Center for Advanced Turbomachinery and Energy Research (CATER)

Cycle Innovation and Optimization
Aerodynamics, Heat Transfer and Durability

Jay Kapat
University of Central Florida
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University R&D Panel
23rd February 2022

Supercritical CO_2 Power Cycles Symposium

Center for Advanced Turbomachinery and Energy Research (CATER)

Cycle Innovation and Optimization
Aerodynamics, Heat Transfer and Durability

Acknowledging Students from the group present in the audience:

Ofek Amasay
Emmanuel Gabriel-Ohanu
Akim Khlyapov
Adil Riahi
Ryan Wardell

Notable Past Members:

Dr. Akshay Khadse (Nikola)
Ian Cormier (8 Rivers)
Dr. Ankur Deshmukh (Siemens)
Dr. Mahmood M. (Mitsubishi)
Josh Schmitt (SwRI)

Home Alone:

John Richardson
Manoj Sargunaraj
Matt Smith

...critical CO_2 ...r Cycles ...sium

CATERing to the energy needs of society

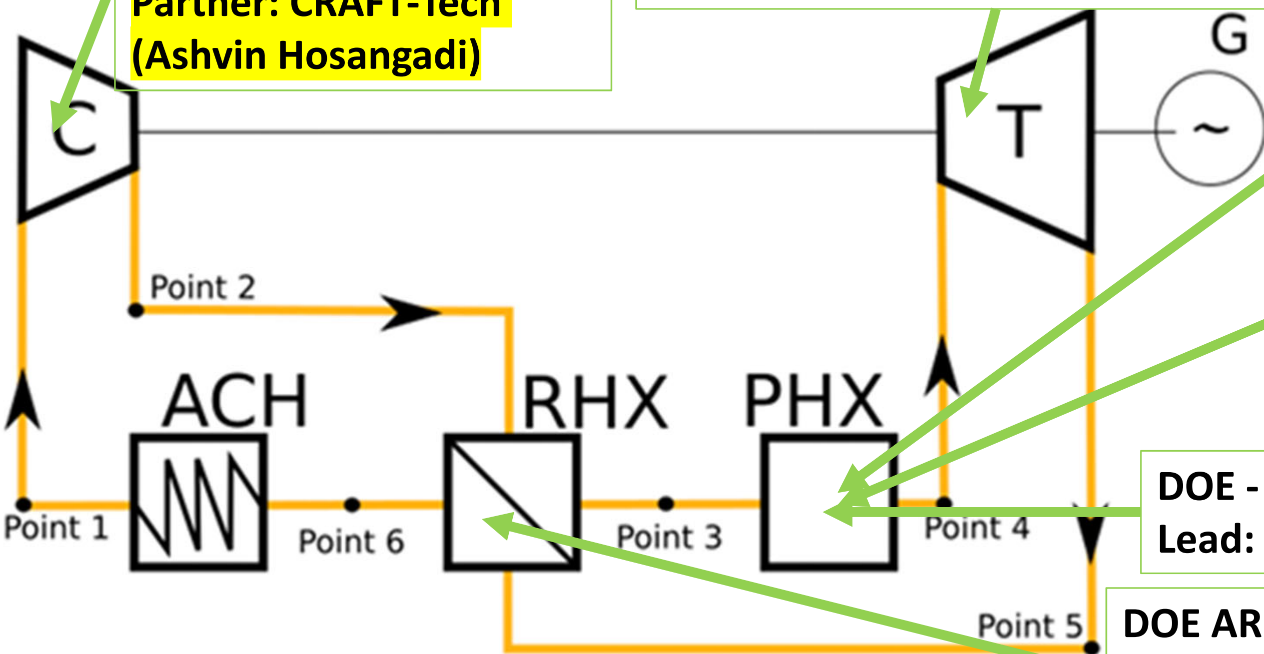
UCF

Various Projects in Non-Combustion Area

SETO EE0009382
sCO_2 compressor;
Partner: CRAFT-Tech
(Ashvin Hosangadi)

NETL FE0031929
sCO_2 cooled Turbine;
Lead: SwRI (Stefan Cich / Jeff Moore)

These efforts are supported by **research on fundamental flow and heat transfer for sCO_2 from DOE (DE-FE0025260) and ONR (N00014-18-1-2362)**



DOE SC 0020796; 2021
Lead: Spectral Energies

Cement WHR in India
Lead: Subbu Subbaraman (paper#181)

DOE - Sandia: WHR for Industry Sector
Lead: Logan Rapp

DOE - NE: Tungsten for Molten Salt /sCO_2 PHX
Lead: Editekk, with Penn St as fab partner

DOE ARPA-E TINA
Lead: Siemens Research; Partner: Siemens Energy
Awarded; Negotiation complete

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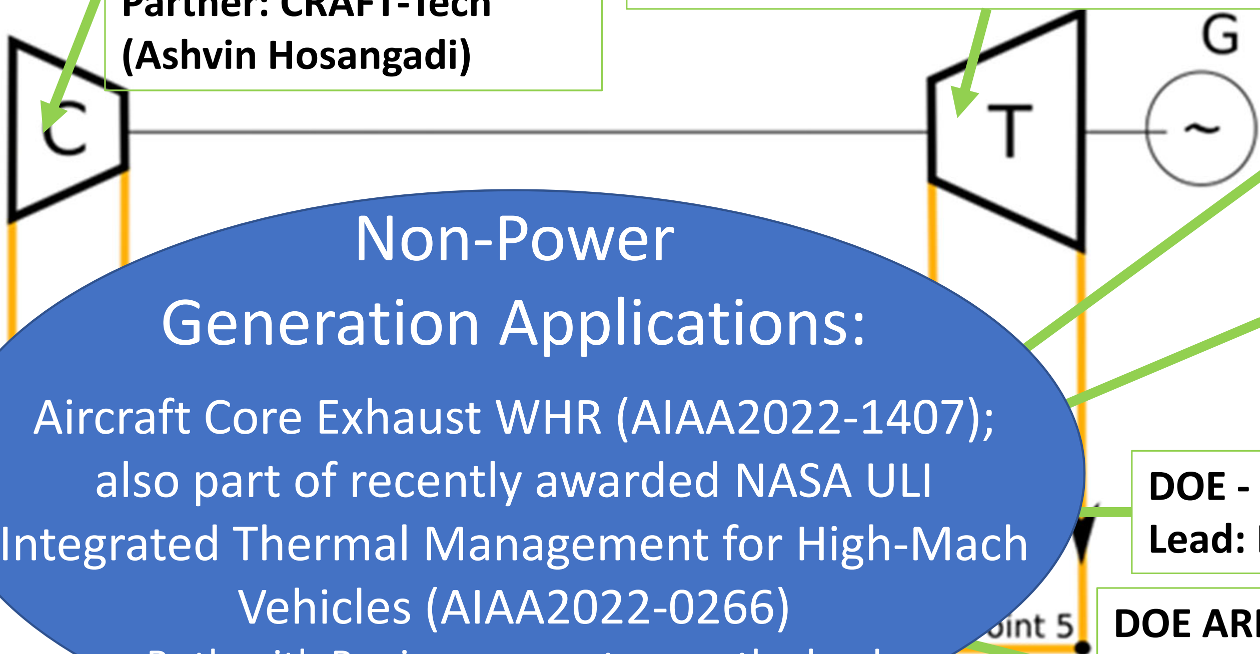

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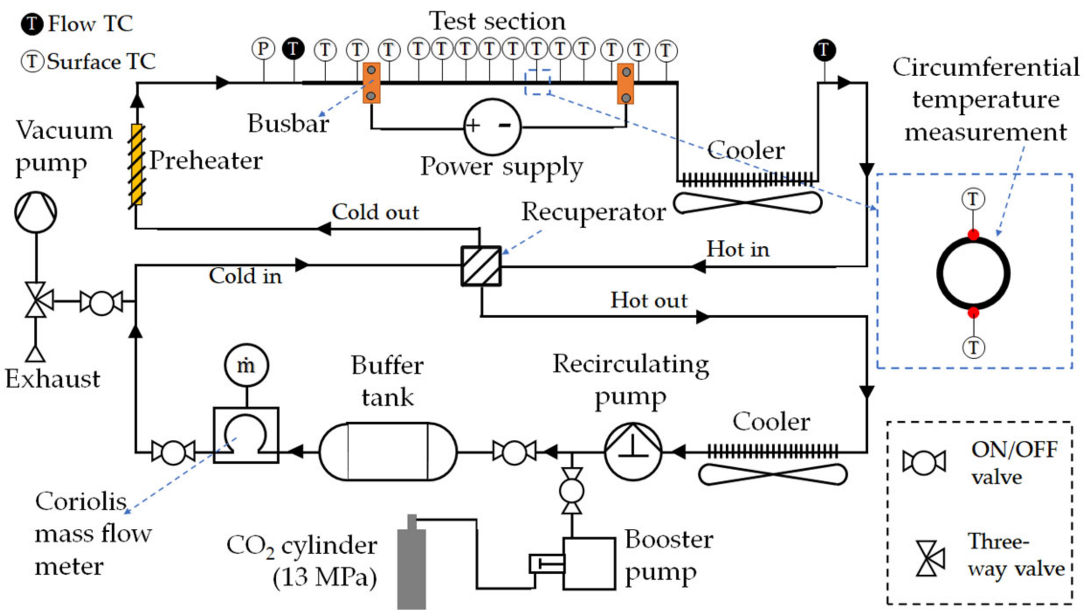
Aircraft Core Exhaust WHR (AIAA2022-1407); also part of recently awarded NASA ULI Integrated Thermal Management for High-Mach Vehicles (AIAA2022-0266)

Both with Boeing as a partner or the lead

Primary sCO_2 Test Loop

- Stainless steel and Inconel test section; rest of the loop: stainless steel
- Heat addition to test section via Joule heating
- Pressure range = 80-200 bar,
- Mass flow rate range (Sigma pump)
  - 0.66-16.5 L/min OR 0.01-0.25kg/s @910 kg/m3
- Temperature up to 700°C for Inconel and 510°C for stainless steel test sections
- Sigma pump (piston driven pump) and recuperator



Schematic of the loop

Heat transfer loop for high pressure, high temperature testing

Circulating pump and recuperator in the loop

Recuperator

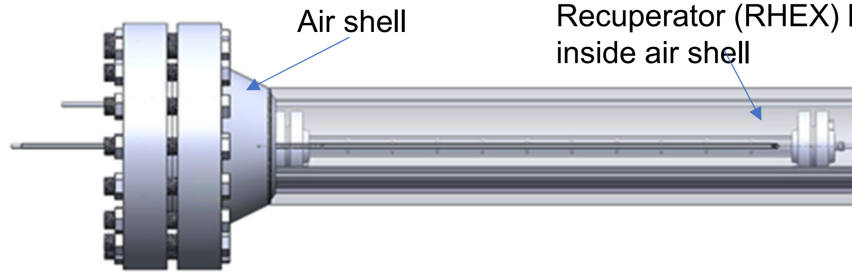
Hot outlet

Hot inlet

Cold inlet

Cold outlet

Line for High pressure N2 fill/exhaust to/from “Air Shell”



