The Aerodynamic Design of a Multiphase-Tolerant Turbine for an sCO2 Heat Pump

Supercritical CO_2 Energy Technologies Symposium 2026
Paper #013

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Development of a Multiphase-Tolerant Turbine for Pumped Thermal Energy Storage

Disclaimer

U.S. DEPARTMENT OF ENERGY

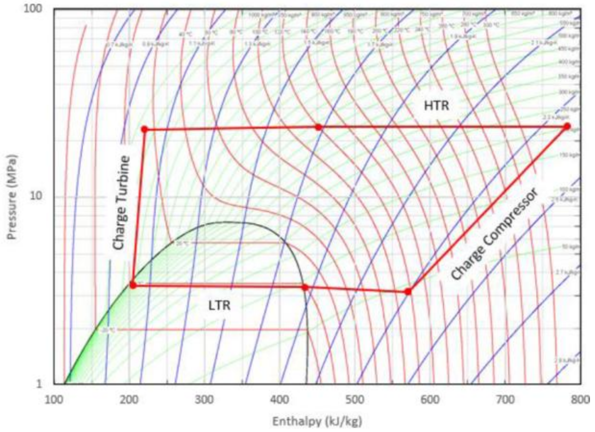
Award No. DE-EE0009815
Office of Energy Efficiency and Renewable Energy
under the Solar Energy Technologies Office

Project Partners:
Echogen & Flowserve

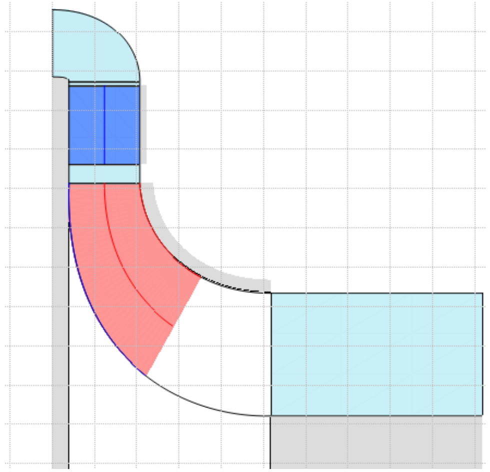
ECHOGEN power systems

FLOWSERVE

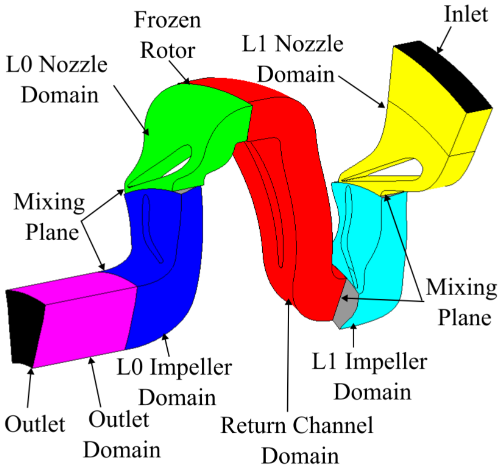
Motivation



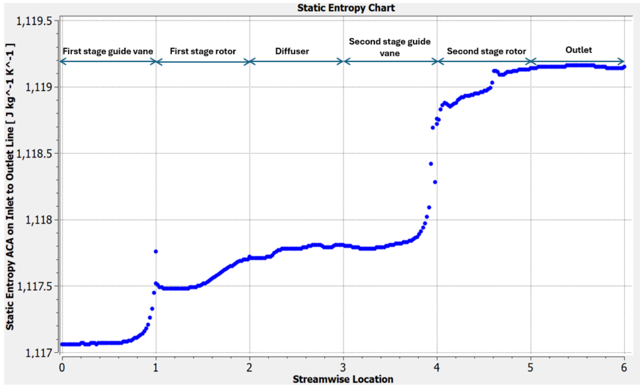
Geometry Design



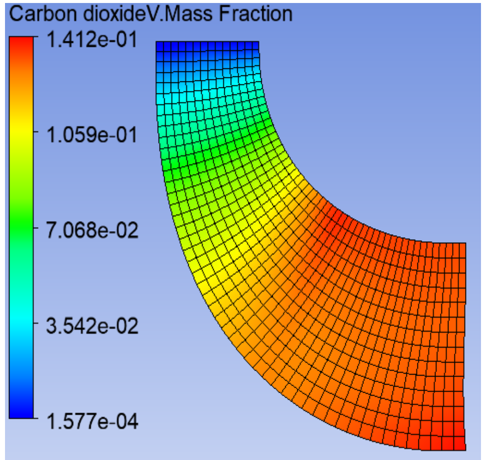
Computational Model



Results



Next Steps and Conclusion



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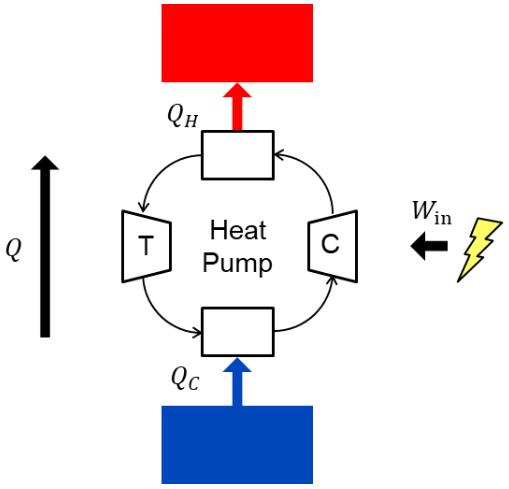
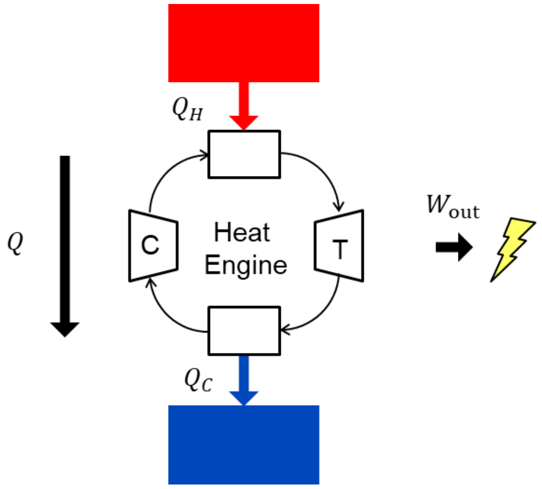
The case for pumped thermal energy storage (PTES)

