Process Improvement Using CO_2 Turbine Expanders

Nick Bogan is a Research and Development Engineer with Ebara Elliott Energy, where his current focus is on the design of liquid and two-phase expanders for cryogenic service. He began his career as a Project Engineer at Ebara Elliott Energy before pivoting to robotics, spending 7 years with Hamilton Company designing medical equipment for laboratory automation. He's now returned to Ebara Elliott Energy in a research and development role, where he's working to improve energy transport efficiency and develop new and improved methods of energy conservation. Nick has a Master of Science Degree in Mechanical Engineering from the University of Nevada, Reno, where his main focus was on two-phase heat transfer.

August Brautigam is a Research and Development Engineer at Ebara Elliott Energy, where he is currently focused on the design of ammonia pumps and expanders. He began his career in rotating machinery as an Organic Rankine Cycle Systems Engineer dealing with two-phase screw expanders for ElectraTherm. He then worked as a Project Engineer and later a Research and Development Engineer at Ebara Elliott Energy. He spent seven years designing medical equipment for laboratory automation at Hamilton Company and has returned to Ebara Elliott Energy to pursue his long-standing interest in turbomachinery. His primary areas of focus include thermodynamic analysis of power cycles, two-phase power recovery, and renewable energy production.

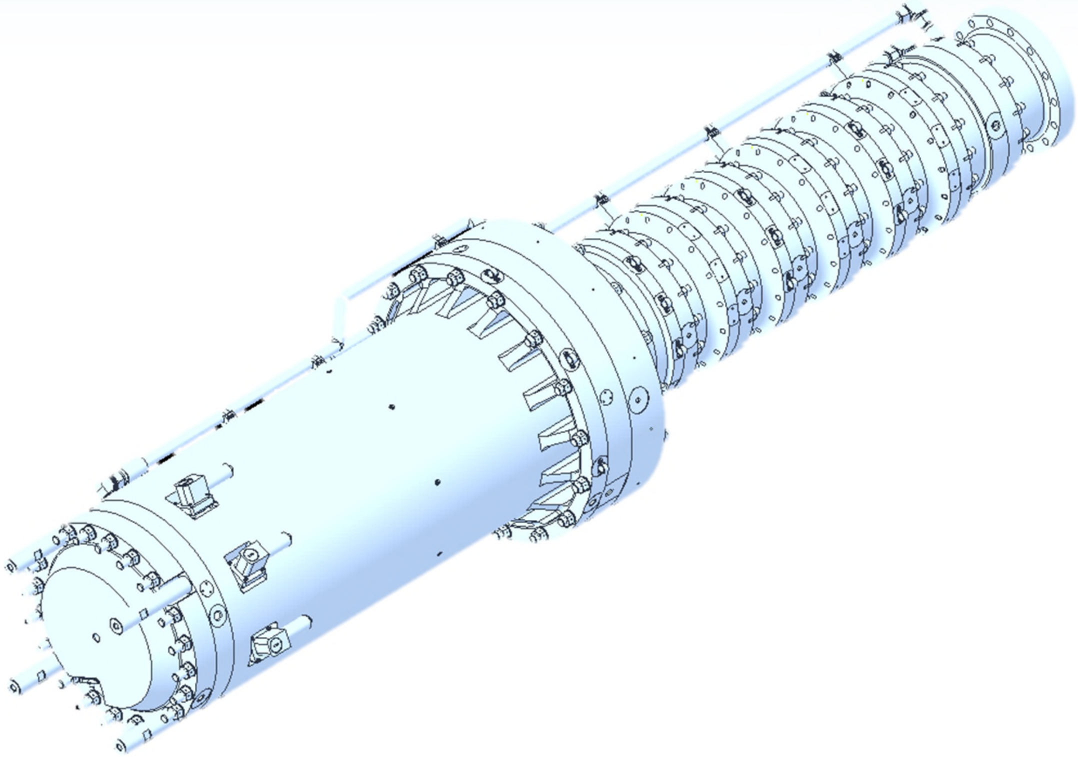
Enver Karakas is a distinguished Fellow Engineer and Senior Manager of Pump and Hydraulic Expander Development Division with over 20 years of experience in design and development of turbomachinery for oil and gas applications. Enver has been working for Ebara Elliott Energy since 2003. Enver specializes in cryogenic pump and hydraulic turbine technologies and is responsible for product development, testing and troubleshooting of cryogenic rotating equipment. Enver has Master of Science and a Doctorate Degree in Mechanical Engineering from the University of Nevada, Reno. He has been a research associate with University of Nevada, Reno and has established and led Turbomachinery Laboratory at University of Nevada, Reno where he studied and investigated cavitation performance of cryogenic centrifugal pumps and multiphase flow in cryogenic turbines.

Abstract Highlights

- Increase in global energy demand has resulted in an overabundance of carbon dioxide (CO_2) in the earth's atmosphere.
- Its high power density makes it a viable working medium in power cycle applications.
- Efficient carbon capture, utilization, and storage (CCUS) is critical to the large-scale efficacy of this thermal energy resource.
- Liquid and two-phase expanders greatly improve the efficiency of an expansion process and have been proven to provide considerable gains with working fluids such as methane and mixed refrigerant.
- Application of this technology to carbon dioxide expansion is reviewed.
- Operational characteristics and overall turbomachinery design are discussed.
- Production gains and electrical regeneration benefits are quantified.

Outline

- Why CO_2?
- How do we capture CO_2?
- CO_2 Applications
- Expander Benefits
- Expander Design
- CO_2-Specific Design Challenges
- CFD Simulation



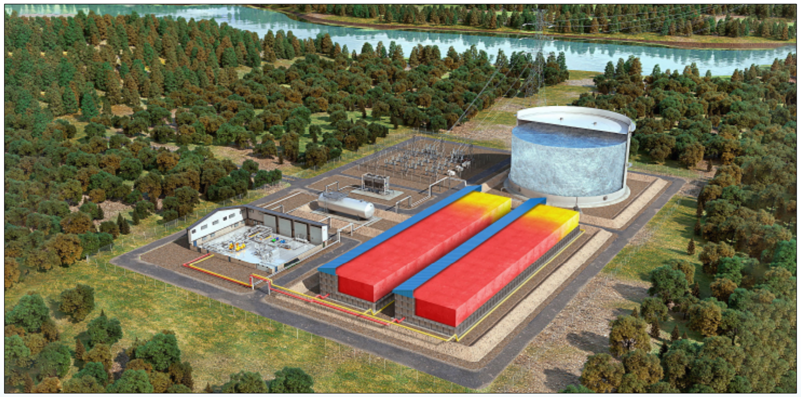
Why CO_2?

- Many fundamental energy-driven processes rely on the combustion of hydrocarbons, which emits greenhouse gases like CO_2 as a byproduct.

- In 2022, CO_2 accounted for nearly 80% of all greenhouse gas emissions.

- Supercritical carbon dioxide (sCO_2) can be used as the working fluid in large scale heat pump applications for power grid energy management.

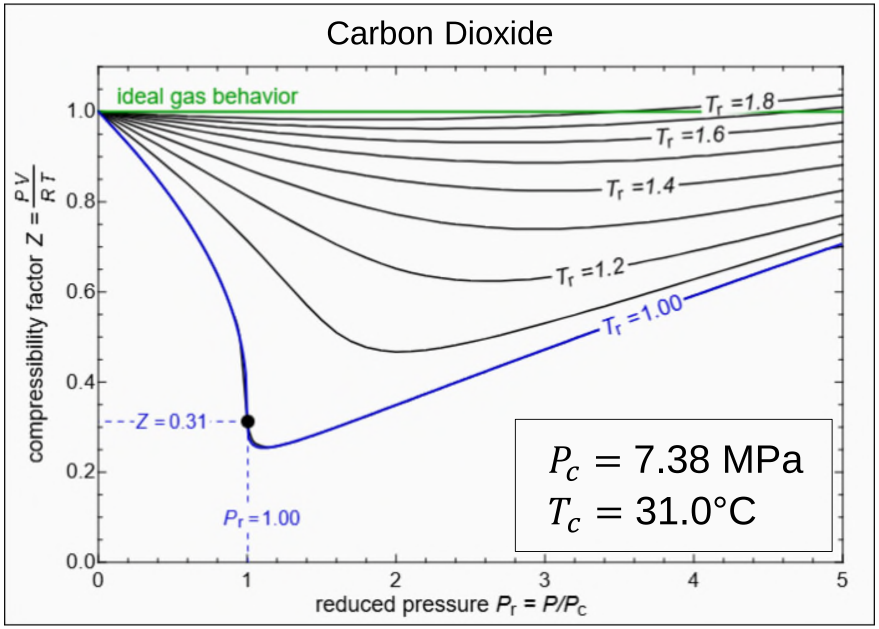
https://www.theengineer.co.uk/content/news/mof-captures-hot-co2-from-industrial-exhaust-streams



https://www.metaltechnews.com/story/2023/09/27/tech-bytes/doe-backs-alaska-thermal-energy-storage/1483.html

CO_2 Applications - Rationale

- **Overabundance** in the earth's atmosphere.
- Behavior of CO_2 near its critical point allows for **reduced compression work** due to its low compressibility factor.
- Increased density near critical point allows for **more mass flow and thus smaller turbomachinery**.
- Increased specific heat near critical point allows for **highly efficient (yet challenging) heat exchange**.