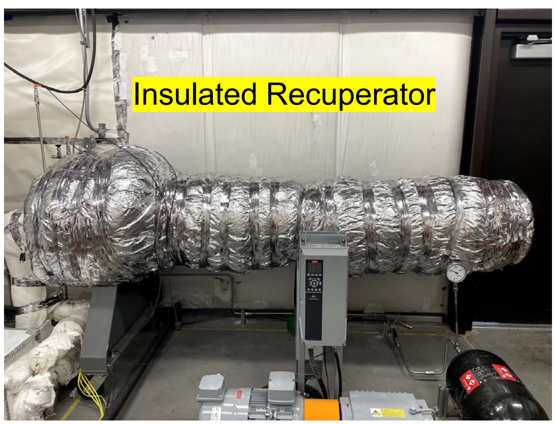
Air shell

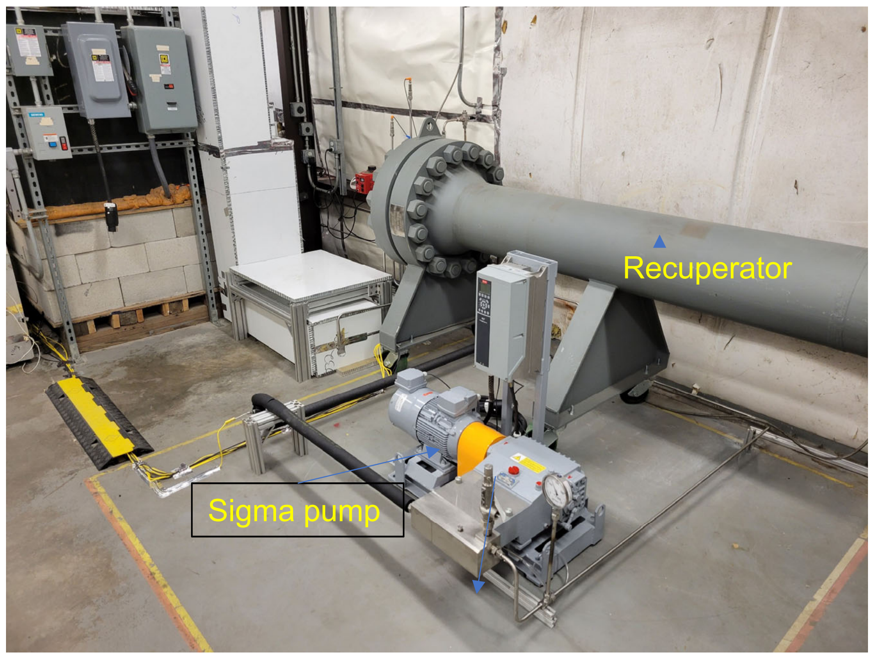
Recuperator (RHEX) located inside air shell

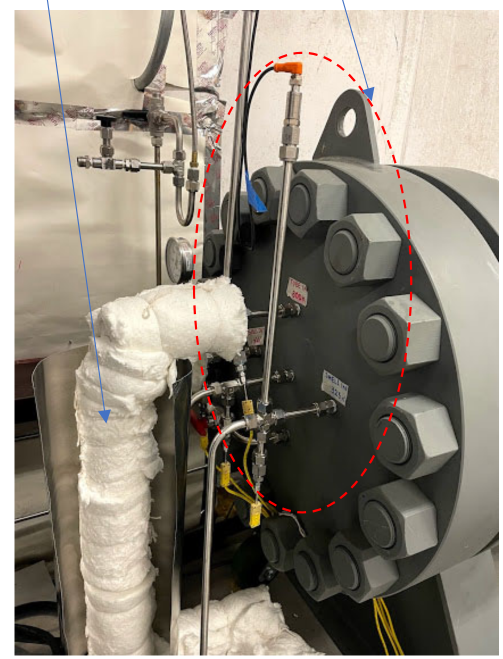
Duct containing insulation for high temp lines

Thermal insulation for high temp lines

Sensors to monitor recuperator performance







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Line for High

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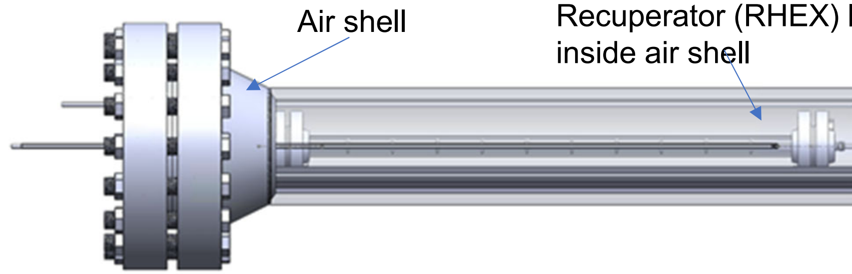
Recuperator (RHEX) located inside air shell



Duct containing

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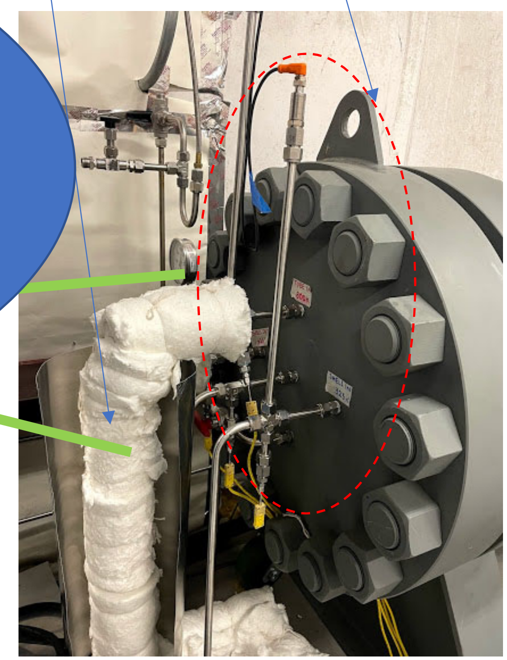
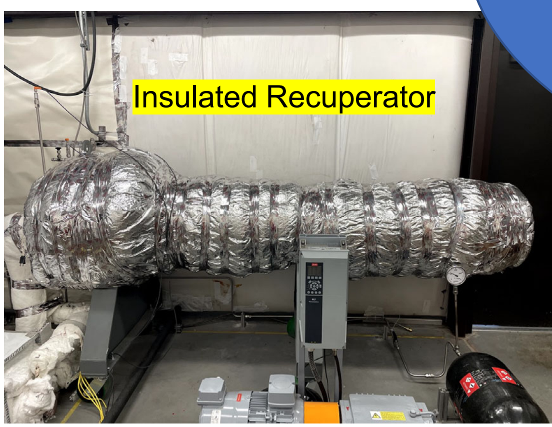
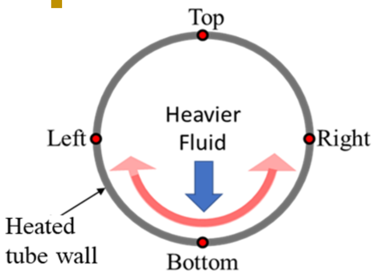


This recuperator will be replaced for testing of ARPA-E TINA Recuperator.

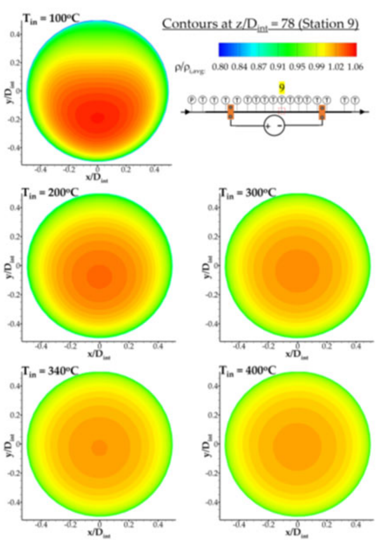


Sigma pump

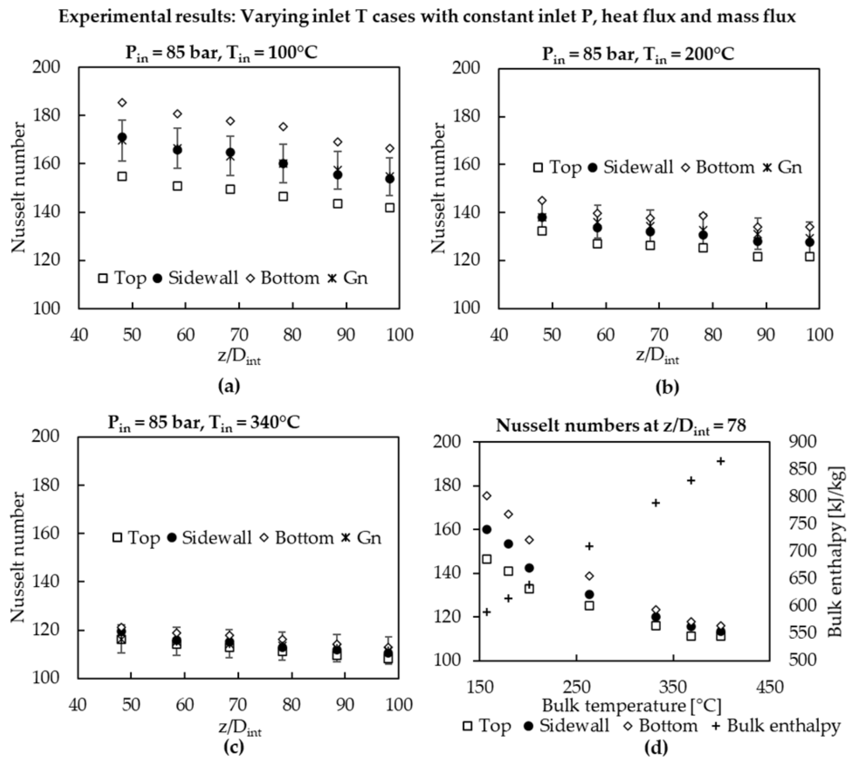
Impact of Inlet Temperature on buoyancy

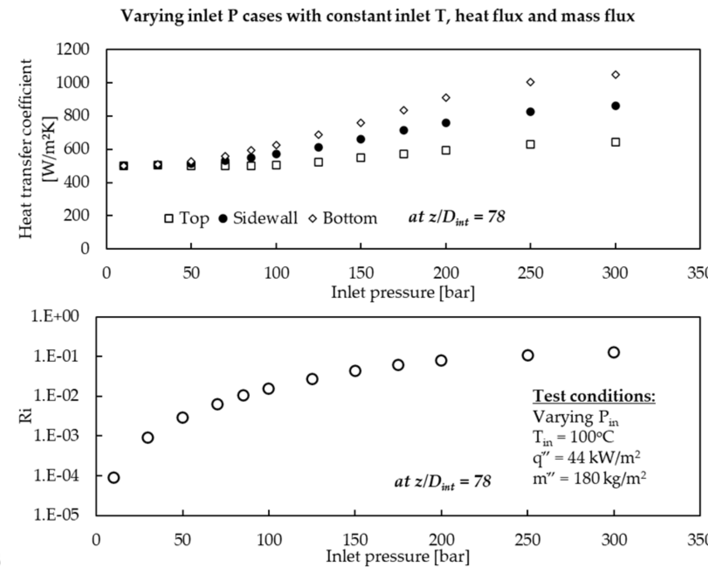


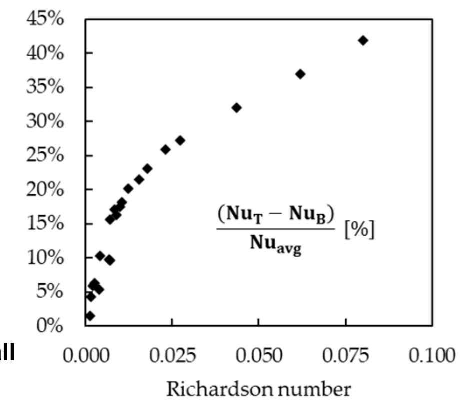
Schematic showing formation of natural convection currents in a cross section of a heated circular tube