"Pumped Heat", "Pumped Thermal", etc. …

Charge Mode
Use excess energy to run heat pump
& store energy in hot and cold reservoirs



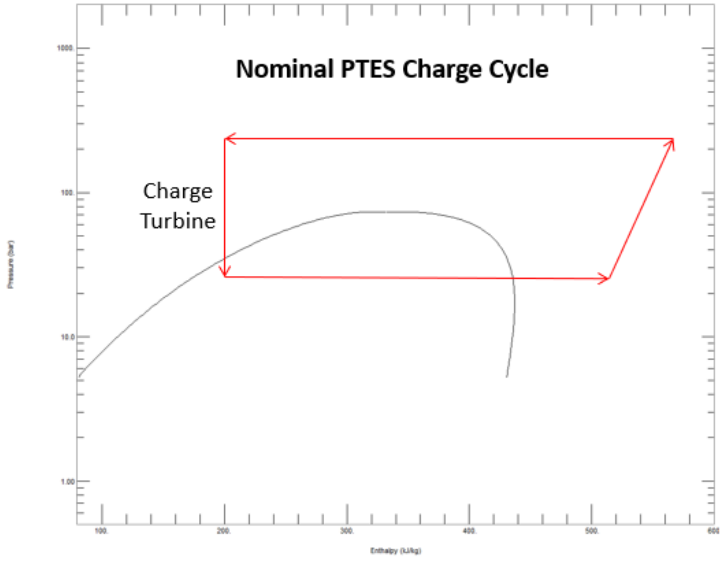
Discharge Mode
Use thermal reservoirs to run heat engine
& generate power



PTES Value Proposition

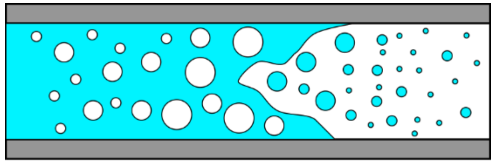
- 10+ hours of storage
- Separation of engine and storage
- Well-established component technologies
- Safer than other thermal-based ES technologies
- Potential for high round trip efficiency (RTE)

Multiphase CO2 turbines can improve cycle efficiency for pumped thermal energy storage, but are difficult to characterize

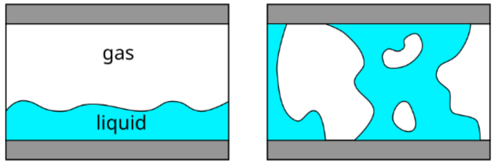


Why is a cold turbine difficult?

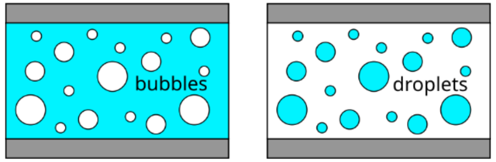
- **Multiphase flow**!
- Lack of validation data for loss models in this flow regime [1-3]
- Lack of turbine design experience in the open literature [4-5]



a) Transient two-phase flow.

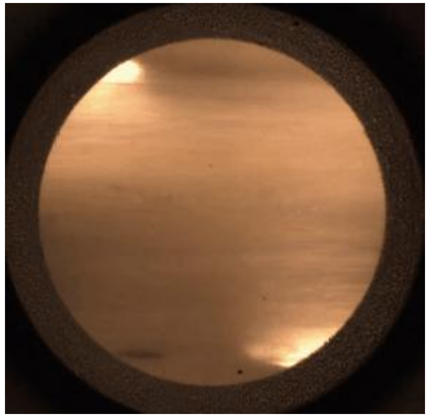


b) Separated two-phase flow.



[1]

c) Dispersed two-phase flow.



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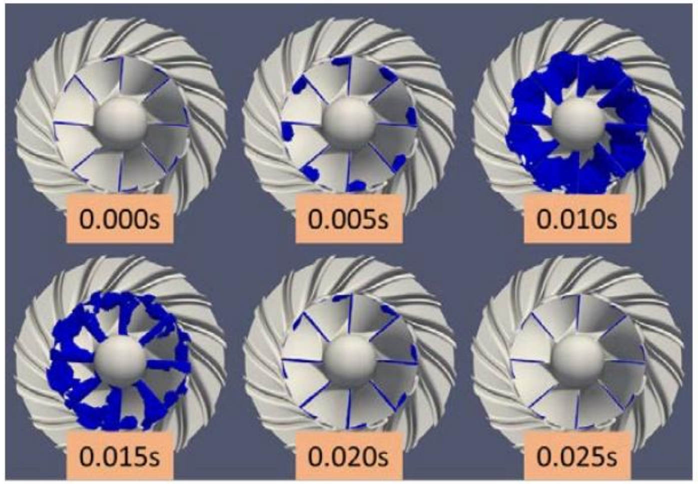