CO_2 Applications – How?

- **Carbon capture, utilization and storage (CCUS)** is a direct means of reducing the amount of CO_2 released into earth's atmosphere.

- Technologies to separate and capture CO_2 from flue gas streams are commercially available. **As of May 2023, over 8 million tons of CO_2 had been captured and stored.**

- These separation and capture processes are **energy intensive**, however, and **efforts to improve their efficiency are critical** to minimizing their net energy demand as well as their resulting economic impact.

- **Liquid and two-phase expanders greatly increase the efficiency** of carbon capture, utilization, and storage processes.

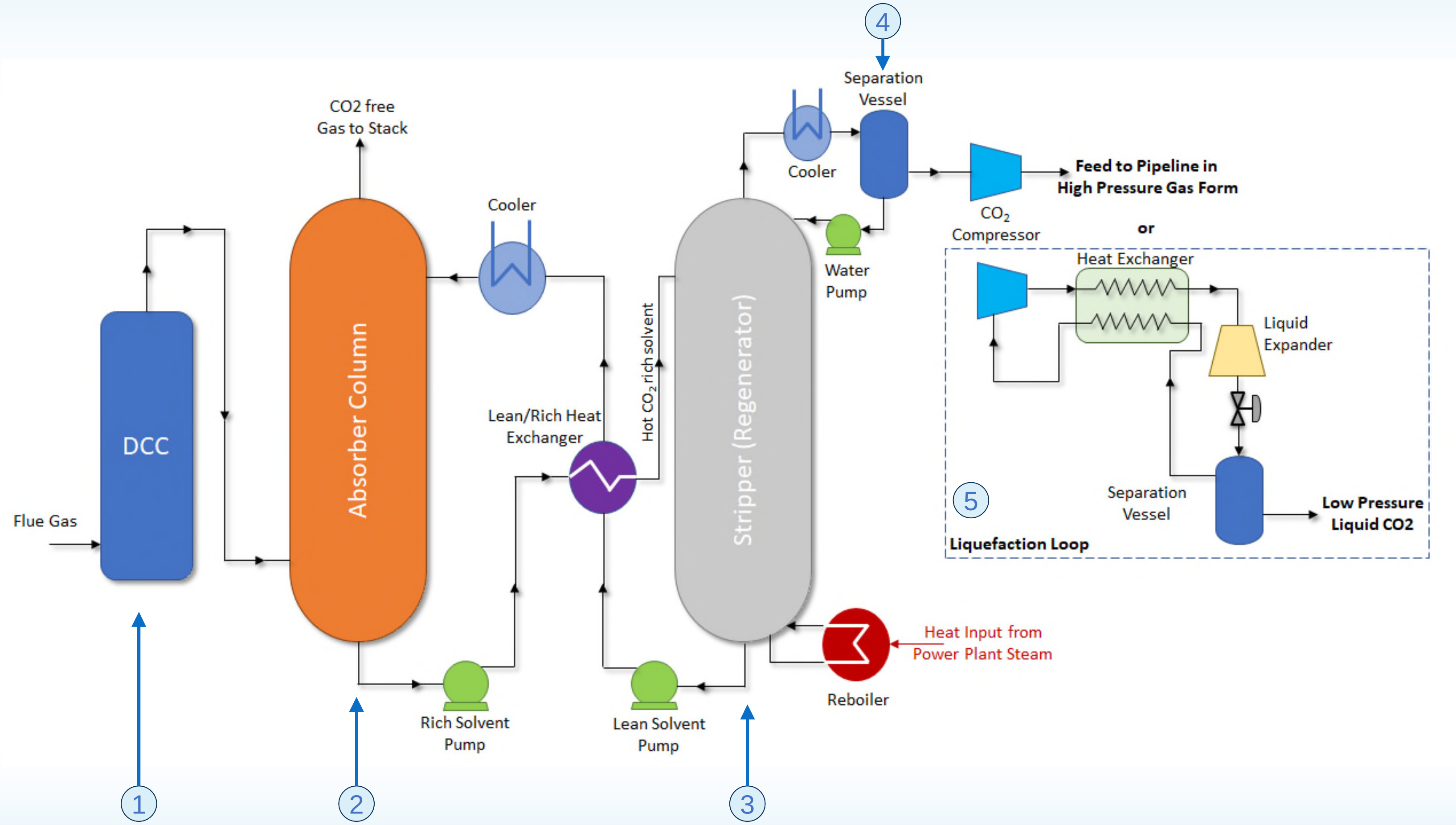
Carbon Capture, Utilization, and Storage (CCUS)

- **Liquid expanders should be utilized** to improve CCUS process efficiency in terms of energy recovery and CO_2 production.

- Post-combustion carbon capture processes focus on **CO_2 capture from flue gas**, which contains CO_2, N_2, O_2, and various other contaminants.

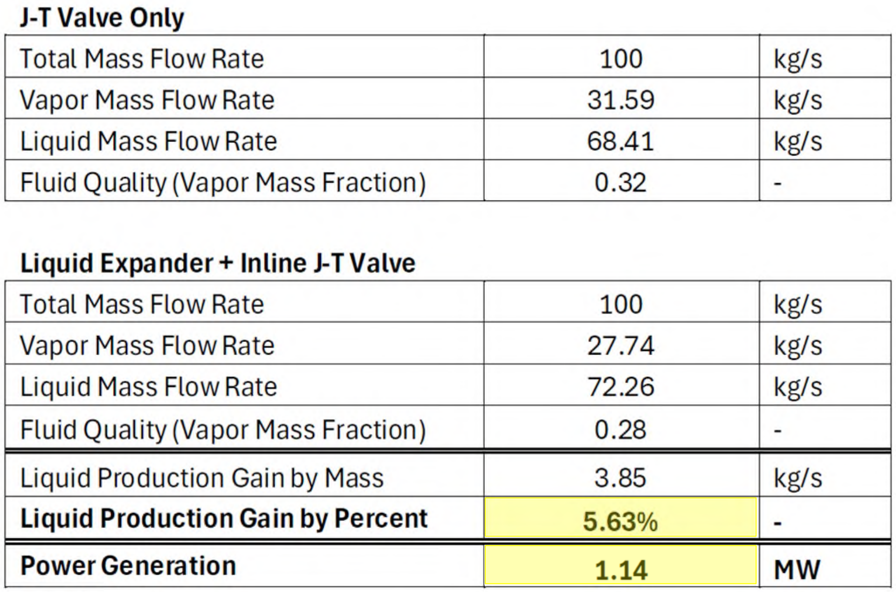
- Three commonly used post-combustion processes are highlighted
  - **Chemical Absorption (Amine Scrubbing)**
  - Membrane Separation
  - Cryogenic Separation

CCUS – Chemical Absorption (Amine Scrubbing)



Expander Liquefaction Benefits – Single-Phase

Inlet Pressure = 20 MPa
Final Pressure = 1.25 MPa



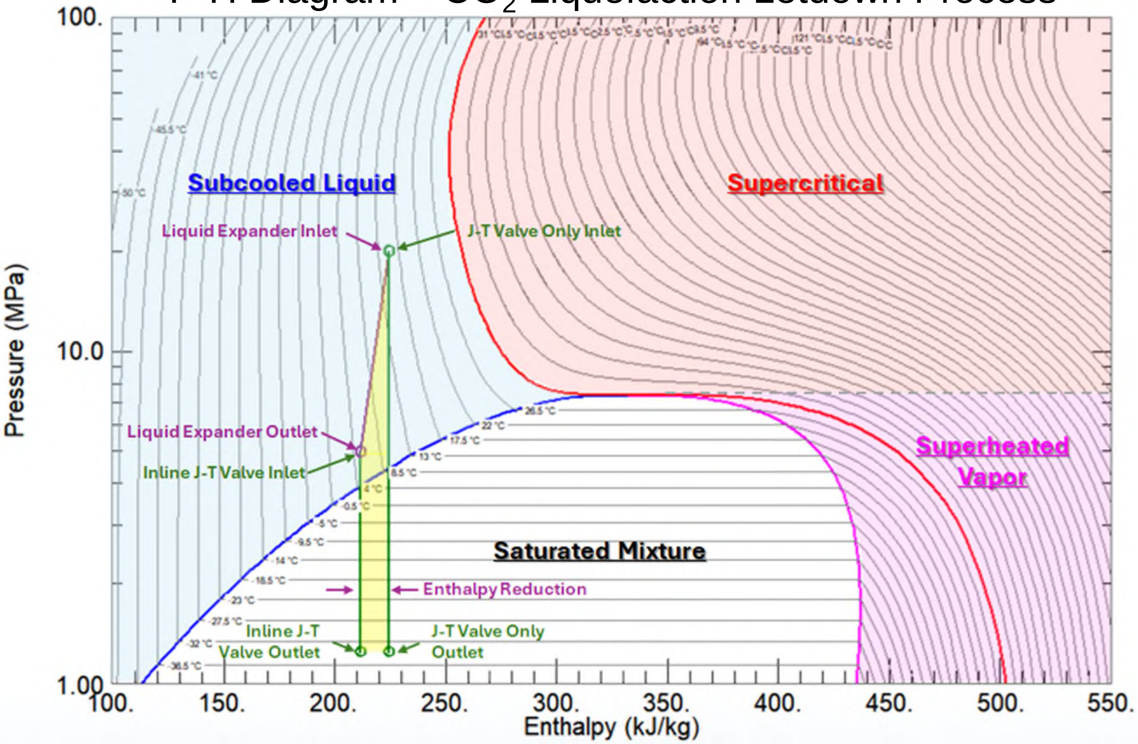
J-T Valve Only

Total Mass Flow Rate	100	kg/s
Vapor Mass Flow Rate	31.59	kg/s
Liquid Mass Flow Rate	68.41	kg/s
Fluid Quality (Vapor Mass Fraction)	0.32	-