Density contours at varying T_{in}



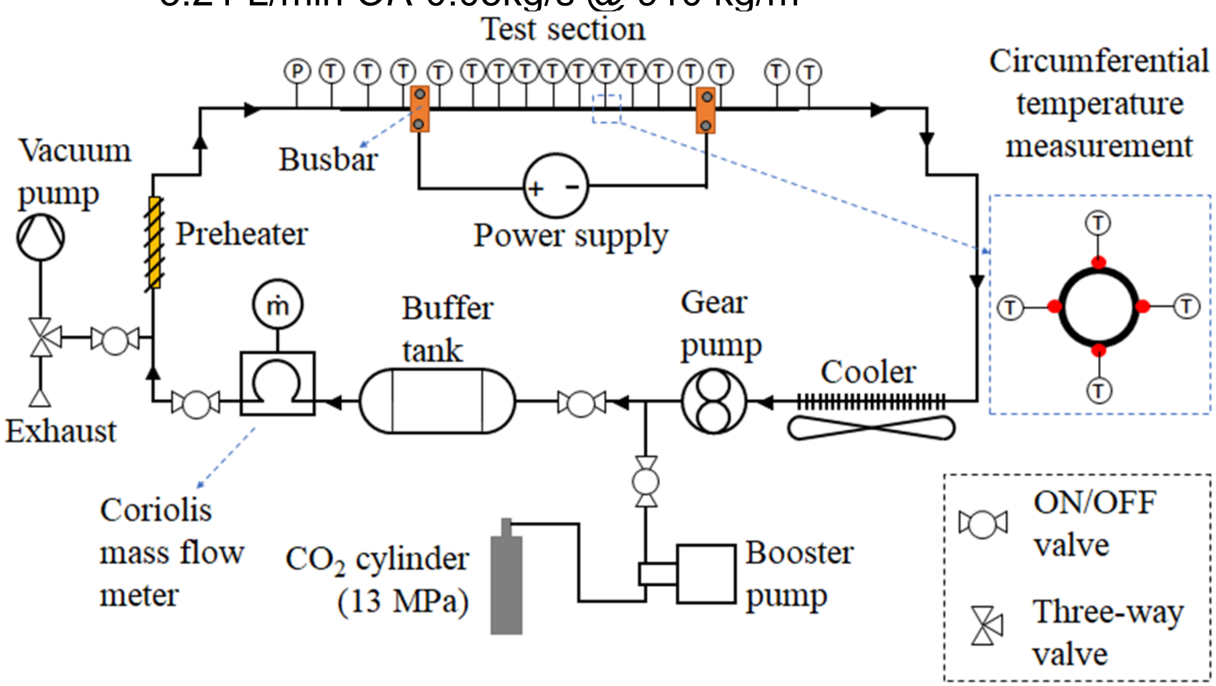




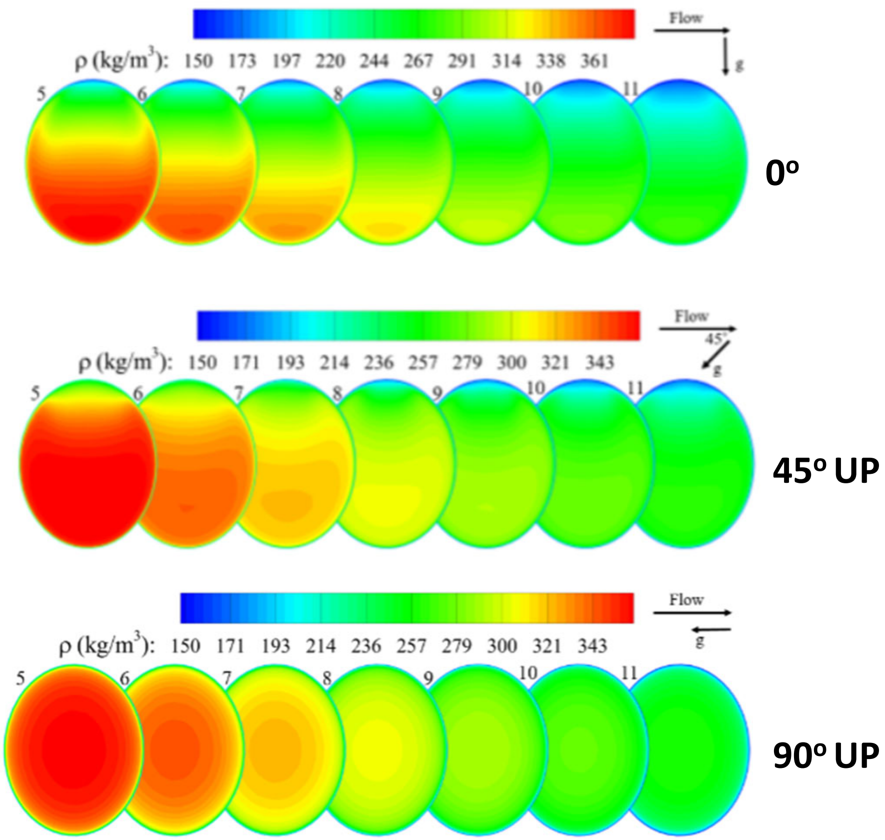
Nu_T = Nusselt number at top wall
Nu_B = Nusselt number at bottom wall
Nu_{avg} = Average Nusselt number

Inclined, Near-Critical Test Rig

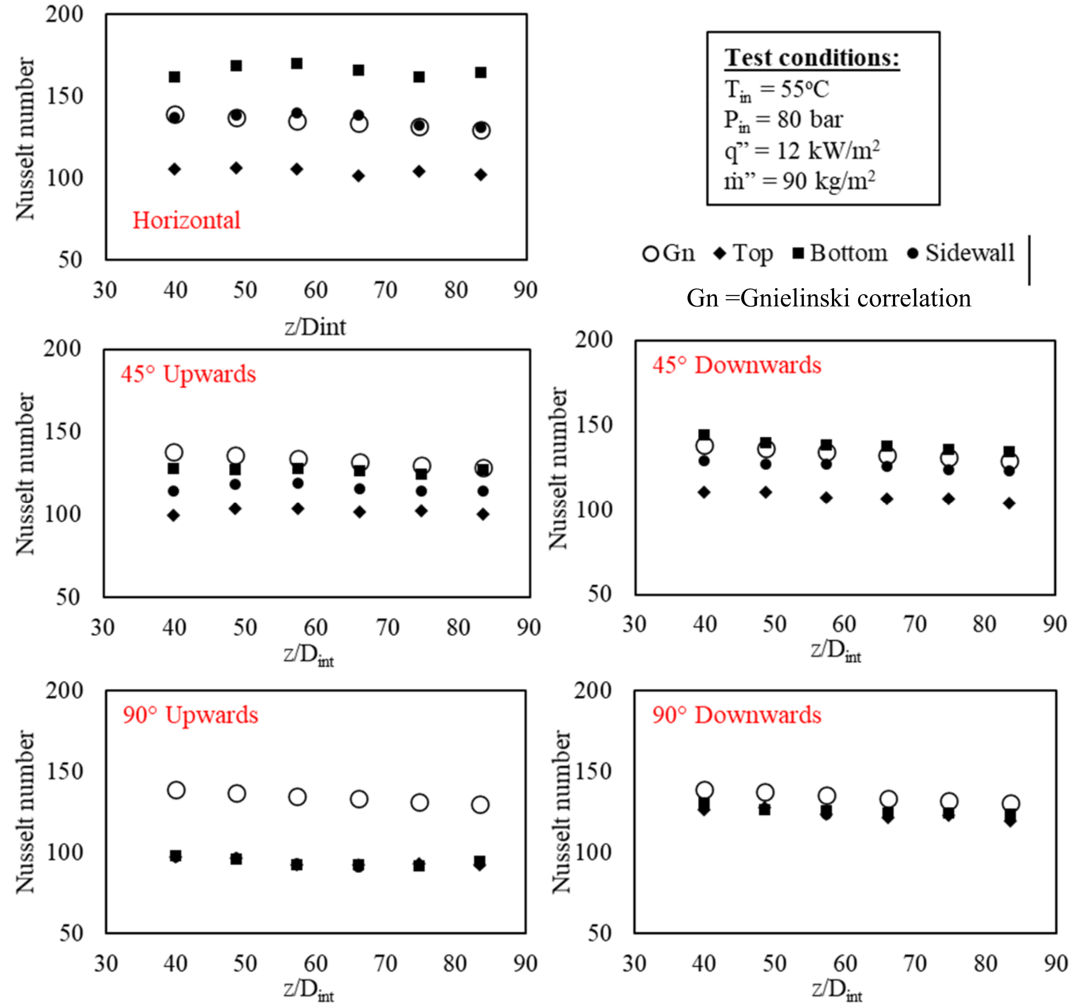
- Capability to test heat transfer in inclined tubes 0-90°
- Pressure up to 100 bar and Inlet temperature range 20-200°C
- Constant heat flux addition to test section via Joule heating
- Micropump pump (gear pump) as recirculating pump
- Flow rate range
  - 3.21 L/min *OR* 0.05kg/s @ 910 kg/m^3



Impact of inclination on sCO_2 heat transfer



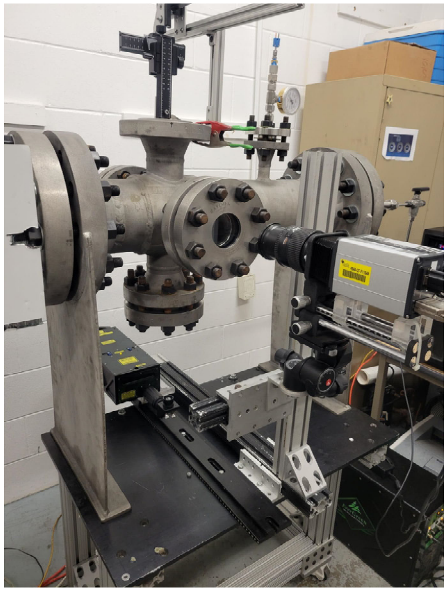
CFD density contours for upward flow 0° to 90°

