Experimental Demonstration of an Advanced CO_2 Axial Compressor for CO_2-based Power Cycles and Energy Storage Systems

The 8th Supercritical CO_2 Power Cycles Symposium

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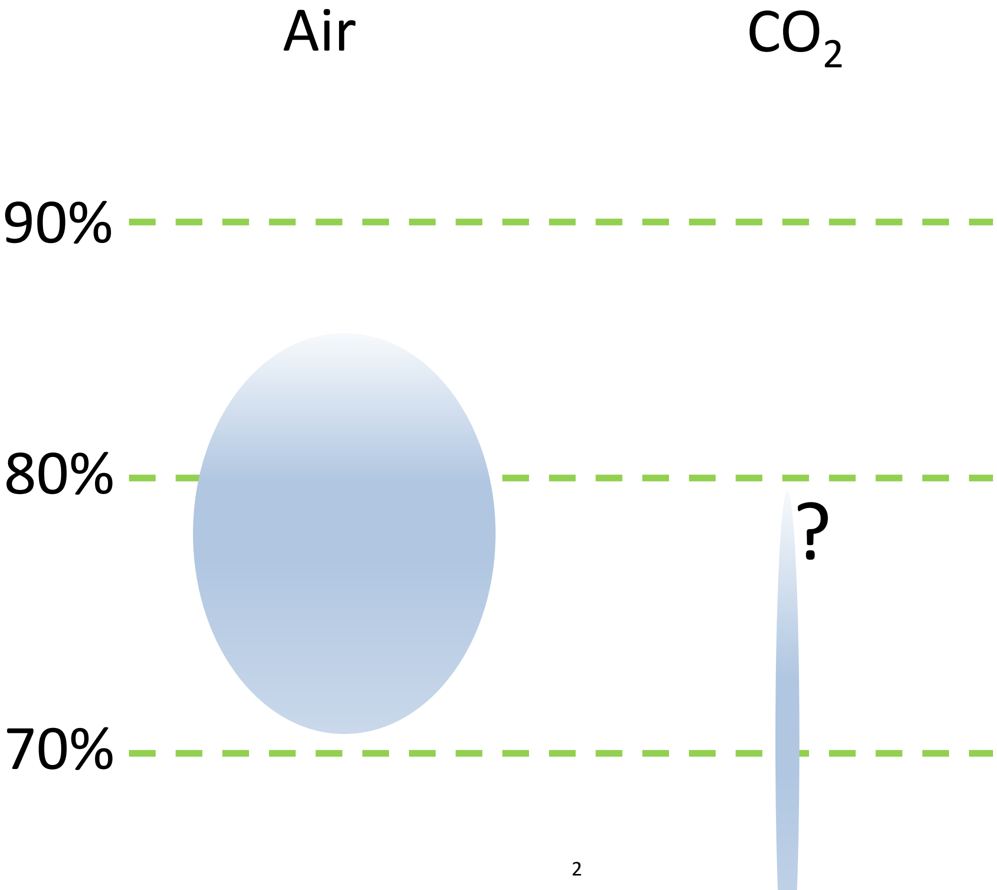
BACKGROUND & RESEARCH QUESTION

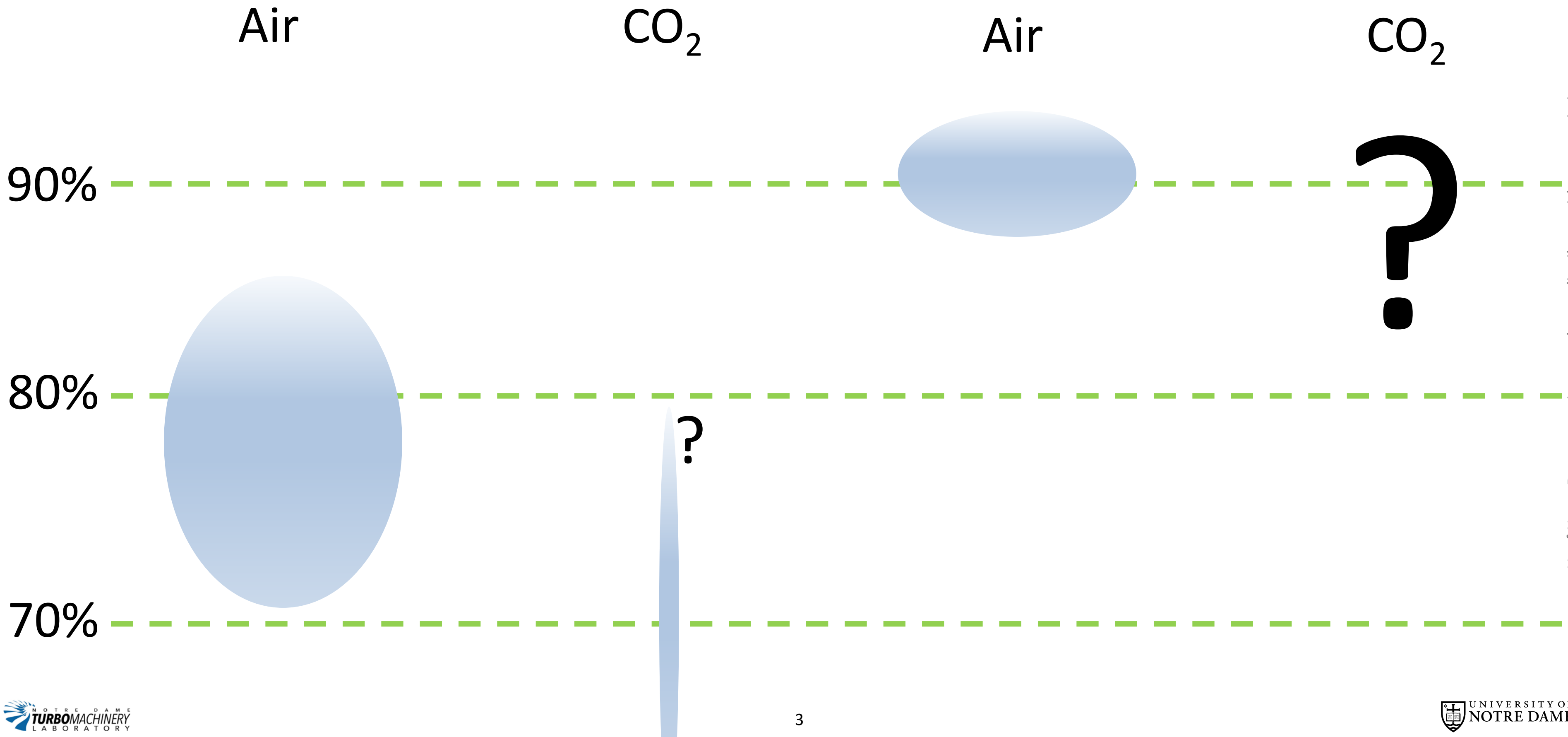
Centrifugal Compressor



BACKGROUND & RESEARCH QUESTION

Centrifugal Compressor

Axial Compressor



RESEARCH QUESTION

❑ Question 1

Does the axial CO_2 compressor have high efficiency/performance potential?

❑ Question 2

Can we evaluate the performance of axial CO_2 compressor(s) experimentally with high fidelity?

TEAM & Co-authors

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Axial Compressor

		IGV	Rotor 1	Stator 1
Number of airfoils	-	43	69	114
Radius of Blade Leading Edge Tip	mm	131	129	128
Radius of Hub	mm	102	102	102
Leading Edge Blade angle at mid-span	deg	0	-58.78	48.53
Trailing Edge Blade angle at mid-span	deg	10.7	-42.46	14.0

Rotational Speed	rpm	19,800
Inlet Total Pressure	kPa	2,770
Inlet Total Temperature	°C	98.0
Total to Total Pressure Ratio	-	1.41
Mass flowrate	kg/s	125

[Stage 1 rotor]

[1] Matthew Ha, Justin Holder, Saugat Ghimire, Adam Ringheisen, and Mark. G. Turner, 2022, “Detailed Design and Optimization of the First Stage of an Axial Supercritical CO2 Compressor,” ASME Turbo Expo 2022, GT2022-82590.