Liquid Expander + Inline J-T Valve

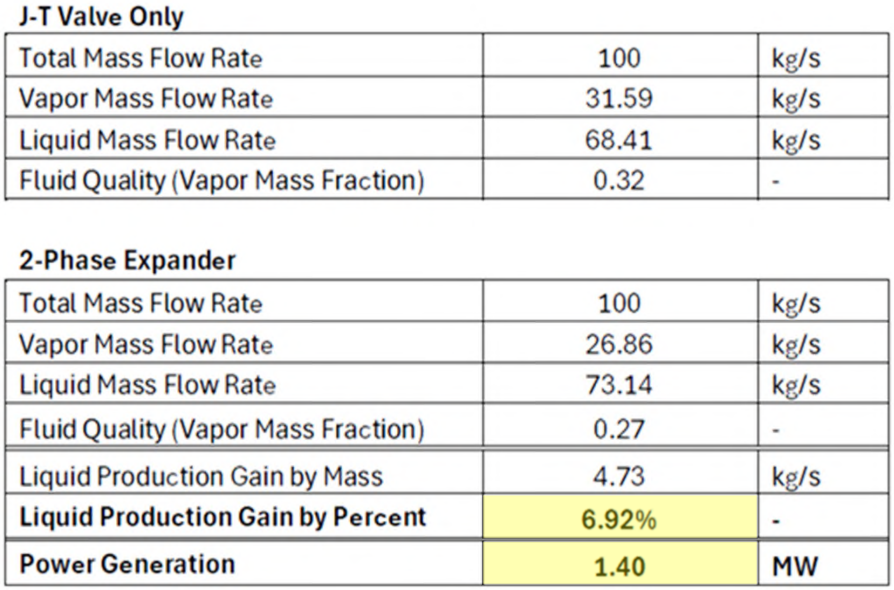
Total Mass Flow Rate	100	kg/s
Vapor Mass Flow Rate	27.74	kg/s
Liquid Mass Flow Rate	72.26	kg/s
Fluid Quality (Vapor Mass Fraction)	0.28	-
Liquid Production Gain by Mass	3.85	kg/s
Liquid Production Gain by Percent	5.63%	-
Power Generation	1.14	MW

P-H Diagram – CO_2 Liquefaction Letdown Process



Expander Liquefaction Benefits – Two-Phase

Inlet Pressure = 20 MPa
Final Pressure = 1.25 MPa



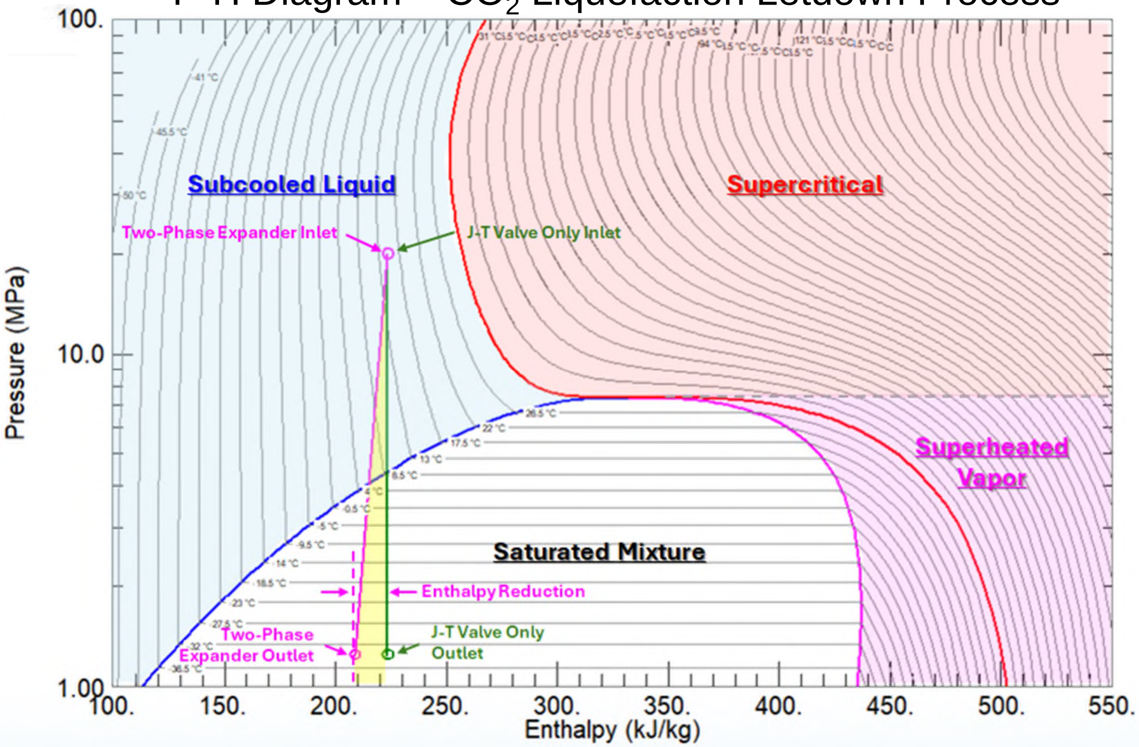
J-T Valve Only

Total Mass Flow Rate	100	kg/s
Vapor Mass Flow Rate	31.59	kg/s
Liquid Mass Flow Rate	68.41	kg/s
Fluid Quality (Vapor Mass Fraction)	0.32	-

2-Phase Expander

Total Mass Flow Rate	100	kg/s
Vapor Mass Flow Rate	26.86	kg/s
Liquid Mass Flow Rate	73.14	kg/s
Fluid Quality (Vapor Mass Fraction)	0.27	-
Liquid Production Gain by Mass	4.73	kg/s
Liquid Production Gain by Percent	6.92%	-
Power Generation	1.40	MW

P-H Diagram – CO_2 Liquefaction Letdown Process



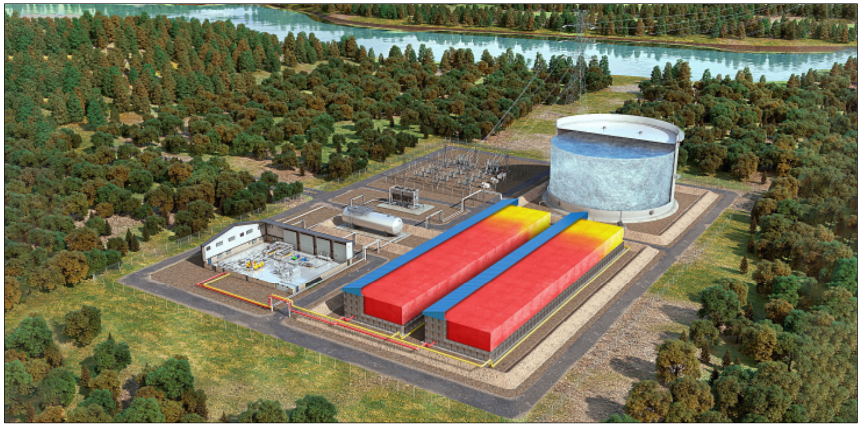
CO_2 Applications – Utilization

- Supercritical carbon dioxide can be used as the **working fluid in large scale heat pump applications** for power grid energy management.

- Heat pump energy storage, known as **Pumped Thermal Energy Storage (PTES),** is a long-duration thermal energy storage technology that **stores surplus electricity as heat**, using CO_2 as the medium to move the energy around.

- PTES can be used as a **non-geographically-limited peak shaving option** when energy demand is high.