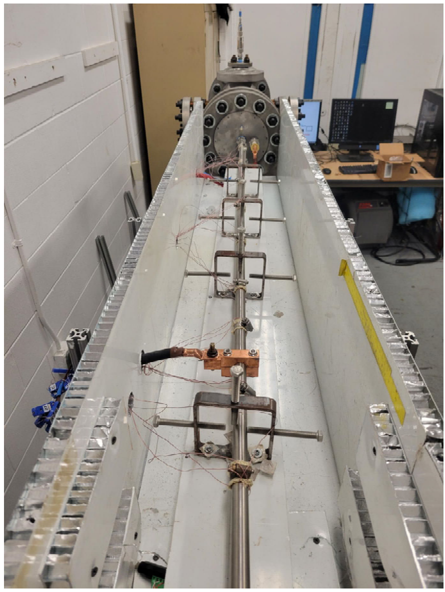


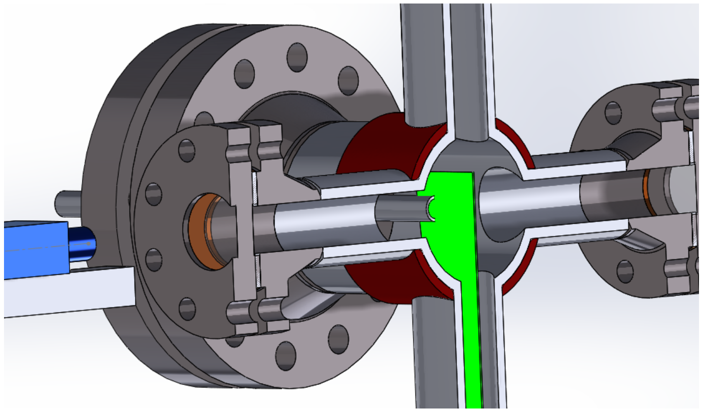
Experimental Nusselt number distribution

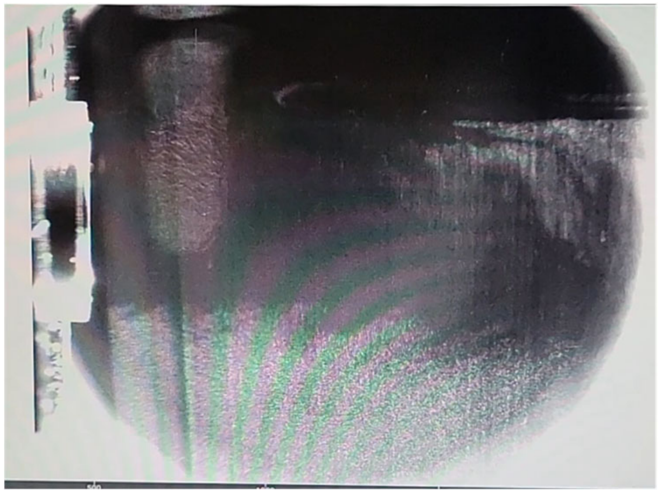
sCO_2 Optical Diagnostic Testing

- 316 Stainless steel vessel
- Modular Internal setup for testing multiple geometries of interest
- High Pressure gland fittings for internal instrumentation
- Four, 3in fused silica optical windows
- Maximum pressure: 100 bar
- Maximum temperature: 90°C
- Diagnostics; Particle Image Velocimetry(PIV), Background Oriented Schlieren (BOS), Schlieren, Thermographic PIV, Laser Doppler Velocimetry (LDV), IR Thermography (with IR transmissive window)









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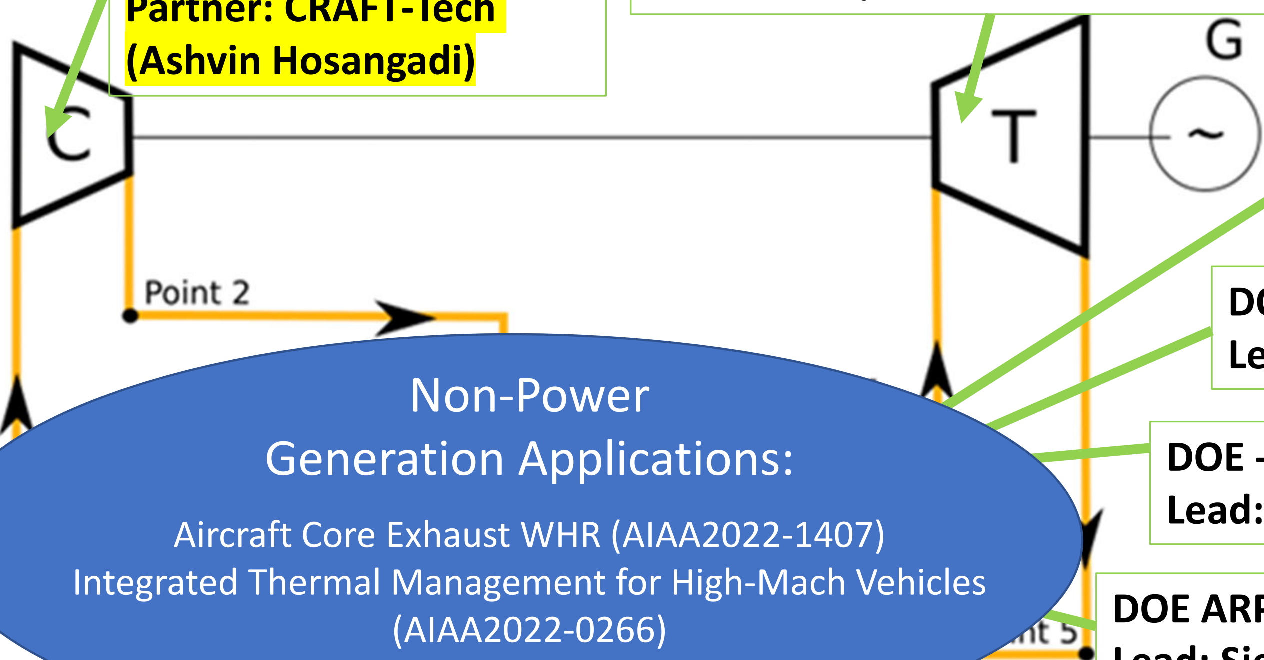

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Lead: Logan Rapp (early version: 181)

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Non-Power
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Integrated Thermal Management for High-Mach Vehicles (AIAA2022-0266)
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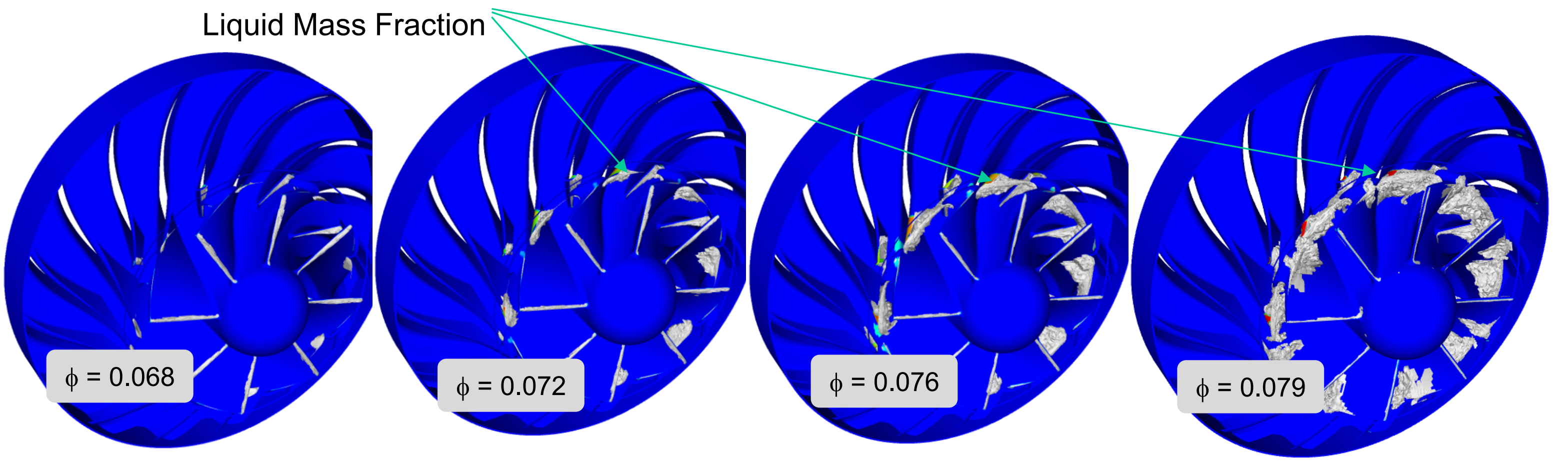
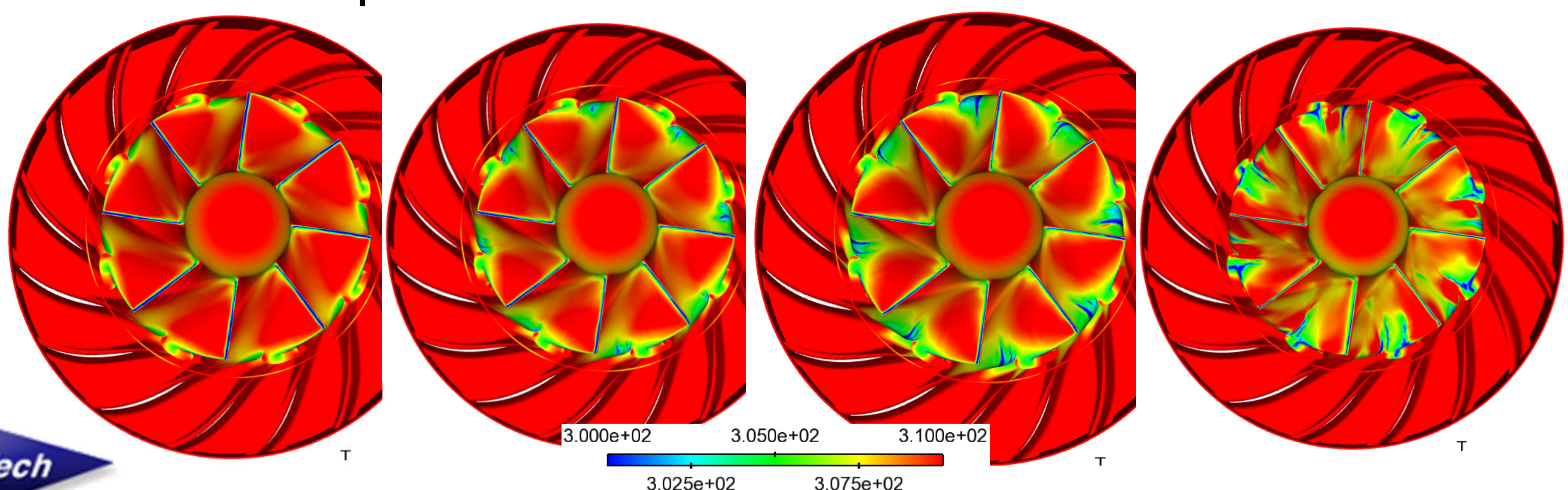
Subcritical Effects at Shroud Inlet At High Flow Rates



