setup

Laser Head

DAQ Computer





High Speed Camera

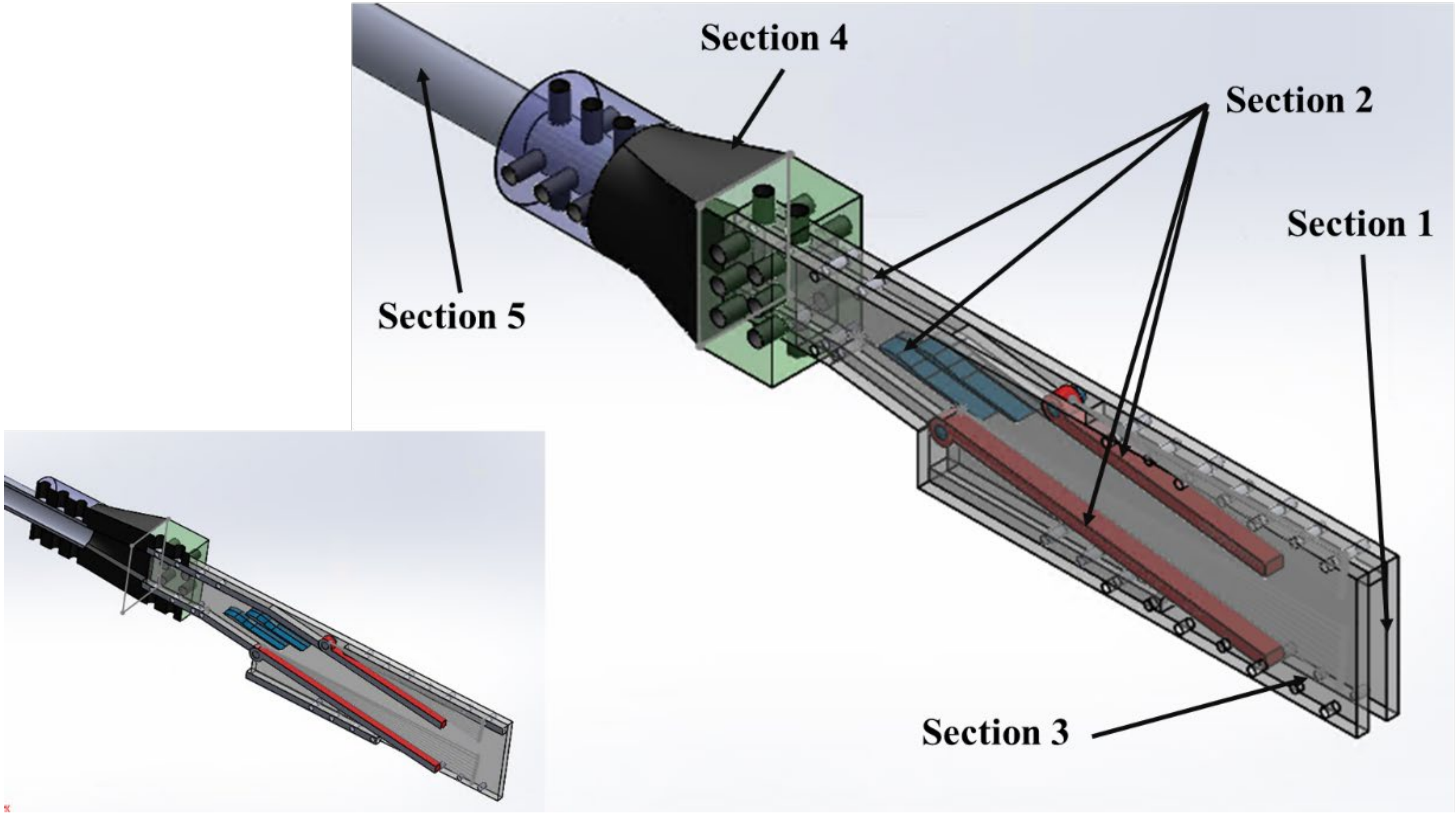
Optical Test Chamber

Inlet Tube

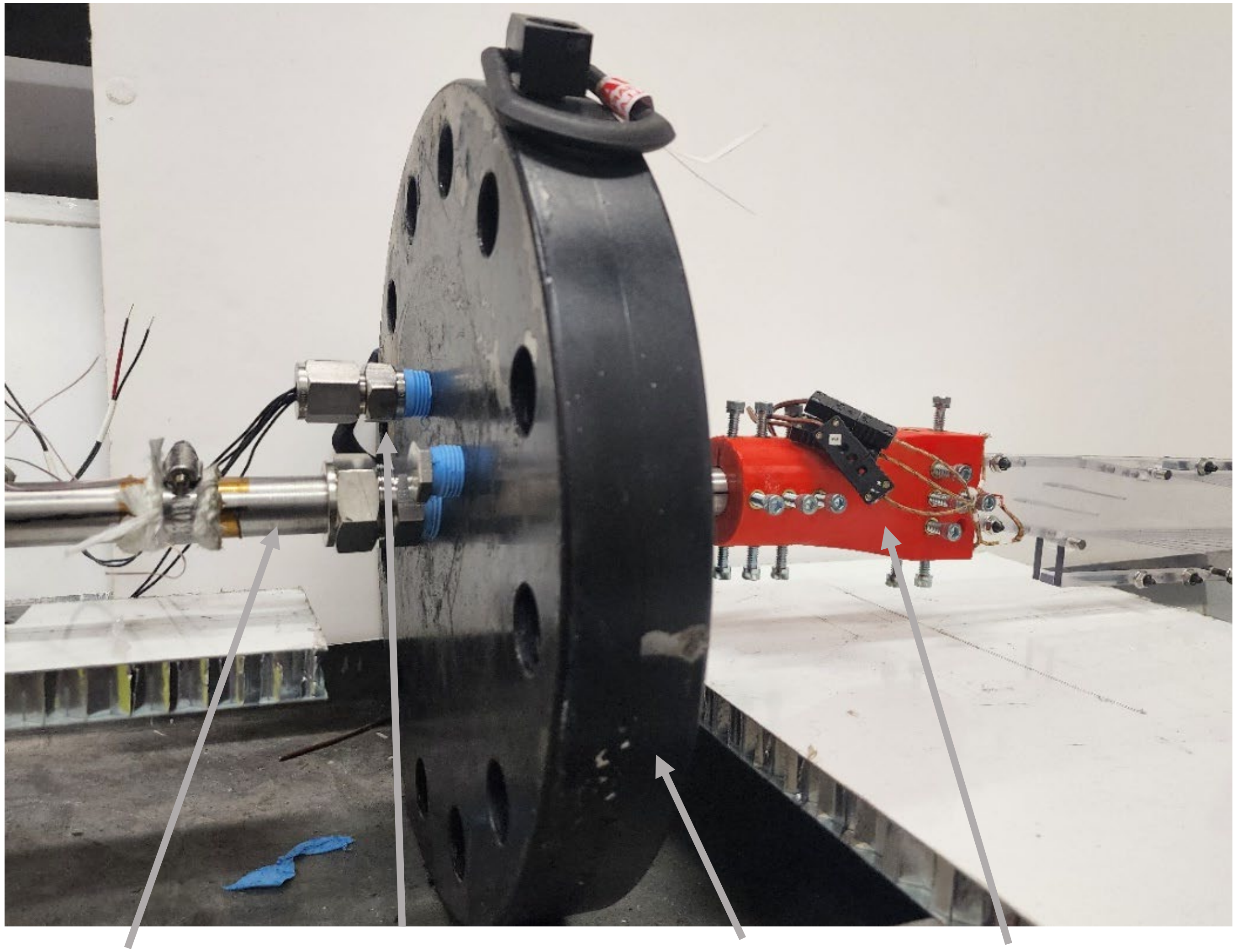
Experimental Cascade Assembly

Test Section design consists of 5 section

- Section 1: Back wall (with blade indent (3/16 inch))
- Section 2: Mid-Wall / Flow region (blades, tailboards and flow walls)
- Section 3: Cover wall
- Section 4: Connecting Nozzle (tube adapter, 5^o nozzle, cascade adapter)
- Section 5: Inlet Tube



