

 ERCOFTAC SPRING FESTIVAL 22.5.2025

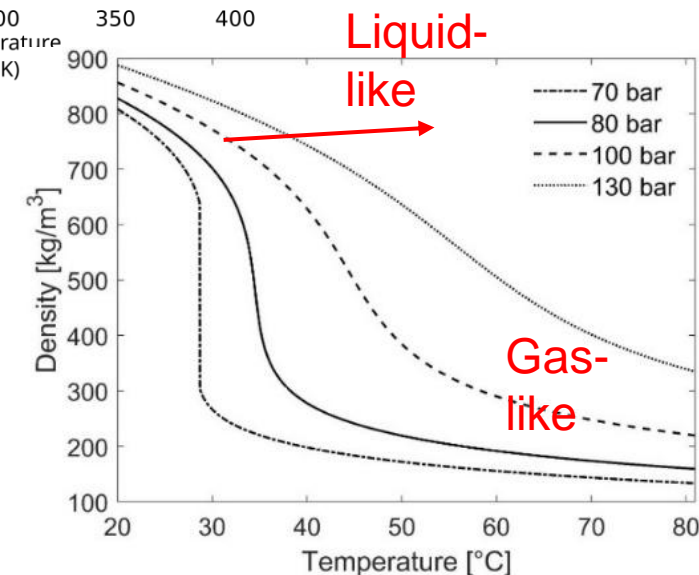
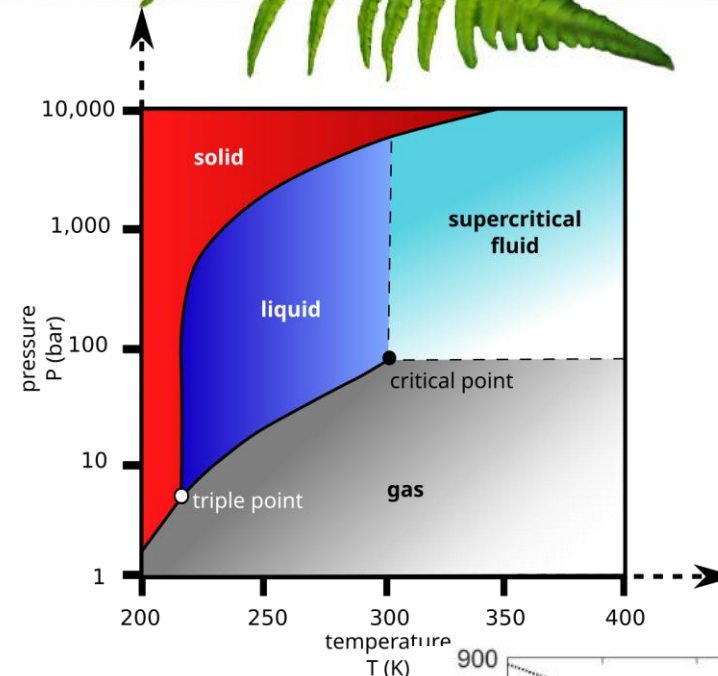
SUPERCRITICAL CO₂ FLOW AND HEAT TRANSFER FOR ENERGY CONVERSION APPLICATIONS

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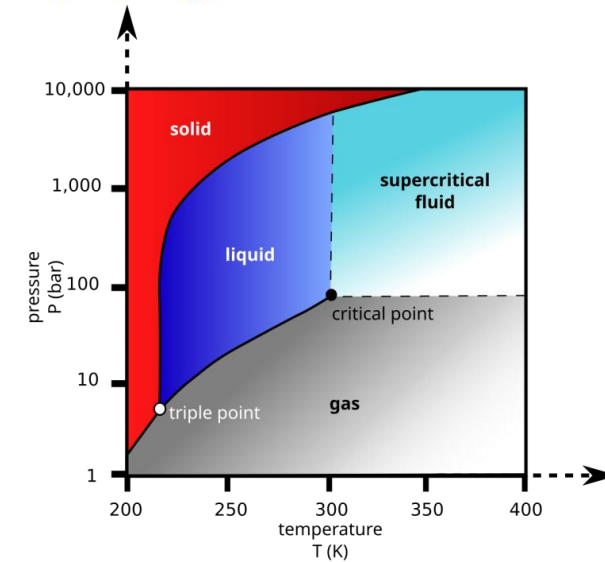
WHAT IS A SUPERCRITICAL FLUID?

- A supercritical fluid is any substance at a temperature and pressure above its critical point
- Distinct liquid and gas phases do not exist
 - High gradients of properties close the critical point and widom –line
- Key properties:
 - High density like liquids
 - Low viscosity like gases
 - Excellent heat transfer characteristics
 - No surface tension
- Behaves like real gas



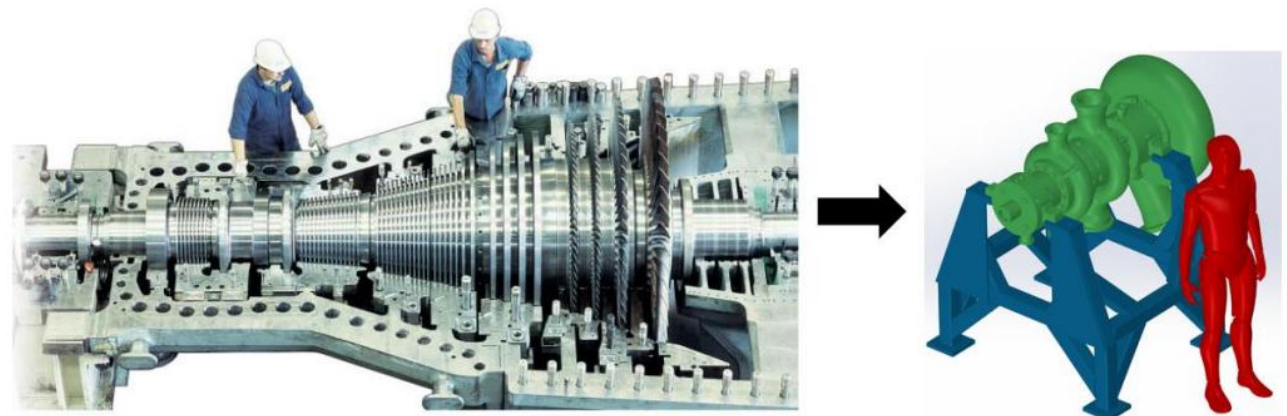
WHY SUPERCRITICAL CO₂ (sCO₂)?