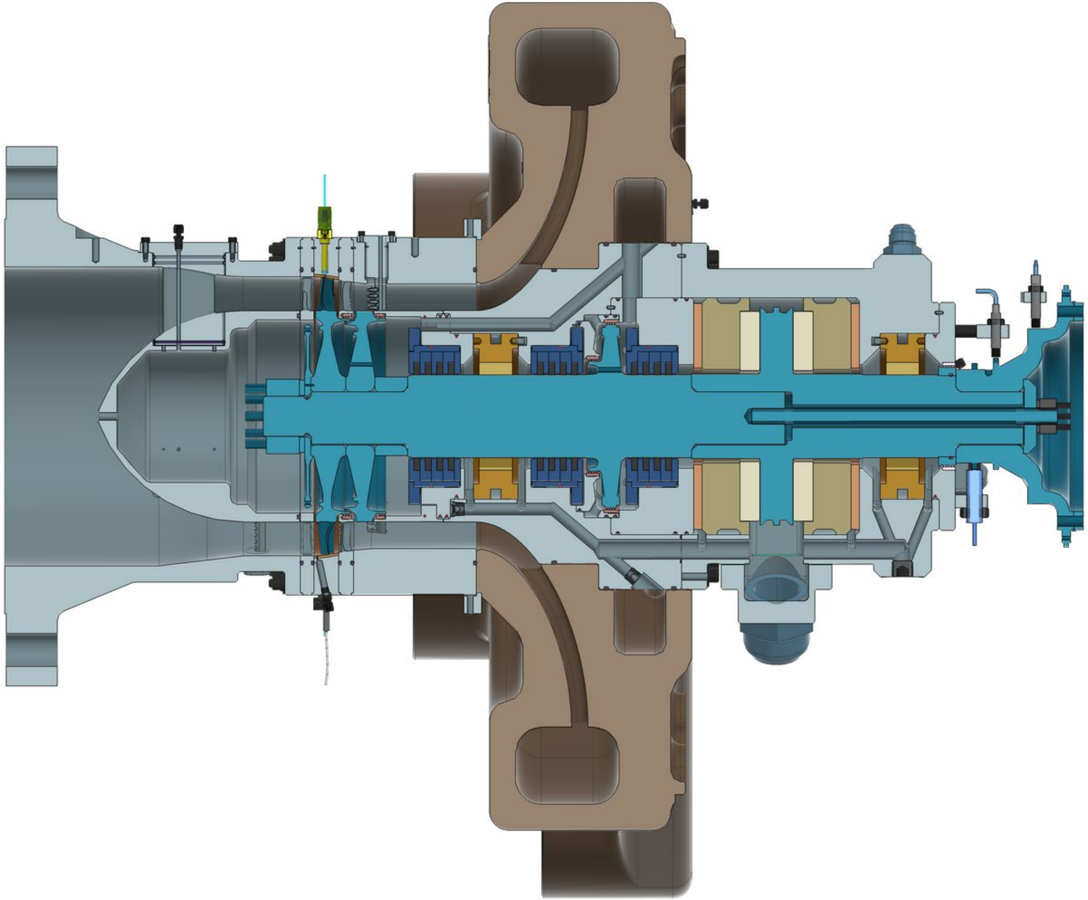
[2] Justin M. Holder, Adam Ringheisen, Matthew Ha, Saugat Ghimire and Mark. G. Turner, 2022, “Improved Automated Turbomachinery Hot-to-Cold Transformation with Cold-to-Hot Capabilities For Off-Design Analysis,” AIAA SciTech 2022 Forum, AIAA2022-2436.

IGV & Stator 1

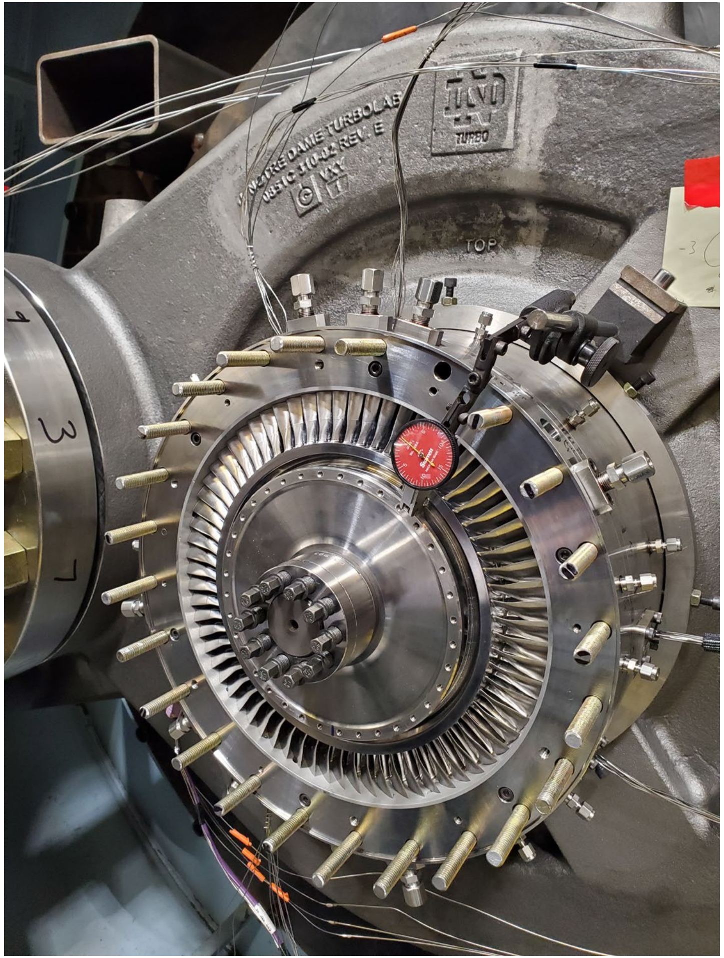
[IGV]

[Stator 1]