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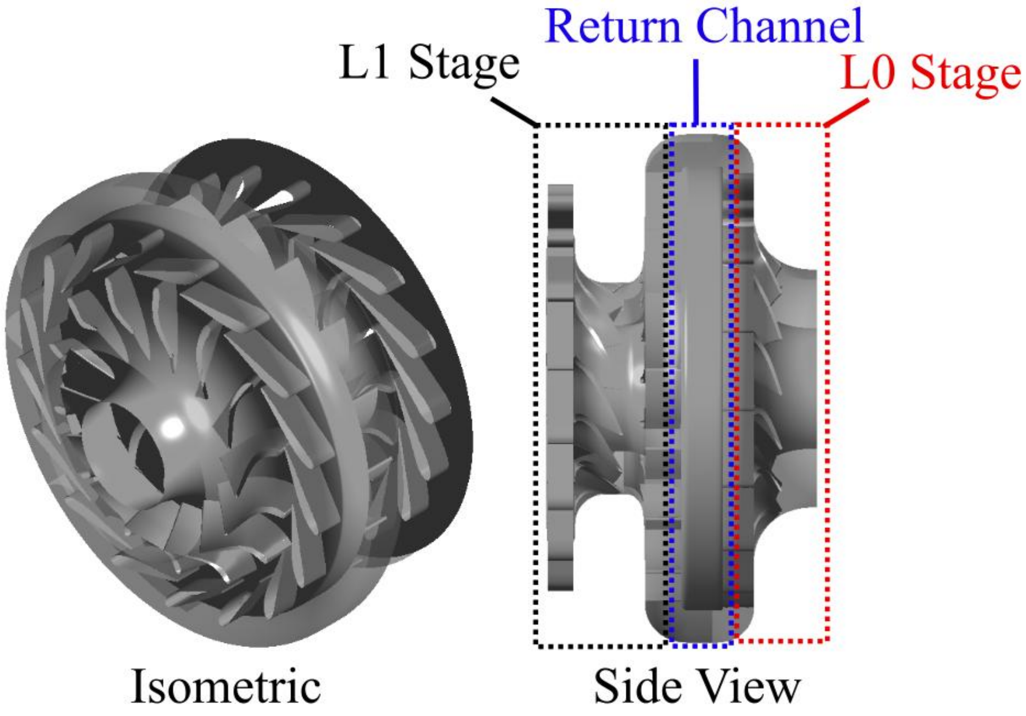
Multiphase-Tolerant CO_2 Turbine

Heat Pump Turbine Selection

- Seven stage synchronous radial liquid turbine
- Preferred cycle conditions require phase change occurs in the last stage (L0)

Turbine for this Study

- L0 was primary interest
- Final two stages are simulated (L1 and L0)
- Design updates only undertaken on final stage (L0)



L0 stage geometry design

Design Tools

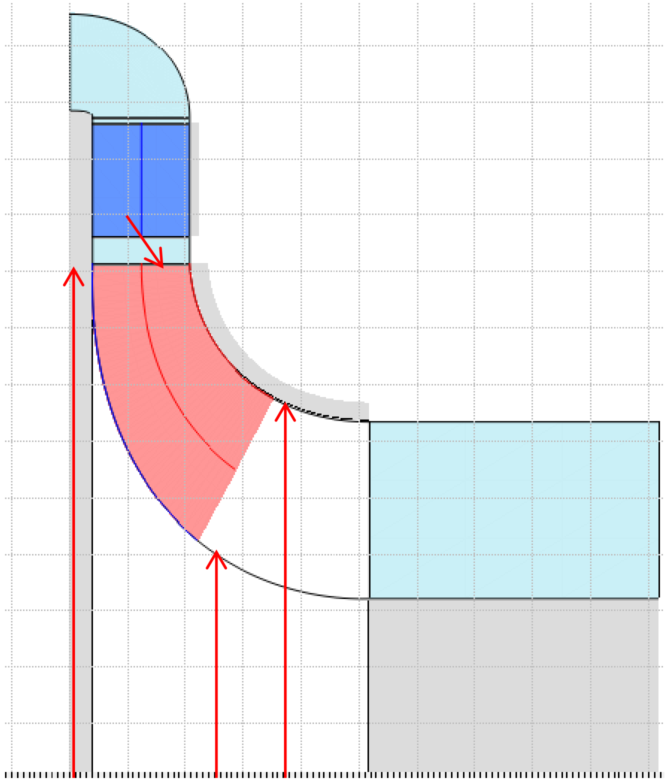
- Meanline analysis conducted using AxSTREAM to iterate on design geometry
- Real gas property tables utilized
- Multi-phase zones treated as a homogenous mixture

Boundary Conditions & Constraints

- L1 stage exit conditions used as inlet boundary conditions
  - Inlet flow angle, total pressure, and total temperature used
- Constrained by upstream geometry and outlet radius limits

Primary design parameters

- Stator exit and rotor inlet metal angles
- Rotor inlet diameter
- Exit hub and shroud diameter