- Moderate conditions for supercritical state
 - CO₂ critical point: 31°C and 74 bar
- Compact system design due to high density
- Availability and low cost
- Non-toxic
- Inert and non-flammable
- Excellent thermal stability



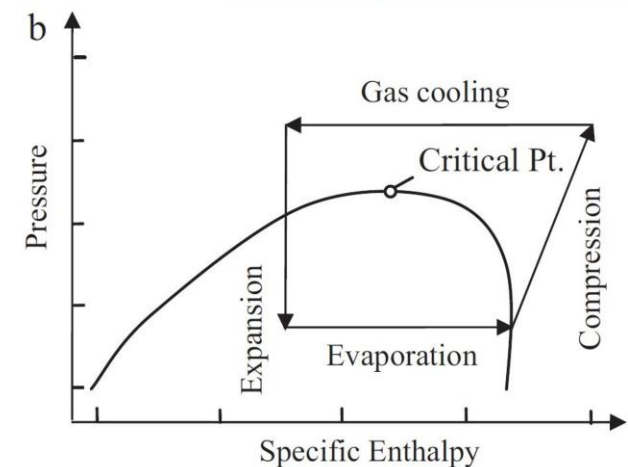
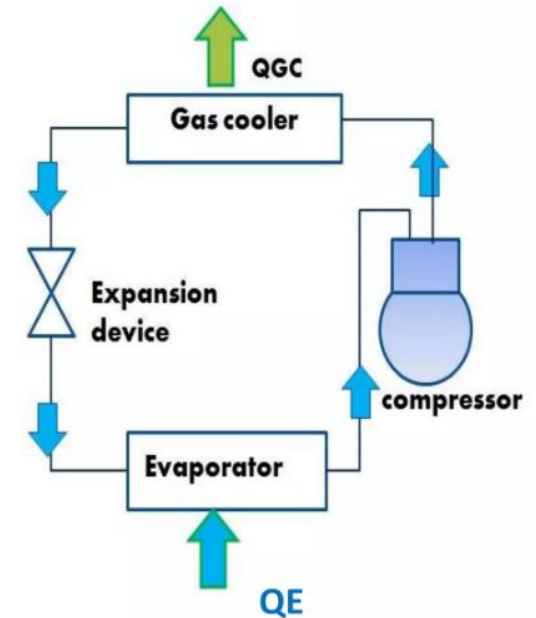
20 MW Steam Turbine

14 MW sCO₂ Turbine



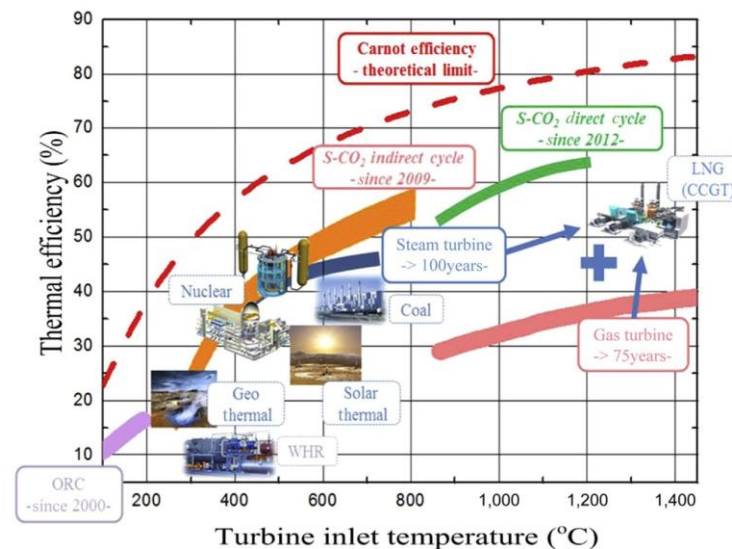
REFRIGERATION AND HEAT PUMPS

- Necessity of reducing or eliminating the use of conventional refrigerants:
 - Hydrofluorocarbons (HCFs)
 - Hydrochlorofluorocarbons (HCFCs)
 - Chlorofluorocarbons (CFCs)
- CO₂ (R744) is a leading natural refrigerant
- Transcritical refrigeration cycle layout
 - Heat rejection at supercritical pressures
- Commercially available
 - Technology is becoming standardized, costs are decreasing
- Safe and environmentally friendly

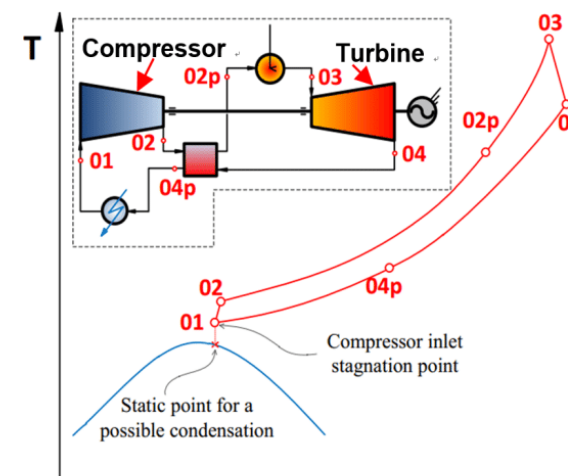


SCO₂ POWER CYCLES

- » sCO₂ can be used for power generation
 - » sCO₂ Brayton cycle
- » Wide range of applications
 - » Nuclear
 - » Concentrated solar power (CSP)
 - » Fossil fuel
 - » Waste heat recovery
- » Compact turbomachines and heat exchangers
- » Simple system configuration
- » High cycle efficiency
 - » Low compression work
- » Reduced emissions
- » Potential for carbon capture and utilization (CCU)
 - » Allam cycle