Experiment Assembly for Optical Test Chamber

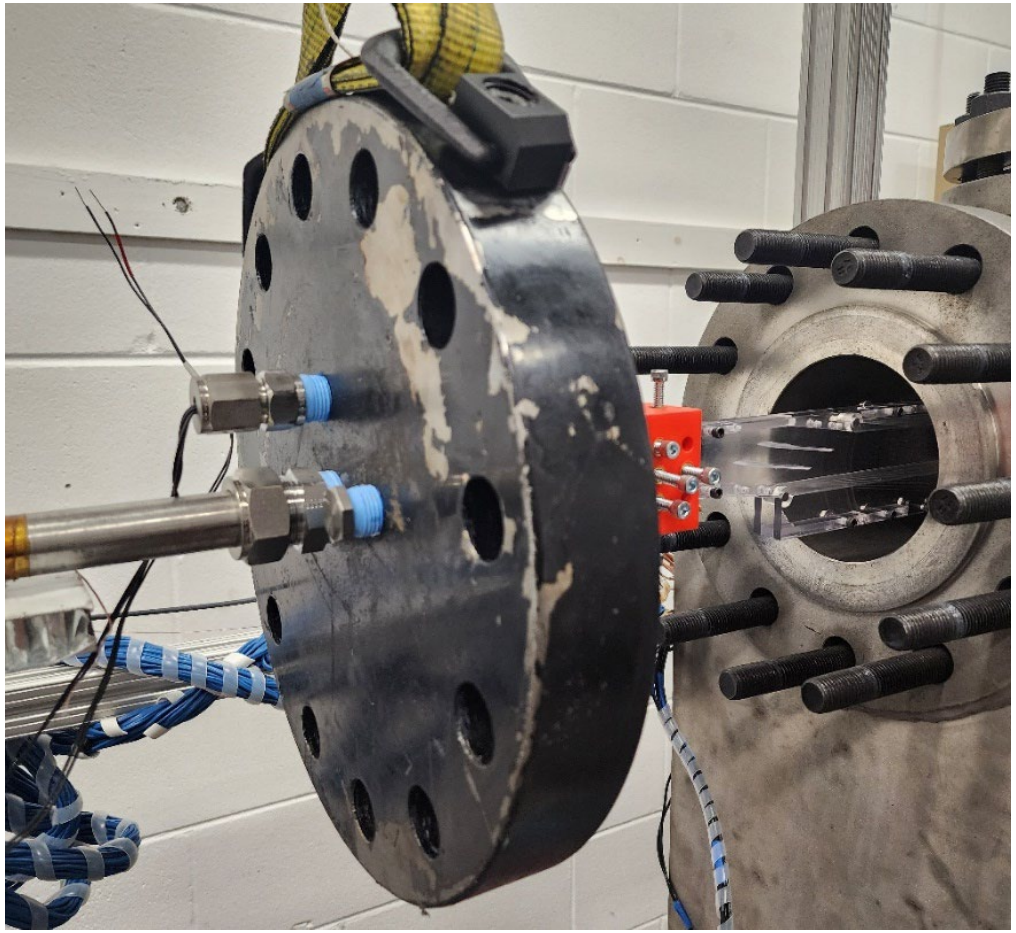


Inlet Tube
L = 80.75 in

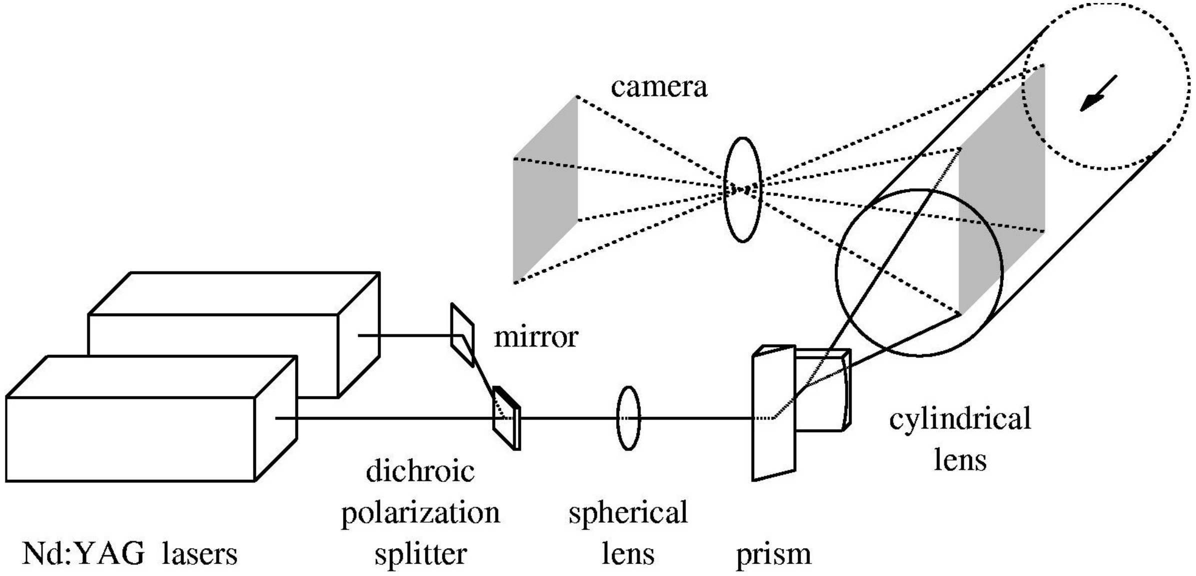
TC gland
Fitting

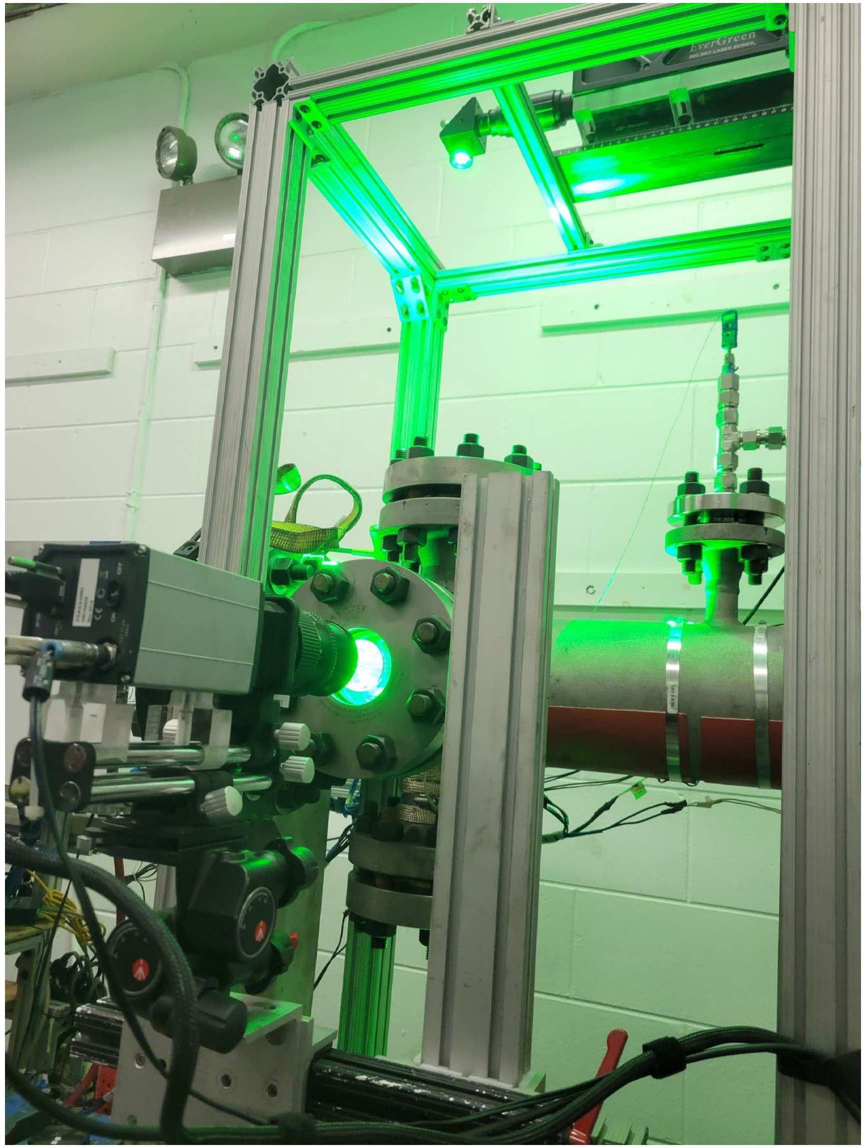
6in RF
Flange

TC
Connections



Particle Image Velocimetry – Optical Configuration





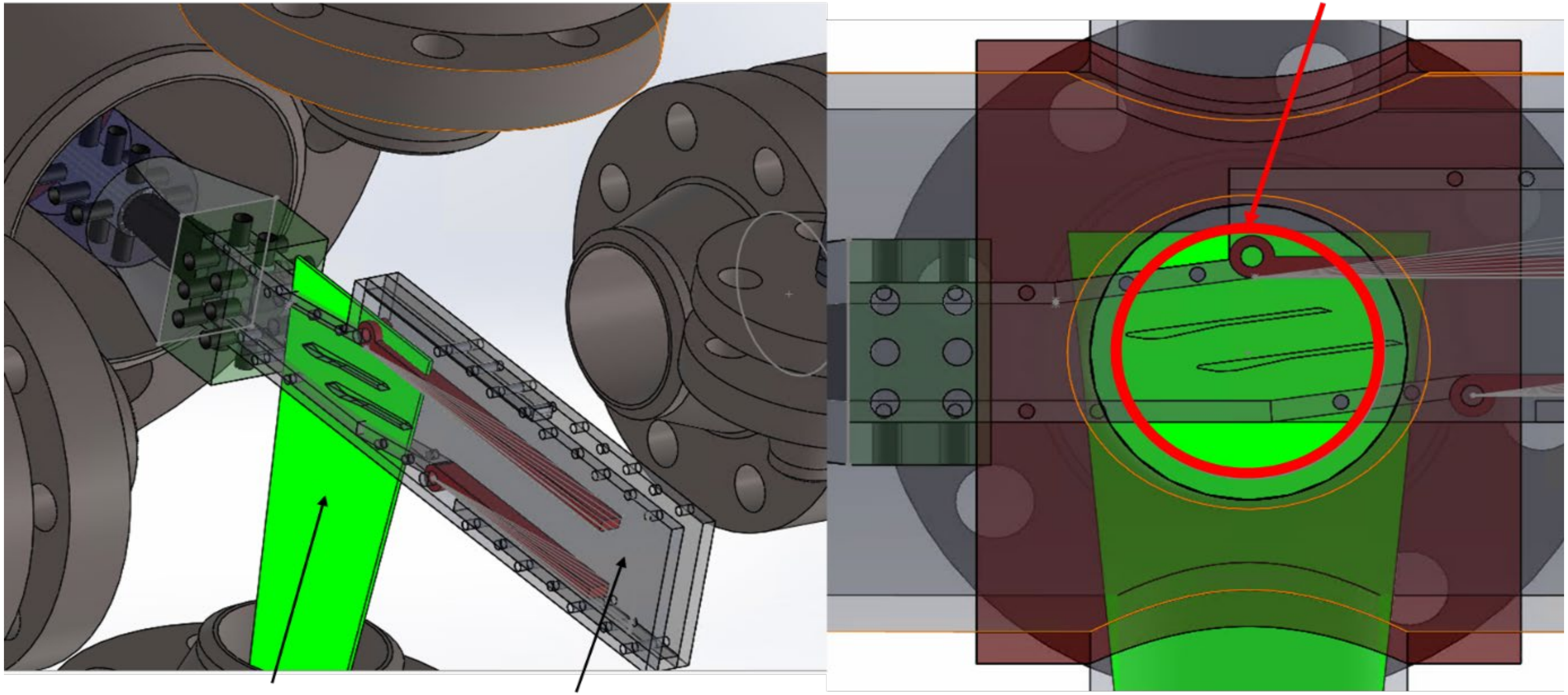
- Thin laser sheet is generated through specialized optics, and illuminates seeded tracer particles (sheet <1mm thick, tracers are ~3µm diameter Alumina particles)

- Laser is dual-pulsed at a specified delta T, and synched with camera

- Camera is oriented perpendicular to planar laser sheet for imaging (2D-PIV)

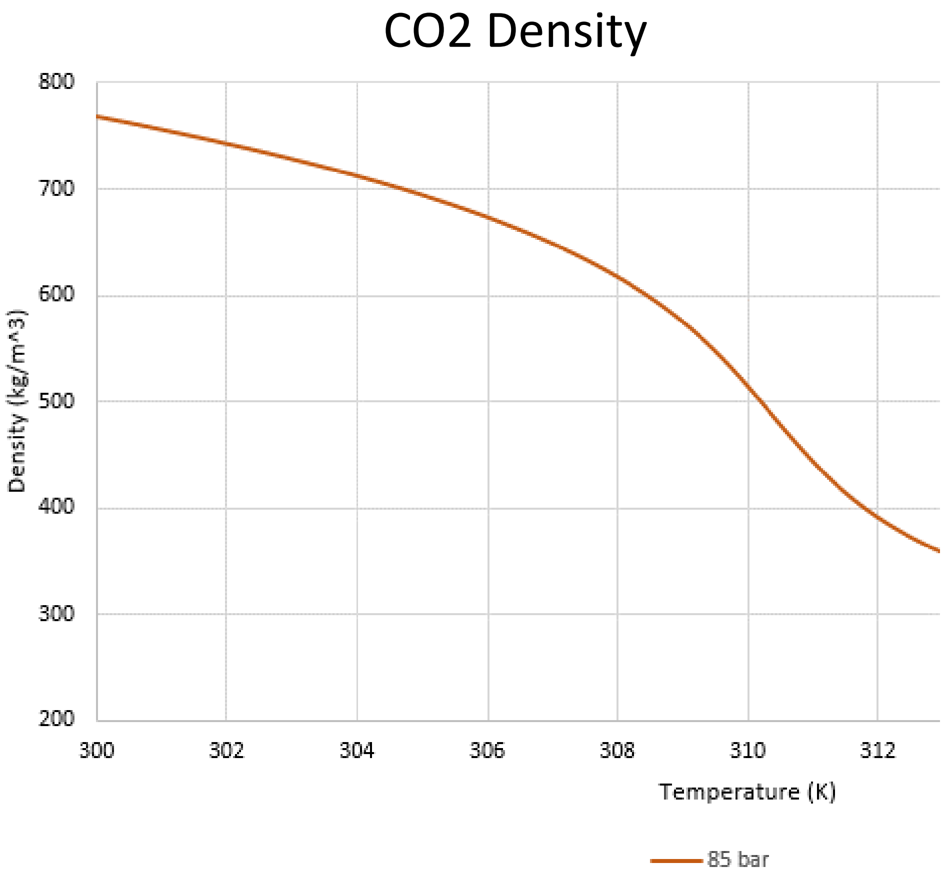
-Westerweel, J. [4]

Cascade Test Model in Test Chamber Showing Optical Access Region



Multiphase Testing Challenges Near Critical Point

- Strong dependence of temperature on thermophysical properties near critical point
- Supercritical fluid entering test section domain can quickly cool and fall below the dome
- Instrumentation and full temperature control of downstream domain is necessary for accurate testing
- Optical Refractive Index is proportional to density.
- Line-of-sight density variations can completely obstruct particle imaging



Liquid CO2 flowing into supercritical vessel domain

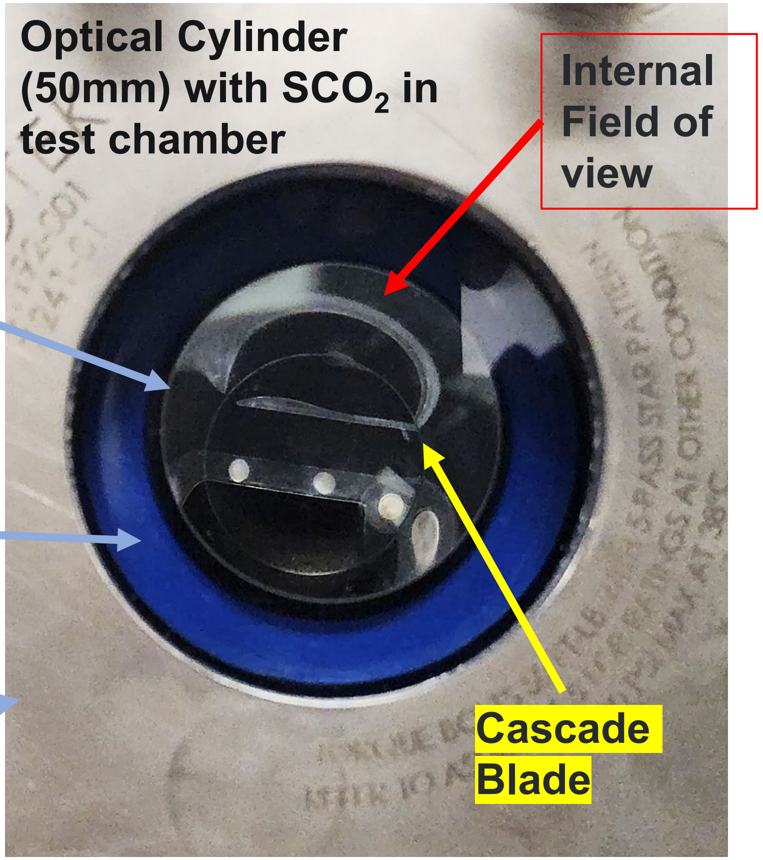
Optical Light Guide Installation

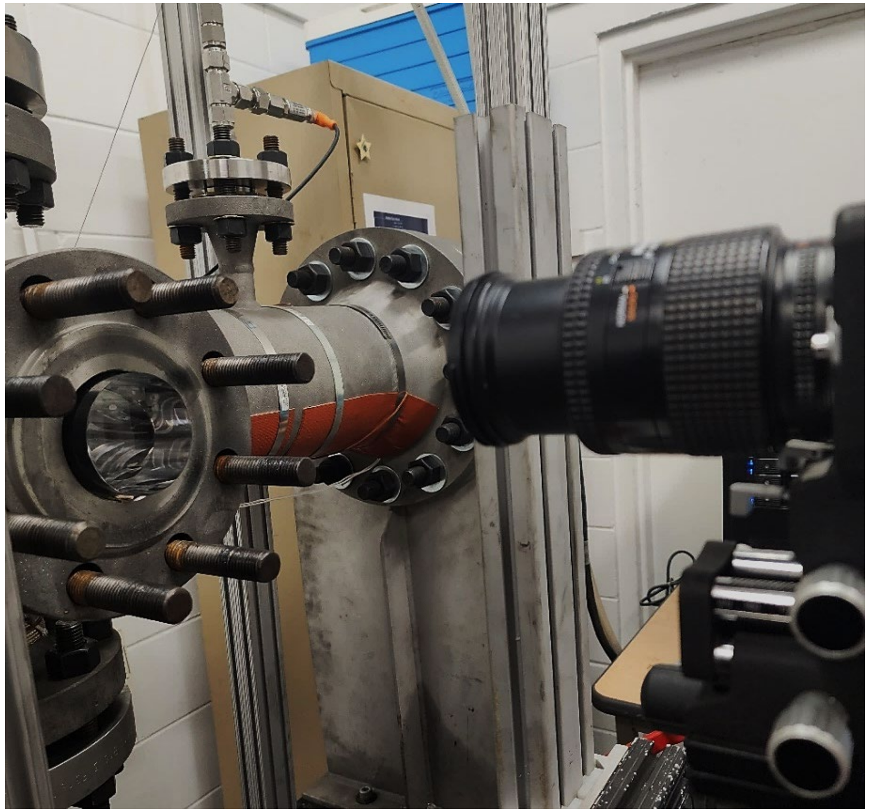
- Image Distortion: The acrylic optical access cylinder (OD = 69mm) worked but due to crazing reaction with SCO_2 at the pressures and temperature, Quartz optical cylinders (OD = 50mm) were used

Quartz cylinder

Cylinder Holder

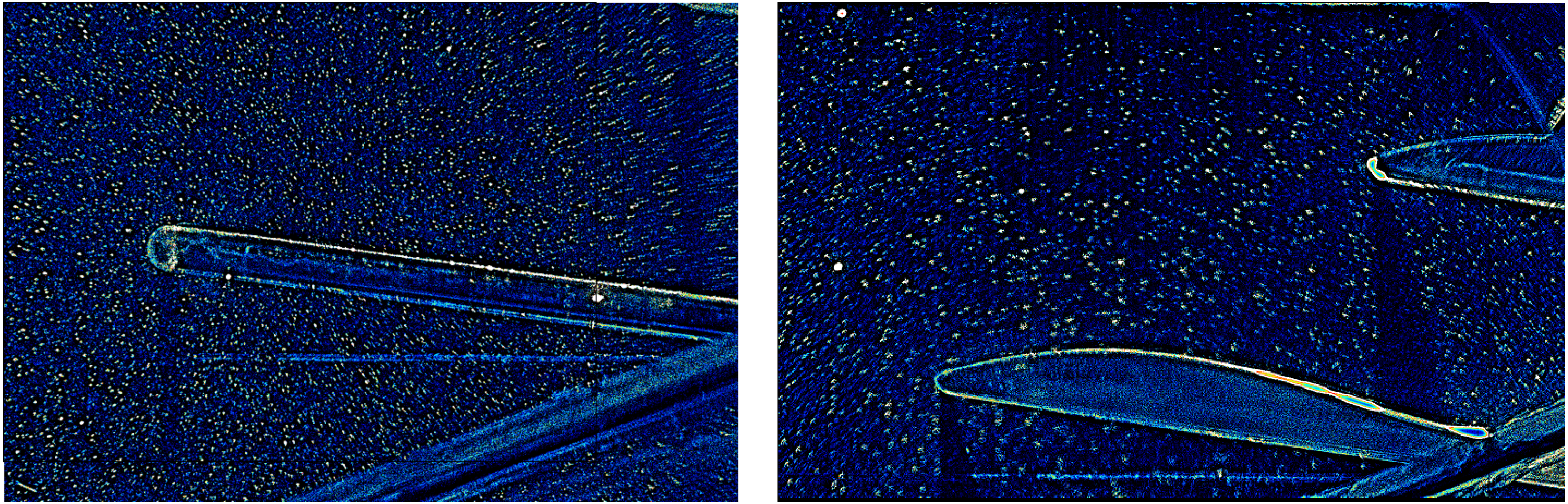
3” viewing window





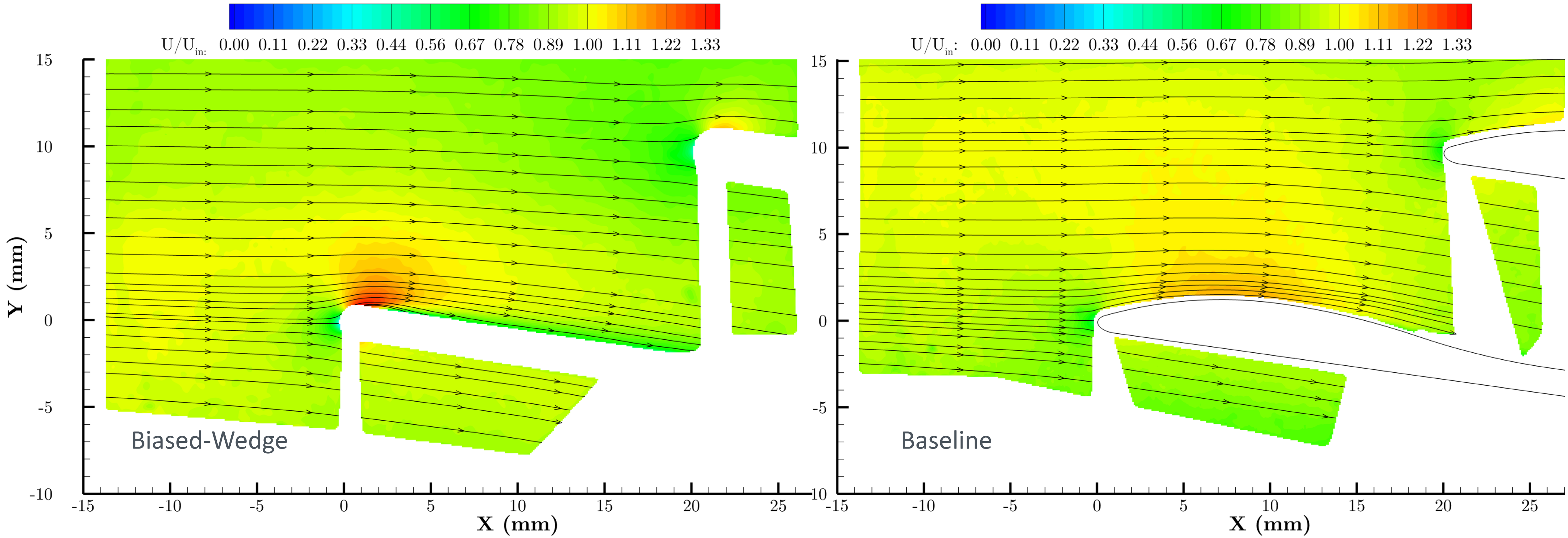
Optical Cylinder placement in the viewing window 3” flange