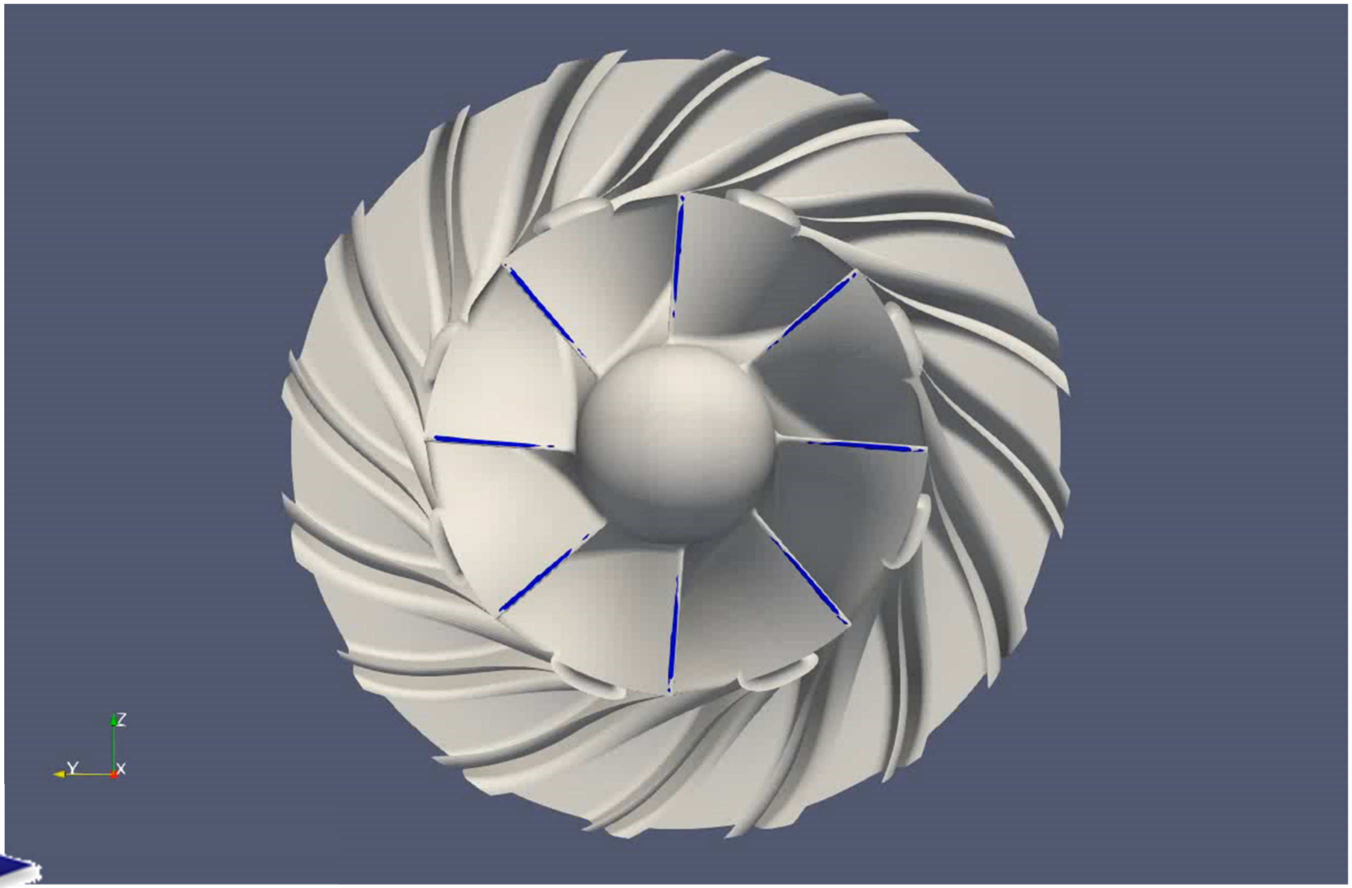
Subcritical Temperature



CRAFT Tech

Combustion Research and Flow Technology, Inc.

High Flow: Pressure Fluctuation Couples with Phase Change to Generate Surge



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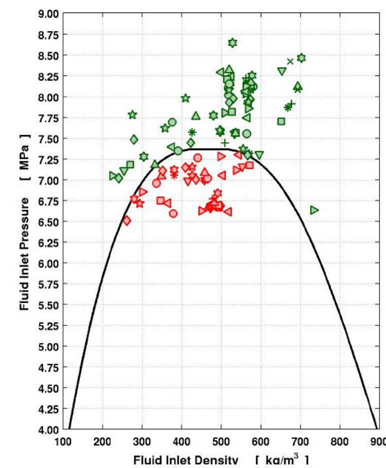
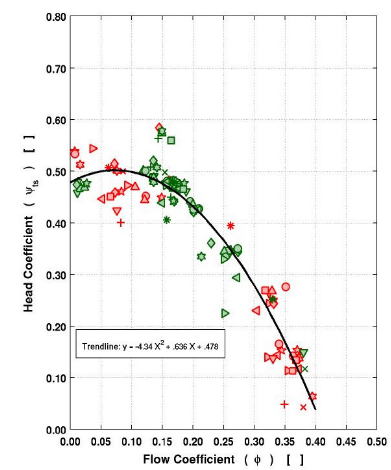
Comparisons with Sandia: Thoughts and Future Direction

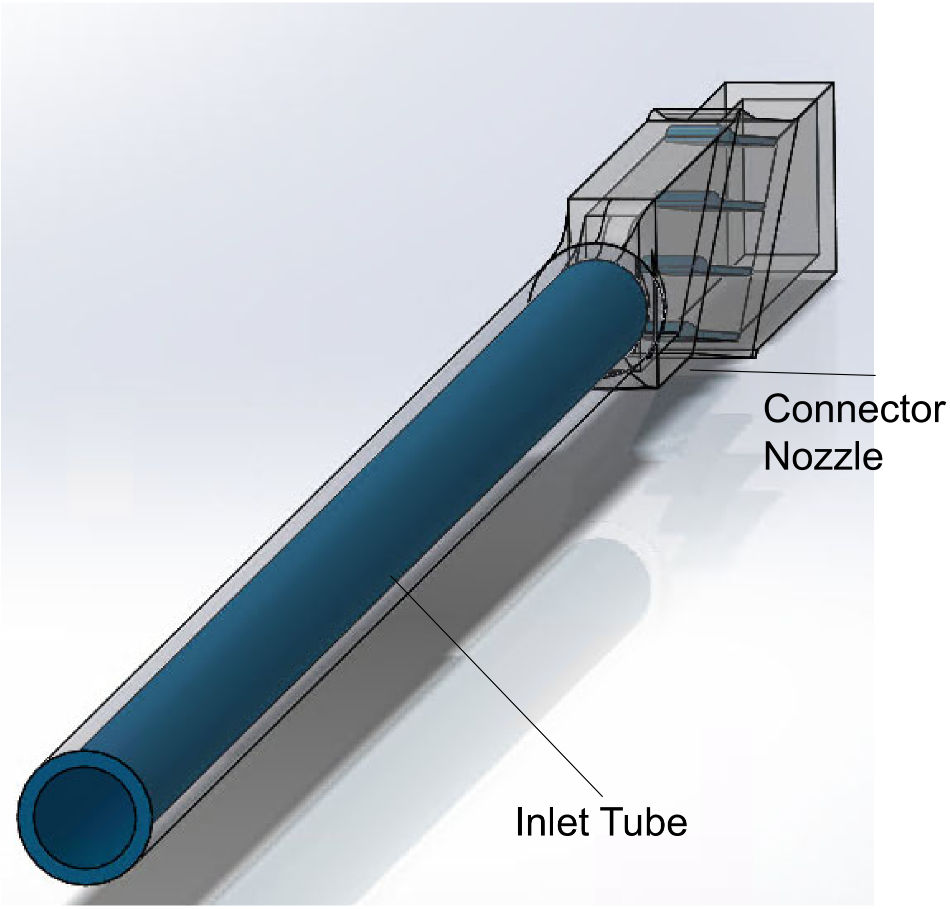
- The Sandia compressor was tested over a broad range of thermodynamic conditions including at the critical point as well as subcritical two-phase inlets
- As per results and discussion in Noall and Pasch, the compressor was stable with minimal vibrations, the head coefficient scaled for all conditions.
- While the efficiency values for Sandia compressor may not be reliable the efficiency curves do NOT show a sharp drop-off at high flow rates unlike the Apollo (Hanwha/GE STEP) compressors
  - Tip Speed for Sandia Compressor at 55 K RPM is 110 m/s and Tip Speed for Hanwha Compressor at 27 K RPM is 167 m/s
- It would be worthwhile in a future effort to investigate what the design differences are and if there are lessons to be learned that can further improve the performance of full scale compressors resulting in improved overall system performance

Sandia Test results (Noall and Pasch)