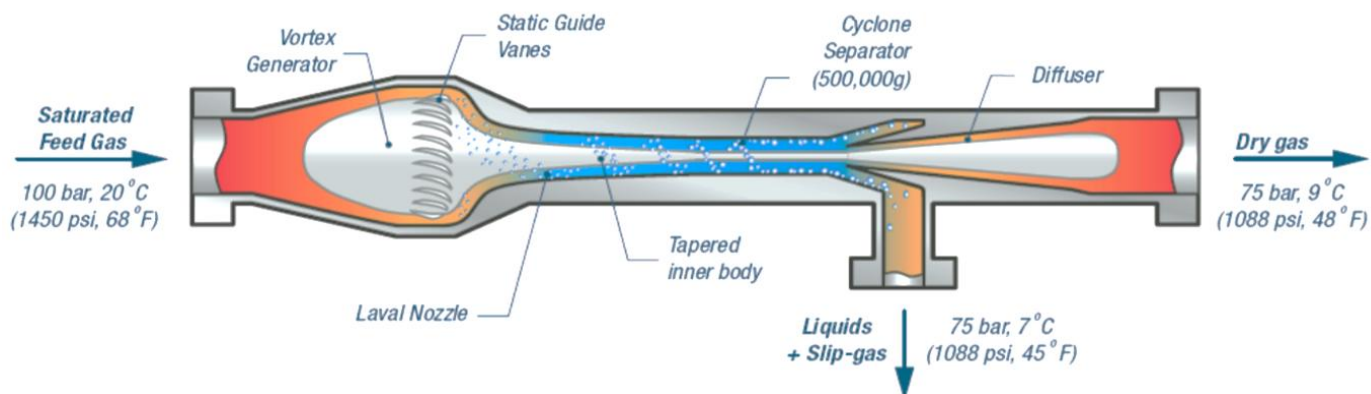
Ahn et al. (2015). *Review of Supercritical CO₂ power cycle technology and current status of research and development.*



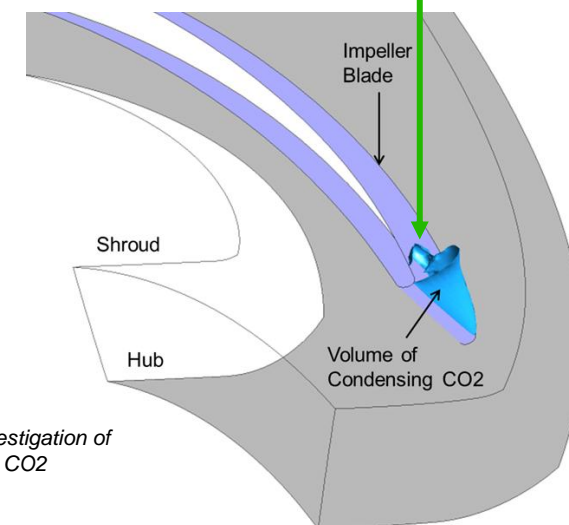
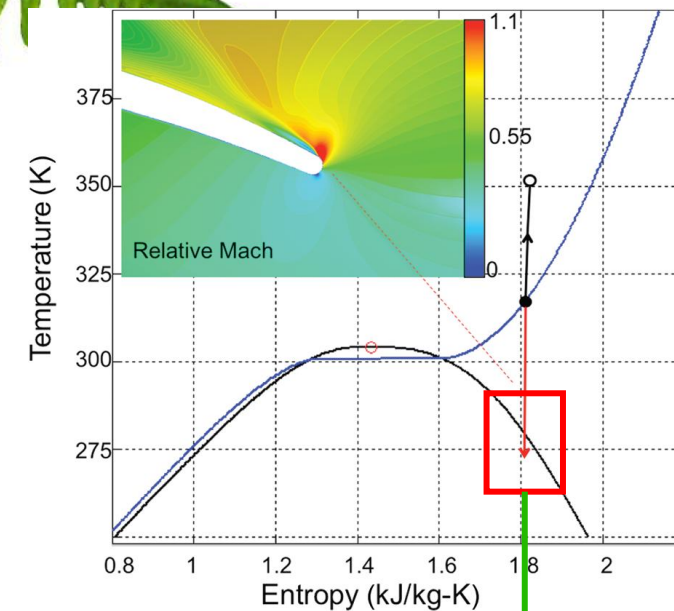
Zhu et al. (2018). *Numerical study of super-critical carbon dioxide flow in stepped-staggered labyrinth seals.*

2-PHASE CO₂ FLOWS

- Centrifugal compressors in sCO₂ power cycles
- Supersonic separators in Carbon Capture and Storage (CCS)
- Supersonic ejectors enhance the performance of transcritical refrigeration cycles