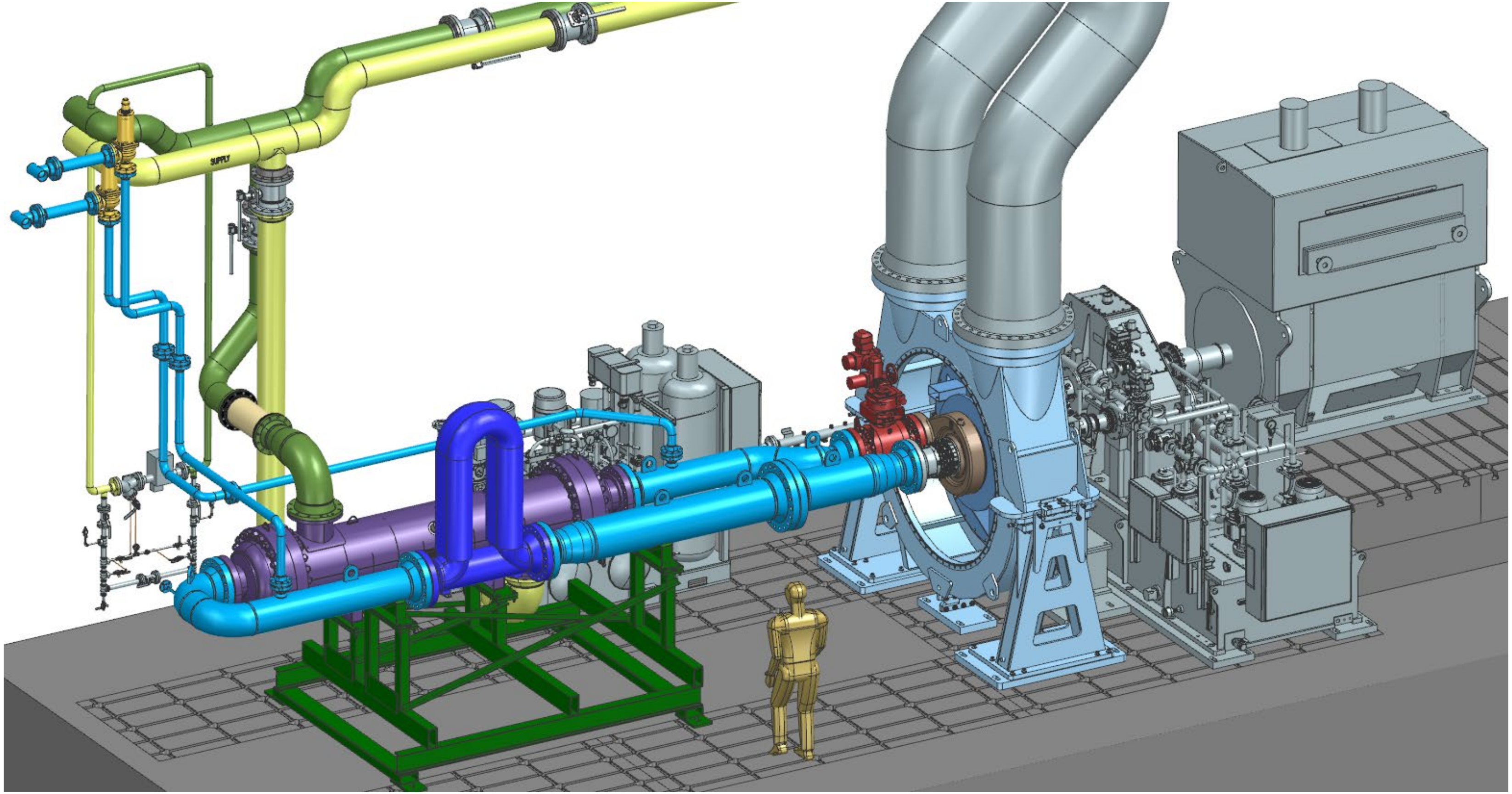
1.5 Stage Compressor Test Rig



Axial Compressor

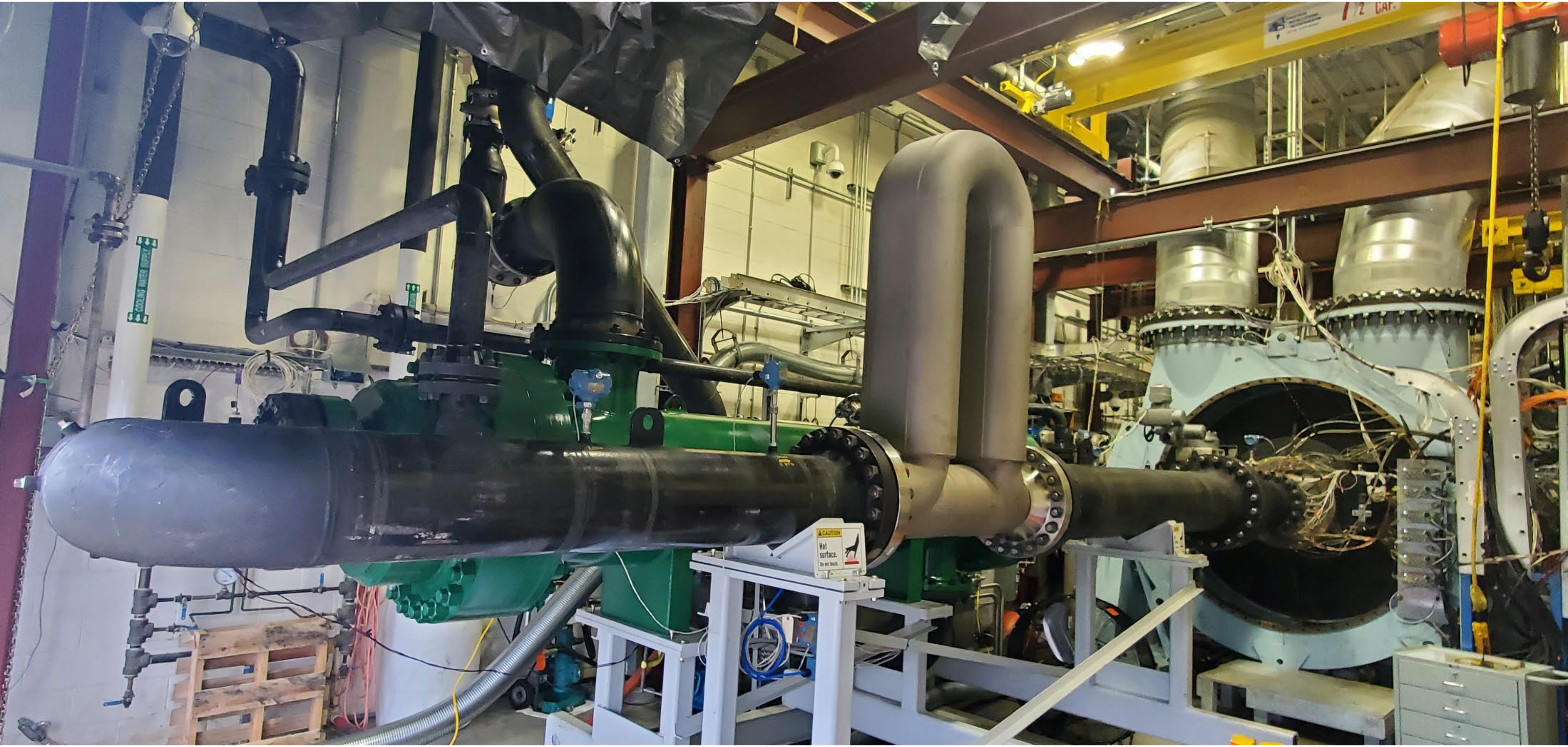


10MW sCO2 Compressor Test Facility @ NDTL



(Ref) Jeongseek Kang, Alex Vorobiev, Joshua D. Cameron, Scott C. Morris, Ryan Wackerly, Kyle P. Sedlacko, Jason D. Miller, and Timothy J. Held, 2021, “10MW-class sCO2 Compressor Test Facility at the University of Notre Dame,” The 4th European sCO2 Conference for Energy Systems, March 22-26, 2021-sCO2.eu-144.

10MW sCO2 Compressor Test Facility @ NDTL



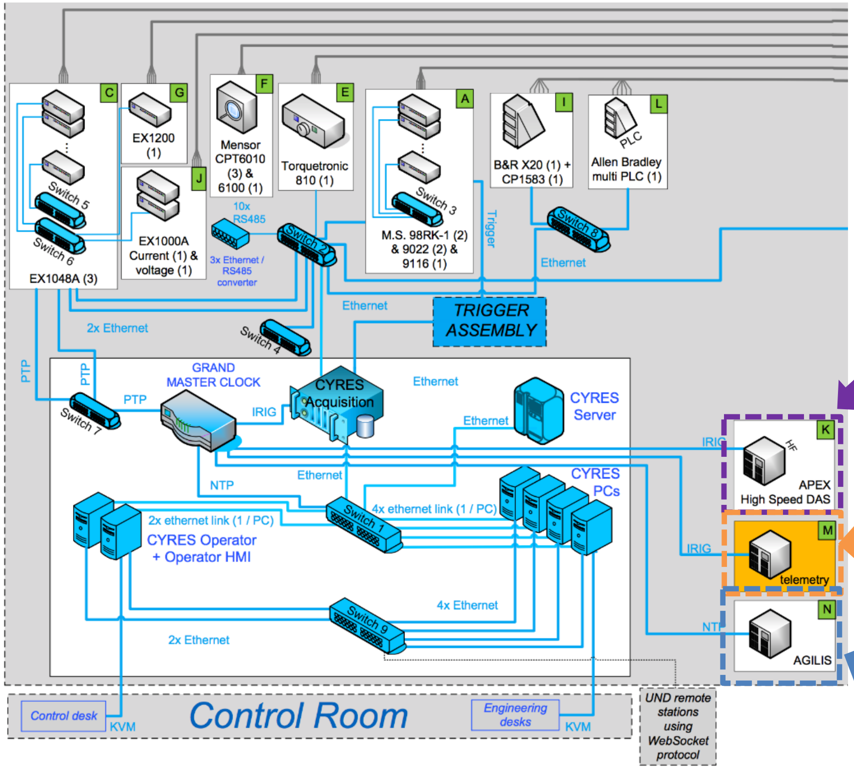
Facility : Cooling Towers & CO2 Inventory System

Cooling towers – 12MW

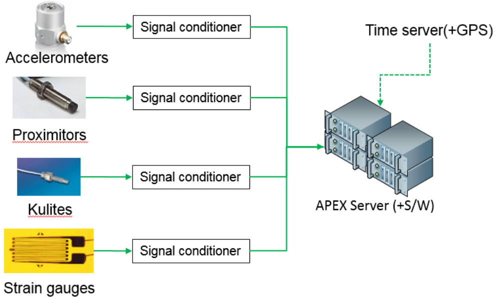
(CO_2 : 99.97% – 99.99%)

2 X 5 Ton (12,000LBS) CO2 tanks

Architecture of Instrumentation & Data Acquisition System

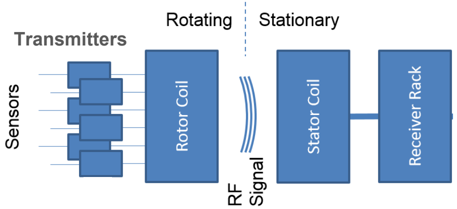


Dynamic Data Acquisition



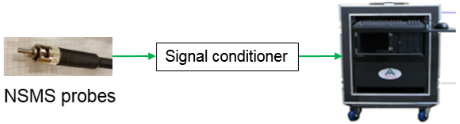
- 4 Dynamic DAQ systems
- 300 Channels
- Precision Filters
- Time stamped data

Telemetry



- 3 Telemetry systems
- Used with strain gages, Kulites, RTDs, TCs, etc.
- Fixed Sampling Frequency at ~100KHz

NSMS



- 2 NSMS systems
- 16 light probes and channels

Compressor Performance (Efficiency & Pressure Ratio)

$$\eta_{TT} = \frac{h_{T2S} - h_{T1}}{h_{T2} - h_{T1}}$$

$$PR(TT) = \frac{P_{\mathrm{T2}}}{P_{\mathrm{T1}}}$$

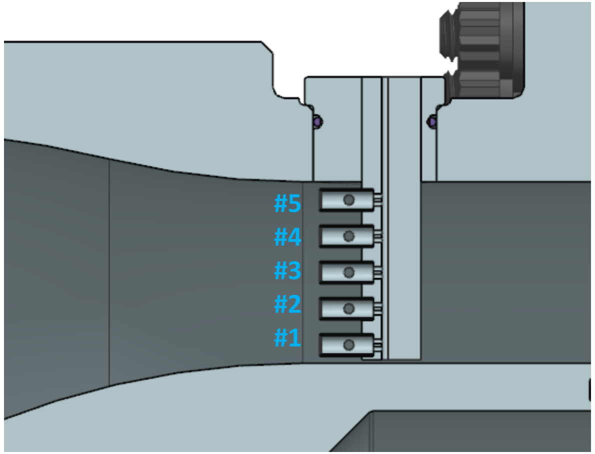
h_{T1} – mass specific total enthalpy, stage inlet
h_{T2} – mass specific total enthalpy, stage exit
h_{T2S} – mass specific total enthalpy for isentropic flow, stage exit

$$h_T = h(T_T, P_T)$$

$$h_{T2S} = h(s_{T1}, P_{T2})$$

$$s_{T1} = s(T_{T1}, P_{T1})$$

Instrumentation – Inlet Rakes

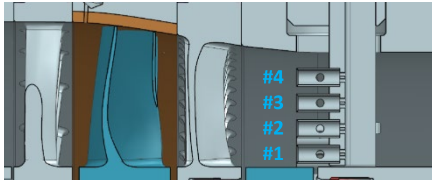


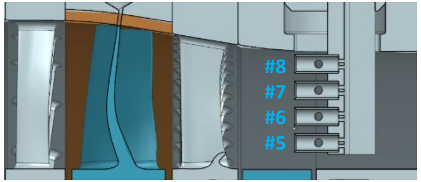
[Inlet Rakes : 3EA]
5 Kielheads per rake
: 10%(#1), 30%(#2), 50%(#3), 70%(#4), and 90%(#5) of the span