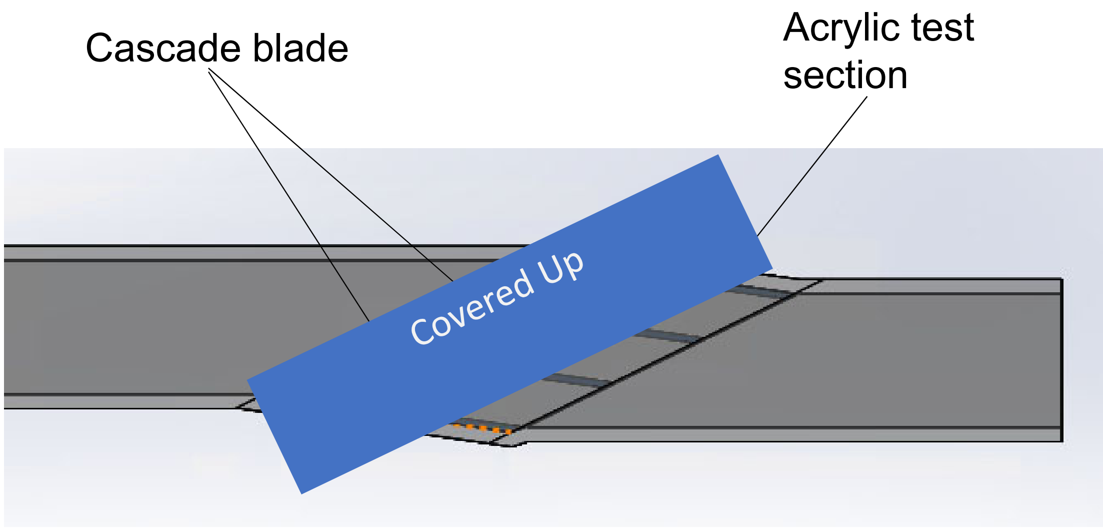




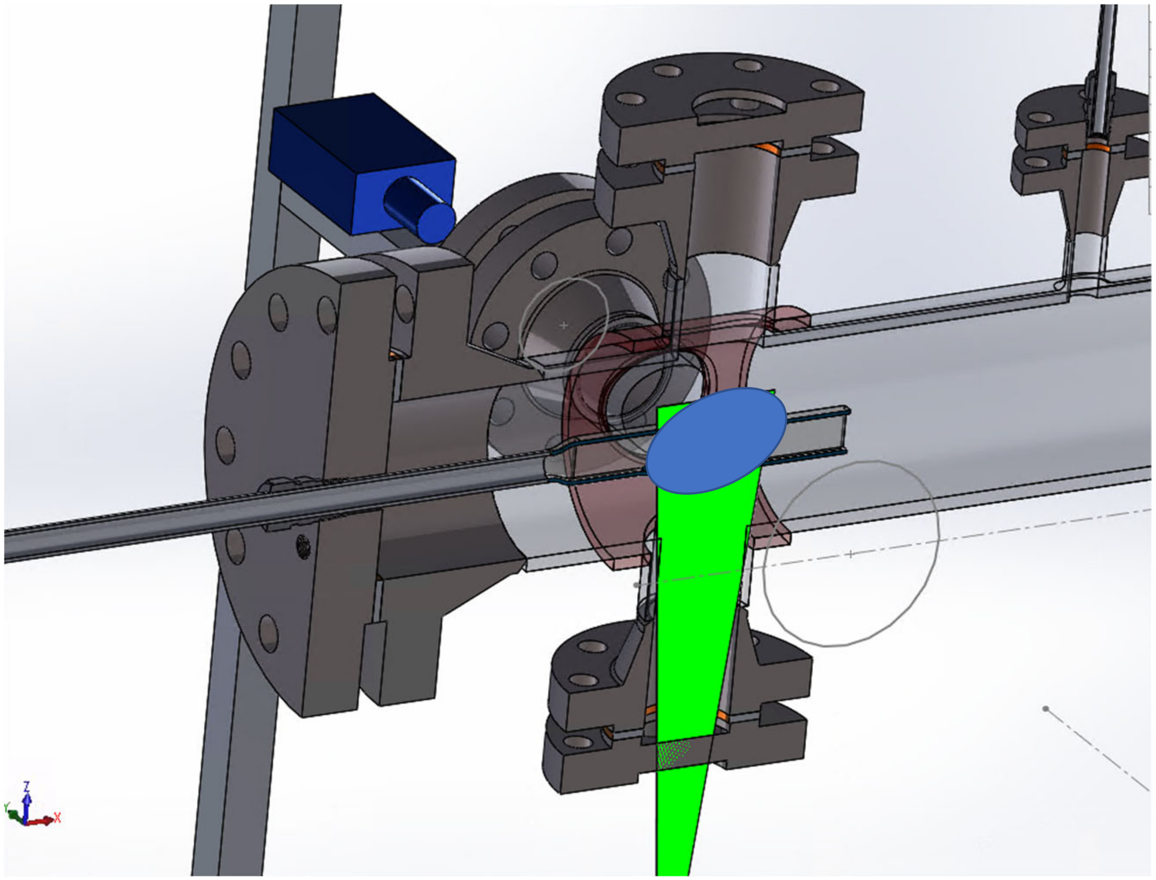
sCO_2 Cascade blade Design

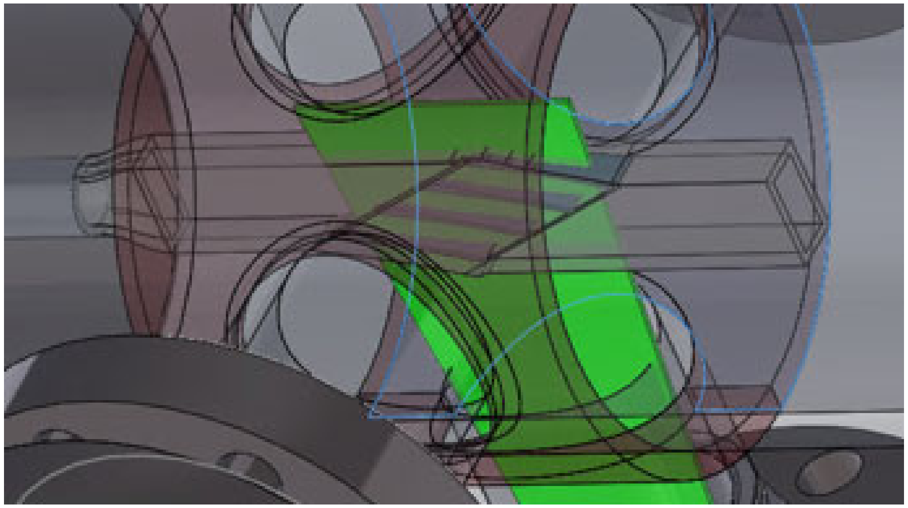


- Inlet Tube with OD of 0.76 inch
  - Seamless stainless steel 316
- Test Section
  - fabricated from acrylic with thickness of 1/8 inch
  - 2 fully immersed cascade blades
  - 2 blades forming the walls
  - Adjustable exit tailboards



sCO_2 PIV Rig with Linear Compressor Cascade





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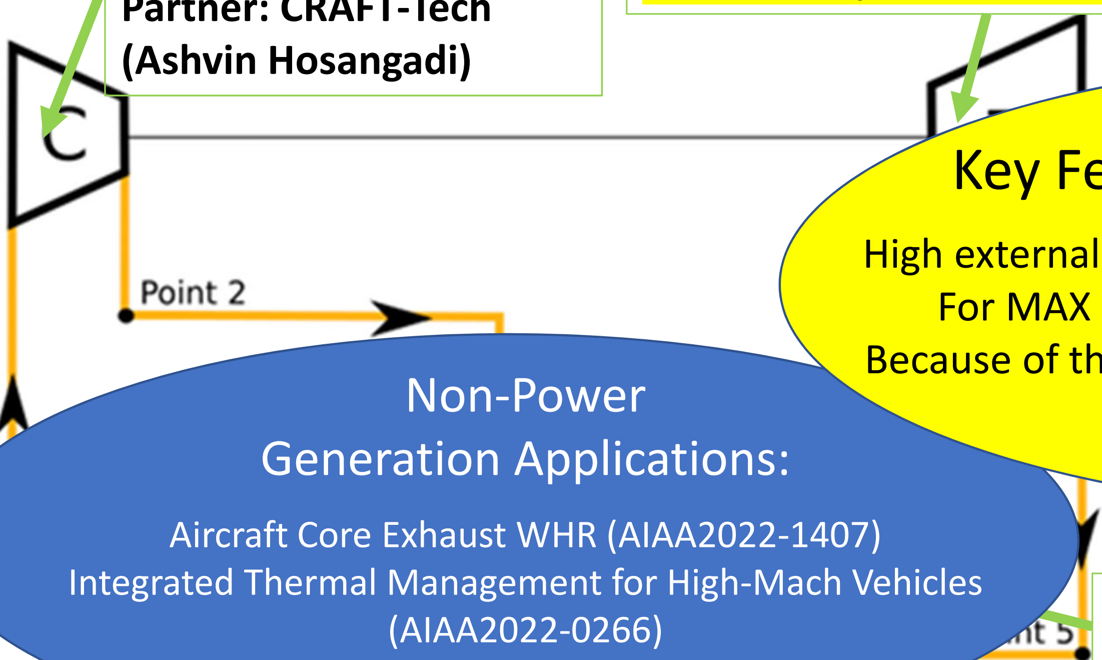

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Key Features in Cooling sCO2 Turbine:

High external Re, leading high external heat transfer coeff (htc)
For MAX metal temp control, ***high internal htc needed***
Because of the cycle, higher potential for cooling requiring low heat load parameter (HLP)

/sCO2 PHX
Lead: ... with Penn St as fab partner

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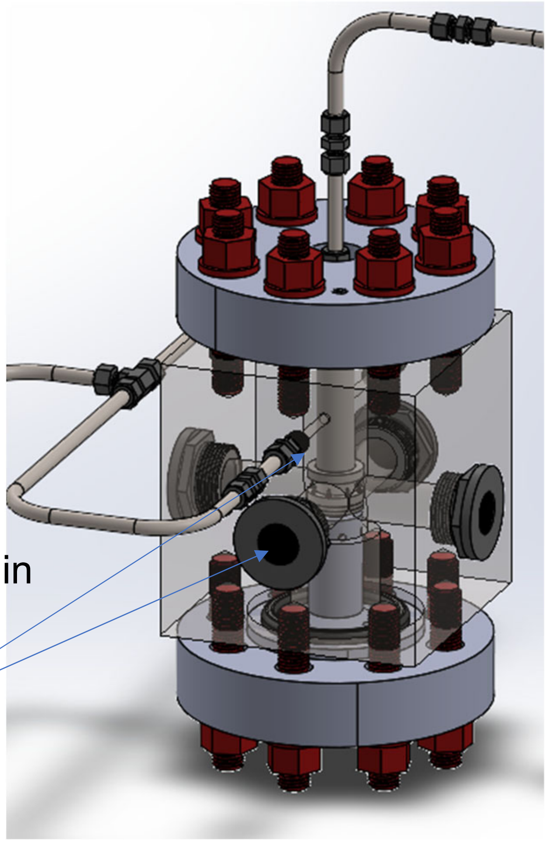
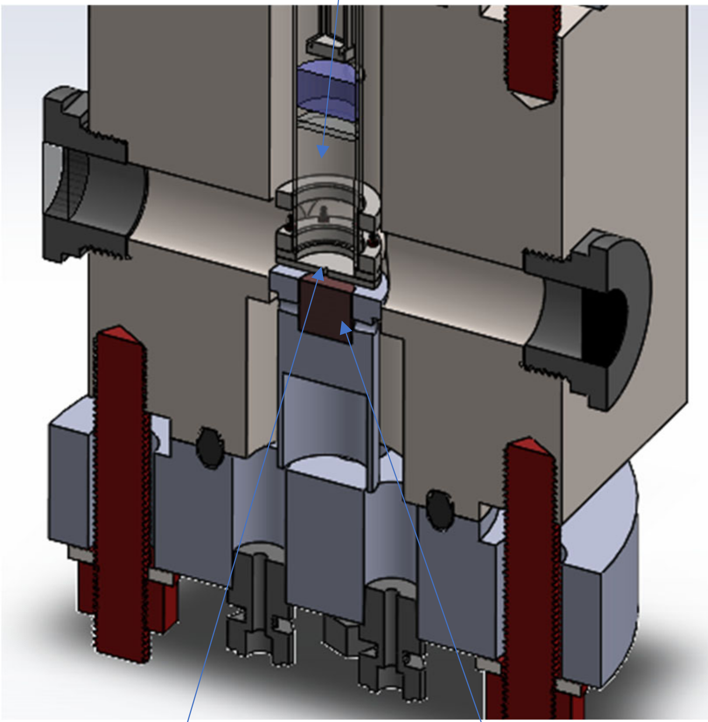
sCO_2 Impingement heat transfer