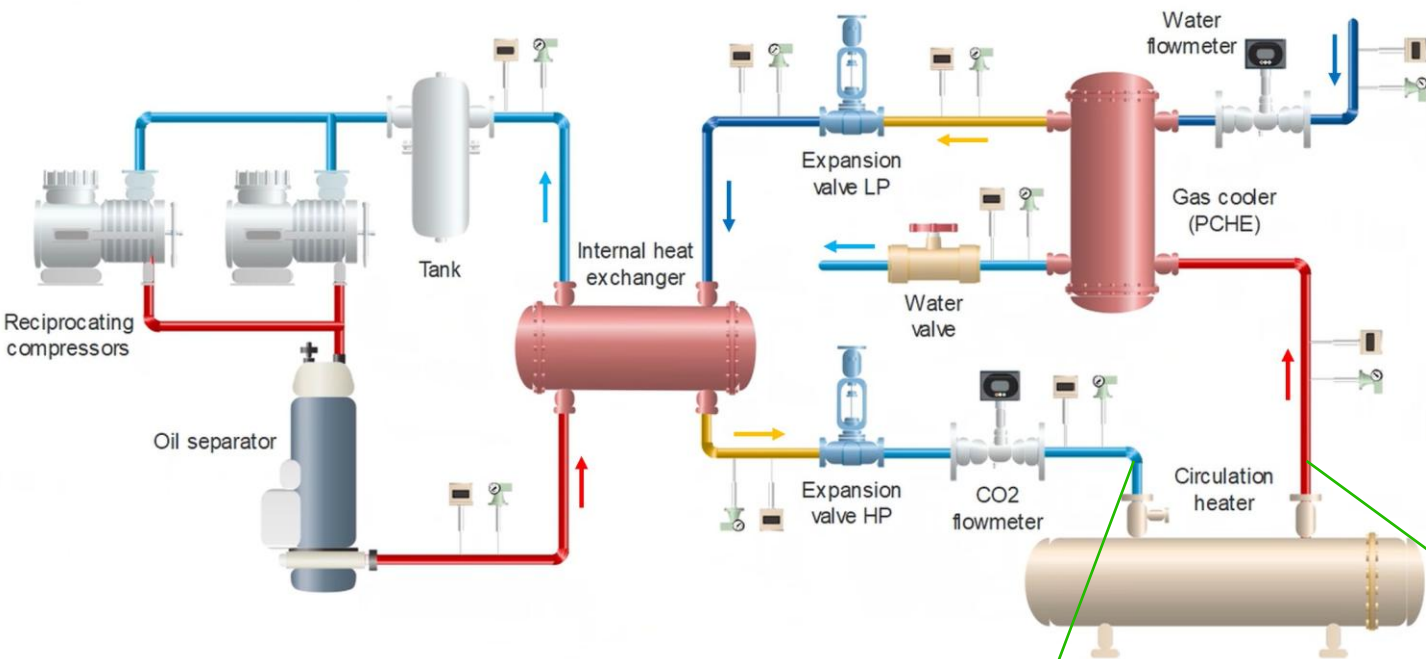


Pires et al. (2017). Numerical study of flow inside supersonic separators.



Baltadjiev et al. (2017). An investigation of real gas effects in supercritical CO₂ compressors.

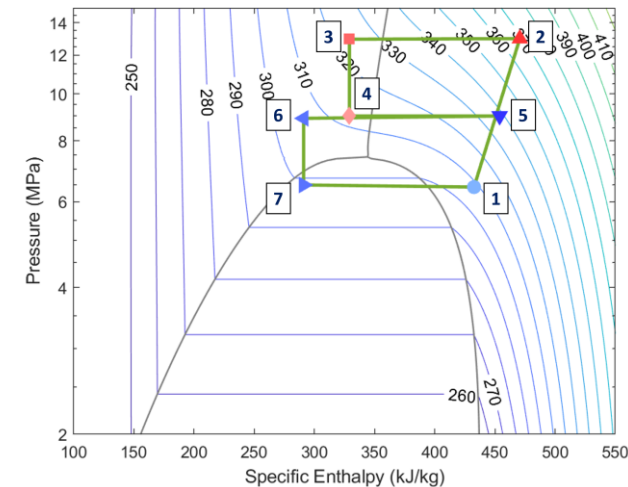
SCO₂ TEST RIG AT LUT UNIVERSITY



Design constraints:

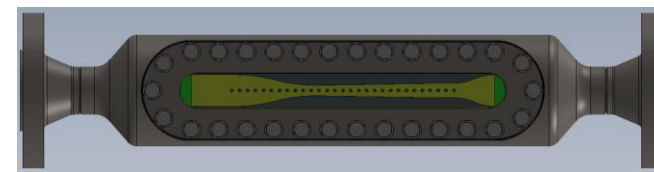
- » Budget
- » Facility dimensions
- » Power required
- » Choked flow (depends on nozzle dimensions)

Transcritical CO₂ refrigeration cycle



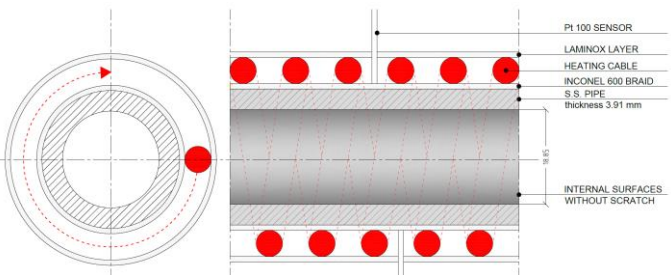
Supersonic test section

- » Expansions from supercritical conditions with non-equilibrium condensation

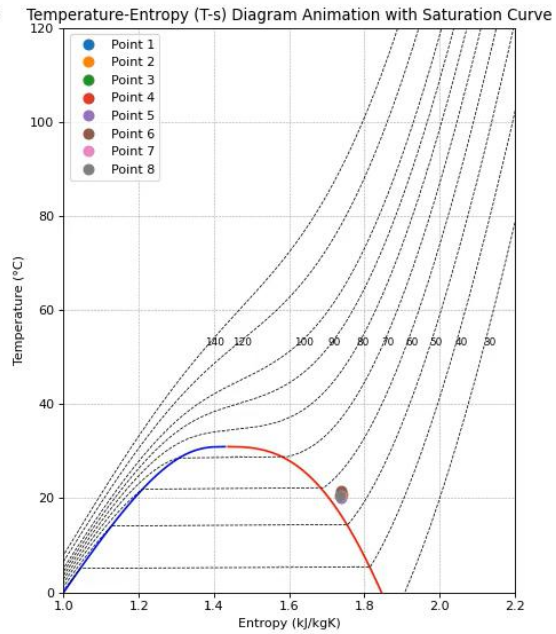
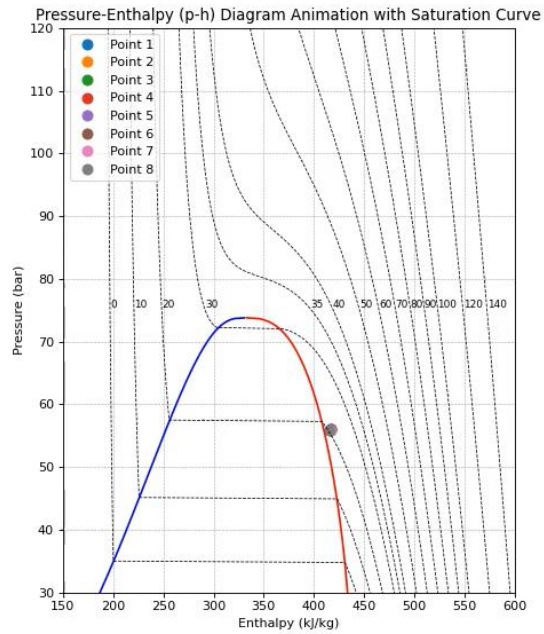