PIV Data Acquisition – Image Post-Processed



- To increase signal-to-noise ratio, a sliding background subtraction is applied
- Note particle shift between Images

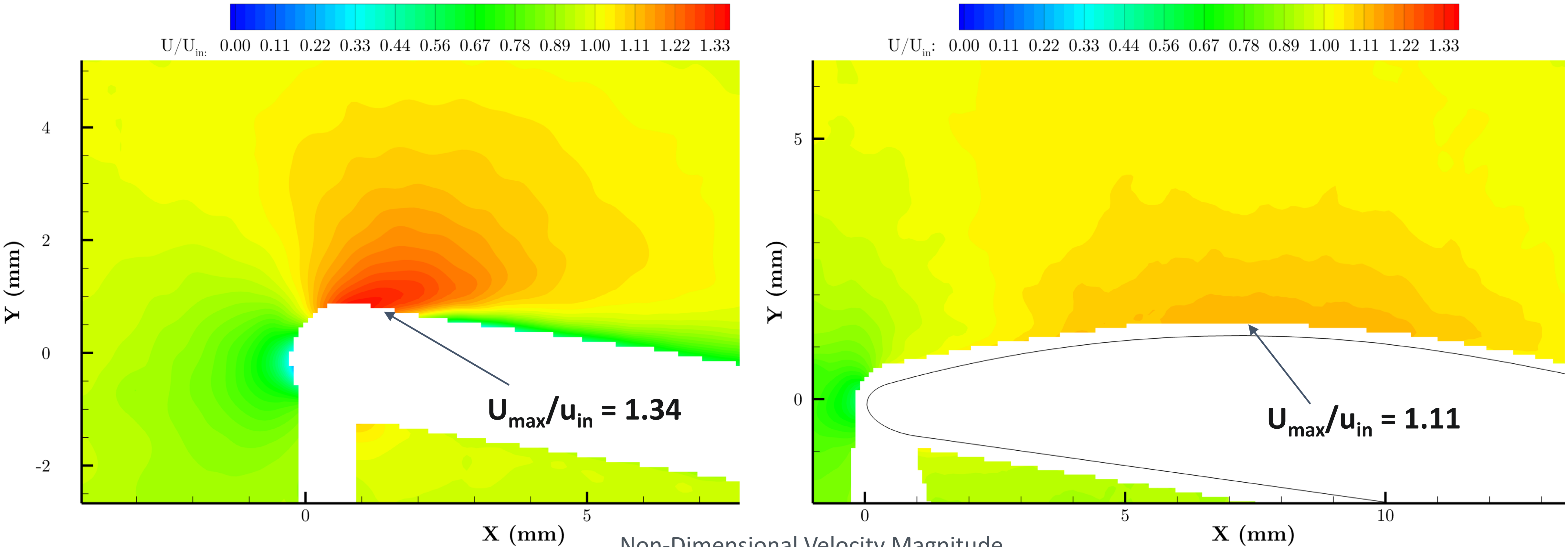
Blade Performance Comparison – 90 Bar



- Contours of Non-dimensional Velocity Magnitude

- Results consist of ~1400 ensemble averaged vector fields with an interrogation window size of 16x16 with 75% overlap. Vector resolution ~0.08mm x 0.08mm

Blade Performance Comparison – 90 Bar



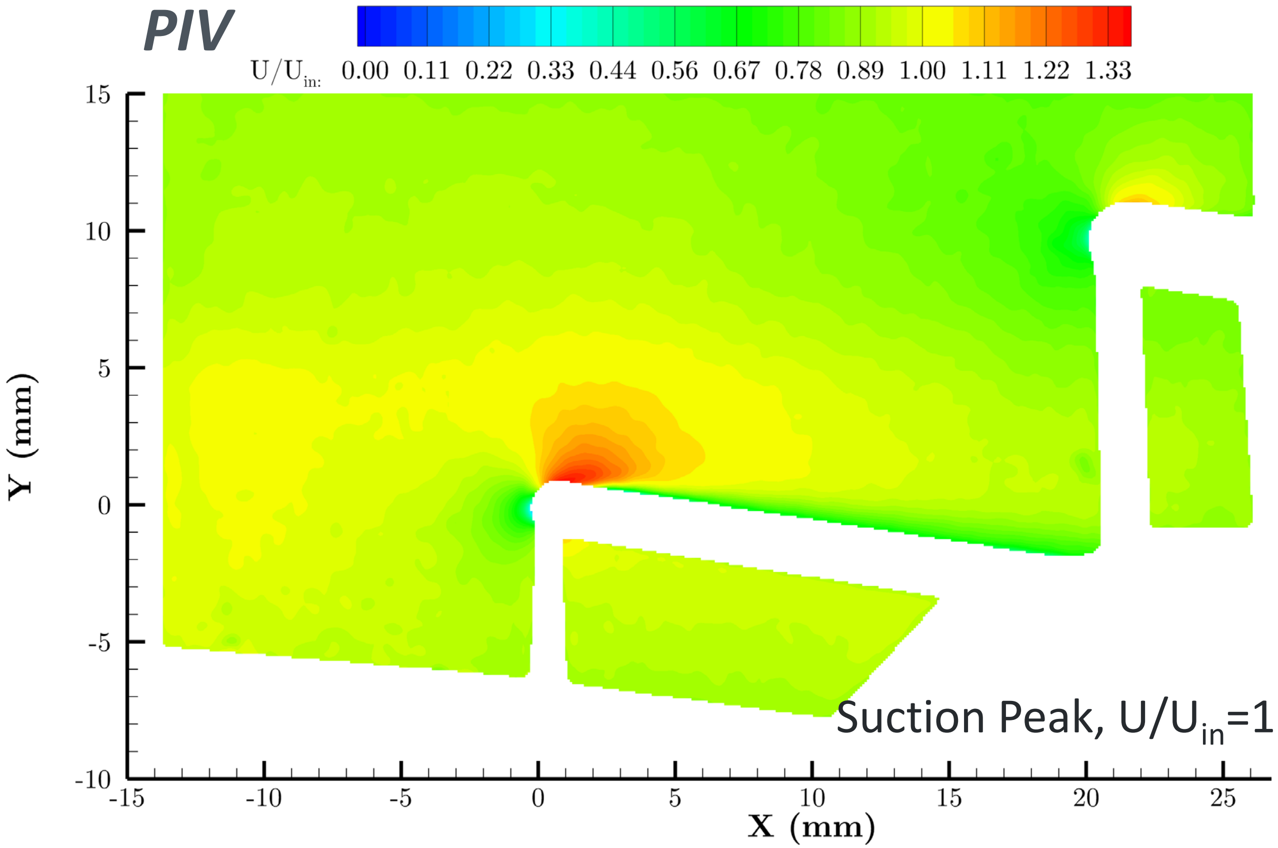
Non-Dimensional Velocity Magnitude

- As seen across the various CFD run regimes, the measured velocity field magnitude, and gradient associated with the Biased-Wedge suction peak is consistently lower than that measured for the baseline, constant radius leading edge.

- ***The baseline blade, at the suction peak is marked by velocities ~20% higher than that of the Biased-Wedge***

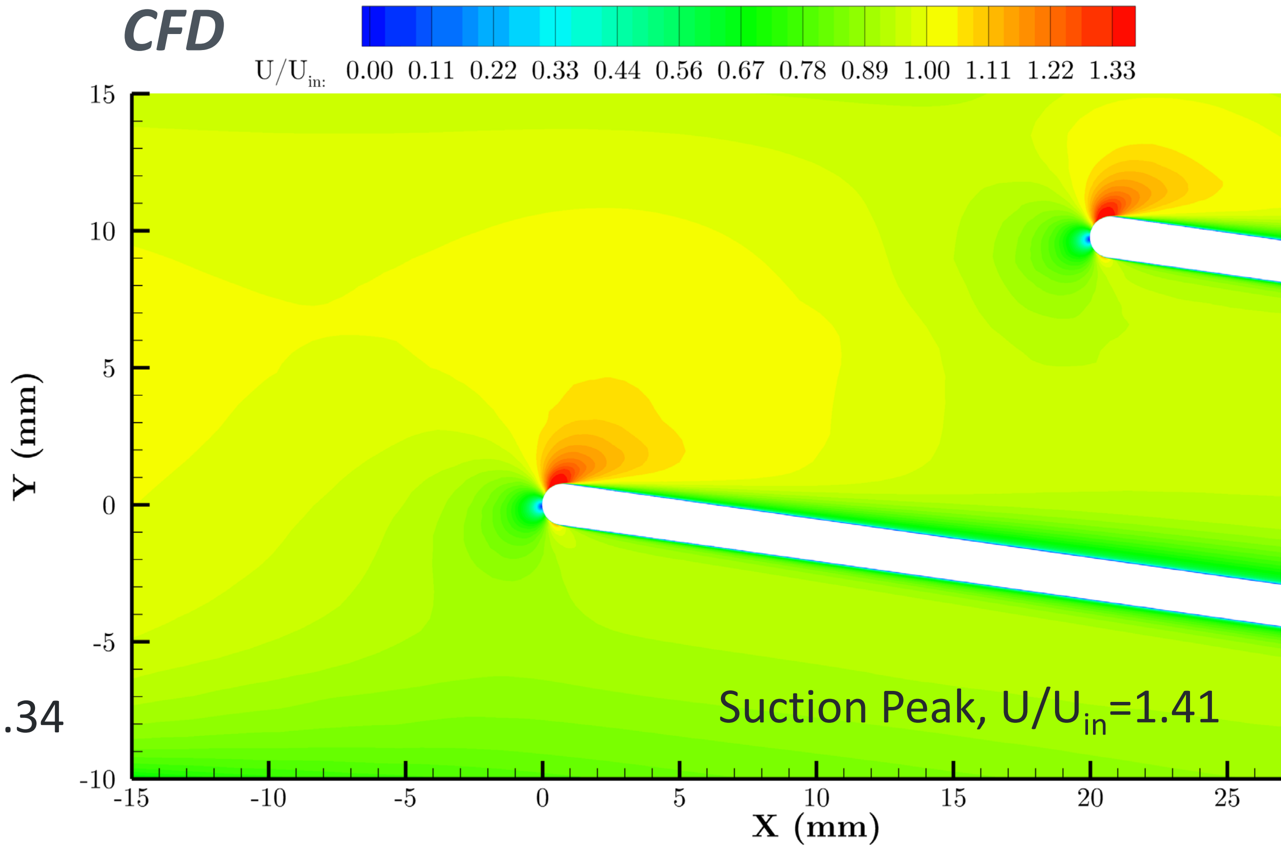
Comparison with CFD - Baseline

PIV



Suction Peak, $U/U_{in}=1.34$

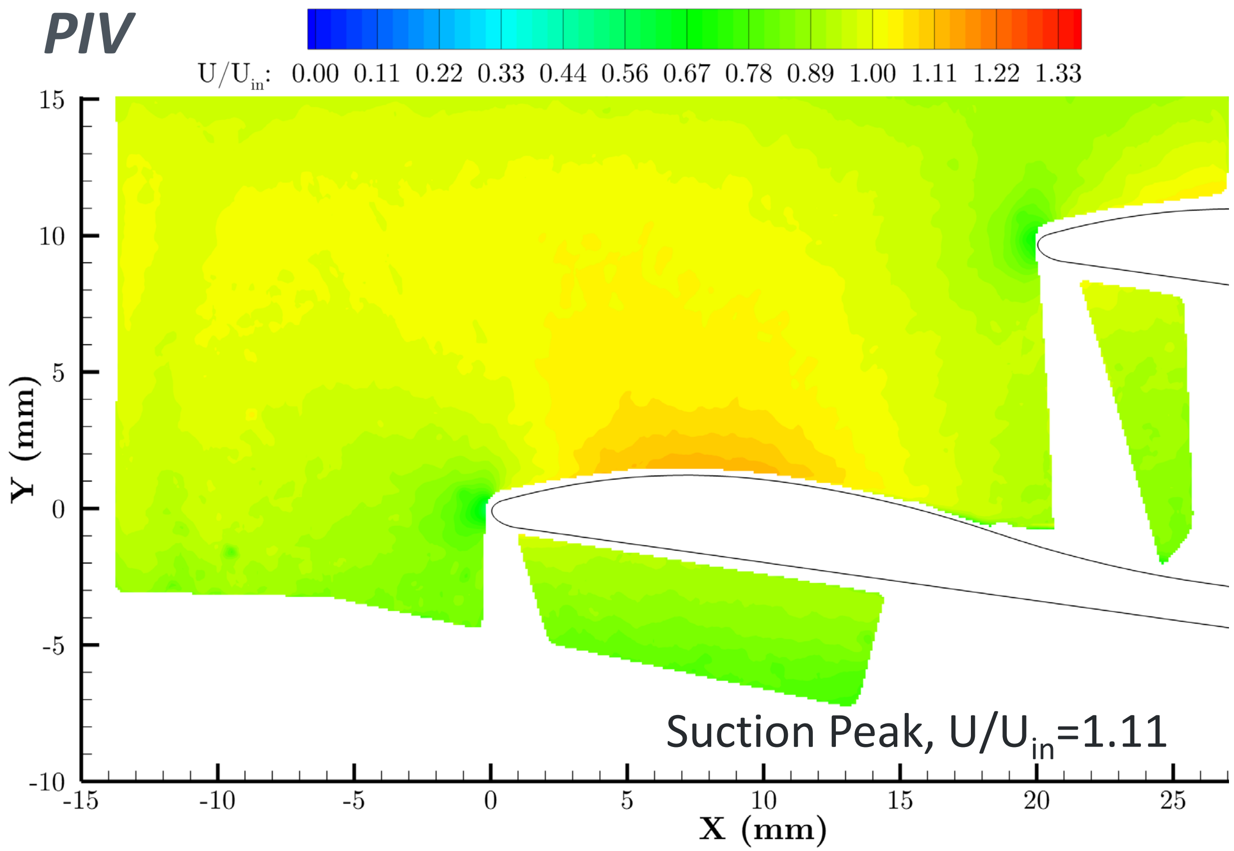
CFD



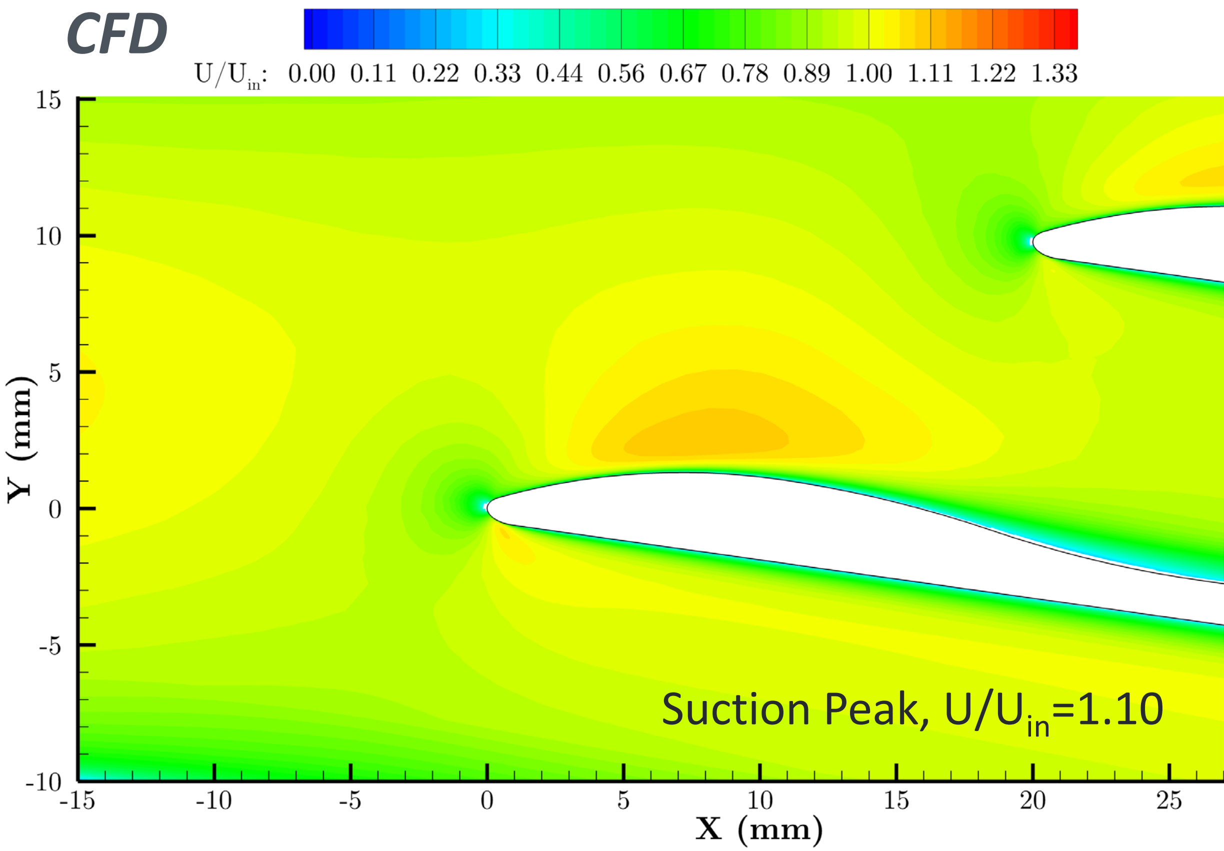
Suction Peak, $U/U_{in}=1.41$

- CFD shows good agreement with experiment. Salient features and local suction peaks are captured. **Suction velocity on Baseline predicted within 5.2%**