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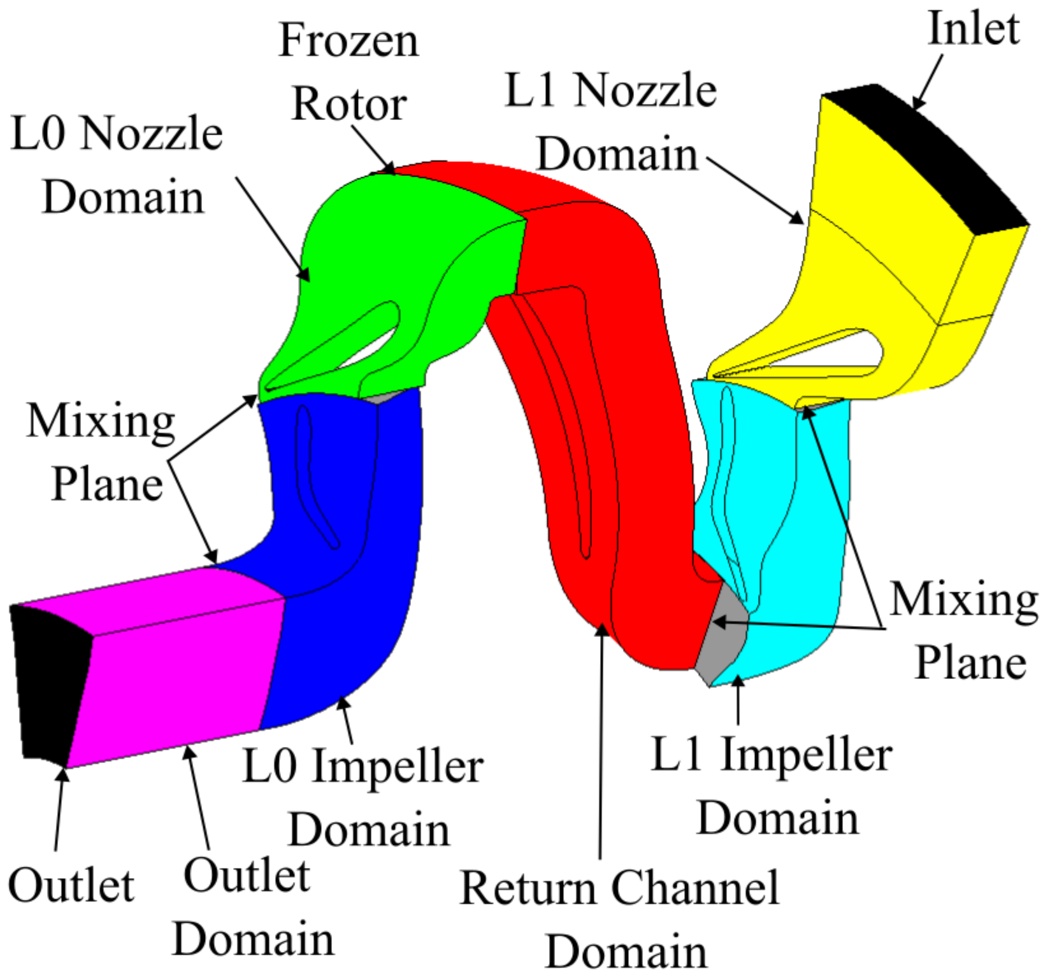
A single passage CFD model of the L1 and L0 stage was generated

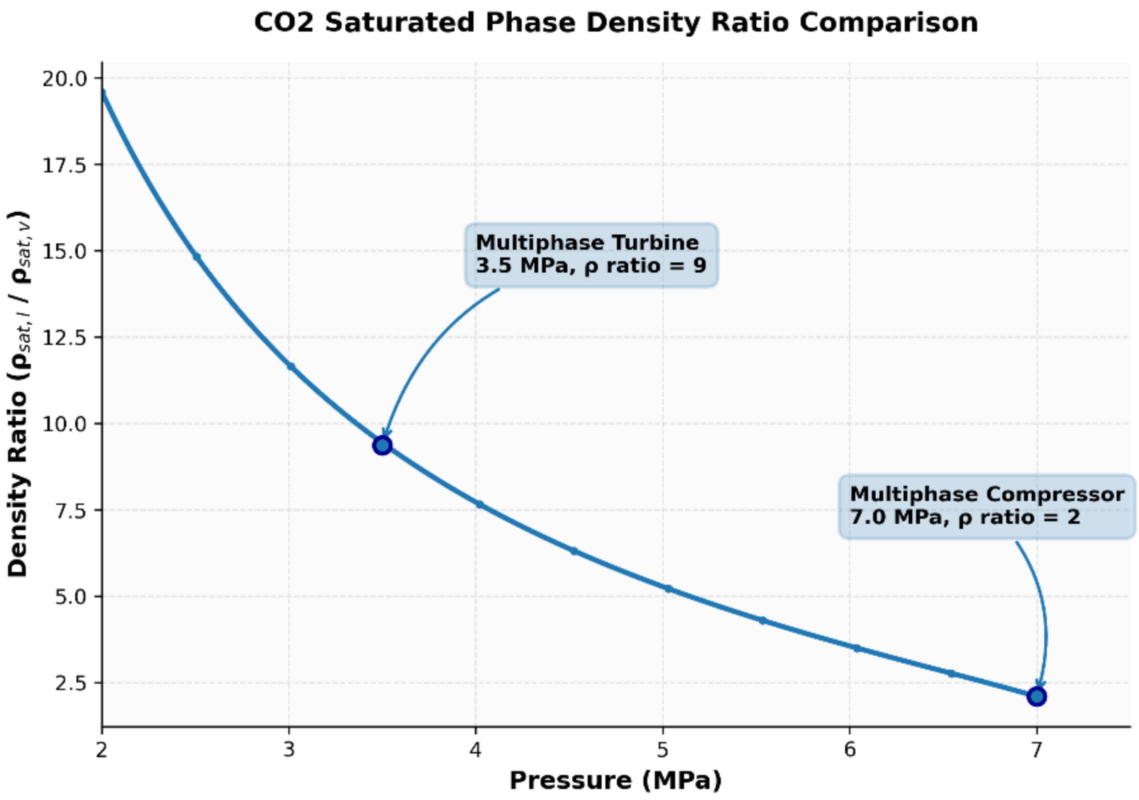
- ANSYS CFX 2024R2 used for all simulations
- Boundary conditions:
  - Static pressure at exit
  - Total pressure, total temperature, and mass fraction at inlet
- SST turbulence model utilized
- 6 million total elements with maximum y+ of 25