- Long-term efficacy relies on **round-trip-efficiency**, i.e. the net work output during the discharge cycle divided by the net work input during the charge cycle


https://www.metaltechnews.com/story/2023/09/27/tech-bytes/doe-backs-alaska-thermal-energy-storage/1483.html

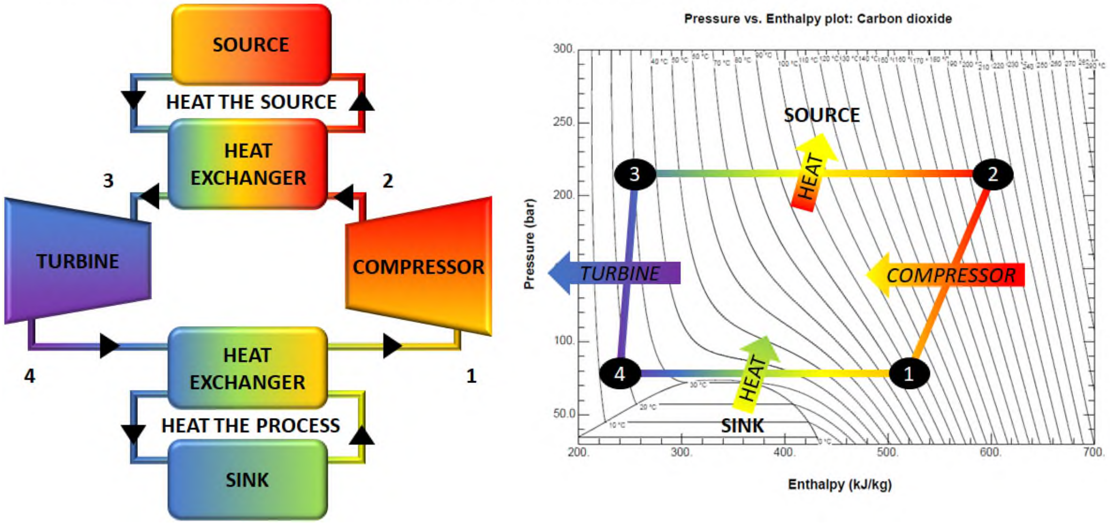
$$\longrightarrow \eta = \frac{Output\ Power, Discharge\ Cycle}{Input\ Power, Charge\ Cycle}$$

PTES – Charge Cycle

Charge Cycle (Heat Pump Mode)

- Excess electricity powers a compressor to pressurize and heat CO_2. Heat is then transferred to the high temperature reservoir (often containing molten salt, rocks, or concrete). The cooled high-pressure CO_2 is then expanded, becoming extremely cold. Cold energy is stored in a low temperature reservoir (often water or ice).

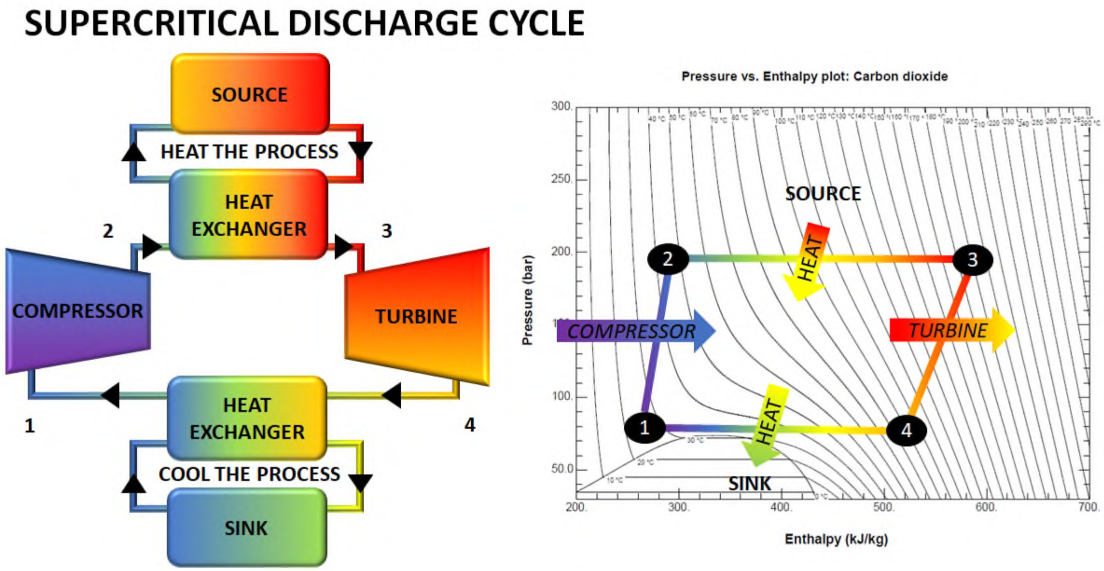
SUPERCRITICAL HEAT PUMP CHARGE CYCLE



PTES – Discharge Cycle

Discharge Cycle (Heat Engine Mode)

- When electricity is needed, the system reverses. CO_2 is compressed before heat is added from the hot reservoir. The resulting high-pressure, high-temperature fluid is sent through a turbine, which spins a generator to produce energy back to the grid. Heat is then rejected to the sink.



PTES – Liquid Expander Benefits

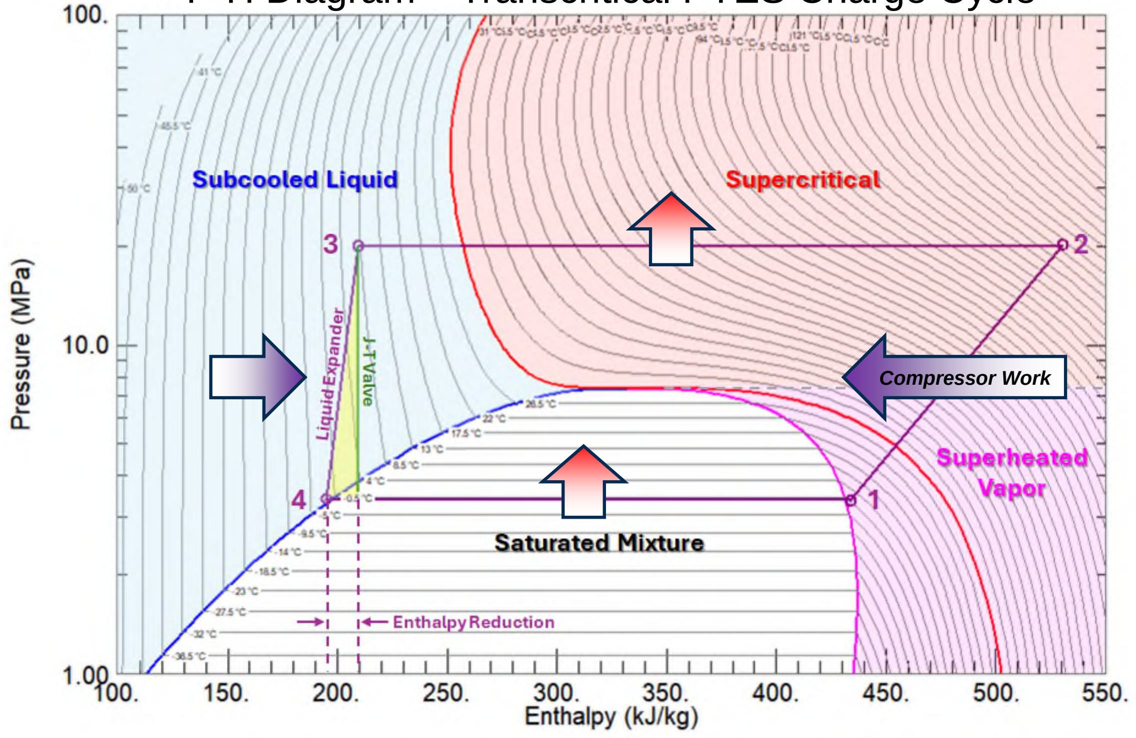
$$\eta = \frac{Output\ Power, Discharge\ Cycle}{Input\ Power, Charge\ Cycle}$$

J-T Valve vs. Liquid Expander

Description	Units	J-T Valve	Liquid Expander
Mass Flow Rate	kg/s	100	100
Inlet Pressure	MPa (a)	20.0	20.0
Inlet Temperature	°C	8.0	8.0
Inlet Enthalpy	kJ/kg-K	209.4	209.4
Outlet Pressure	MPa (a)	3.4	3.4
Outlet Temperature	°C	-0.9	-1.4
Outlet Enthalpy	kJ/kg-K	209.4	196.6
Expander Efficiency	%	N/A	71.25
Power Generated	**MW**	**N/A**	**1.22**

14% increase in round trip efficiency

P-H Diagram – Transcritical PTES Charge Cycle



Ebara Elliott Energy – Liquid Expanders

Total Number of Units in Service: 163 (Year 1997 – 2024)

Process Fluid: Methane, MR (Mixed Refrigerant), CO_2*, NH_3*

Operating Temperature Range: +15.5°C to -165 °C

Volumetric Flow Rate: 225 to 2200 m^3/hr

Generator Rating: 90 kW – 3MW

Maximum Differential Pressure: 150 bar (15 MPa)