Instrumentation – Exit Rakes

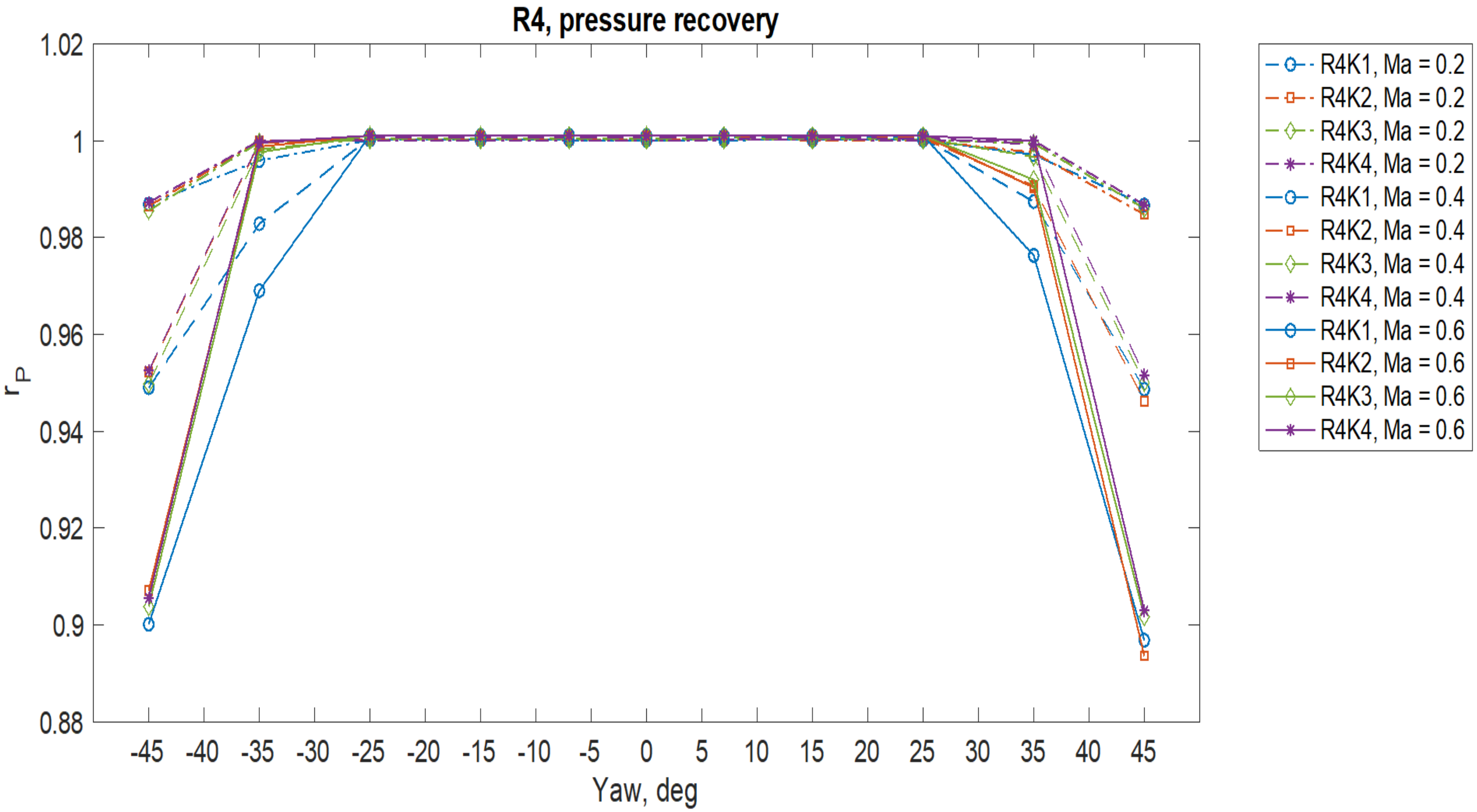
[Exit Rakes : 6EA]
4 Kielheads per rake X 2 set with different insertion depth

11.4%(#1), 22.5%(#3), 33.5(#3), 44.6%(#4), 55.7%(#5), 66.8%(#6), 77.8%(#7), and 88.9%(#8) of the span

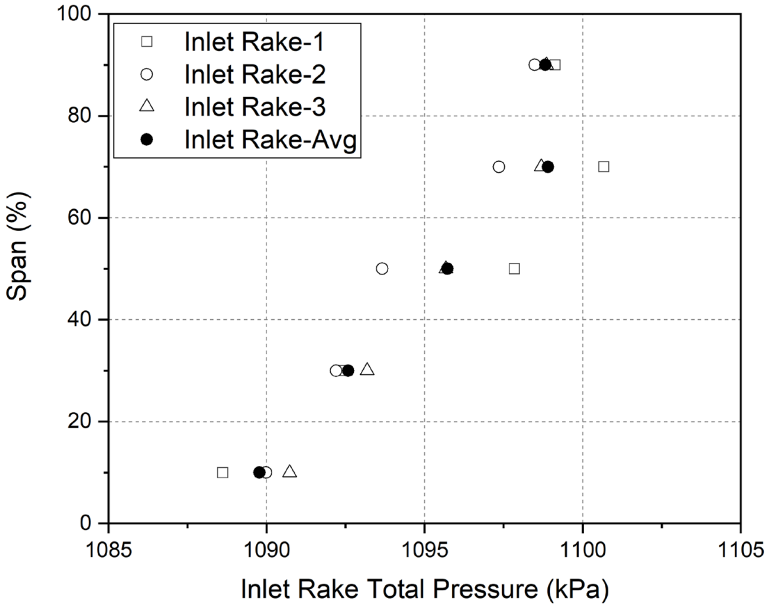


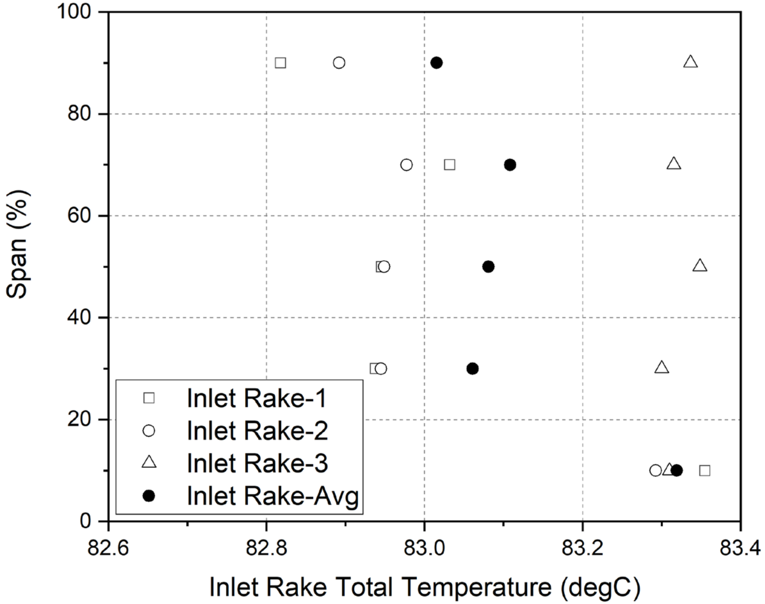


Rake Calibration

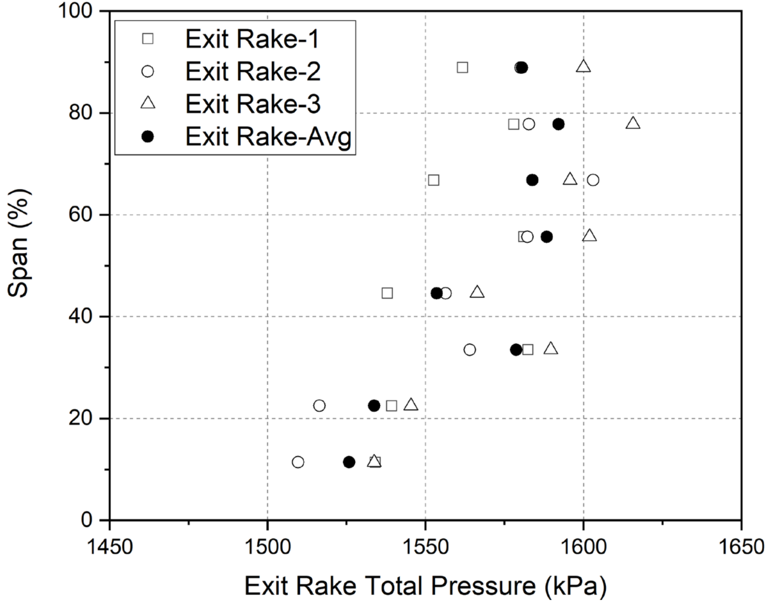


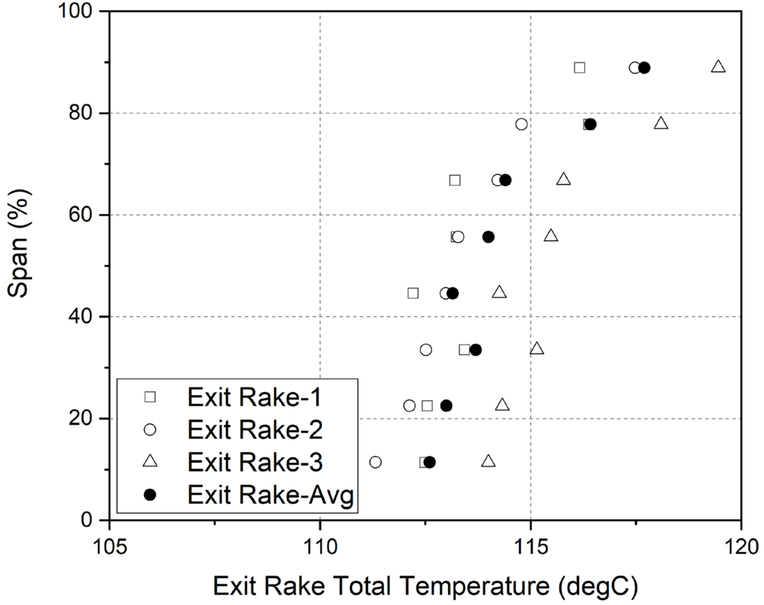
Example Data from Inlet Rakes (100% speed)





Example Data from Exit Rakes (100% speed)