Multiphase fluid modelled using homogenous mixture

- For the design iteration cycle of the turbine, the homogenous mixture model was utilized
  - Higher order models are computational costly and can lead to numerical instabilities

- Homogenous modelling often justified for sCO_2 compressors
  - Density ratio for these machines can be as low as two near the critical region
  - This machine has a density ratio of approximately 9



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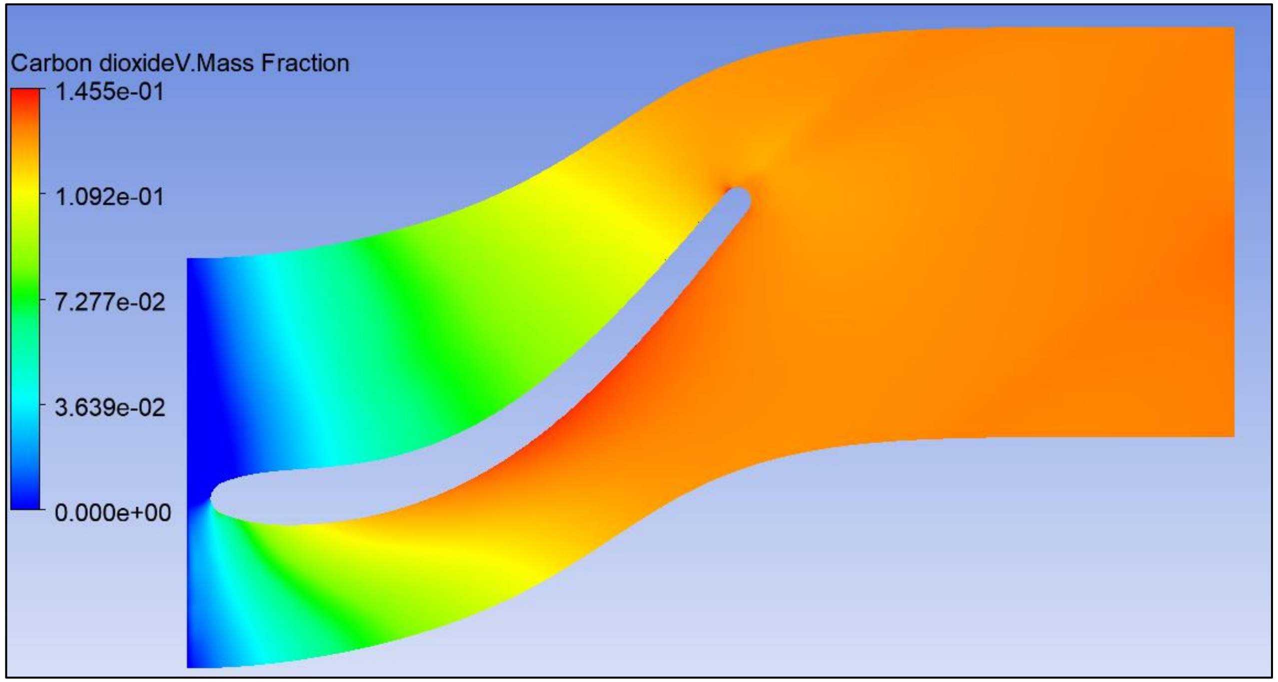
CFD results showed significant deviation from meanline

- Major discrepancy in flow angles at rotor leading and trailing edges
- Justifies use of CFD for further analysis of designs
  - CFD results were used to update stator and rotor metal angles in AxSTREAM
- Multiphase flow causes strong 3D gradients not captured in meanline analysis