Comparison with CFD – Biased Wedge



Suction Peak, U/U_{in}=1.11



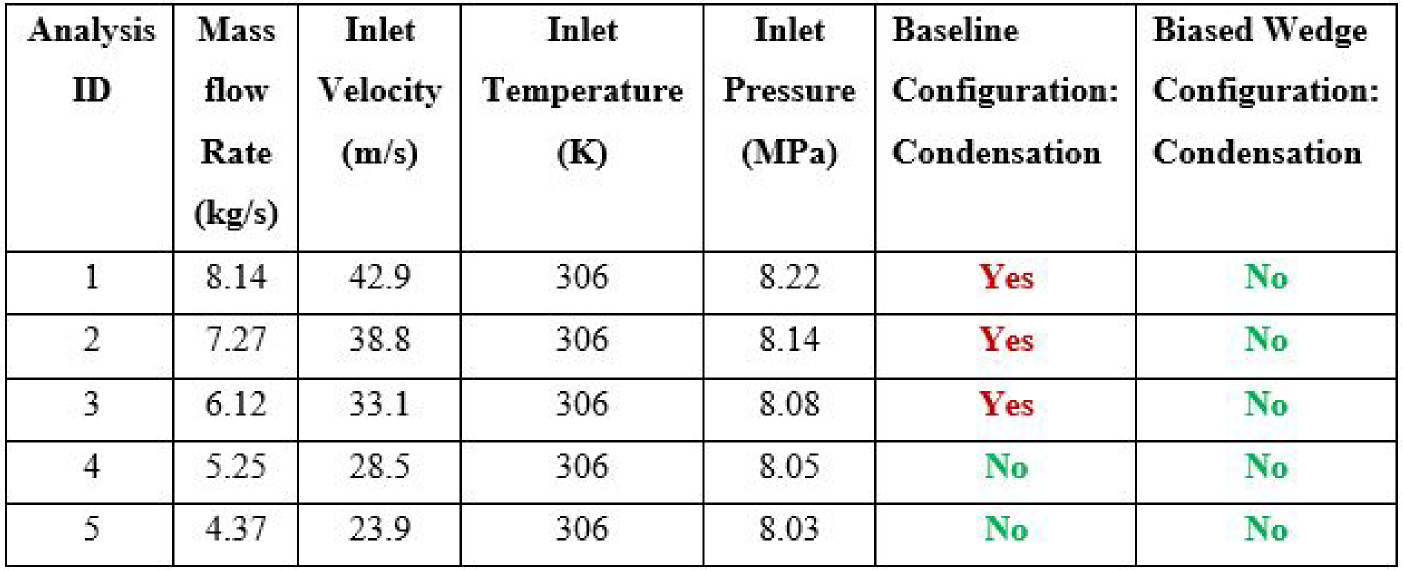
Suction Peak, U/U_{in}=1.10

- CFD shows excellent agreement with experiment. Salient features and local suction peaks are captured. **Suction velocity on Biased Wedge predicted within 1%**

Parametric Studies of Baseline and Biased Wedge Design at Elevated Flow Rates

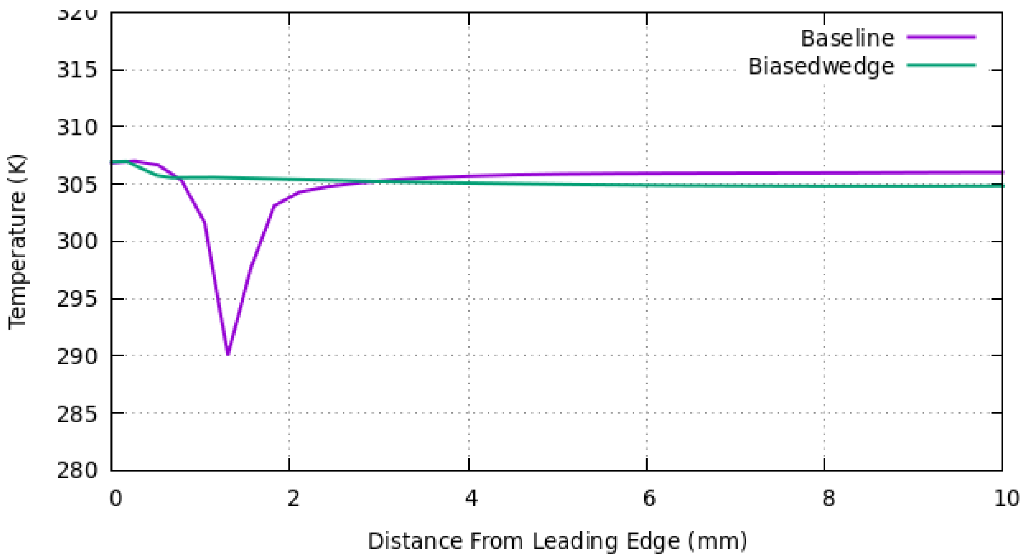
Parametric Study at Near Critical Conditions

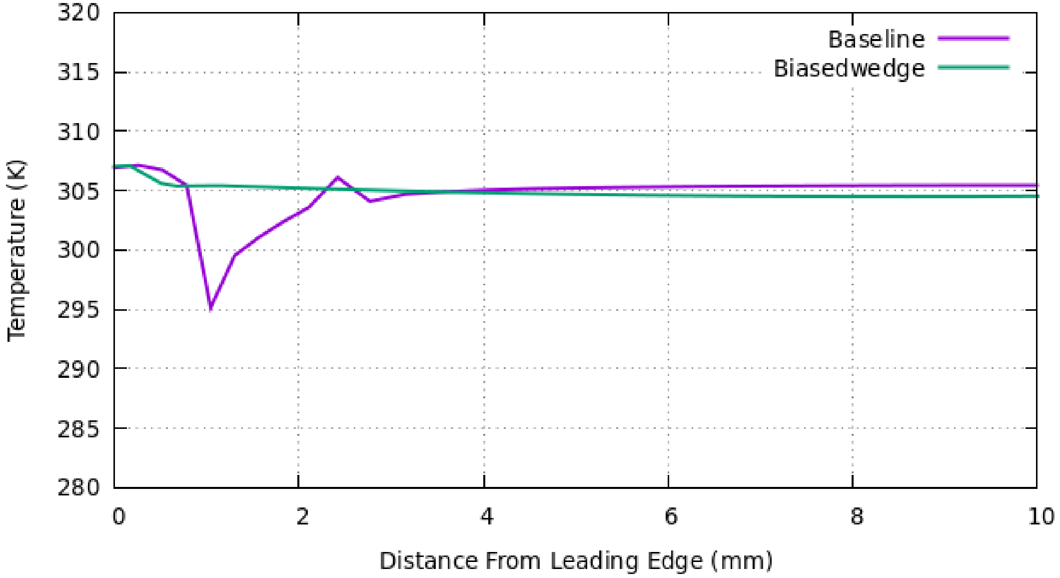
- Parametric study conducted at conditions closer to critical point (306 K, 80 Bar) over a range of velocities to characterize potential for condensation at conditions closer to compressor operation

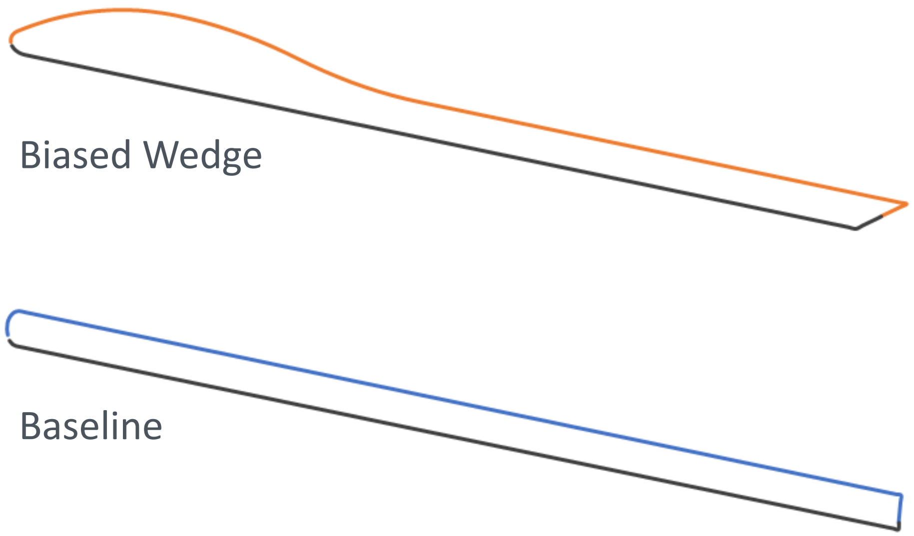


Analysis ID	Mass flow Rate (kg/s)	Inlet Velocity (m/s)	Inlet Temperature (K)	Inlet Pressure (MPa)	Baseline Configuration: Condensation	Biased Wedge Configuration: Condensation
1	8.14	42.9	306	8.22	Yes	No
2	7.27	38.8	306	8.14	Yes	No
3	6.12	33.1	306	8.08	Yes	No
4	5.25	28.5	306	8.05	No	No
5	4.37	23.9	306	8.03	No	No

Blade Temperature Profile







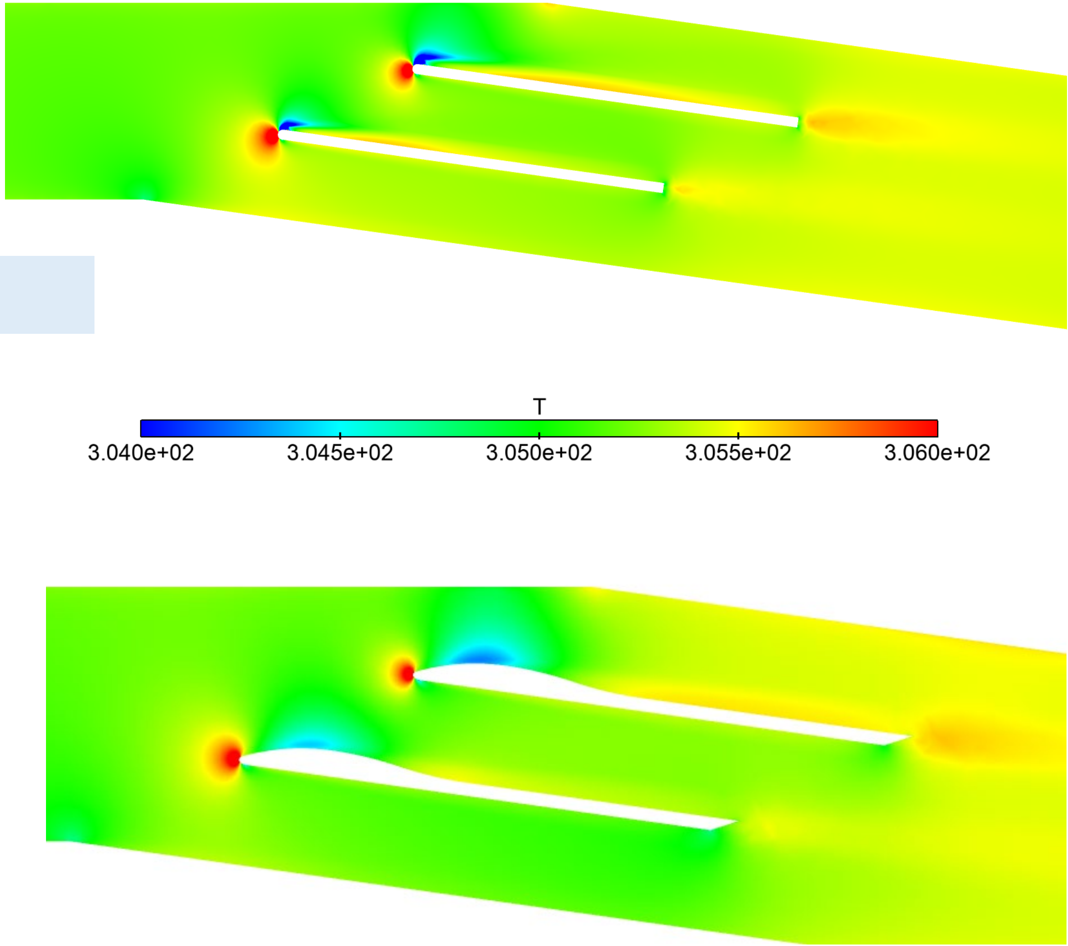
Profiles plotted at two largest velocities: 42.9 m/s and 38.8 m/s

Temperature Contours 8.14 kg/s

Baseline

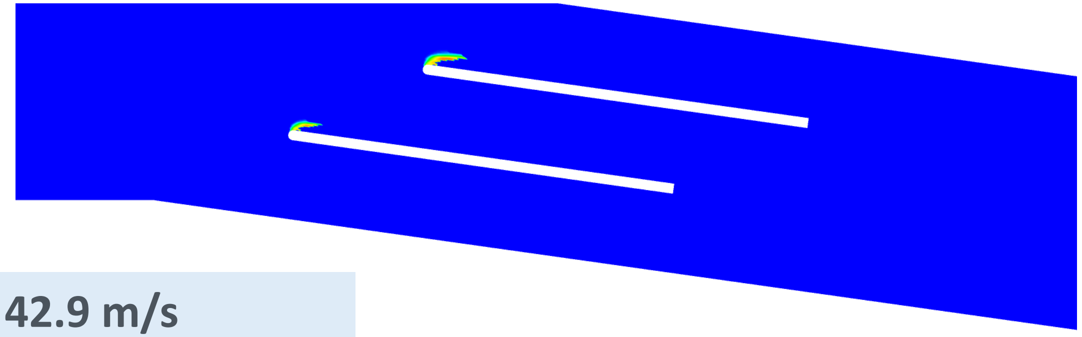
Solution for 42.9 m/s

Biased Wedge

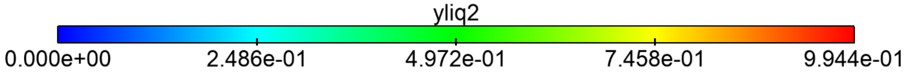


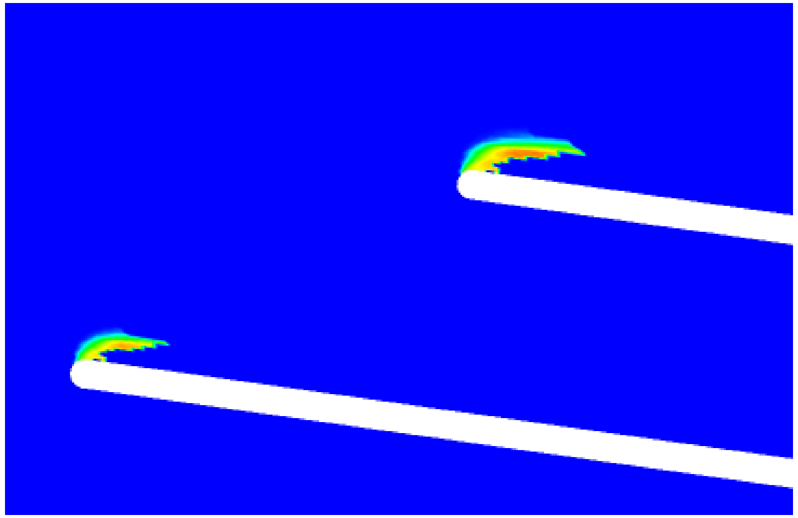
Liquid Condensate Concentration: 8.14 kg/s