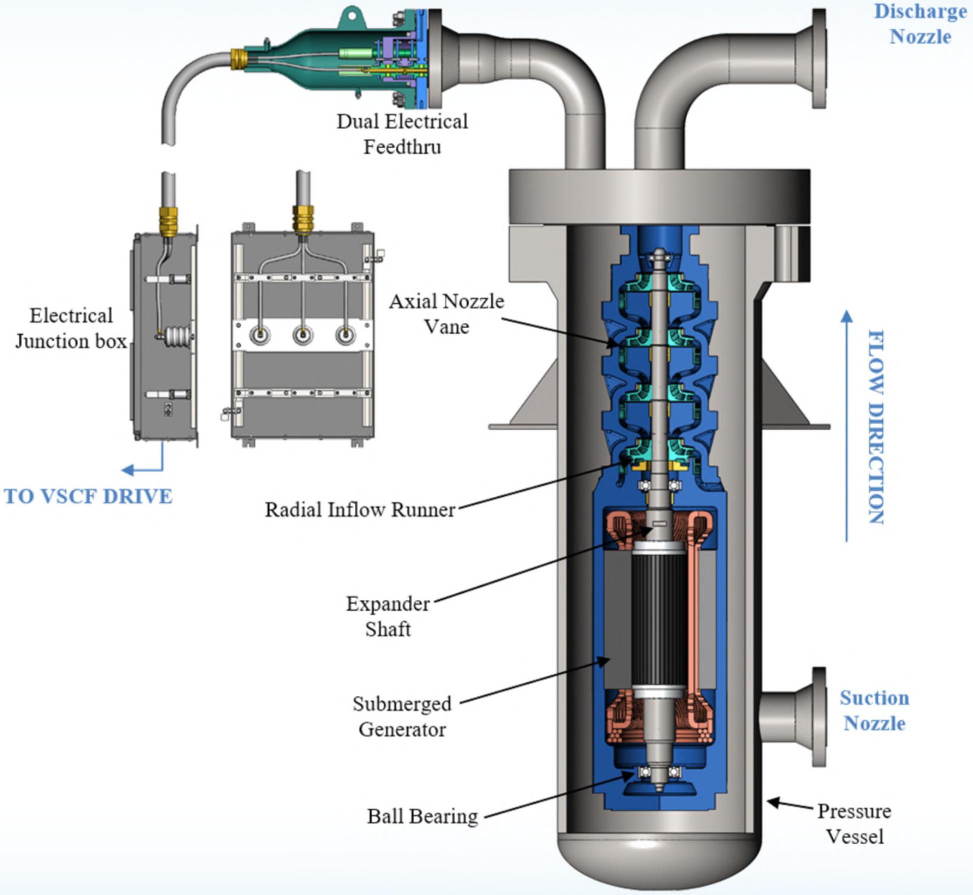
Isentropic Efficiency: 70% to 85%

* Product development is completed.

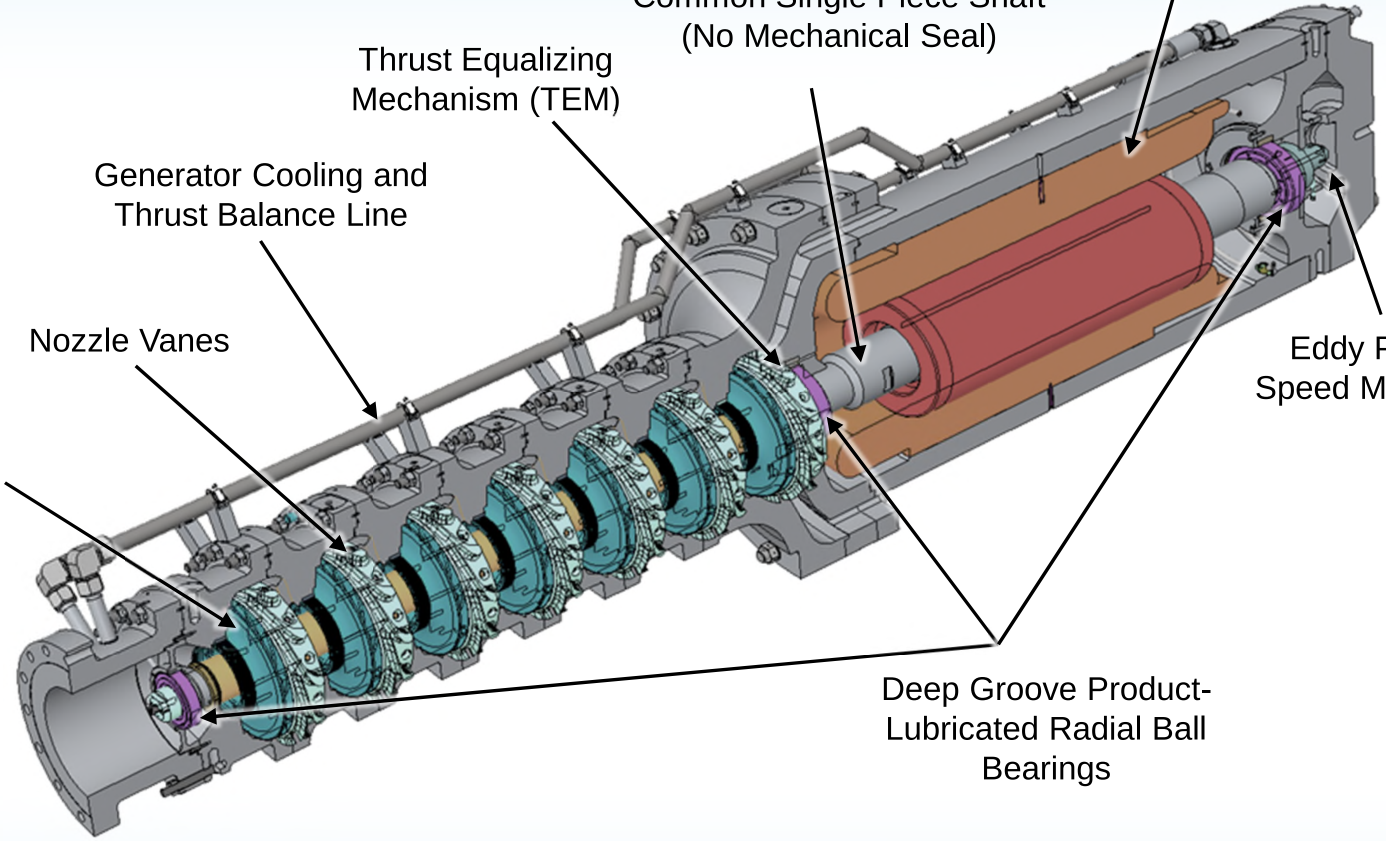
Expander Design Details

3rd Generation Liquid Expanders by EEE:

- **Submerged Turbine Generator** for efficient cooling and reliability (no mechanical seals)
- Compact Design – **Single shaft** for generator and hydraulic rotating components
- **Reduced overall foot print** with vertically suspended machine, casings subjected to external pressure → smaller flanges, bolting, wall thicknesses results in smaller diameter pressure vessel.
- **Reduced thrust load** – Upward flow means rotor weight counteracts thrust load.
- Utilizes **process lubricated bearings and process-driven Thrust Equalizing Mechanism (TEM)** to improve maintenance intervals.



Expander Design Details



Submerged Generator

Common Single Piece Shaft
(No Mechanical Seal)

Thrust Equalizing
Mechanism (TEM)