Heating test section

- » Supercritical heat transfer in a pipe

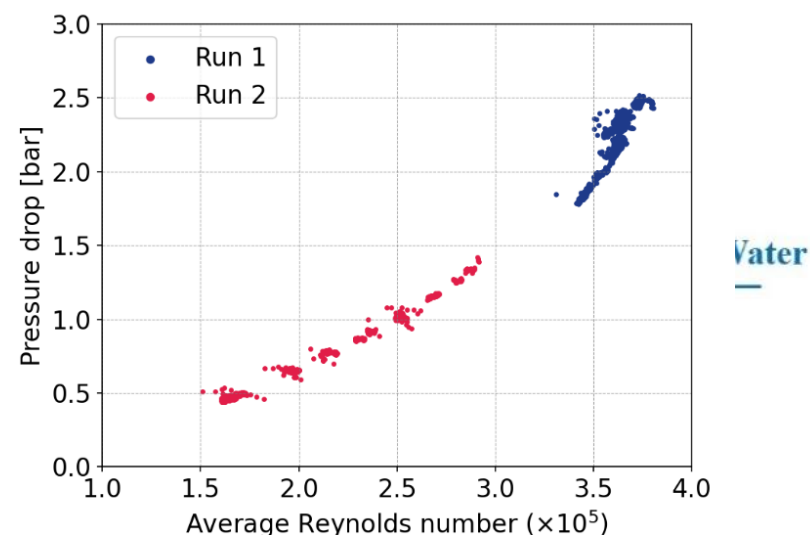
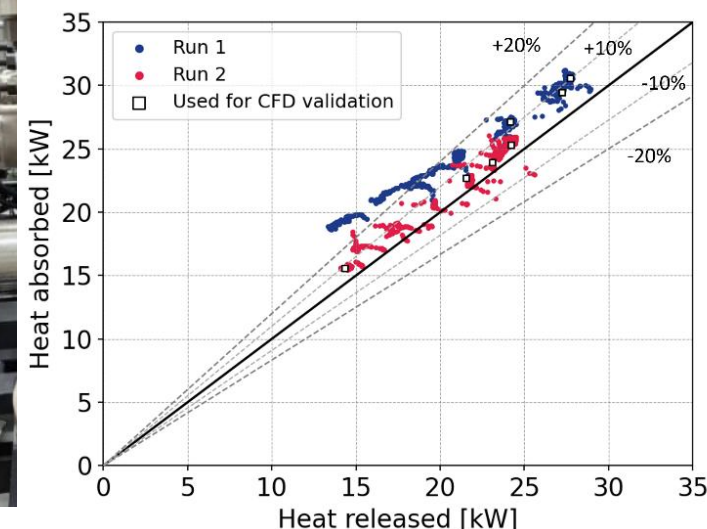
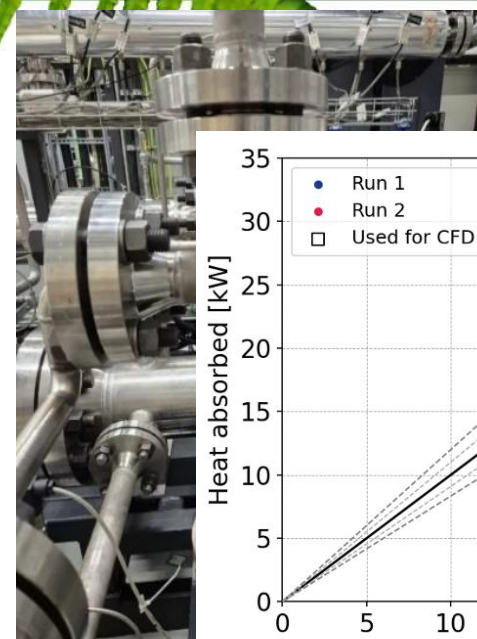


SCO₂ TEST RIG AT LUT UNIVERSITY



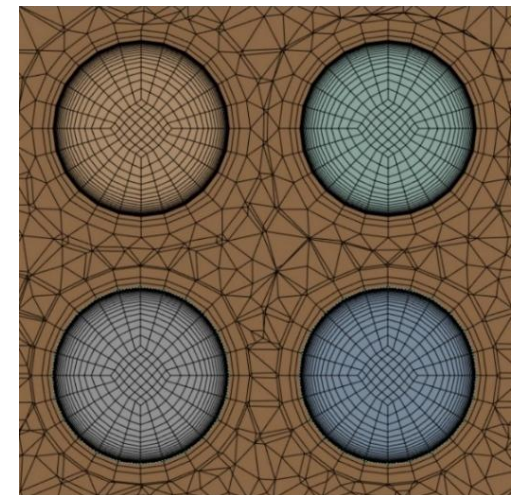
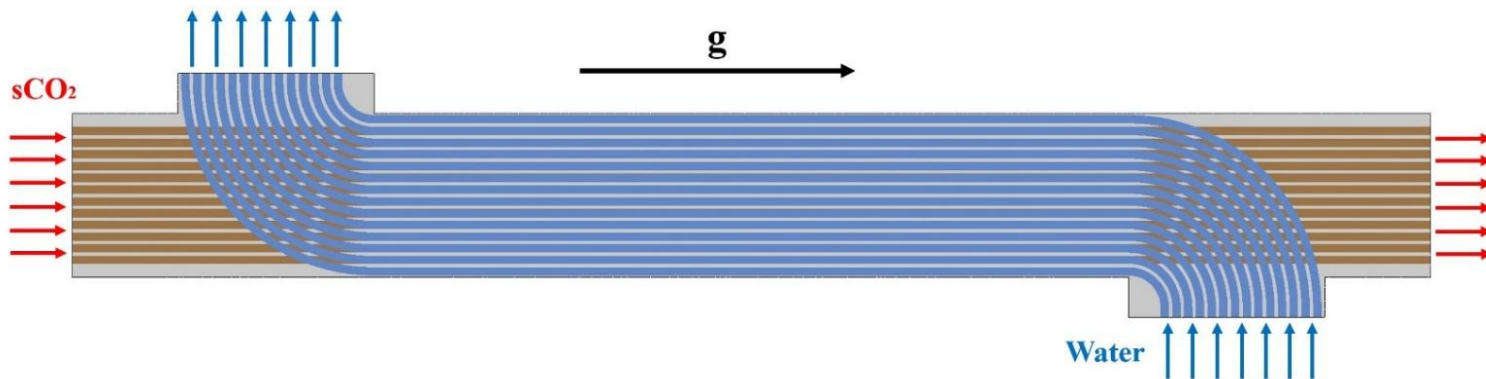
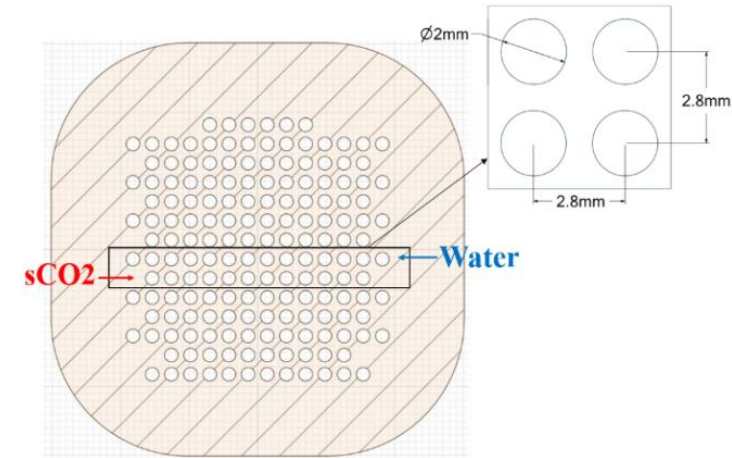
EXPERIMENTAL DATA ANALYSIS