Baseline



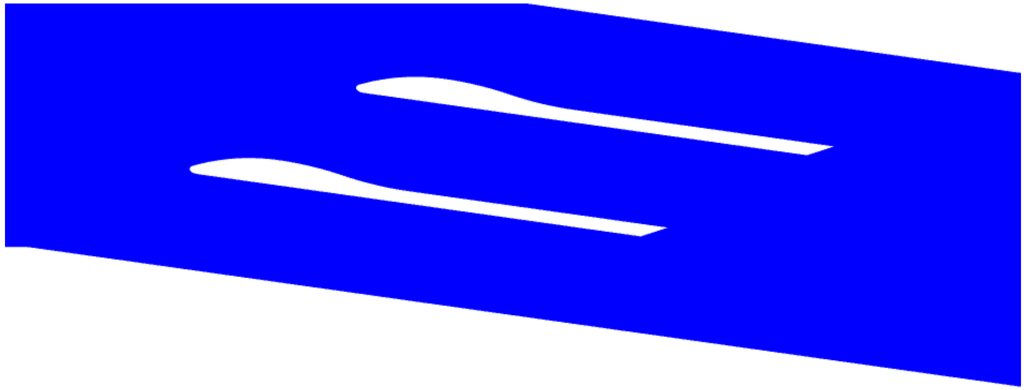
Solution for 42.9 m/s





Leading-edge

Biased Wedge



Biased Wedge Performance For 10 MWe Class Compressor Conditions in Sunshot Program

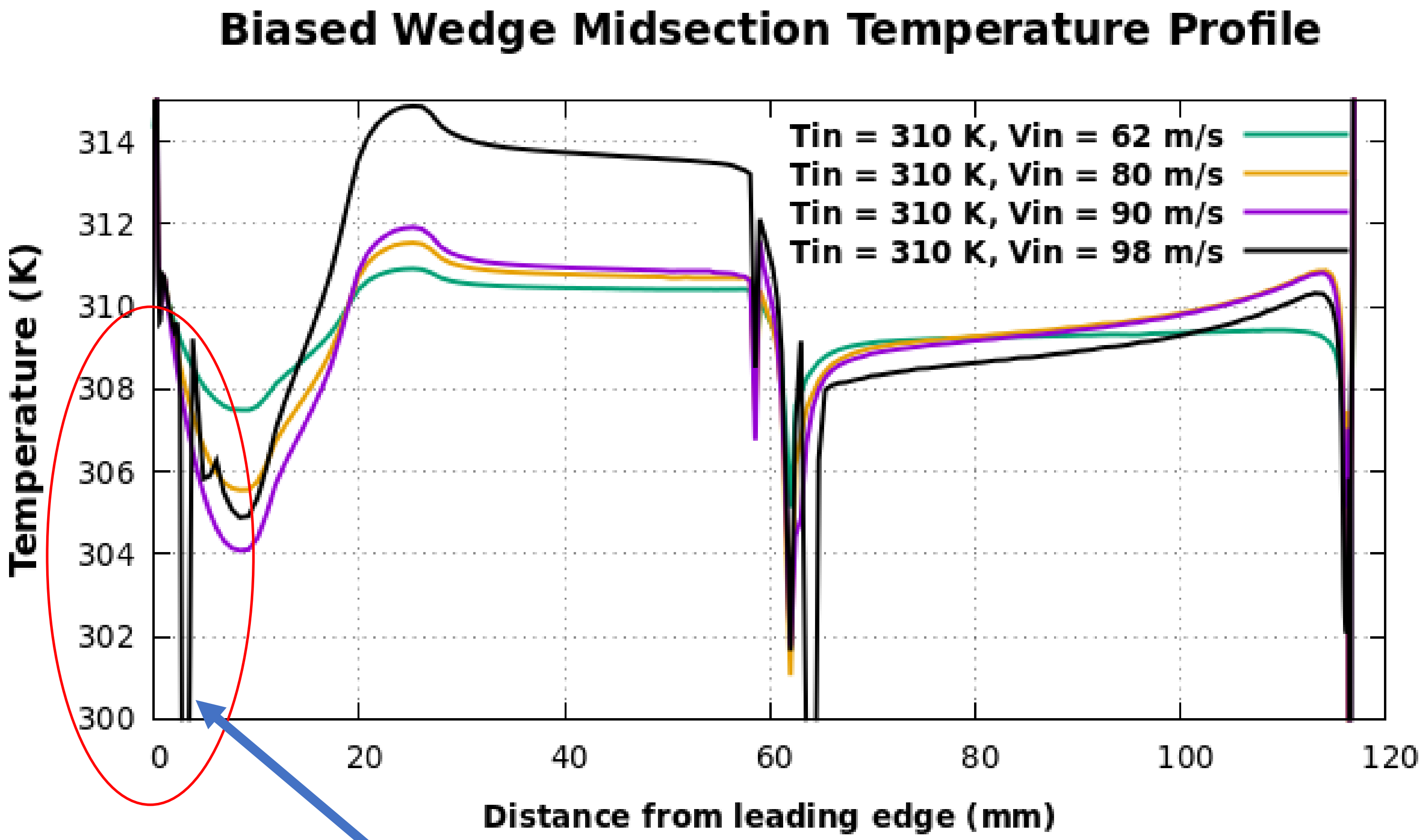
Parametric Study for Biased Wedge Performance at 310 K

- Biased wedge calculations were performed at conditions representing the inlet tip relative velocity for a 10MWe class compressor
  - Biased wedge design provides liquid-free performance for inlet velocity range of 62-92 m/s.
- Hanwha compressor inlet tip speed is 83.43 m/s; this indicates that biased wedge design may be a viable candidate for improving main compressor performance in 10MWe class

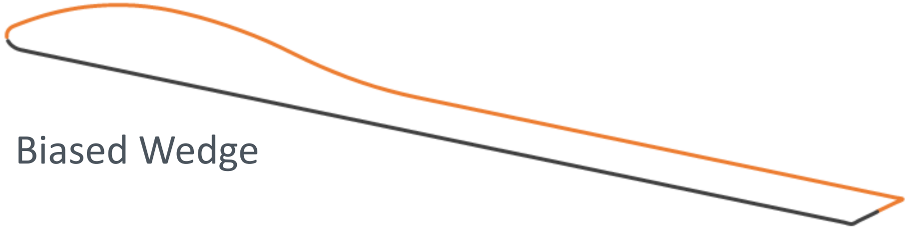
INLET VELOCITY (m/s)	INLET TEMPERATURE (K)	INLET PRESSURE (MPa)	Phase Change
62	310	7.94	No
80	310	7.91	No
92	310	7.88	No
98	310	7.88	Yes

Blade Temperature Profile

Inlet Temperature = 310 K



Inlet Phase Change at 98 m/s



Summary

- An improved sCO2 compressor leading edge profile (Biased-Wedge) was developed for the mitigation of liquid phase formation at the leading edge.

- A linear cascade geometry was designed, manufactured and implemented into an sCO2 test loop for evaluation of Biased-Wedge profile performance, and CFD validation.
  - ***PIV was demonstrated in a first of its kind experiment in sCO2, for an engineering geometry of this scale, and flow condition***
  - CFD results showed excellent agreement with experimental flow fields in capturing the magnitude of the leading-edge acceleration region/suction peak

- Numerical simulations were run at elevated flow rates for relevant compressor inlet conditions, including those of the Hanwha 10MWe compressor
  - *Results show the Biased-Wedge blade greatly reduces suction side liquid phase formation even at application relevant conditions*

Acknowledgments

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U.S. Department Of Energy

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Thank you for your attention

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Center for Advanced Turbomachinery
and Energy Research

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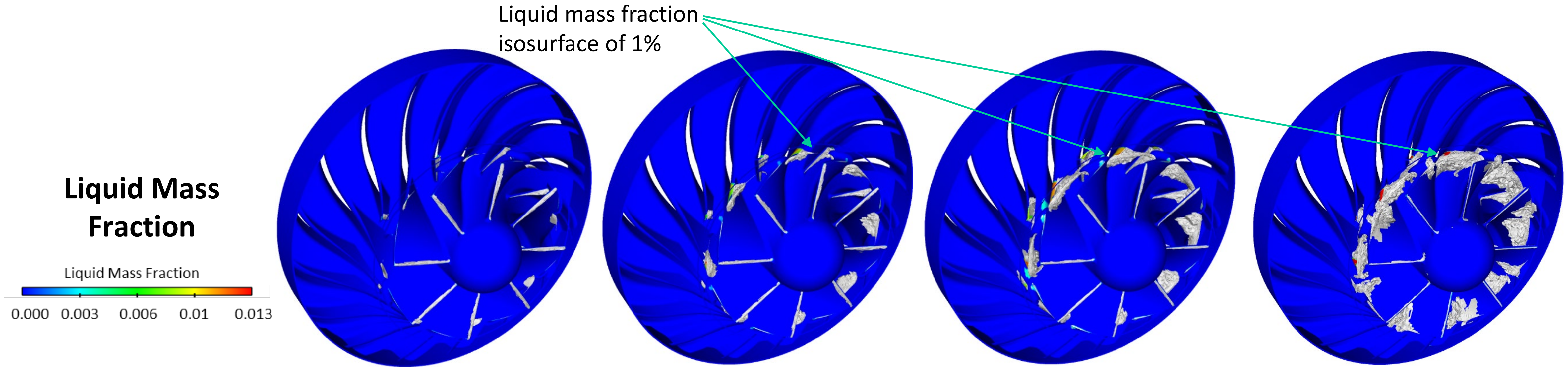
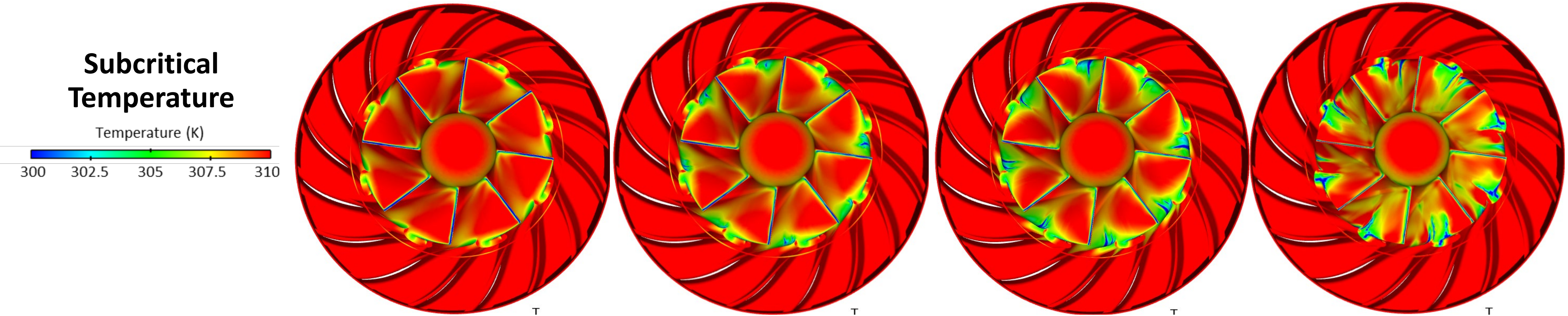
Motivation - Subcritical Effects at Shroud Inlet At High Flow Rates