Uncertainty Analysis (1) - Efficiency

$$\eta_{TT} = \frac{h_{T2S} - h_{T1}}{h_{T2} - h_{T1}}$$

$$\delta\eta^2 = \left(\frac{\partial\eta}{\partial h_{T1}}\delta h_{T1}\right)^2 + \left(\frac{\partial\eta}{\partial h_{T2}}\delta h_{T2}\right)^2 + \left(\frac{\partial\eta}{\partial h_{T2S}}\delta h_{T2S}\right)^2$$

$$\delta\eta^2 = \left(\frac{\eta - 1}{h_{T2} - h_{T1}}\delta h_{T1}\right)^2 + \left(\frac{\eta}{h_{T2} - h_{T1}}\delta h_{T2}\right)^2 + \left(\frac{1}{h_{T2} - h_{T1}}\delta h_{T2S}\right)^2$$

$$\delta h^2 = \left(\frac{\partial h(T,P)}{\partial T}\delta T\right)^2 + \left(\frac{\partial h(T,P)}{\partial P}\delta P\right)^2$$

$$\delta h^2 = \left(\frac{\partial h(s,P)}{\partial s}\delta s\right)^2 + \left(\frac{\partial h(s,P)}{\partial P}\delta P\right)^2$$

$$\delta s^2 = \left(\frac{\partial s(T,P)}{\partial T}\delta T\right)^2 + \left(\frac{\partial s(T,P)}{\partial P}\delta P\right)^2$$

Uncertainty Analysis (1) - Efficiency

$$
\begin{aligned}
&\delta\eta^2 \\
&= \frac{1}{(h_{T2} - h_{T1})^2}\left\{(\eta - 1)^2\left[\left(\left.\frac{\partial h(T,P)}{\partial T}\right|_{T1}\delta T\right)^2 + \left(\left.\frac{\partial h(T,P)}{\partial P}\right|_{T1}\delta P\right)^2\right]\right. \\
&+ \eta^2\left[\left(\left.\frac{\partial h(T,P)}{\partial T}\right|_{T2}\delta T\right)^2 + \left(\left.\frac{\partial h(T,P)}{\partial P}\right|_{T2}\delta P\right)^2\right] \\
&\left.+ \left(\left.\frac{\partial h(s,P)}{\partial s}\right|_{T2S}\right)^2\left[\left(\left.\frac{\partial s(T,P)}{\partial T}\right|_{T2S}\delta T\right)^2 + \left(\left.\frac{\partial s(T,P)}{\partial P}\right|_{T2S}\delta P\right)^2\right] + \left(\left.\frac{\partial h(s,P)}{\partial P}\right|_{T2S}\delta P\right)^2\right\}
\end{aligned}
$$

Uncertainty Analysis (1) - Efficiency

❑ Total uncertainty of the isentropic efficiency (η_{TT}) = ±1.96%

* Including

- ✓ Calibrated E-Type Thermocouple
- ✓ DAQ system uncertainty
- ✓ Accuracy of pressure scanner
- ✓ CO2 property (Refprop 10.0)

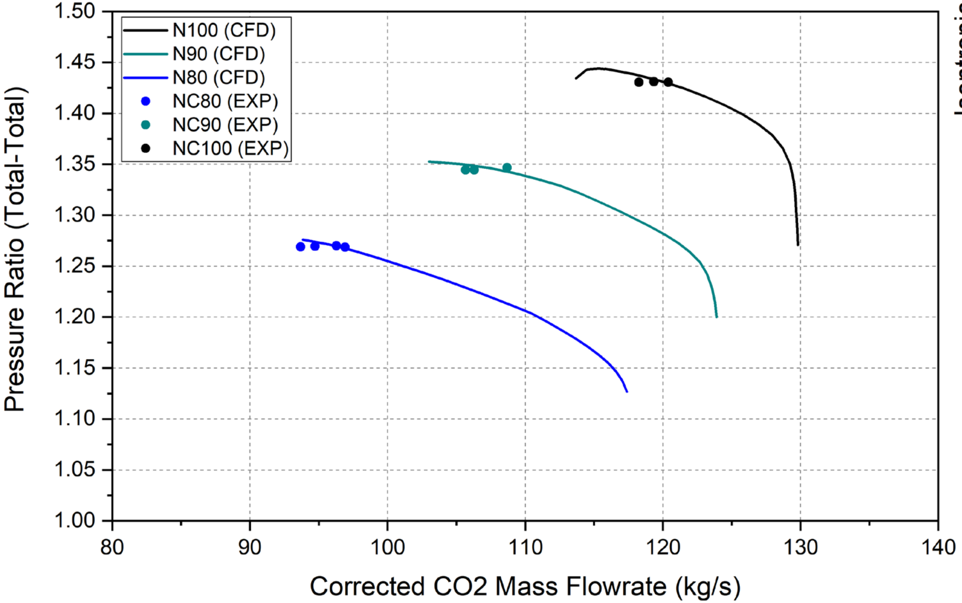
Uncertainty Analysis (2) – Pressure Ratio

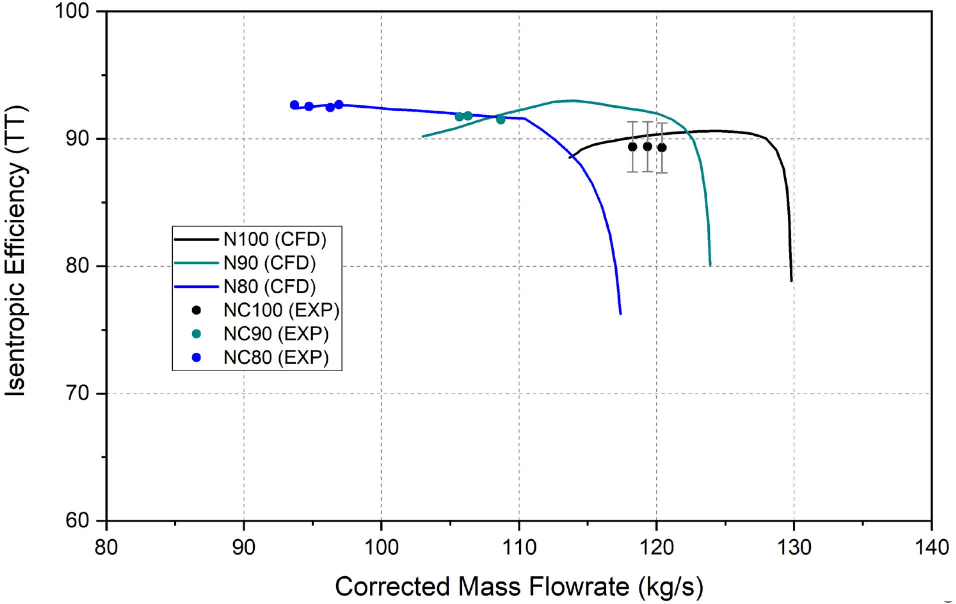
$$PR(TT) = \frac{P_{T2}}{P_{T1}} = \frac{P_{REF} + P_{NS02}}{P_{REF} + P_{NS01}}$$

$$\left(\frac{\delta PR}{PR}\right)^2 = \frac{\delta P_{REF}{}^2 + \delta P_{NS01}{}^2}{\left(P_{REF} + P_{NS01}\right)^2} + \frac{\delta P_{REF}{}^2 + \delta P_{NS02}{}^2}{\left(P_{REF} + P_{NS02}\right)^2}$$

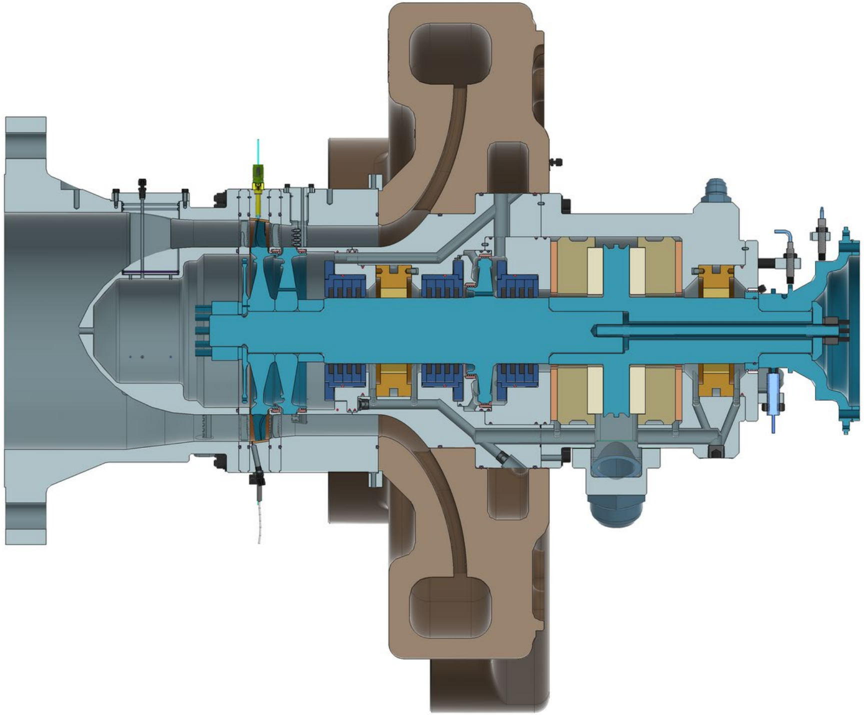
- ☐ Total uncertainty of the pressure ratio (TT) @ 100% speed= ±0.0028

Isentropic Efficiency & Pressure Ratio (TT)