- » Two separate test runs to cover a wide range of operating conditions
- » Measurements and sensor accuracy:
 - » CO₂ mass flow rate – Coriolis flowmeter ($\pm 0.25\%$)
 - » Pressures – high-pressure transmitters ($\pm 0.1\%$)
 - » Temperatures – PT100 sensors ($\pm 0.1\text{K}$)
 - » Water mass flow rate – paddle wheel sensor ($\pm 1\%$)
- » Each sensor was connected to a data acquisition system
 - » Sampling rate of 2 samples per second.
- » Data filtering: quasi-steady conditions
 - » Percentage variations of operating conditions lower than 0.1% compared to the previous recorded time step
- » Low noise levels: smaller than sensor accuracies



NUMERICAL SETUP – GEOMETRY AND MESH

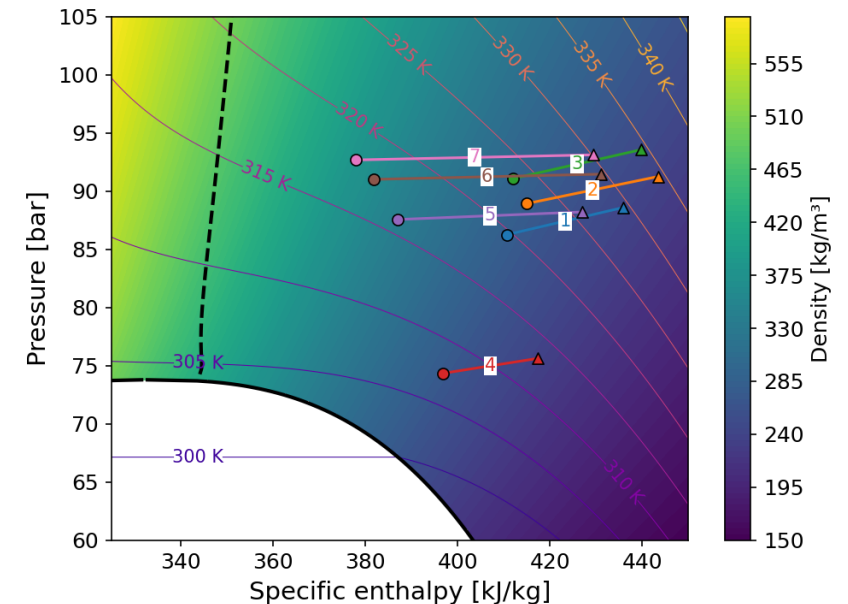
- Only one row for each fluid was simulated to minimize computational effort
 - 12 channels for the sCO₂
 - 14 channels for the cooling water
- Periodic boundary conditions were applied at the top and bottom surfaces
- Conformal mesh at the fluid-solid interface
- First layer thickness near the wall was small enough to obtain a y^+ value below one
 - Large property variations across the pseudo-critical line
- Grid-independent mesh containing 13.5 millions elements



NUMERICAL SETUP

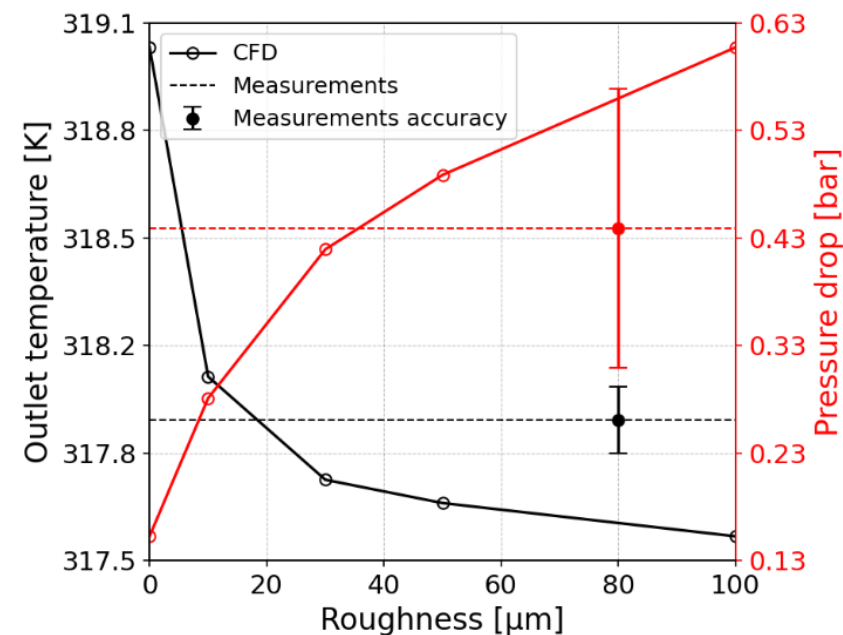
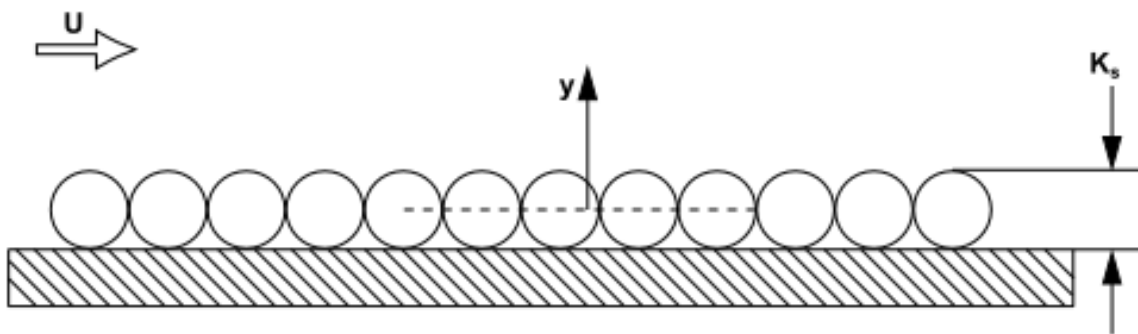
- Seven cases were selected for numerical validation
 - Steady-state flow within the sCO₂ setup
 - Small measured energy imbalances
- Property look-up tables were generated from NIST Refprop in Ansys Fluent
- Pseudo-transient pressure-based coupled solver
- Two-equation $k-\omega$ SST turbulence model for closure of RANS
- Boundary conditions for both hot and cold fluids:
 - Mass flow rate and total temperature at the inlet
 - Static pressure at the outlet