Liquid Mass Fraction



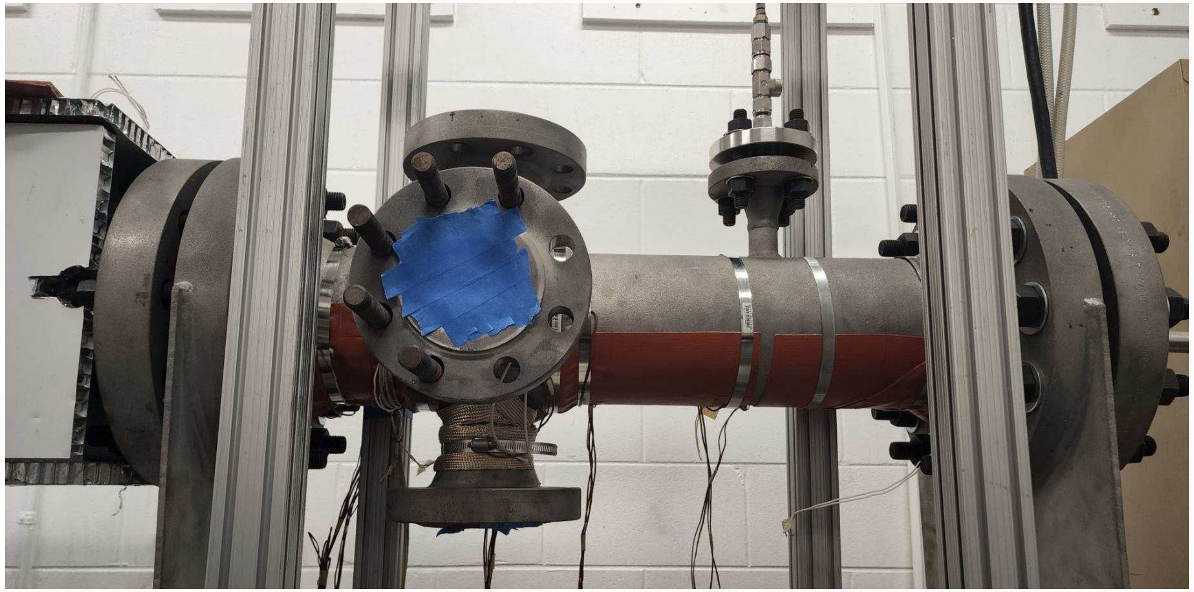
ϕ = 0.068 ϕ = 0.072 ϕ = 0.076 ϕ = 0.079

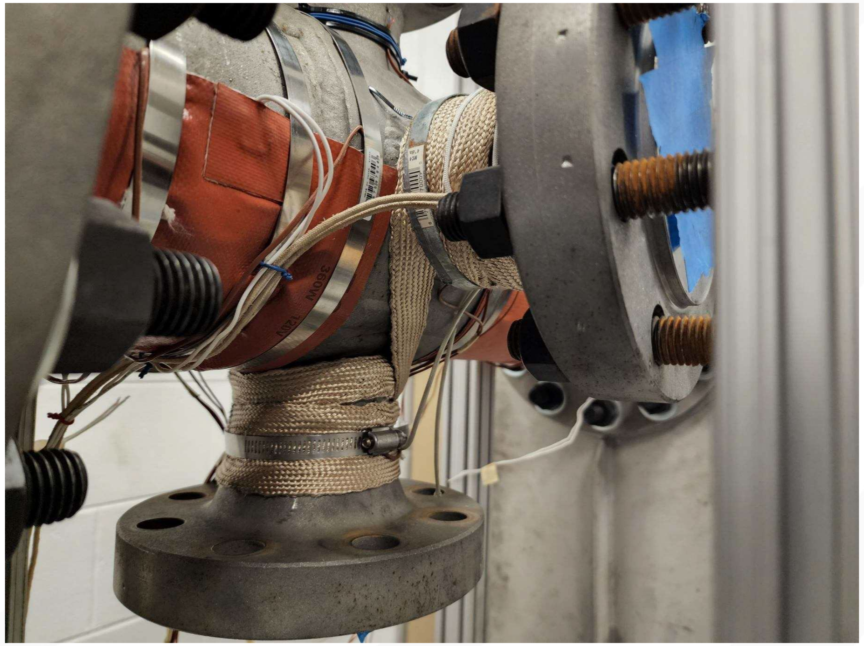
Subcritical Temperature

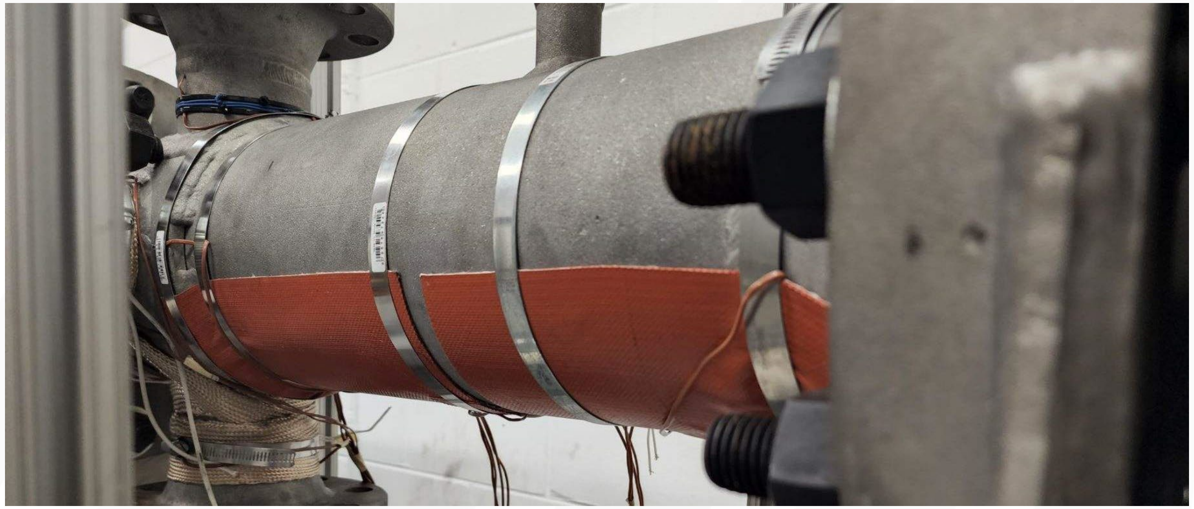


Segmented Vessel Temperature Control

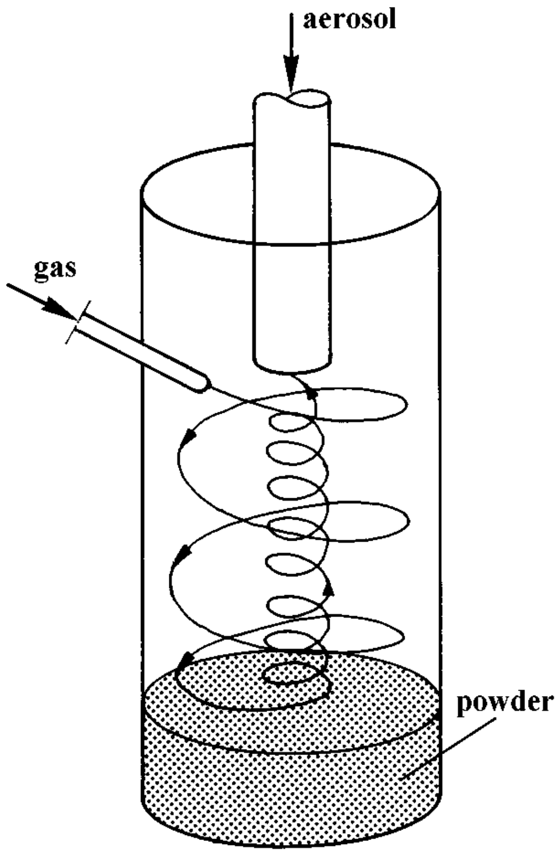
- Thermocouples are instrumented throughout the vessel interior and exterior to monitor circumferential temperature variations
- Segmented heaters with individual control are used to maintain close to an isothermal condition on the walls



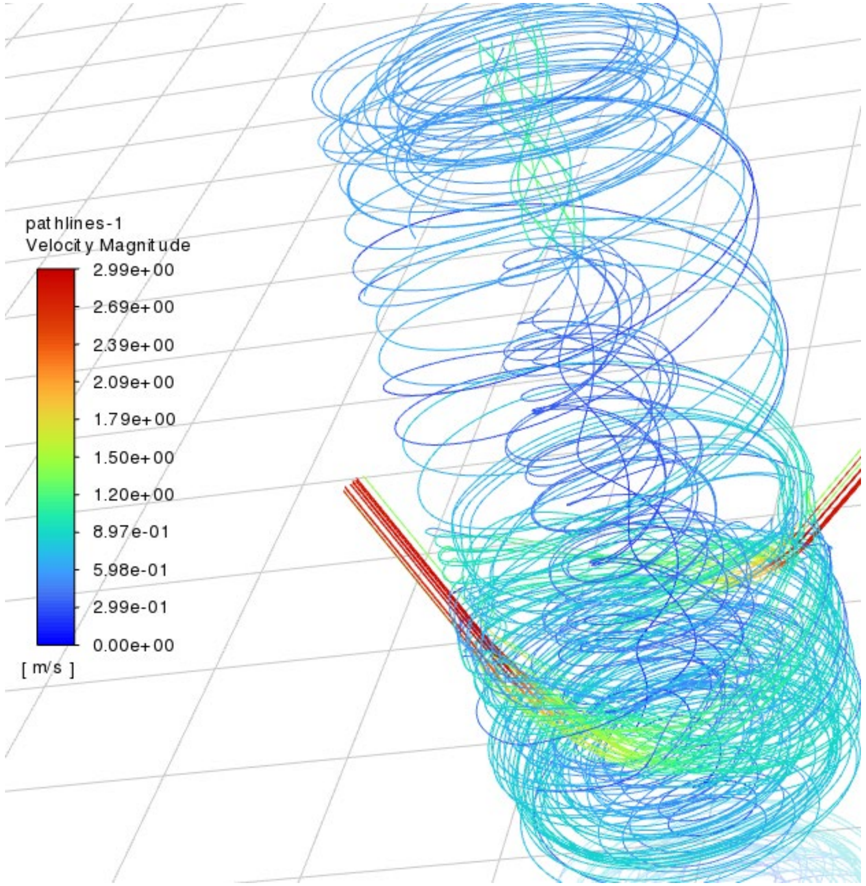




Particle Seeder



Cyclone Aerosol Generator [1]



CFD simulation for current seeder design (at test conditions)

- Particle seeding for PIV is one of the greatest challenges for closed loop/high-pressure applications
- Pressurizing from outside source not feasible due to variation of properties and inventory control
- Need a closed loop solution, with fine particle delivery control
- Seeder will allow for consistent seeding across a long duration PIV acquisition (leads to higher number of samples for improving statistical uncertainty)

[1] Glass, M.,Kennedy, I.M., “An Improved Seeding Method for High Temperature Laser Doppler Velocimetry,” Combustion Flame, Vol. 49, 1977.

Particle Seeder Hardware

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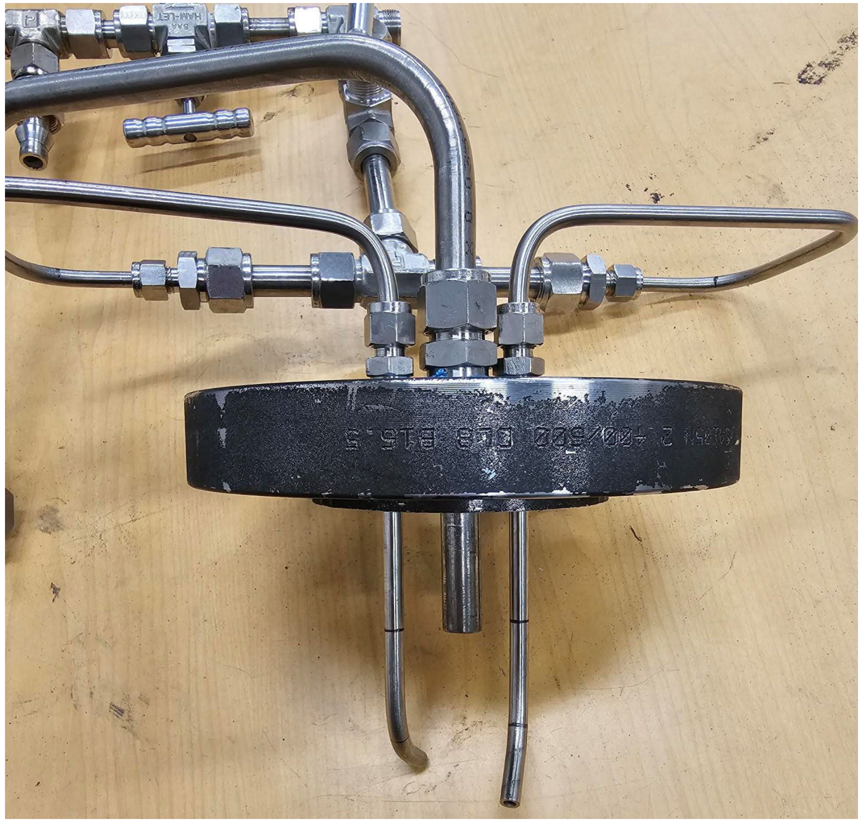
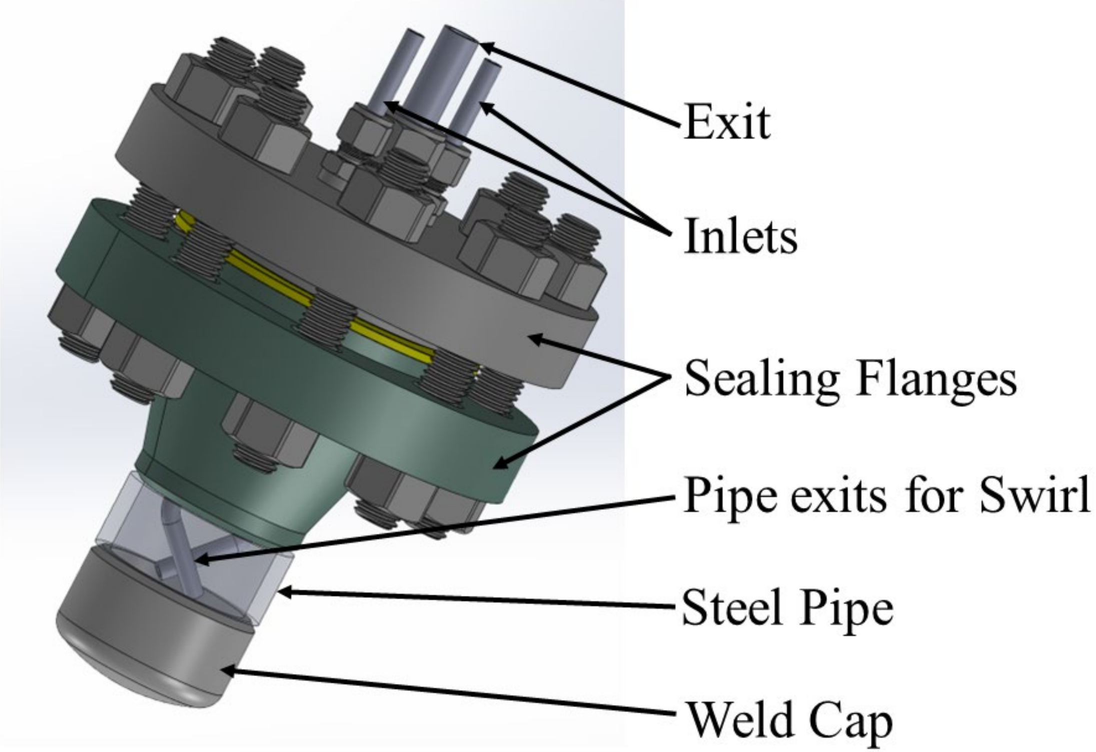


Seeder Top Flange with Injection Hardware



Seeder Assembly

- Constructed from #600 class steel flanges and Sch. 80 Pipe

  Maximum working pressure 100 Bar

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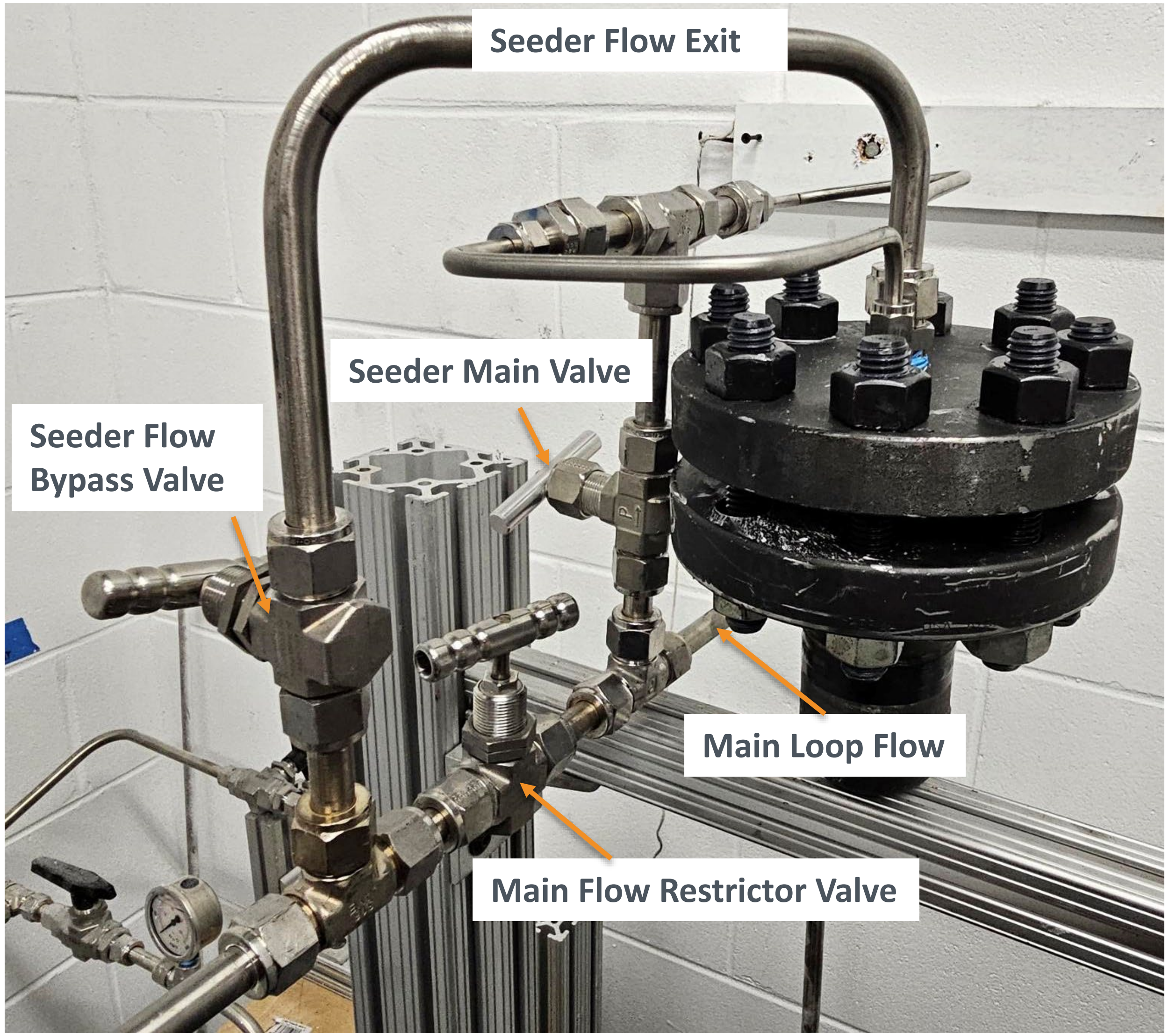
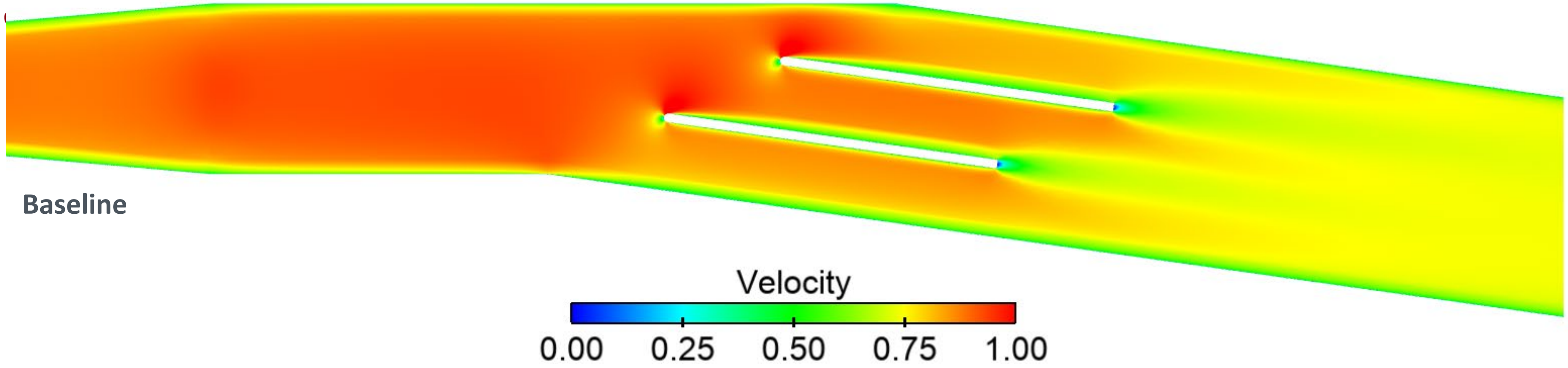
Improved Particle Seeder