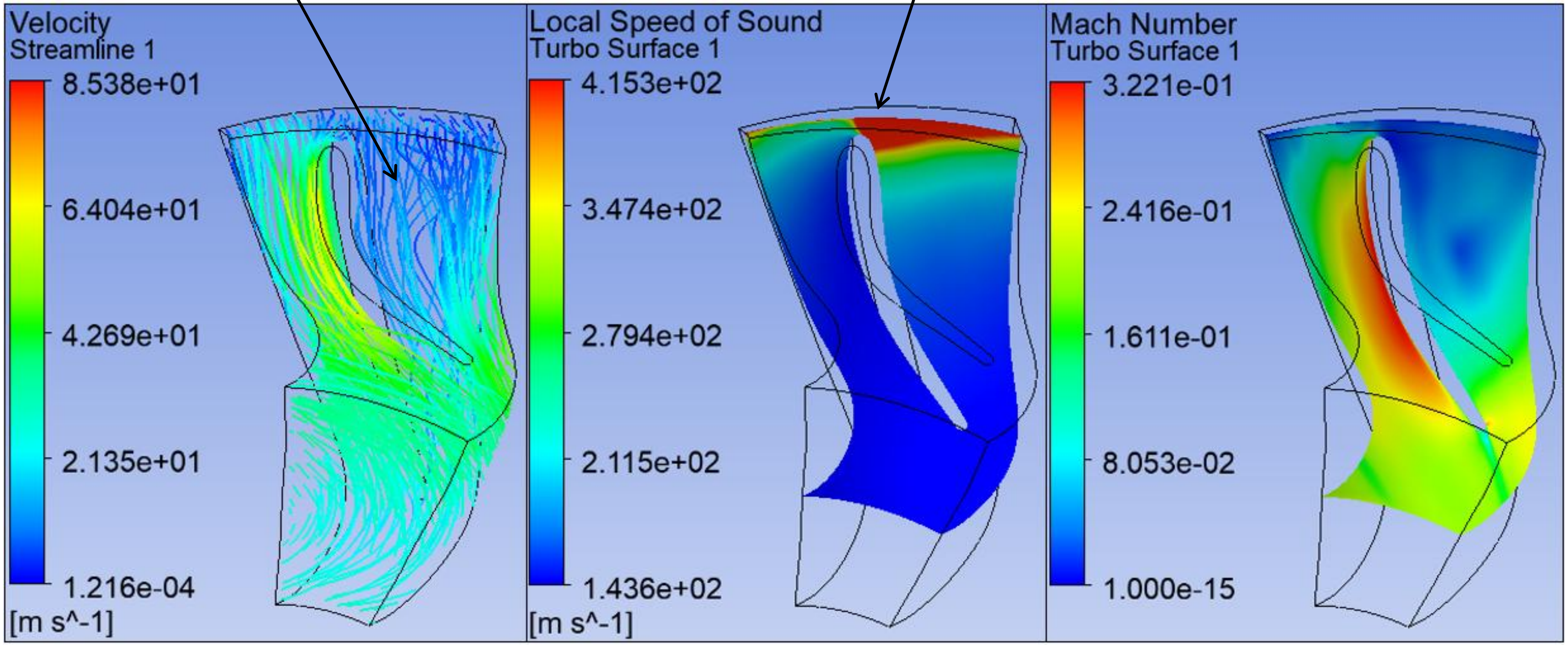
	Unit	Meanline	3D CFD
Mass flow	*kg/s*	336	369
Rotor inlet relative flow angle	*deg*	24	-2
Rotor exit swirl angle	*deg*	71	44
Isentropic efficiency	*%*	86.9	87.3

Vapor formation at leading edge cause of discrepancy

- Vapor formation initiated at the rotor leading edge at the design point
- Vaneless space size had significant impact of performance
  - This shifted the location of the vapor formation
  - Larger vaneless spaces improved performance
    - Potentially a limitation of using RANS CFD with mixing planes