Parameter	Range
CO ₂ mass flow rate [kg/s]	0.44 – 0.97
CO ₂ mass flux [kg/m ² s]	1823 – 4064
CO ₂ bulk temperature [K]	307.0 – 334.7
CO ₂ pressure [bar]	73.8 – 92.3
CO ₂ Reynolds number	$1.5 \cdot 10^5$ – $3.7 \cdot 10^5$
Water mass flow rate [kg/s]	1.26 – 1.95
Water bulk temperature [K]	286.3 – 291.4



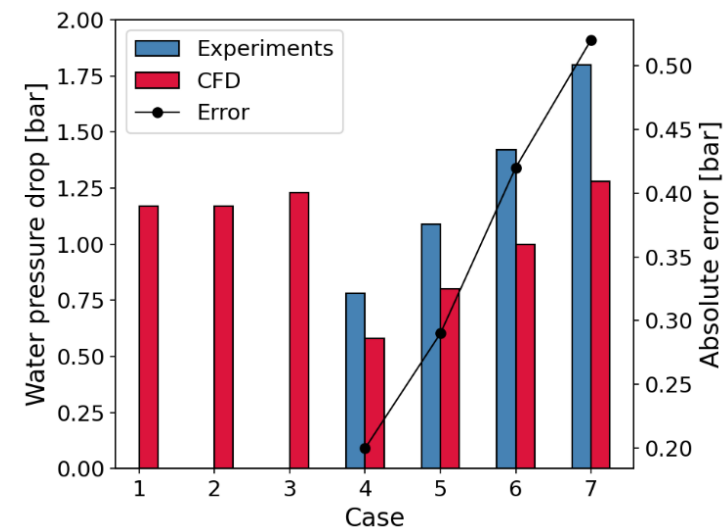
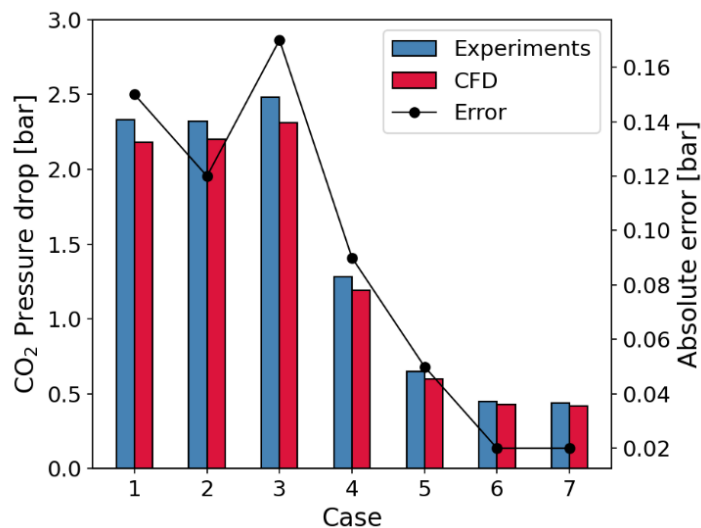
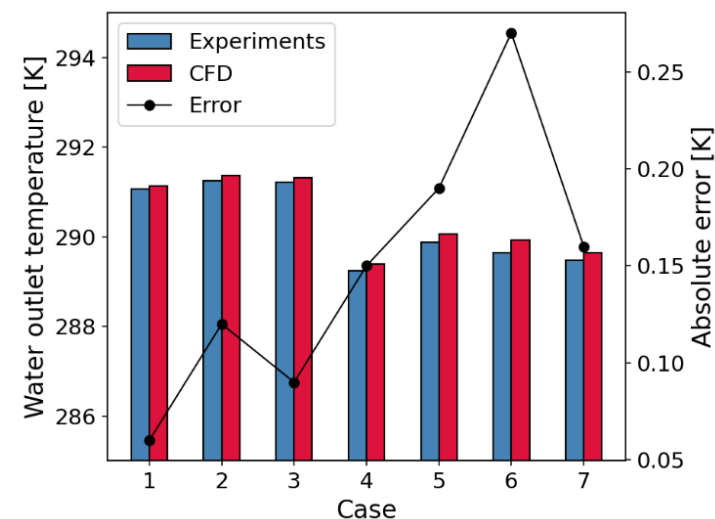
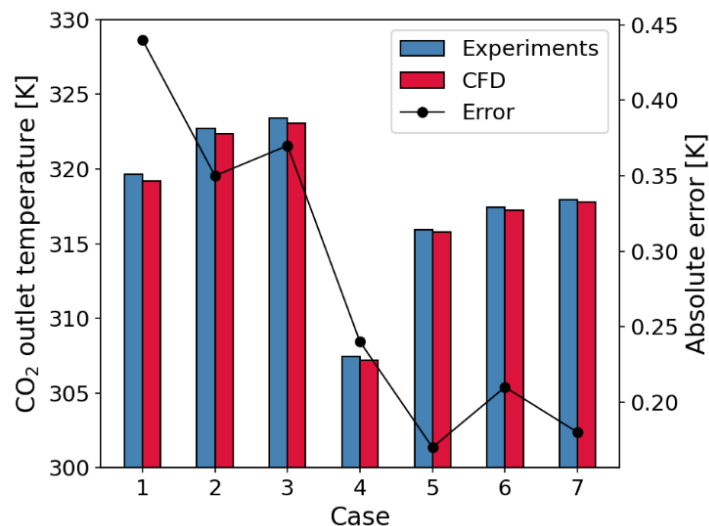
WALL ROUGHNESS EFFECTS