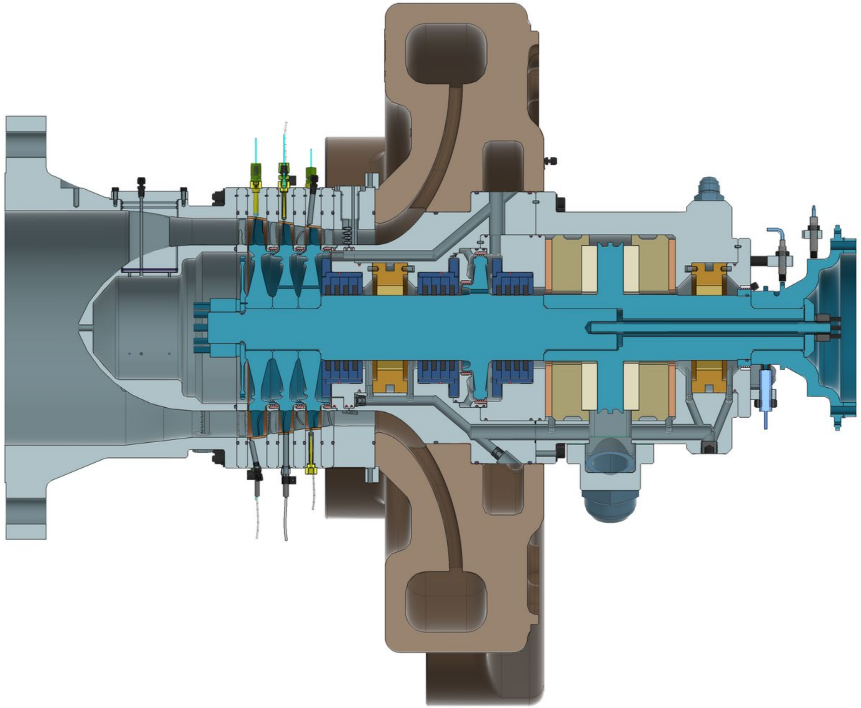




0850 Test Rig (Single and Three Stage)

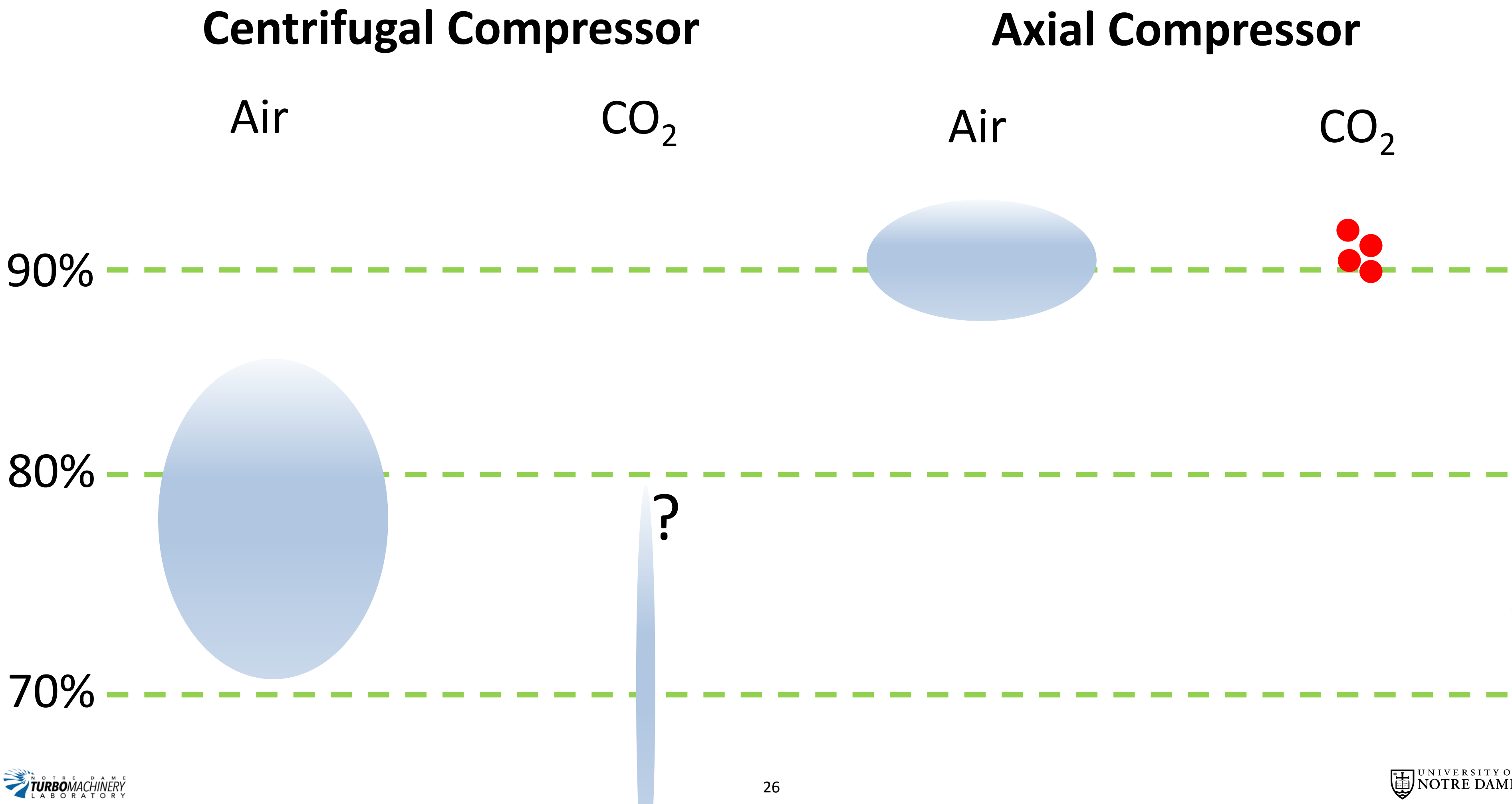


Single Stage



Three Stage

BACKGROUND & RESEARCH QUESTION



RESEARCH QUESTION

- ☐ **Question 1**

Does the axial CO_2 compressor have high efficiency/performance potential?

- ☐ **Question 2**

Can we evaluate the performance of axial CO_2 compressor(s) experimentally with high fidelity?

CONCLUSION

I

A performance of a **1.5 stage axial CO_2 compressor** has been experimentally measured at the 10MW-class sCO_2 compressor test facility at the University of Notre Dame. The goal of the research is to measure compressor performance with **high fidelity** and to demonstrate the high efficiency potential of the axial-type CO_2 compressor for various CO_2 cycle application.

II

The measured total-to-total isentropic efficiency of the compressor at 80%, 90%, and 100% of the speed was about **92.6%, 91.7%, and 89.3%** respectively with the total uncertainty of the isentropic efficiency at 100% speed (19,800rpm) was ±1.96% which is well above the reported highest isentropic efficiency of the compressor so far.

Q & A

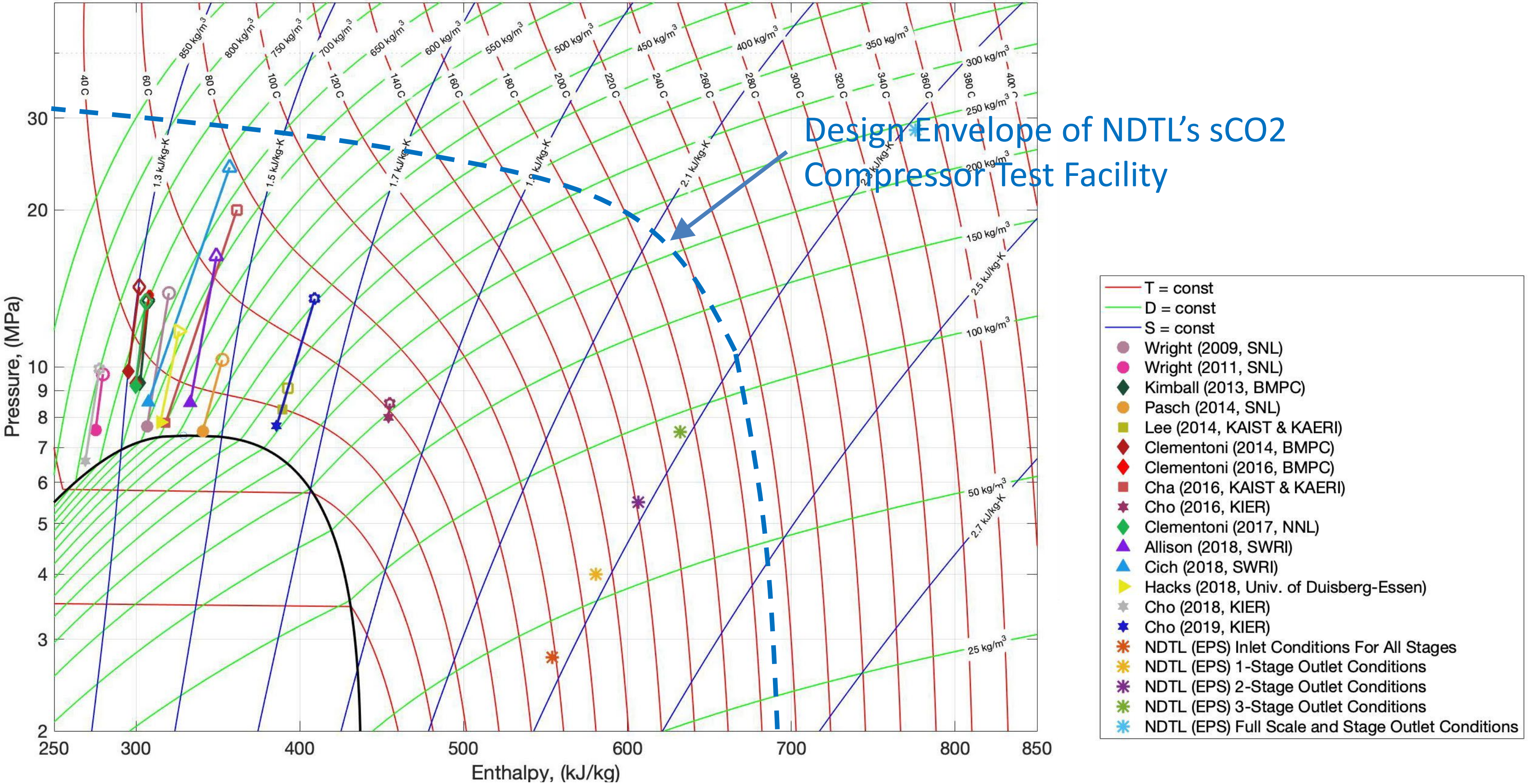
- ☐ **Acknowledgement**

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number DE-EE0008997.