Formation of vapor at impeller caused high positive incidence

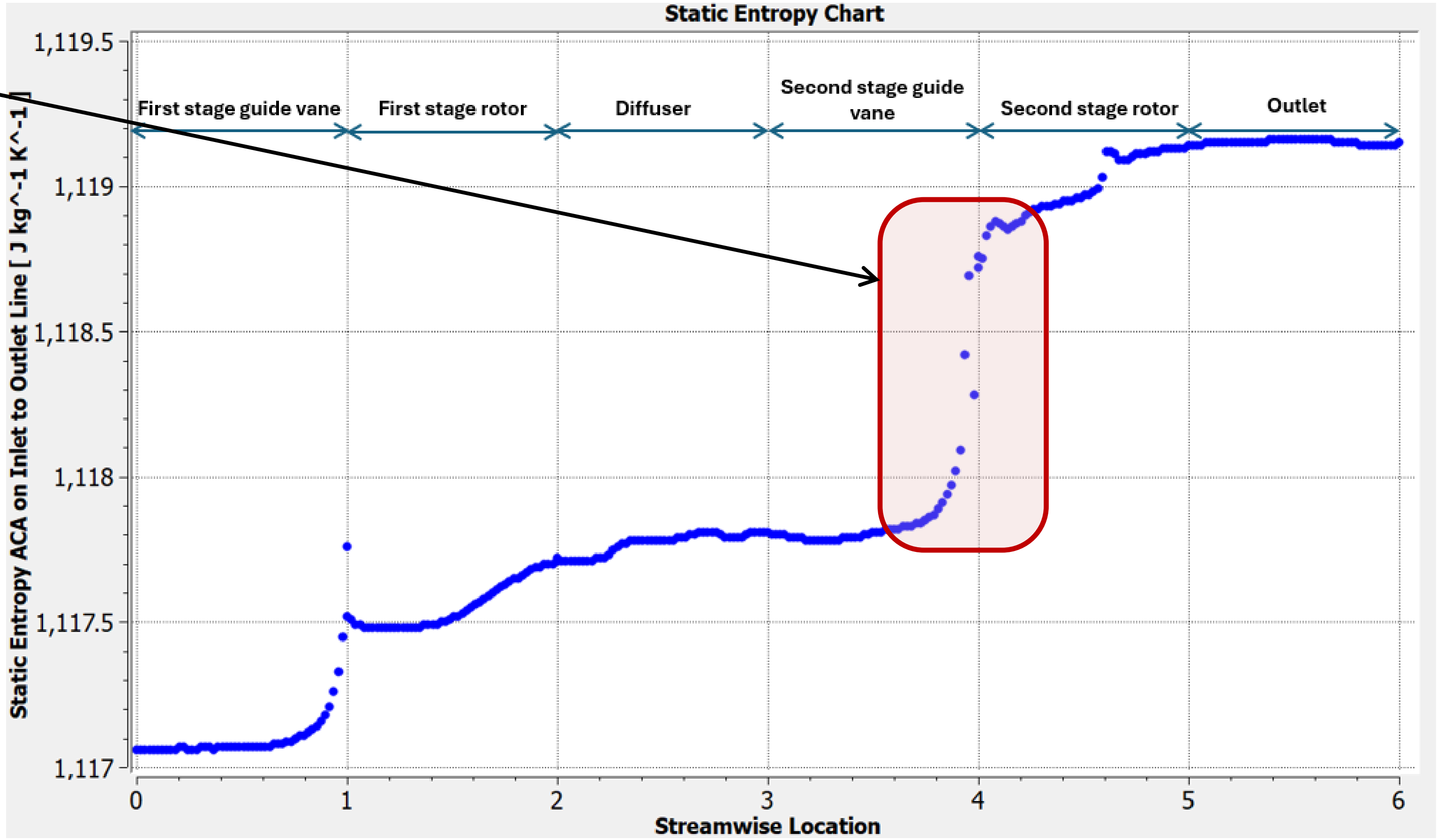


Significant recirculation on pressure side of rotor

Formation of vapor significantly reduced local speed of sound and density

Entropy through the 2-stages shows higher loss in second stage (L0)

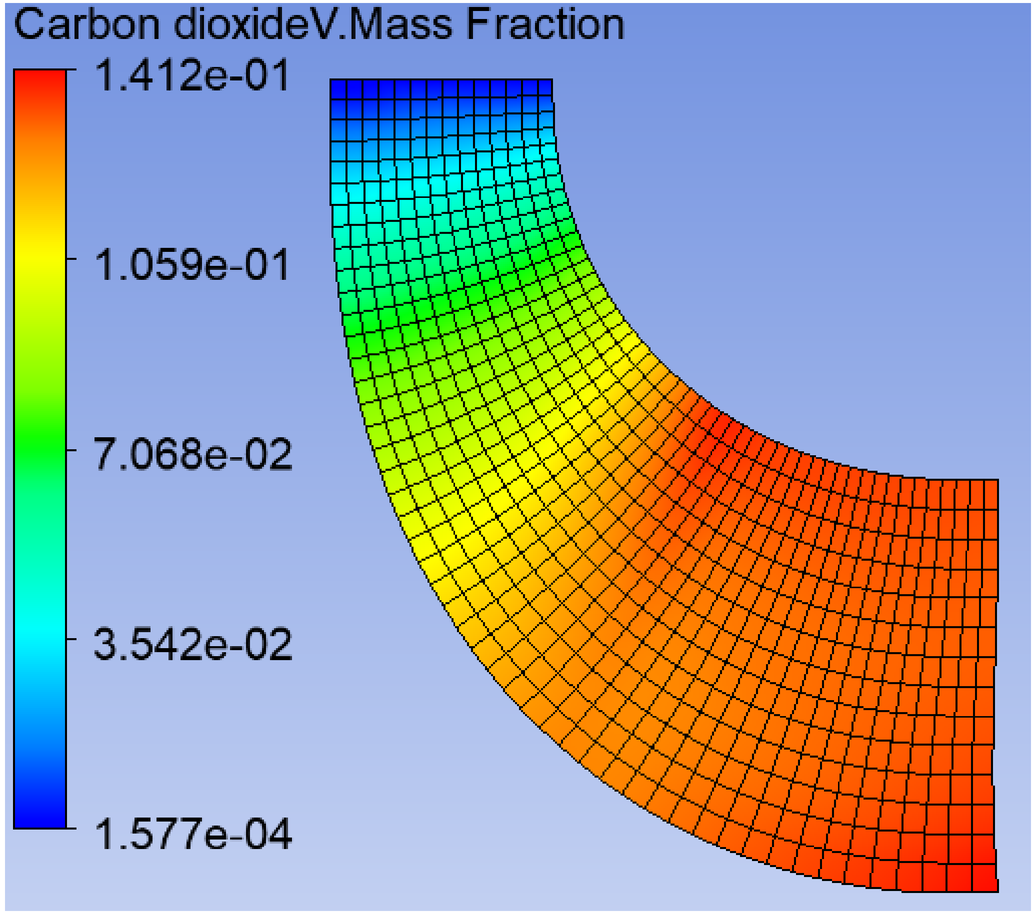
- Most loss generated in the machine at the L0 stage trailing edge
- Consistent across all boundary conditions and designs simulated
- Increasing the vaneless space reduced this loss
  - Likely an effect of RANS mixing plane interface
  - Vapor formation occurs near mixing plane



Minimal spanwise variation in phase noted in impeller

- Potentially due to the homogenous mixture model

- Rotor blade thickness distribution and metal angles were not significantly modified from baseline during design iterations



Final geometry performance and operating conditions

	Inlet	Outlet	Units
Density	833.0	440.0	[kg m^-3]
Vapor Mass Fraction	0.0046	0.1345	
Static Pressure	4823450	3465900	[Pa]
Total Pressure	6954830	3710800	[Pa]
Static Temperature	286.32	274.01	[K]
Total Temperature	289.09	276.77	[K]
Entropy	1118.58	1119.03	[J kg^-1 K^-1]
Relative Mach No.	0.03	0.21	

Isentropic Efficiency (Last Stage GV and Rotor)	87.29	[%]
Mass flow / Target Mass Flow	99	[%]
Rotor Incidence	-5	[degree]
Rotor Exit Swirl	44	[degree]