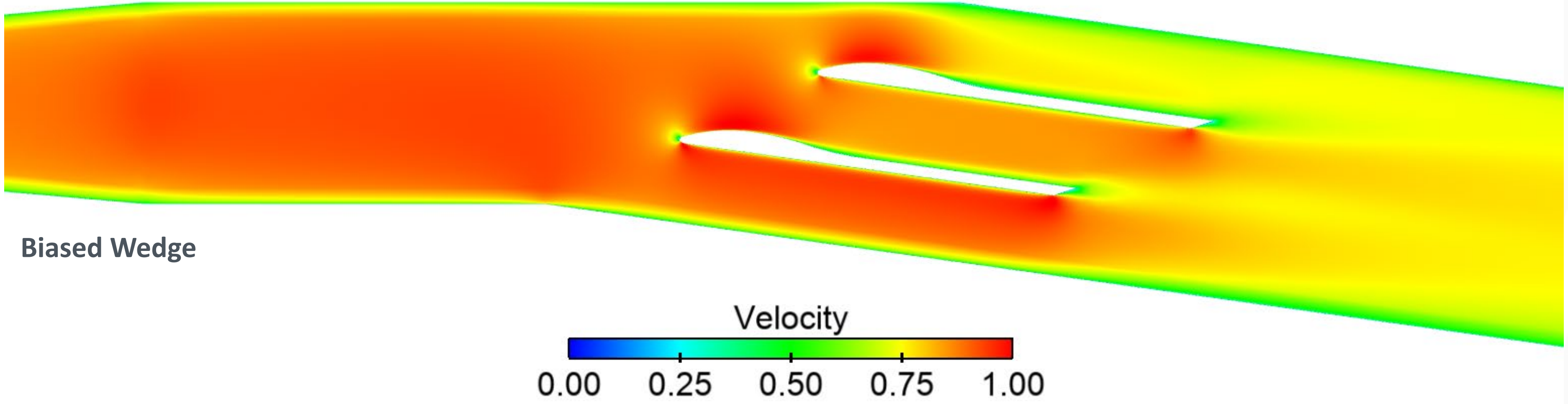
- Particle injection concentration is controlled via two valves (Main flow restrictor and seeder bypass)
- To increase particle injection concentration, main loop flow is bypassed, so it runs through the seeder
- Larger fractions of bypassed CO2 flow into the seeder lead to higher particle concentration
- Enable homogenous particle distributions for longer durations

Results – Numerical (Experimental Flow Rate `

Inlet Conditions
Flow Rate 0.118 kg/s
Temperature 310K
Pressure 85 Bar



Baseline

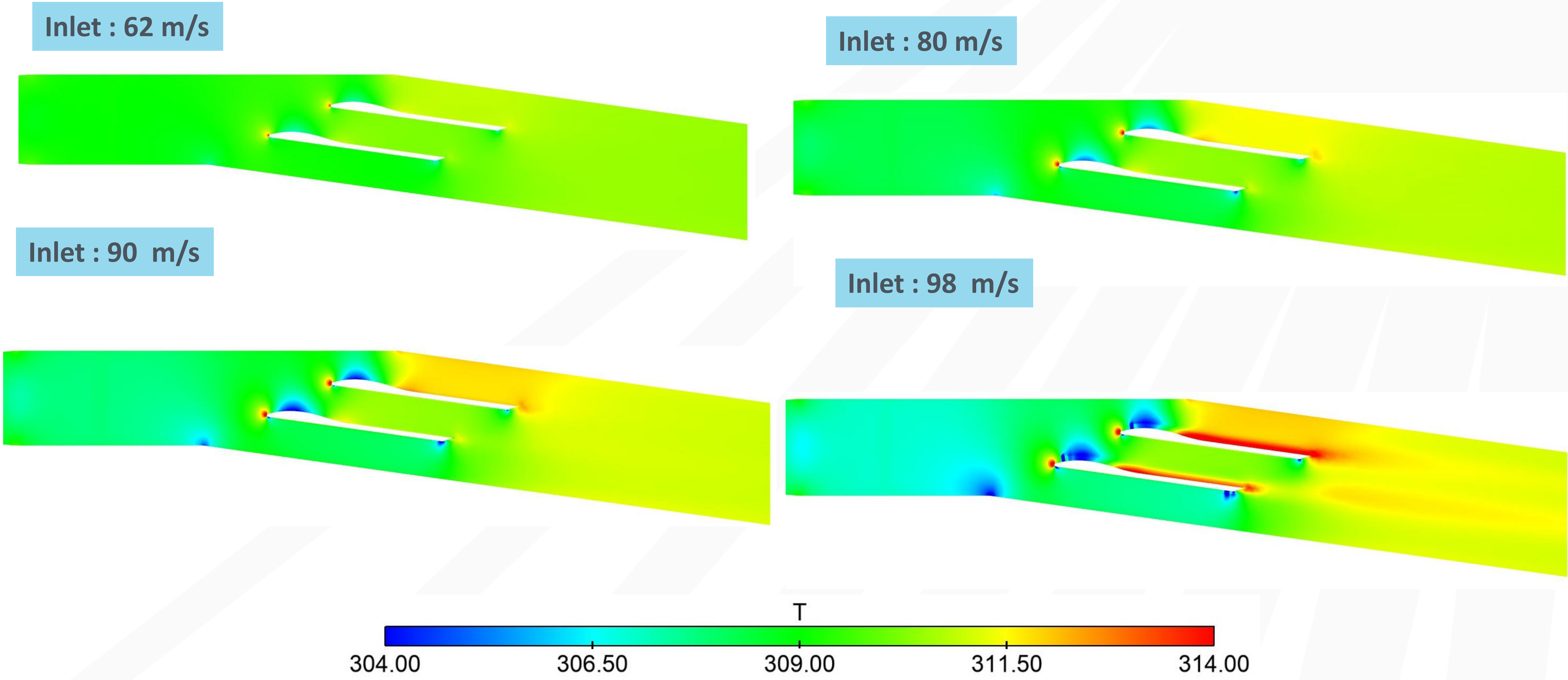


Biased Wedge

Blade Midspan Velocity Contours

Biased Wedge Performance

Inlet Temperature of 310 K: Temperature (K) Contours at Different Inlet Velocities



Inlet : 62 m/s

Inlet : 80 m/s

Inlet : 90 m/s

Inlet : 98 m/s

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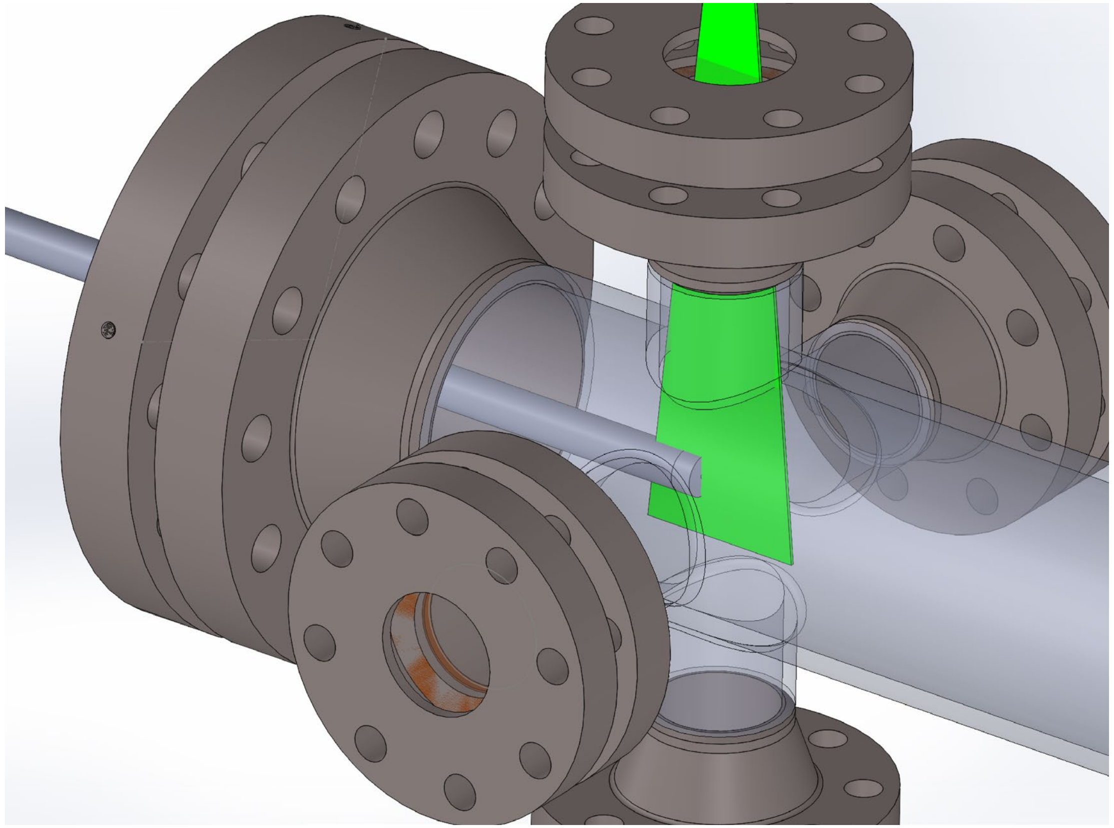
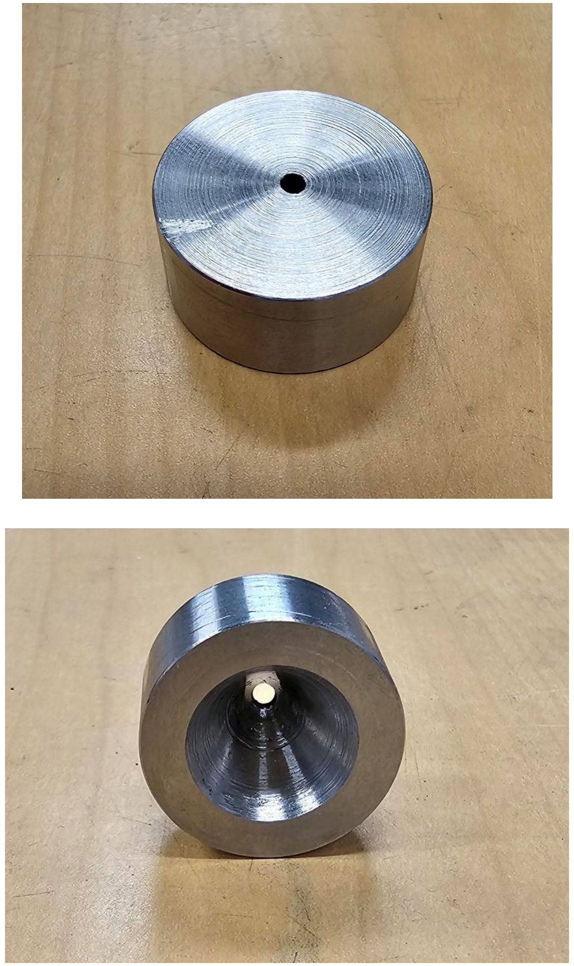
Liquid Phase Evaluation Method – Hardware



CAD assembly of orifice flow test



Converging Nozzle as fabricated

- Pipe with welded orifice is centered in optical domain
- Thermocouples are instrumented just upstream of orifice exit to measure bulk fluid temperature
- During testing, the pressure vessel heaters are used to maintain supercritical conditions in the main domain, regardless of orifice exit conditions

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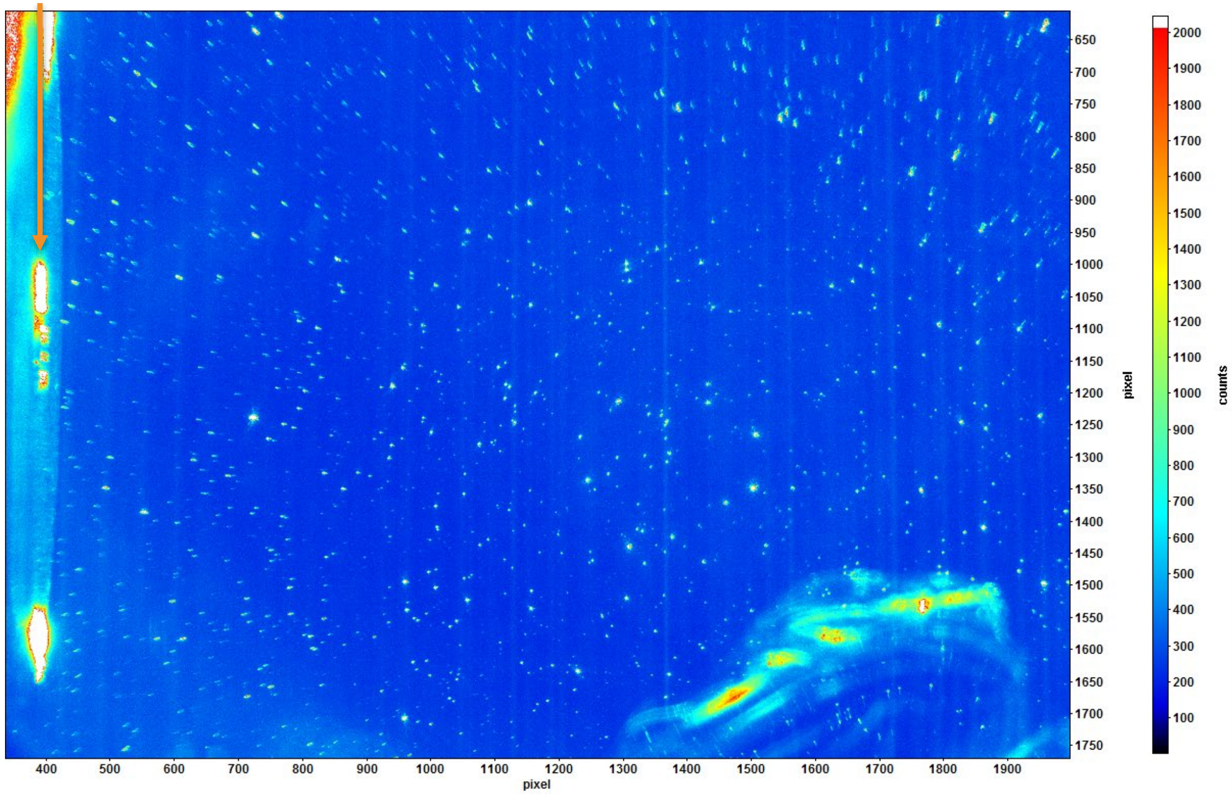
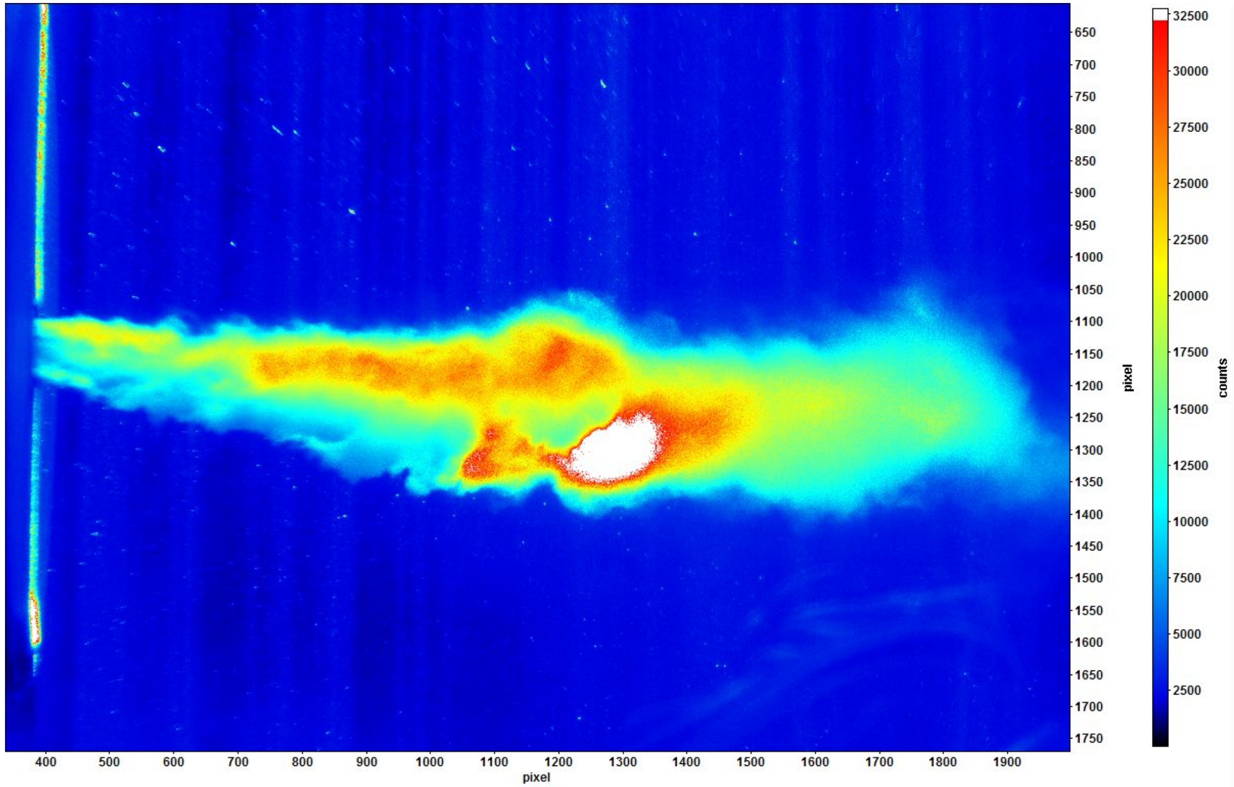
Liquid Phase Evaluation – Results