- 316 Stainless steel forging with flanges act as pressure vessel
- Maximum operating pressure 200 bar
- Maximum operating temperature 450°C
- Maximum Mass Flow Rate: 0.2 kg/s
- Instrumentation for heat transfer coefficient estimation
- High pressure gland fittings for power transmission and instrumentation
- Variable orifice diameter (> 1mm)
- Variable jet to target spacing
- Copper Impingement target diameter 1.5 in
- Capability for optical diagnostics





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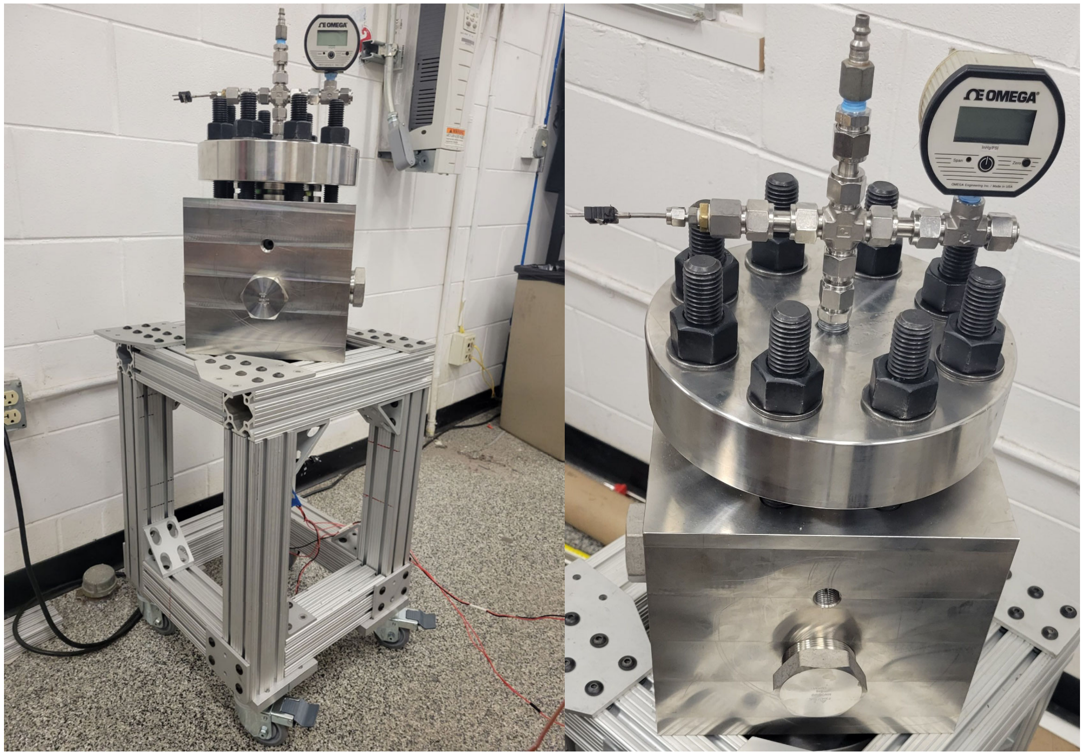
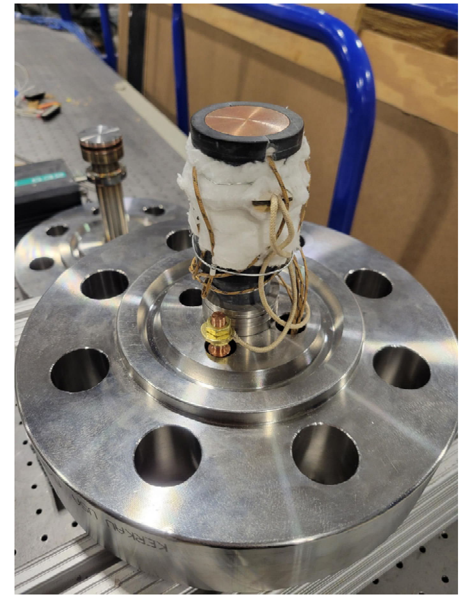
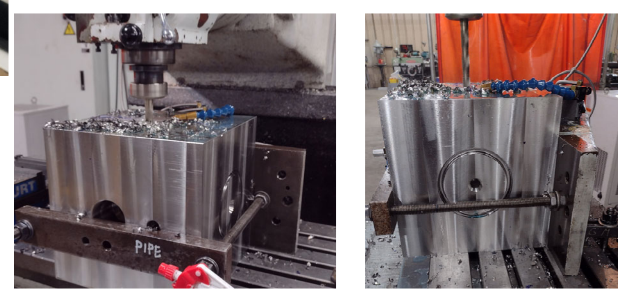


Impingement heat transfer rig (Air validation configuration)

Jet plenum and orifice assembly



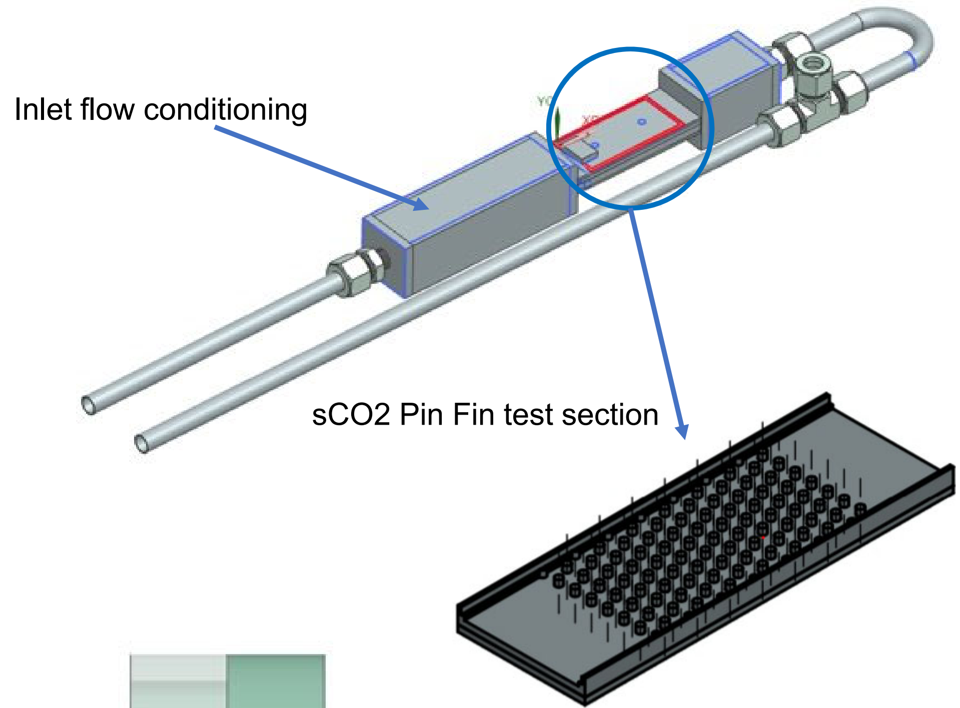
Heat transfer feature assembly with heater and instrumentation



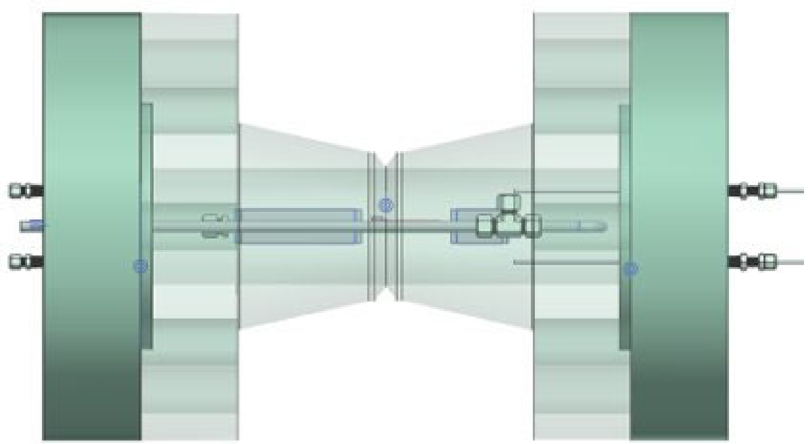
Vessel manufacturing

sCO_2 Pin Fin heat transfer

- Pin Fin test section, housed within steel pressure vessel
- Maximum operating pressure 200 bar
- Maximum operating temperature 450^{o}C
- Maximum Mass Flow Rate: 0.2 kg/s
- Instrumentation for pin fin array averaged heat transfer coefficient estimation
- High pressure gland fittings for power transmission and instrumentation
- 14 pin rows in test section. Geometry based on Ames pin fin study



sCO2 Pin Fin Rig – Test Section Internal

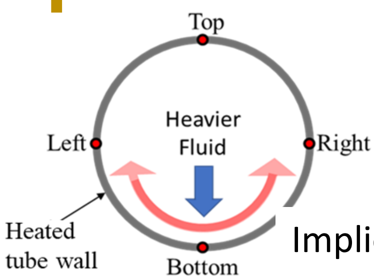


Test section pressure vessel

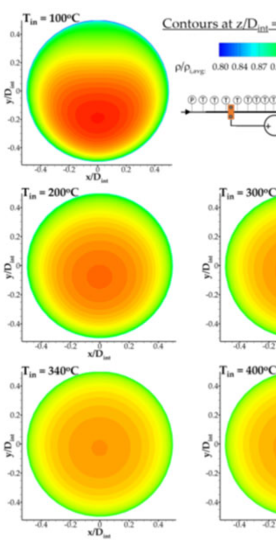
THANK YOU

Back up slide

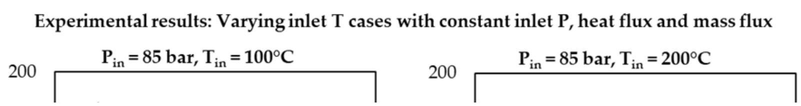
Impact of Inlet Temperature on buoyancy



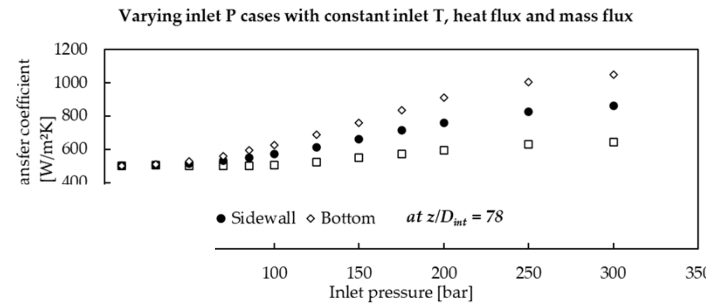
Schematic showing formati
convection currents in a crc
a heated circular t