Generator Cooling and
Thrust Balance Line

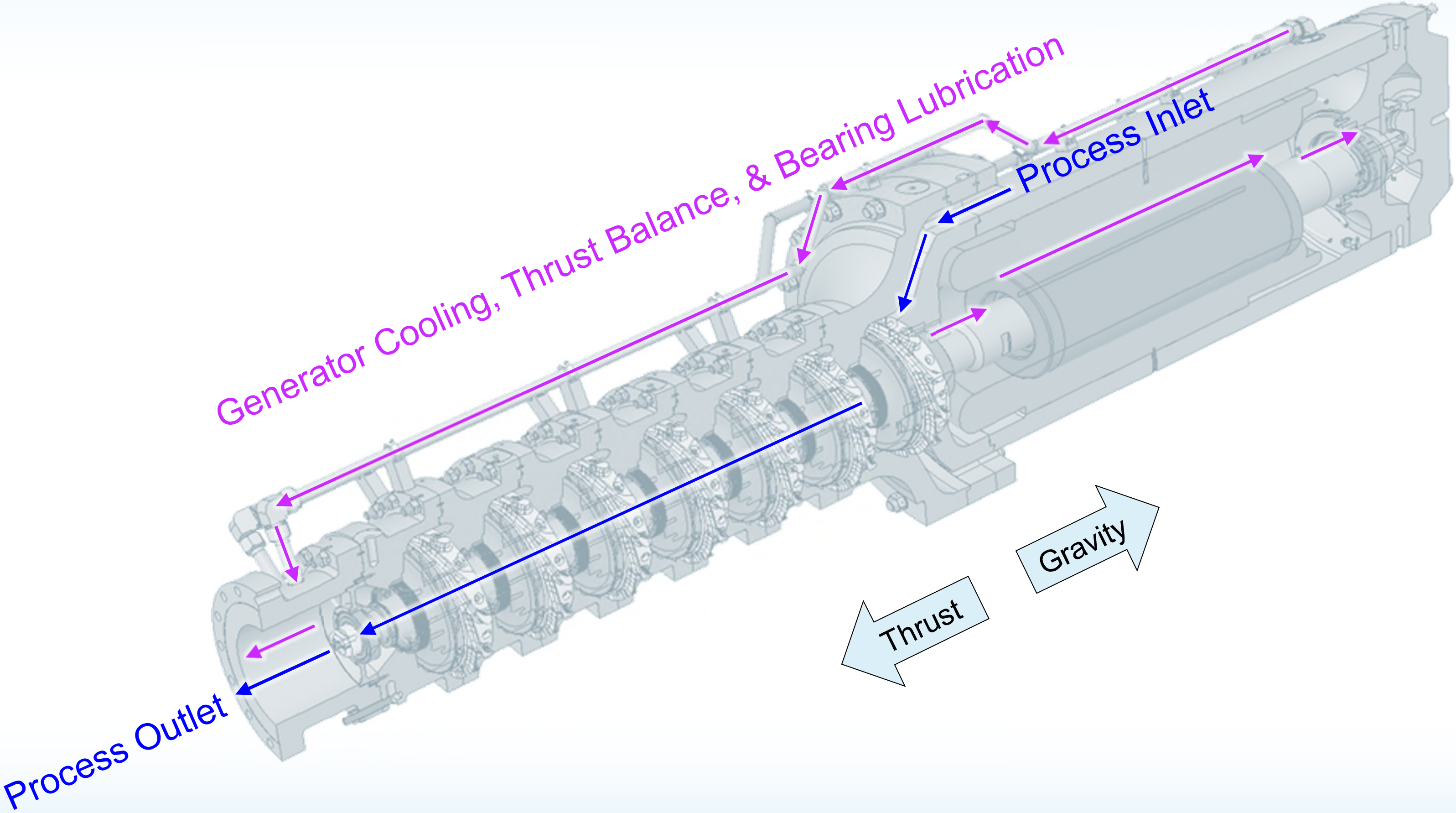
Nozzle Vanes

Runner Assembly
High-Strength
SST 304/304L

Eddy Probes for
Speed Measurement

Deep Groove Product-
Lubricated Radial Ball
Bearings

Expander Design Details



CO_2 Expanders – Design Challenges

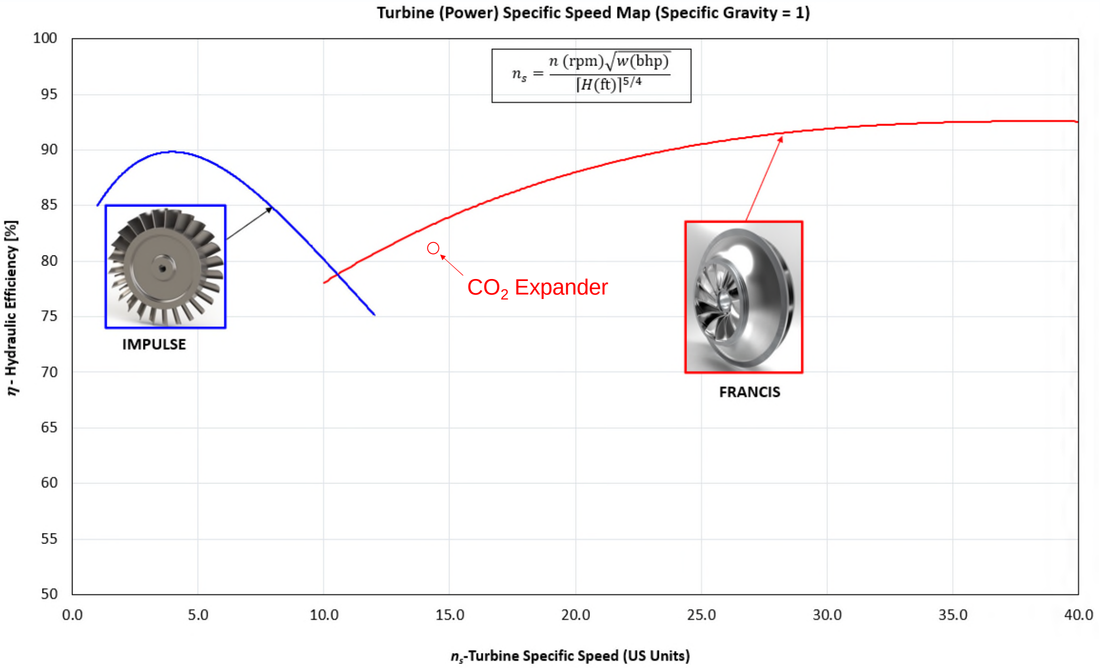
- Operating Temperature
  - Minimum operating temperature is typically around **-5°C for CO_2** compared to **-165°C for LNG**.
  - **Differential shrink rates** between dissimilar materials can **result in radial thermal stresses** and changes the alignment of axial components. Because CO_2 operates much warmer than LNG, **differential shrink rates are of less concern**.

- Density
  - **Density of CO_2 is more than 2x density of LNG**.
  - Requires **higher torque to move the fluid → AISI 304 runners and vanes, increased shaft diameter**
  - **Flow rates are lower**, lower specific speed → **lower attainable efficiency**
  - **Higher pressures → more stages → rotordynamic considerations**

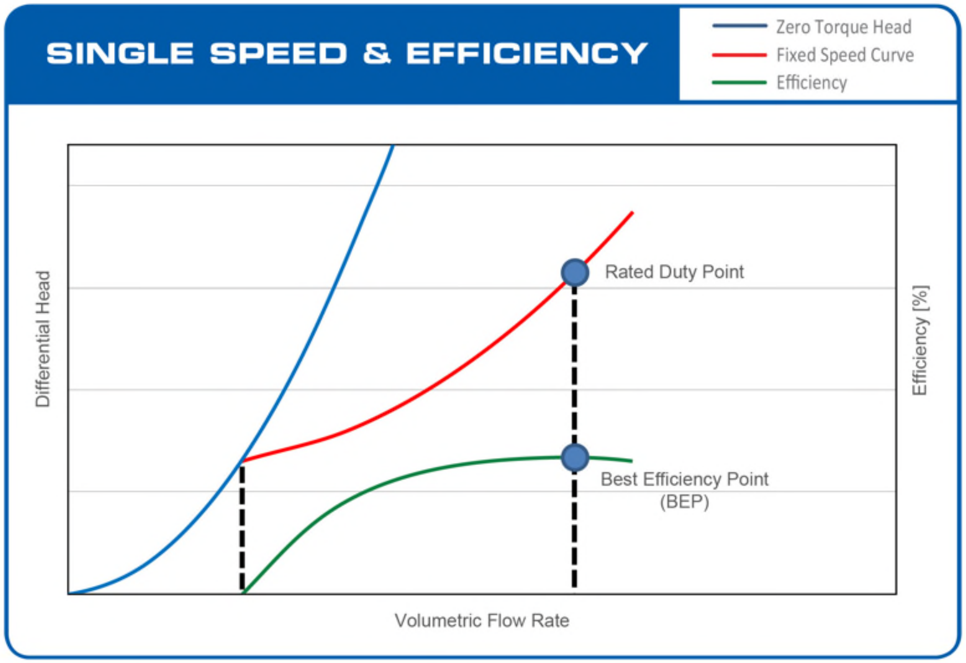
- Bearing Lubrication
  - Process-lubricated bearings require a **minimum viscosity of 0.045 cP → Viscosity of CO_2 is well above this value.**
  - **Dry ice formation in the bearings can be dismissed**, as the pressures associated with operation are **well below the melting line of CO_2.**

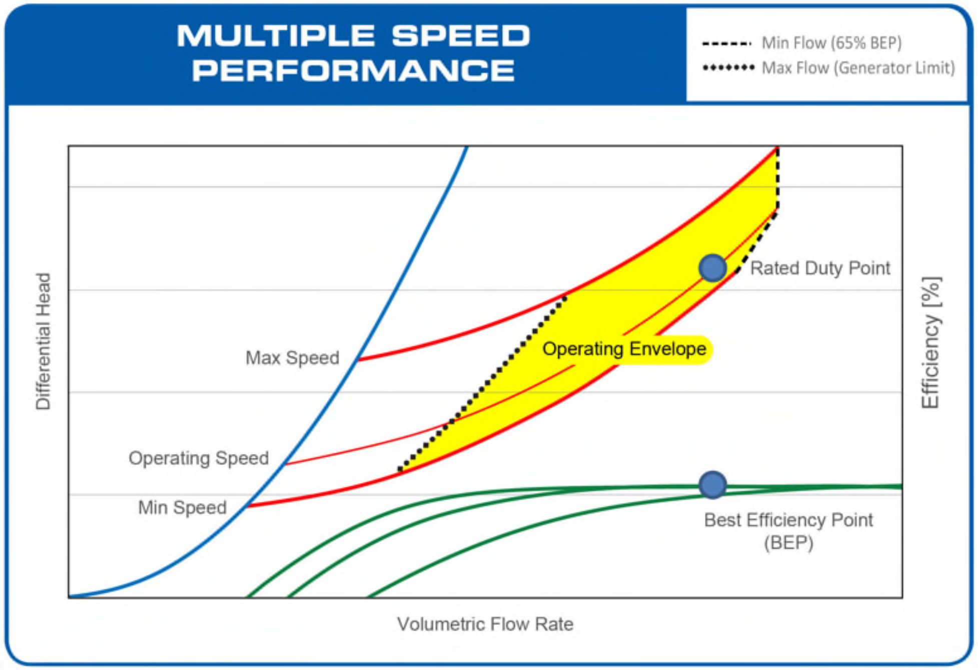
Expanders for CO_2 – Specific Speed Map

- **Turbine specific speed** is a guideline for design and process engineers to determine the turbine type and estimate the expected hydraulic efficiency of a turbine.
- $n_s > 12$ (U.S. Units) are Reaction Turbines
  $n_s < 12$ (U.S. Units) are Impulse Turbines
- **n_s changes proportionally with rotational speed**, which in turn **varies the head and flow rate according to affinity laws** for centrifugal turbine applications.
- **Most common way to adjust specific speed is by changing the number of stages.**
- **Variable Frequency Drives (VFD)** drives create an **operating envelope** rather than an operating curve.