- ☐ **Thank you for your attention! Q & A**

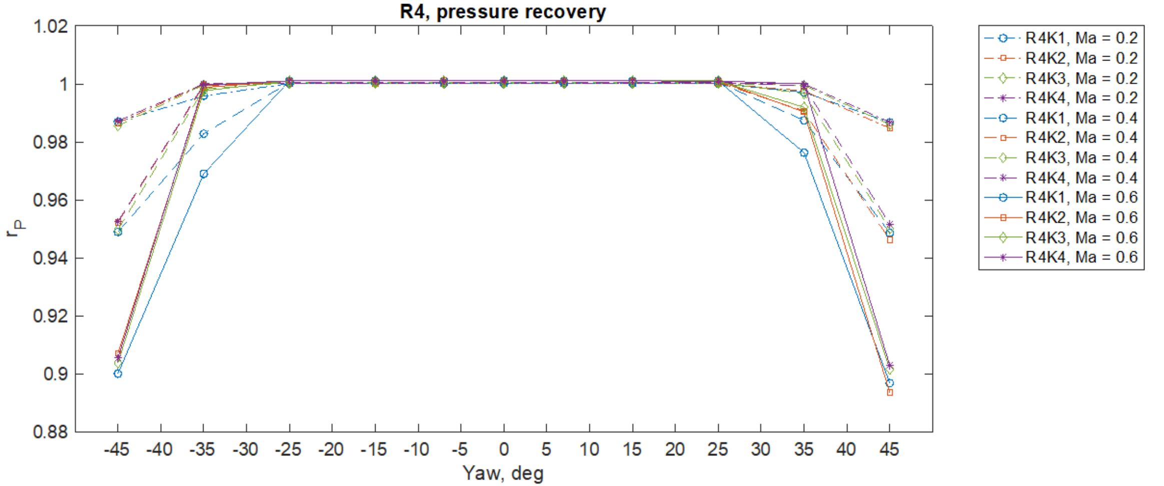
[Appendix]

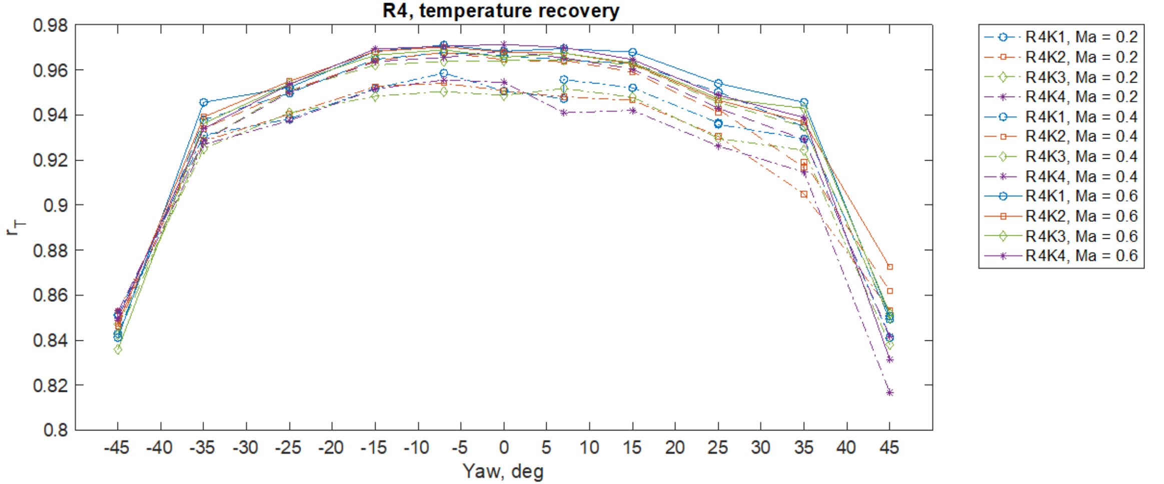
Design Envelope of NDTL sCO2 Compressor Test facility



Design Envelope of NDTL's sCO2 Compressor Test Facility

Rake Calibration


R4, pressure recovery


R4, temperature recovery

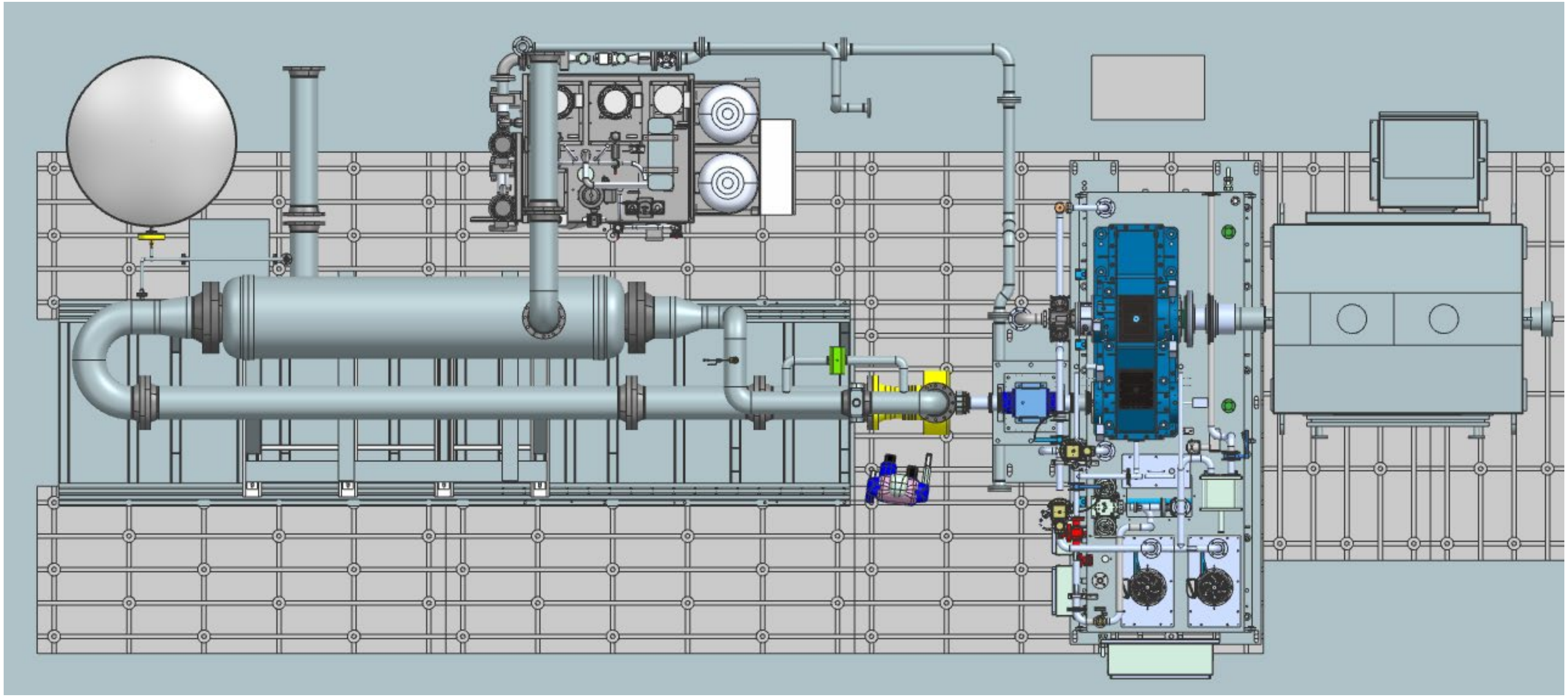
BACKGROUND

❑ sCO2 Compressors – Type, Flowrate, Efficiency

Main Author	Year	Institution	Compressor Type	Compressor Driving Power
Steven A. Wright	2009	Sandia National Laboratories	Centrifugal	50 kWe
Masanori Aritomi	2011	Tokyo Institute of Technology	Centrifugal	
Jeff S. Noall	2014	Barber Nichols Inc., Sandia National Laboratories	Centrifugal	55 kW
Jekyoung Lee	2014	Korea Advanced Institute of Science and Technology	Centrifugal	
Timothy Held	2014	Echogen Power Systems	Centrifugal	2.7MW
Eric M. Clementoni	2016	Bechtel Marine Propulsion Corporation	Centrifugal	36.8 - 15.8 kW
Jae Eun Cha	2016	Korea Advanced Institute of Science and Technology	Centrifugal	
Junhyun Cho	2016	Korea Institute of Energy Research	Centrifugal	90 kW
Eric M. Clementoni	2017	Naval Nuclear Laboratory	Centrifugal	
Timothy C. Allison	2018	Southwest Research Institute	Centrifugal	
Eric M. Clementoni	2018	Naval Nuclear Laboratory	Centrifugal	
Jacqueline Lewis	2018	Naval Nuclear Laboratory	Centrifugal	
Alexander Hacks	2018	University of Duisburg-Essen, Research Center Rez	Centrifugal	7 kW
Seungjoon Baik	2018	Korea Advanced Institute of Science and Technology	Centrifugal	26 kW
Stefan D. Cich	2018	Southwest Research Institute, GE Global Research	Centrifugal	4.9 MW
Bongsu Choi	2019	Korea Institute of Energy Research	Centrifugal	90 kW
Yann Le Moullec	2019	EDF R&D China, Shouhang IHW		2.4 MW
Junhyun Cho	2019	Korea Institute of Energy Research	Centrifugal	90 kW
Eduardo Anselmi	2019	Cranfield University	Centrifugal	45 kW
Logan Rapp	2019	Sandia National Laboratories		1MW