Orifice



Baseline Flow (All Supercritical), Jet temperature ~38C
Vessel Domain Temperature ~38C



Liquid Jet into Supercritical Vessel
Vessel Domain Temperature ~38C

- Liquid phase pixel intensities >> 5x that of background domain pixel intensity
- Note: small particles in background are residual PIV seed particles
- Sharp interface between liquid and supercritical phases can be seen, and are captured with high spatial resolution

Liquid Phase Evaluation – Results

Liquid Jet into Supercritical Vessel
Vessel Domain Temperature ~38C

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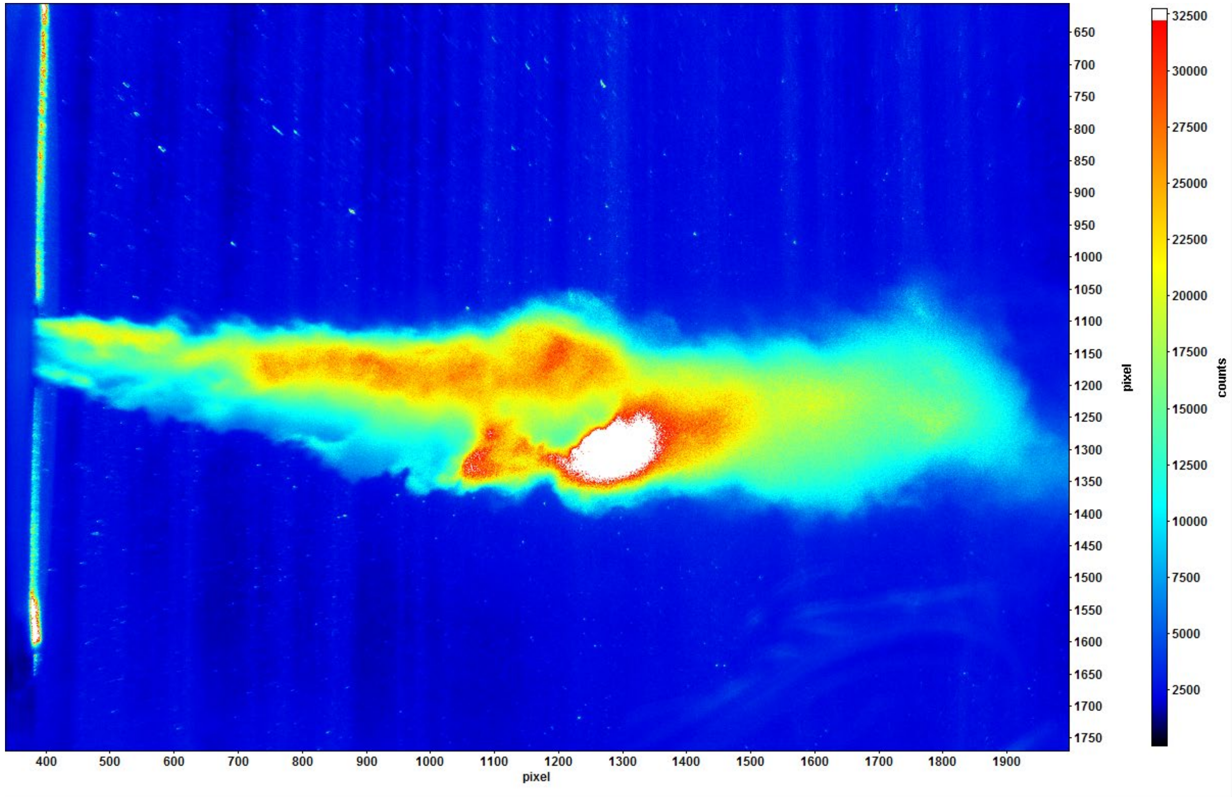
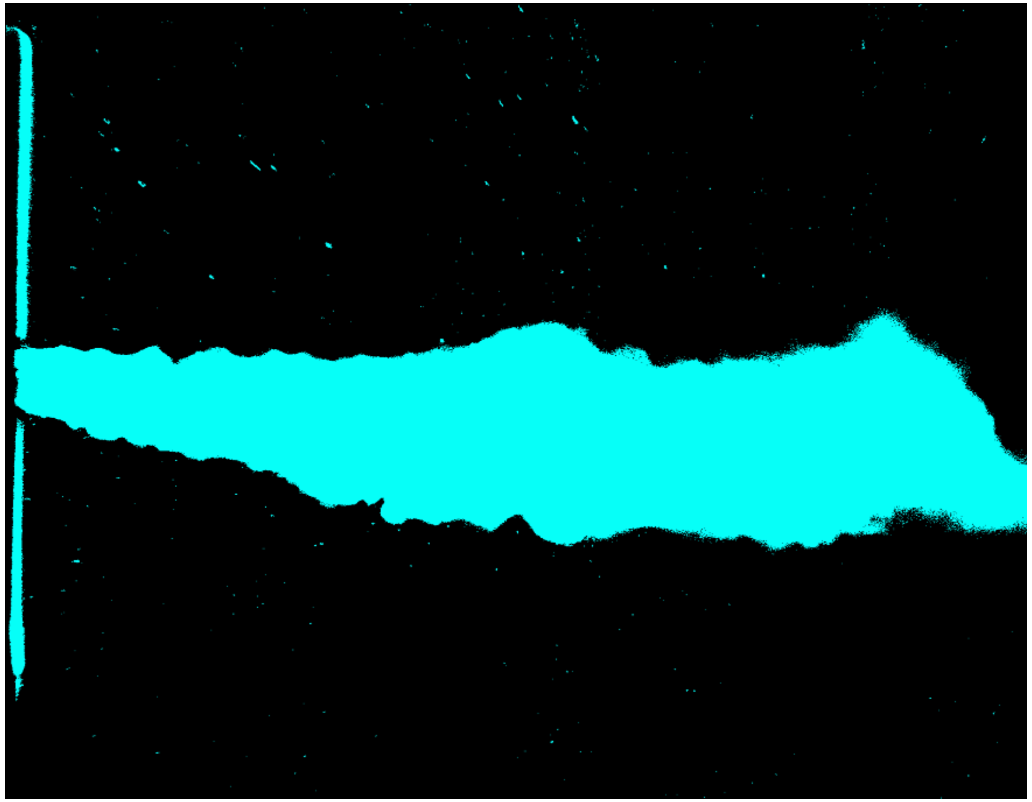
Liquid Phase Evaluation – Binarized



Liquid Jet into Supercritical Vessel
Vessel Domain Temperature ~38C



Liquid Jet into Supercritical Vessel Binarized
Vessel Domain Temperature ~38C

- Note: small particles in background are residual PIV seed particles
- ***Sharp interface between liquid and supercritical phases can be seen, and are captured with high spatial resolution***
- Interface between phases can be visualized through image threshold binarization

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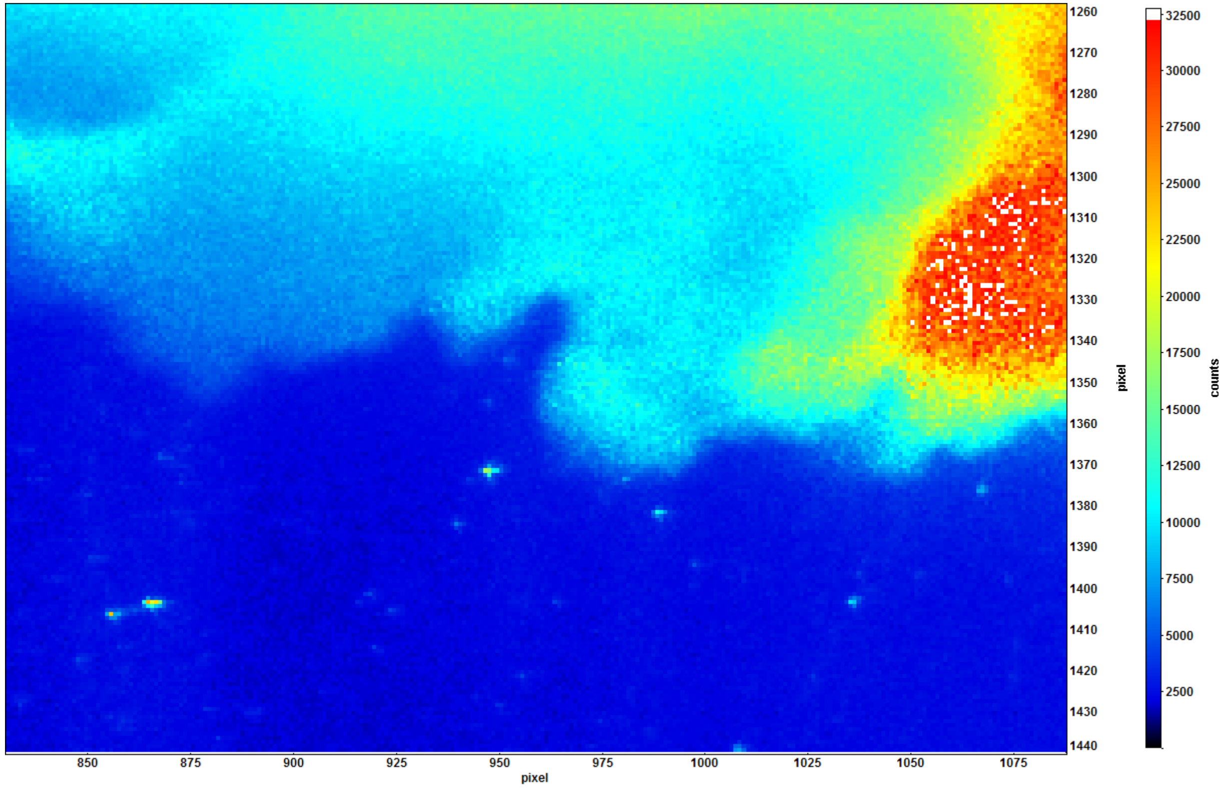
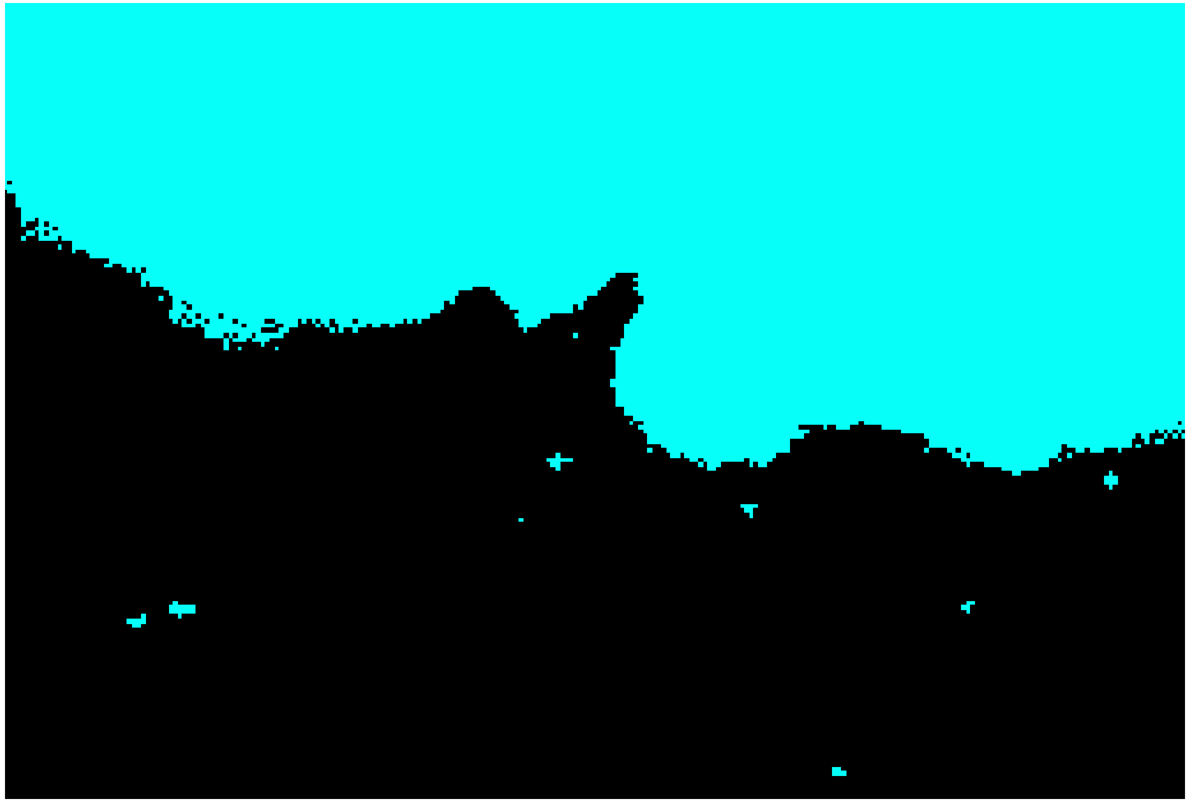
Liquid Phase Evaluation – Binarized Zoomed



Liquid Jet into Supercritical Vessel
Vessel Domain Temperature ~38C



Liquid Jet into Supercritical Vessel Binarized
Vessel Domain Temperature ~38C

- Note: small particles in background are residual PIV seed particles
- ***Sharp interface between liquid and supercritical phases can be seen, and are captured with high spatial resolution***
- Interface between phases can be visualized through image threshold binarization

Liquid Phase Evaluation – Binarized

Liquid Jet into Supercritical Vessel
Vessel Domain Temperature ~38C

Thank you for your attention

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