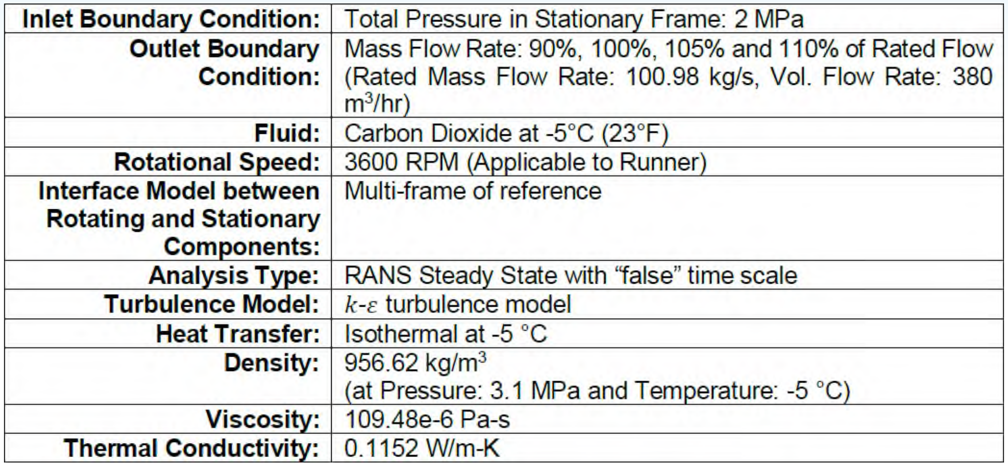


Expanders for CO_2 – Performance Curves



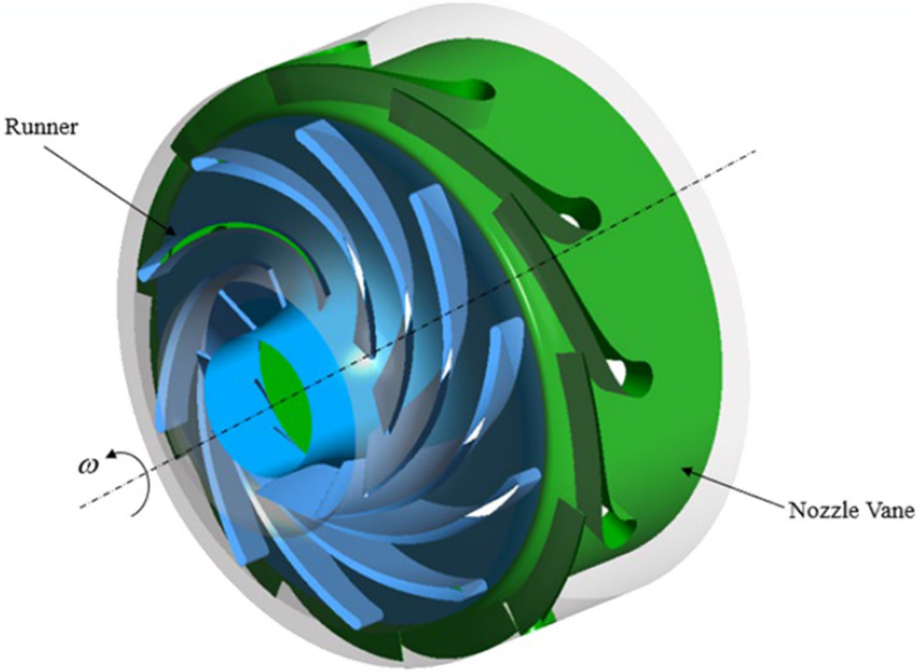


Expanders for CO_2 – Computational Fluid Dynamics



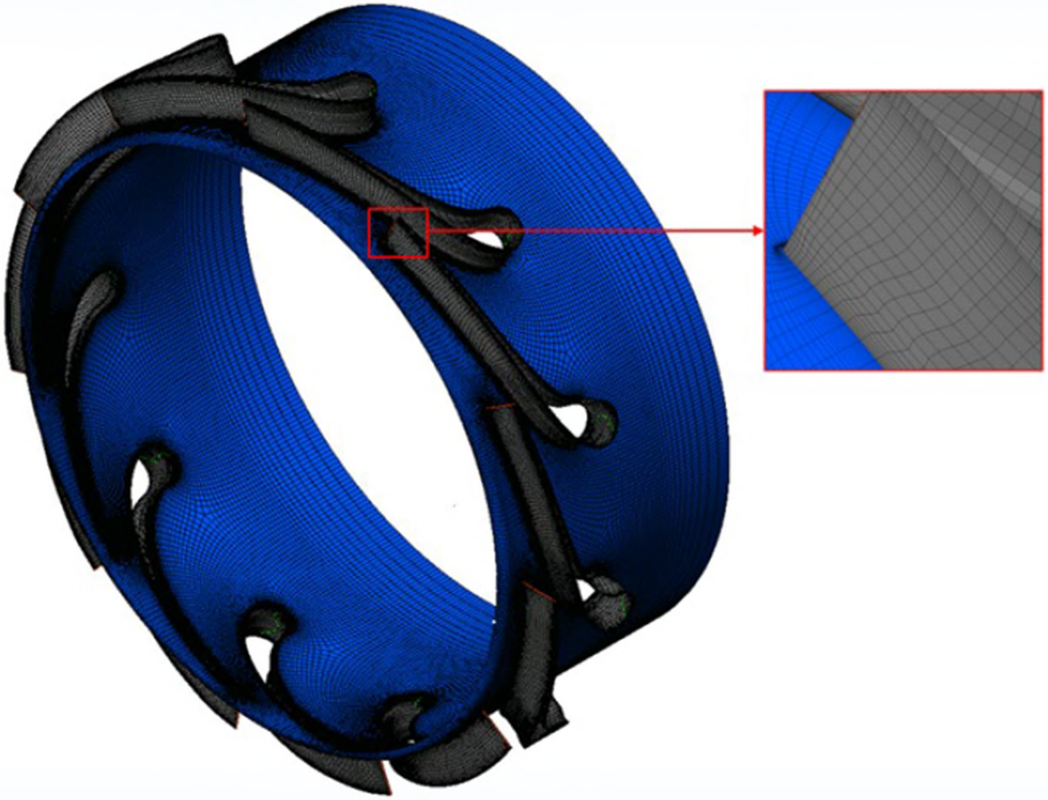
Inlet Boundary Condition:	Total Pressure in Stationary Frame: 2 MPa
Outlet Boundary Condition:	Mass Flow Rate: 90%, 100%, 105% and 110% of Rated Flow (Rated Mass Flow Rate: 100.98 kg/s, Vol. Flow Rate: 380 m^3/hr)
Fluid:	Carbon Dioxide at -5°C (23°F)
Rotational Speed:	3600 RPM (Applicable to Runner)
Interface Model between Rotating and Stationary Components:	Multi-frame of reference
Analysis Type:	RANS Steady State with “false” time scale
Turbulence Model:	k-ε turbulence model
Heat Transfer:	Isothermal at -5 °C
Density:	956.62 kg/m^3 (at Pressure: 3.1 MPa and Temperature: -5 °C)
Viscosity:	109.48e-6 Pa-s
Thermal Conductivity:	0.1152 W/m-K

- **Inputs**: Fluid medium, inlet pressure, mass flow
- **Reynolds Averaged Navier Stokes (RANS)** approach with ***k*-ε Turbulence Model** to achieve closure.
- Process fluid is assumed to be **incompressible**, with a **negligible density variation** that is typically less than 5% between the turbine expander inlet and outlet conditions.
- **Outputs**: All property gradients, power generation



Expanders for CO_2 – Computational Fluid Dynamics

- Meshed using Turbogrid software to obtain a structured grid, ensuring mesh independence.
- Fine mesh resolution implemented at wall sections to accurately capture the boundary layer effects.
- To ensure convergence, residuals for mass flow and momentum in each direction are monitored during the study
  - Maximum Root Mean Squared (RMS) residuals to be less than 1e-5.
- In addition, the turbine head is monitored to ensure that the percentage variation of head drop is less than 0.5% over the last 250 iterations.
- Differential pressure across a single stage is reviewed. Total pressure drop is equal to the single stage pressure drop multiplied by the number of stages (7 stages for this study).