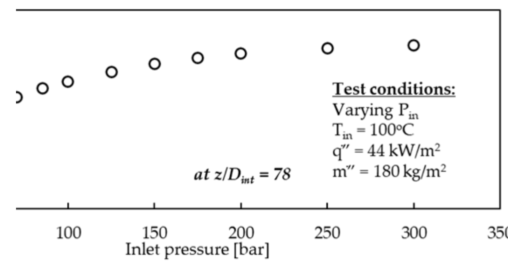


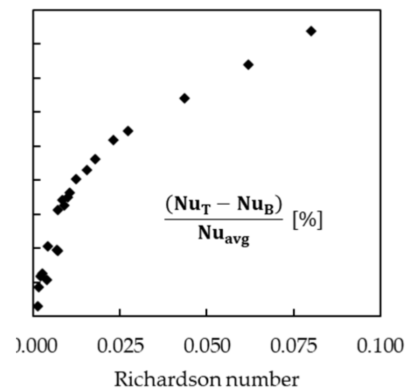
Density contours at var



Implications to Cooling and compressor

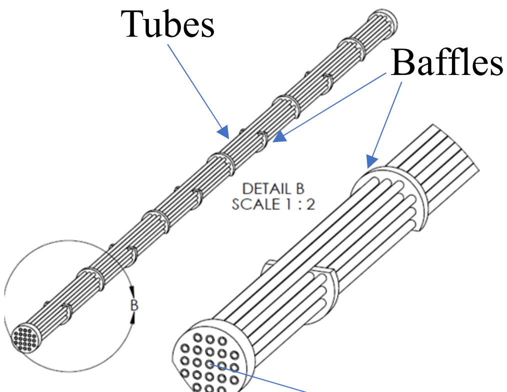


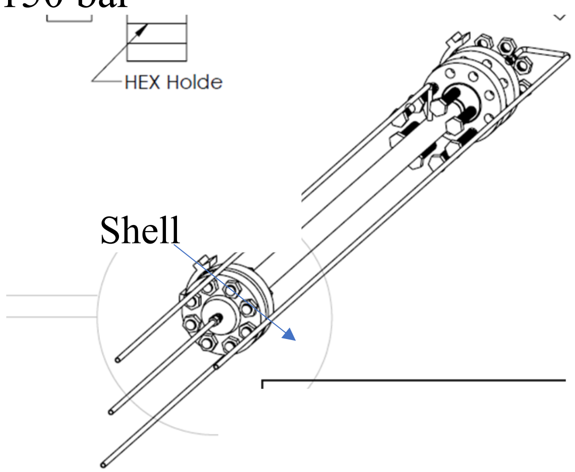


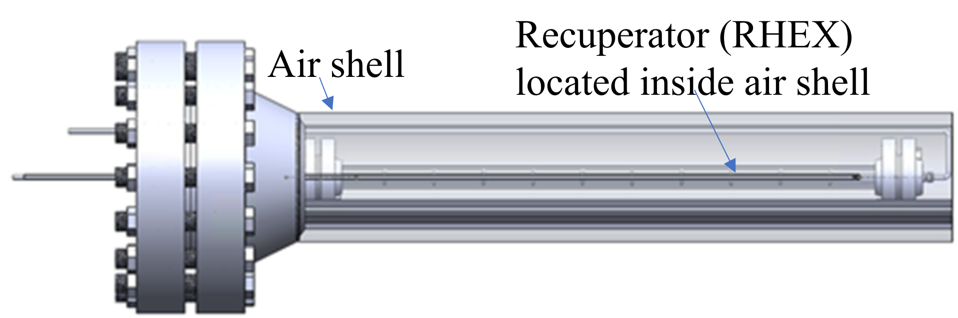


Recuperator

- Recuperator is used to reduce heating and cooling requirements of the loop
- Shell and Tube design with tubes carrying hot CO_2
- 1D design validated using conjugate heat transfer CFD simulations before fabrication
- Design Effectiveness = 70%
- Tested Effectiveness = 63%
- HEX Shell pressure rating 150 bar
- Located inside air shell (as ing 150 bar



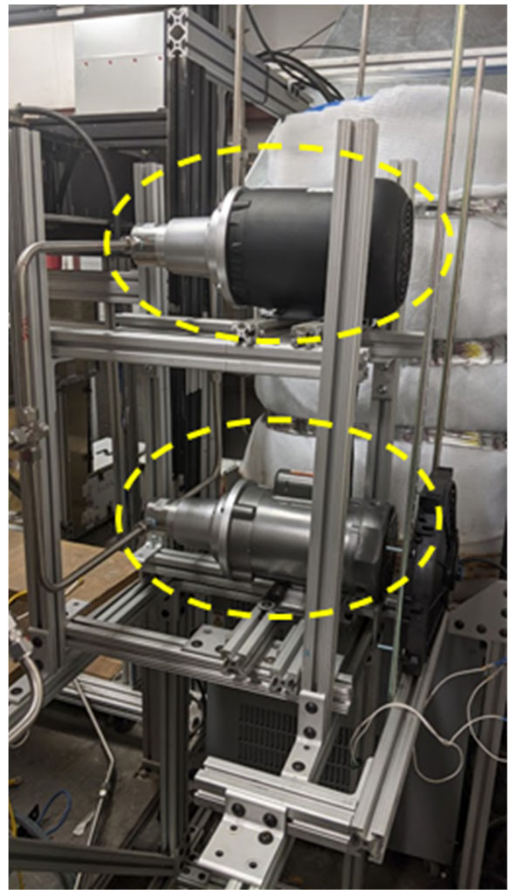




Pumps in the loops

<u>Sigma pump plunger pump</u>

- Max inlet temperature = 37^{o}C
- Pressure on suction inlet of the pump
    - Min 80 bar, Max 260 bar
- Pressure on discharge outlet of the pump
    - Min 120 bar, Max 300 bar
- Max differential pressure = 40 bar
- Mass flow rate range
    - 0.66-16.5 L/min *OR* 0.01-0.25kg/s @910 kg/m^3



<u>Micropump gear pump</u>

- Max inlet temperature = 150^{o}C
- Maximum system pressure = 103 bar
- Max differential pressure = 8.7 bar
- Mass flow rate range
    - 3.21 L/min *OR* 0.05kg/s @910 kg/m^3

Coolers in the loop

- ***Each heat exchanger is custom-designed and in-house fabricated***
- Air cooler to cool CO2 from higher temperatures to 50-80^{o}C
- Water cooler to cool CO2 to 25-30^{o}C (required at inlet of recirculating pump)

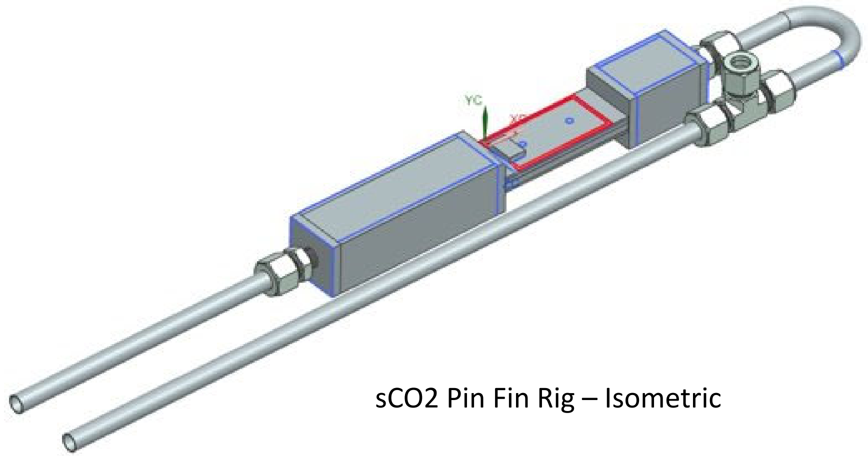
Air cooler

- Finned tube bank over the fan (left bottom)
- Canopy+duct for fan exhaust out of the room
- Dielectric union is connected between air cooler and water cooler
- Flow TC between air and water cooler to monitor temperature going into water cooler below ~90^{o}C

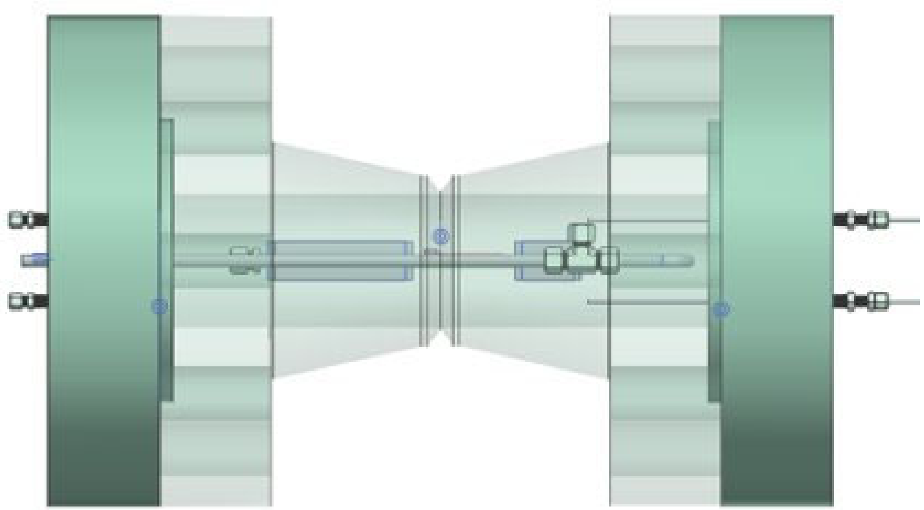
Water cooler

- Tube bank for CO2
- Insulated water drum with distilled water (right bottom)
- 2 re-circulating pumps inside for increased convection
  - Bottom to top and Tangential to inner

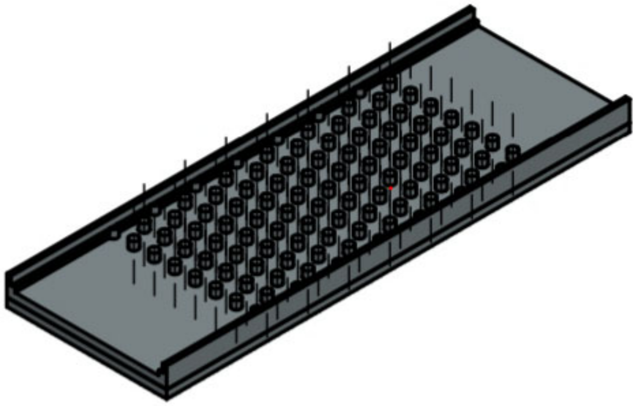
Pin Fin Rig – Part Allocation



sCO2 Pin Fin Rig – Isometric



Rig Design for Experimental Processes



sCO2 Pin Fin Rig – Test Section Internal