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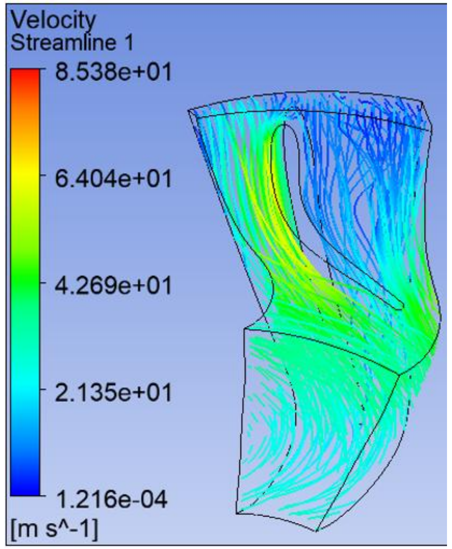
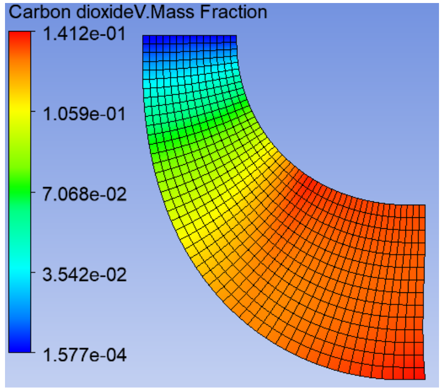
Multiphase-Tolerant Turbine Design Conclusions

- High efficiencies are achievable for a radial turbine even when entering the vapor dome
- Velocity triangles differ substantially from single phase machines
  - Phase change density variation alters incidence
- Meanline modelling cannot accurately predict multi-phase effects
  - Cannot capture 3D gradients, blockage, and density changes



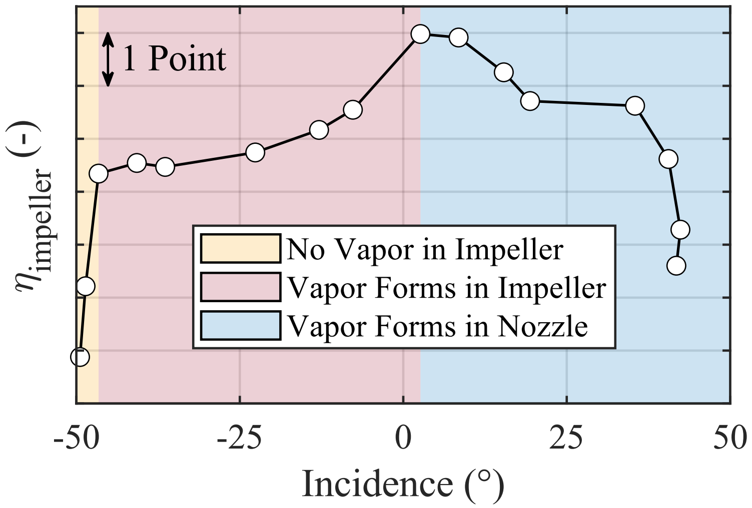


On-going & Future Work

- Performance mapping of final design using RANS and URANS simulations
  - Completed
  - To be presented at Turbo Expo 2026
  - Teasers shown

- Incorporate a higher order multiphase model into CFD simulations (late 2026)

- Scaled testing of the L1 and L0 stages for experimental validation (late 2027)



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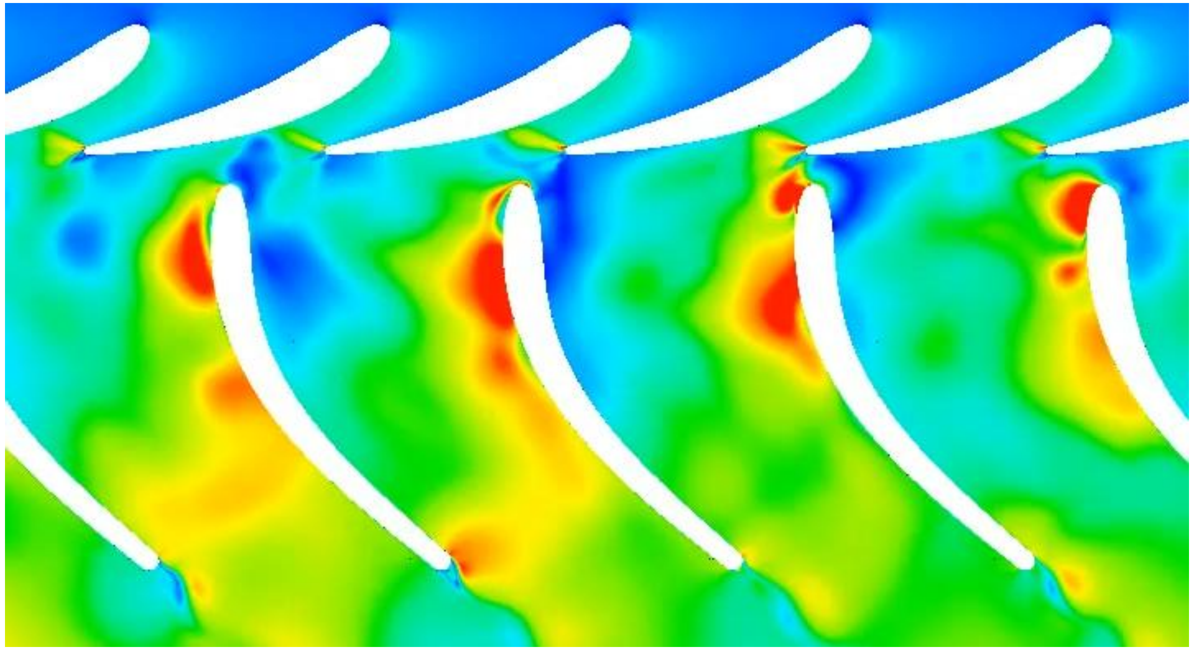

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