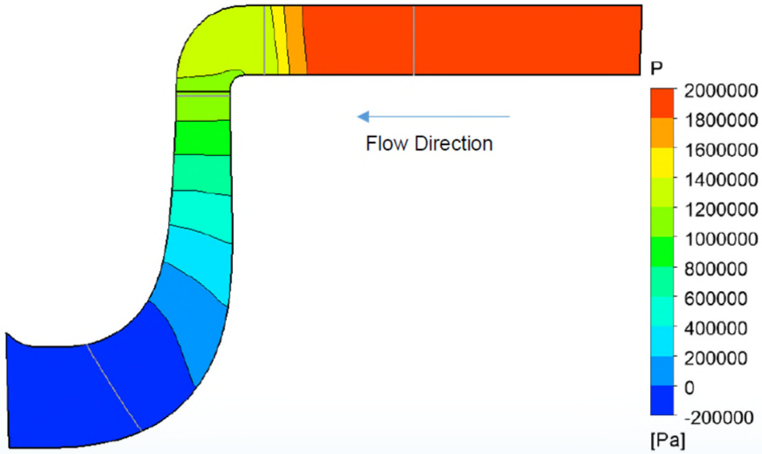


Expanders for CO_2 – Computational Fluid Dynamics

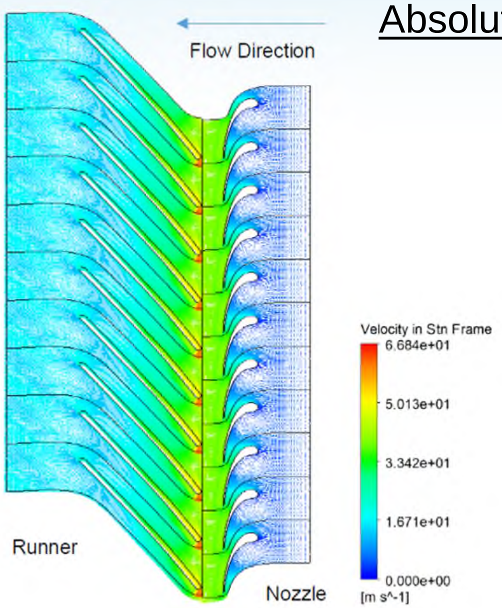
Static Pressure

- The plot below depicts the **area-averaged static pressure distribution** across a single stage of the turbine at the meridional (primary flow) axis and plane.

- Single-stage static pressure differential is 2.15 MPa, which corresponds to 227 meters of head per stage at rated flow.



Absolute Velocity



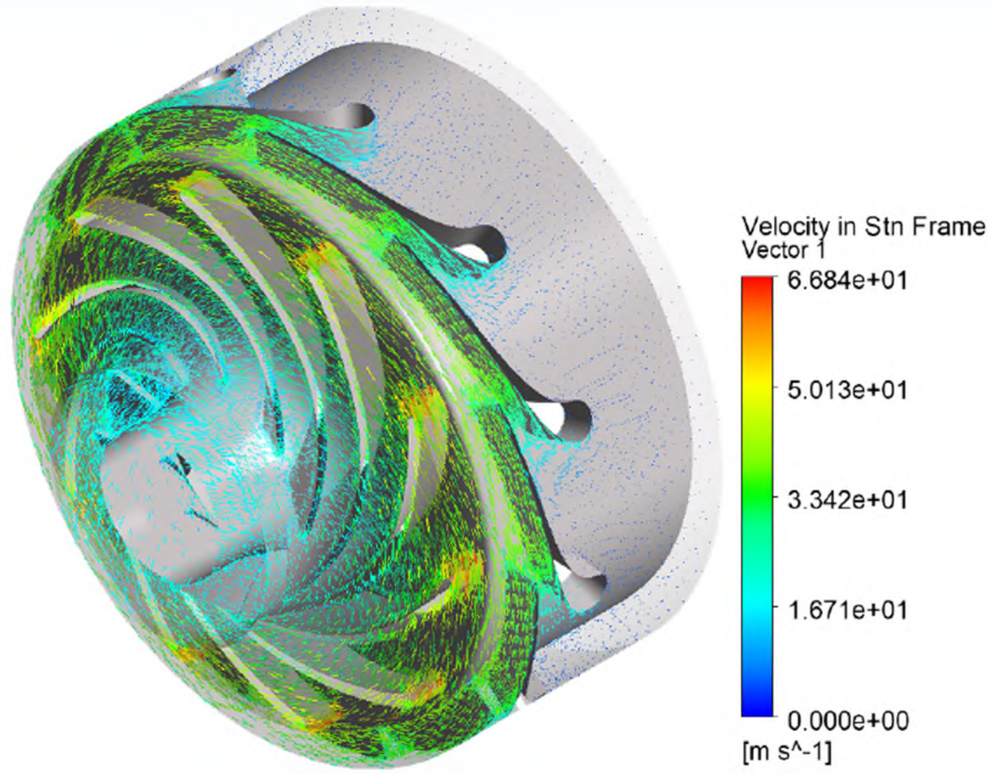
- Fluid enters the nozzle axially. **The nozzle vane increases the fluid's momentum and redirects some of the flow tangentially** as it enters the runner.

- At the runner, this **tangential momentum is effectively reduced via torque transfer to the shaft.**

Expanders for CO_2 – Computational Fluid Dynamics

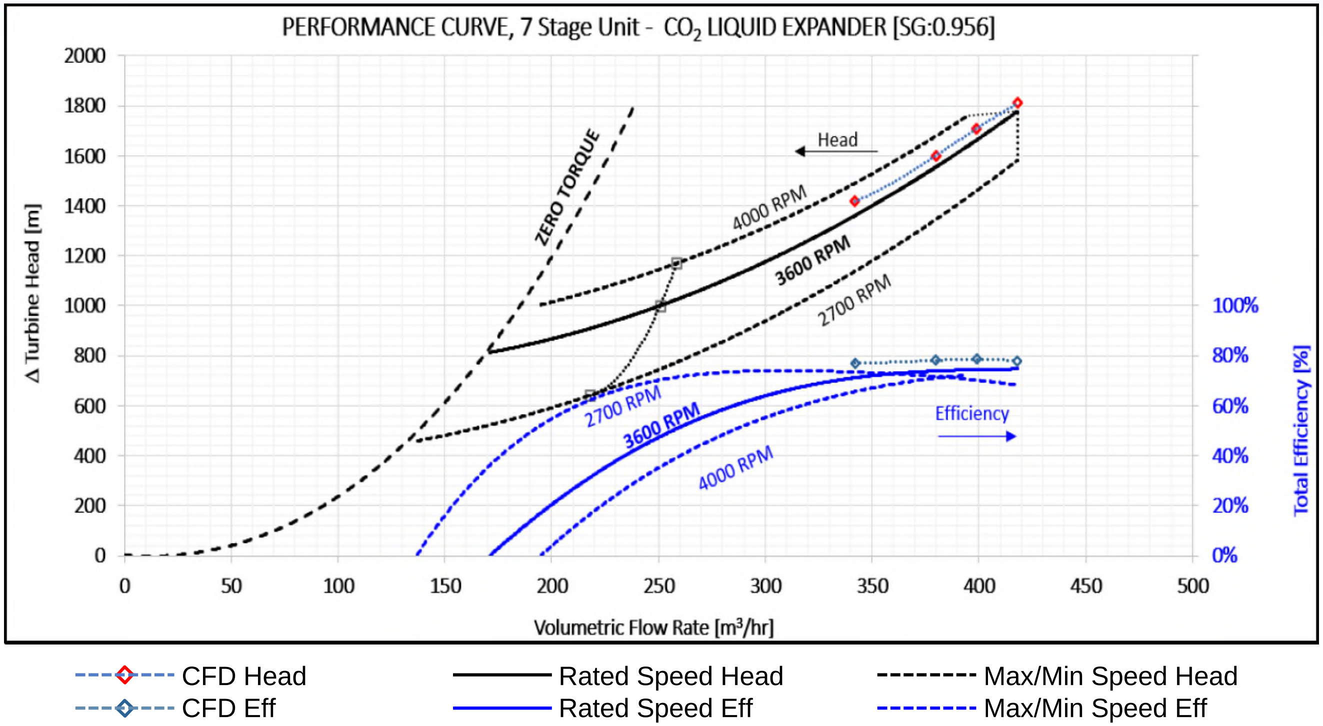
Absolute Velocity

- The figure to the right shows a three-dimensional absolute velocity plot to illustrate the momentum transfer.
- Angular momentum is increased across the nozzle vane as static pressure is converted to dynamic pressure.
- The fluid enters the runner with a significant amount of tangential (whirl) velocity, which is then transferred to the shaft as momentum (torque).
- Ideally, the fluid leaves the runner axially with minimal recirculation (swirl), as shown.



Expanders for CO_2 – Computational Fluid Dynamics

- The figure to the right shows actual test data compared to the CFD simulated performance for the expander.
- Differential head and efficiency for rated, maximum, and minimum speeds are shown.
- CFD performance predictions are slightly higher than actual test results.
- Performance discrepancy is attributed to the leakage and losses associated with the thrust balancing system, generator cooling, and stage back leakages.



Expanders for CO_2 – Conclusion

- **Increased global energy demand** has resulted in an **abundance of carbon dioxide (CO_2)** in the earth's atmosphere.
- Its **high power density** makes CO_2 a **viable working medium in power cycle applications**.
- Efficient **carbon capture, utilization, and storage (CCUS) is critical to the large-scale efficacy** of this thermal energy resource.
- Liquid and two-phase **expanders greatly improve the efficiency** of an expansion process, providing considerable **gains in liquid throughput** as well as **regenerated electrical power**.