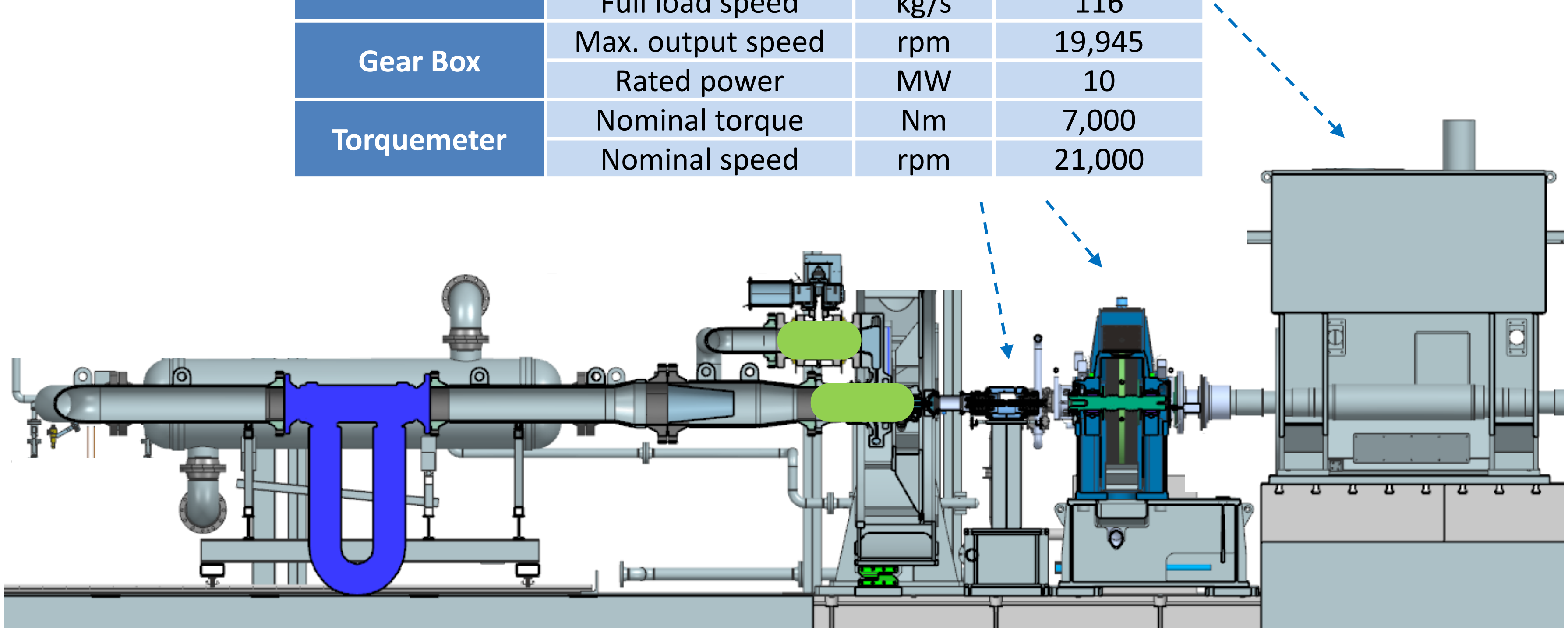
Capacity of Test Facility

sCO2 Compressor Test Facility (Top view)



sCO2 Compressor Test Facility – Specification of Drive System

Motor	Max. power	MW	10
	Full load speed	kg/s	116
Gear Box	Max. output speed	rpm	19,945
	Rated power	MW	10
Torquemeter	Nominal torque	Nm	7,000
	Nominal speed	rpm	21,000

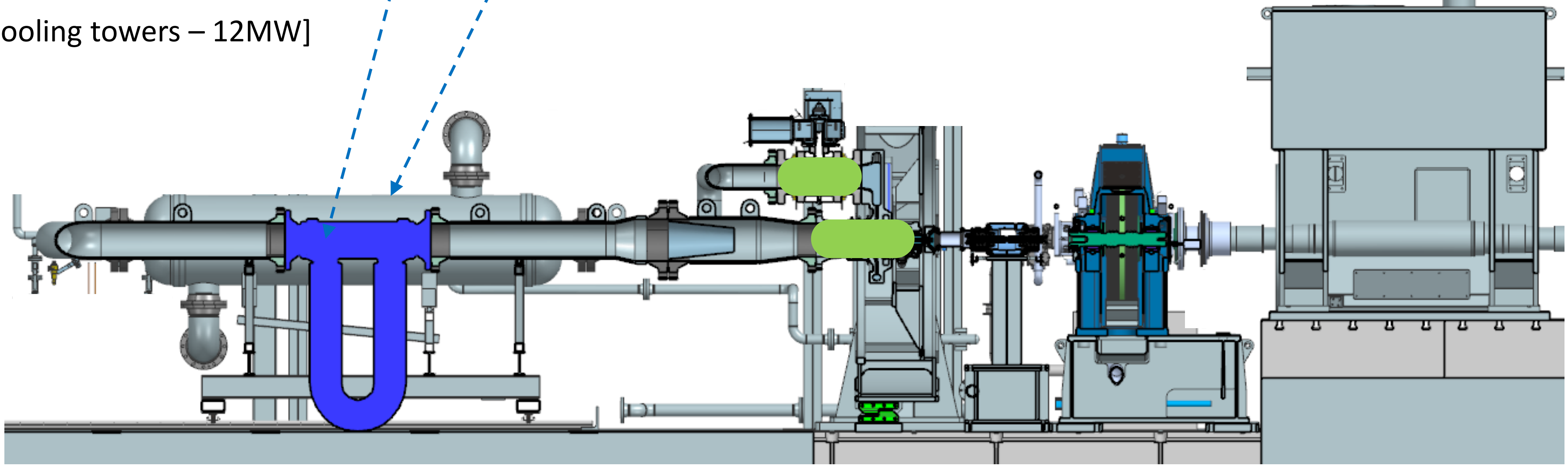


sCO2 Compressor Test Facility – Specification of Main Loop

[Cooling towers – 12MW]

[Specification of a main CO2 Loop]

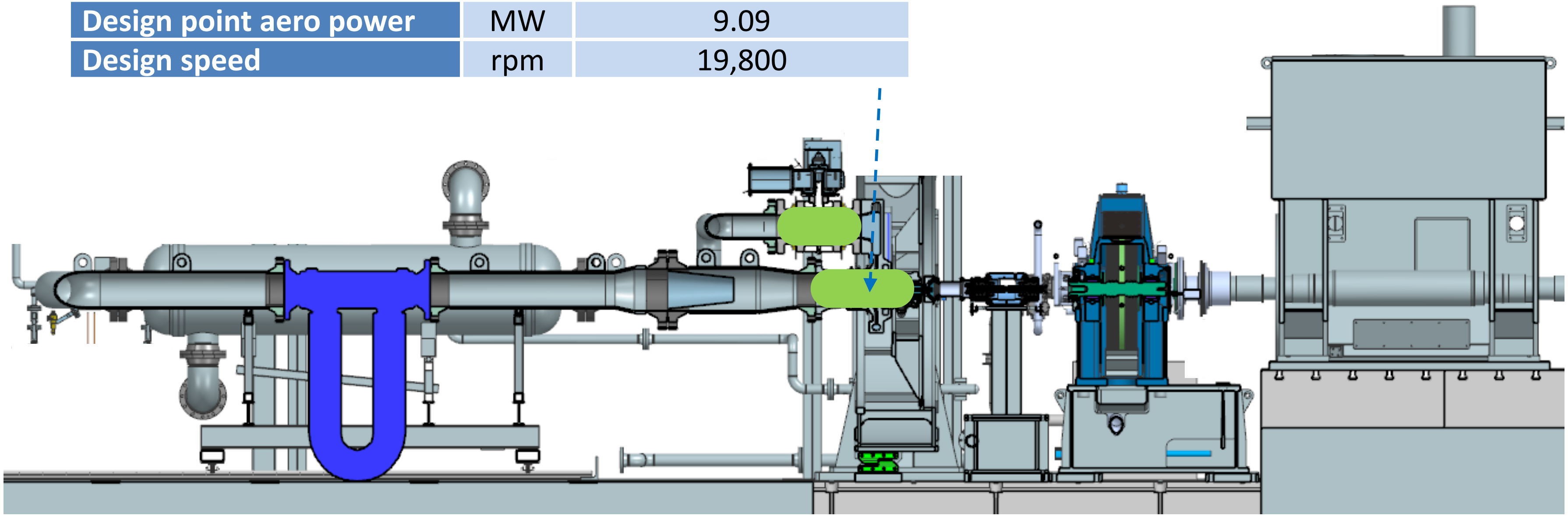
Flowmeter	Type	-	Coriolis
	Size	in	12
	Mass flow rate accuracy	%	0.10
	Max. flowrate	kg/s	907
Heat Exchanger	Type	-	Shell and tube
	Heat Exchange Capacity	MW	10.6



First Compressor to Test

Compressor type		Axial compressor
# of compressor stages	-	1 / 2 / 3
Inlet total pressure	MPa	2.77
Inlet total temperature	˚C	97.94
Mass flow rate	kg/s	116
Pressure ratio	-	2.706
Design point aero power	MW	9.09
Design speed	rpm	19,800

- ➢ Aerodynamic performance
- ➢ Aeromechanic characteristics
- ➢ Detail Flow survey



OBJECTIVE

I Development of Advanced High Efficiency **Axial** Compressor

- Aero Design : 90+% (Ha et al., 2022)
- Experimental Evaluation : Current Study