- One test case was simulated applying different roughness heights (K_s)
 - 0, 10, 30, 50, and 100 μm
- Large variations in sCO_2 outlet temperature and pressure drop
 - Particularly between 0 and 30 μm
- A roughness height of 30 μm was chosen as a trade-off between heat transfer and wall friction errors



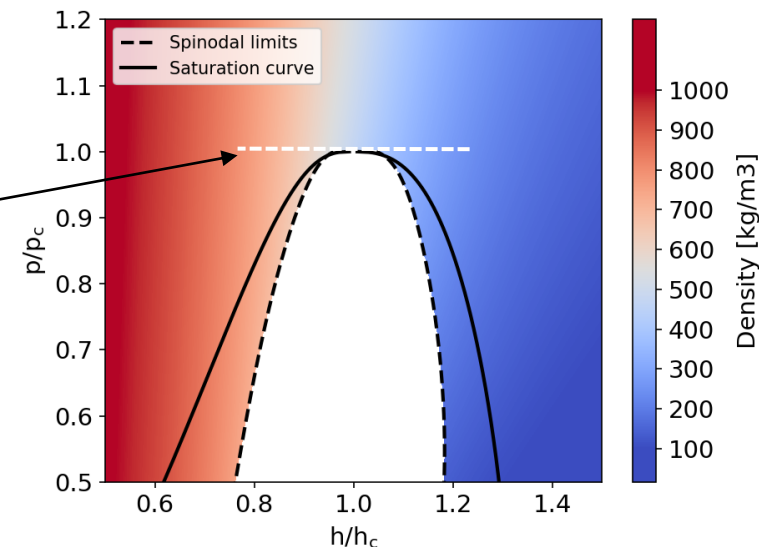
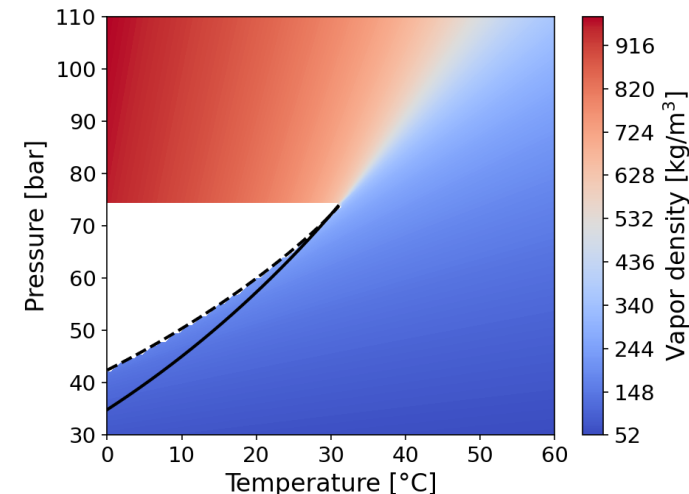
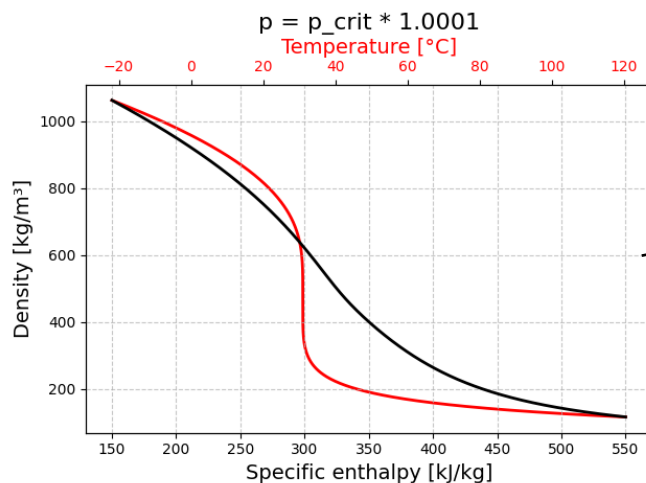
CFD VALIDATION

- Outlet temperatures and pressure drops were compared between CFD and experiments
- Small temperature (up to 0.44 K) and pressure drop (up to 0.17 bar) errors on the CO₂ side
- The pressure drop on the water side was not measured for the first cycle run
- Water pressure drops are consistently underpredicted by CFD for all cases



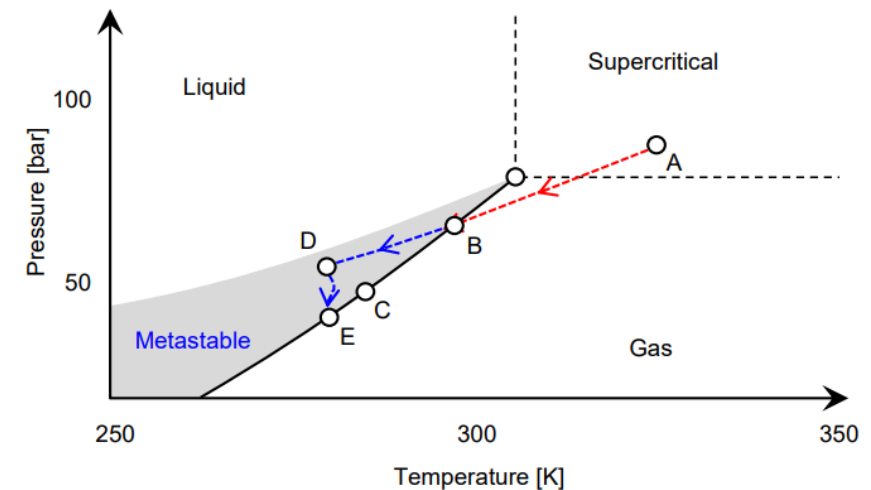
SCO₂ PROPERTIES IN NUMERICAL SIMULATIONS FOR 2-PHASE FLOWS

- sCO₂ properties can be calculated using thermodynamic libraries (e.g., Refprop) and stored in lookup tables
 - Solving the Span-Wagner EoS is computationally expensive
 - Lookup tables interpolation is significantly faster (10x to 100x)
- Calculation of metastable properties through EoS extrapolation
- Reduced property gradients using specific enthalpy as independent variable, rather than temperature
 - Possibility of uniform grids with high-accuracy

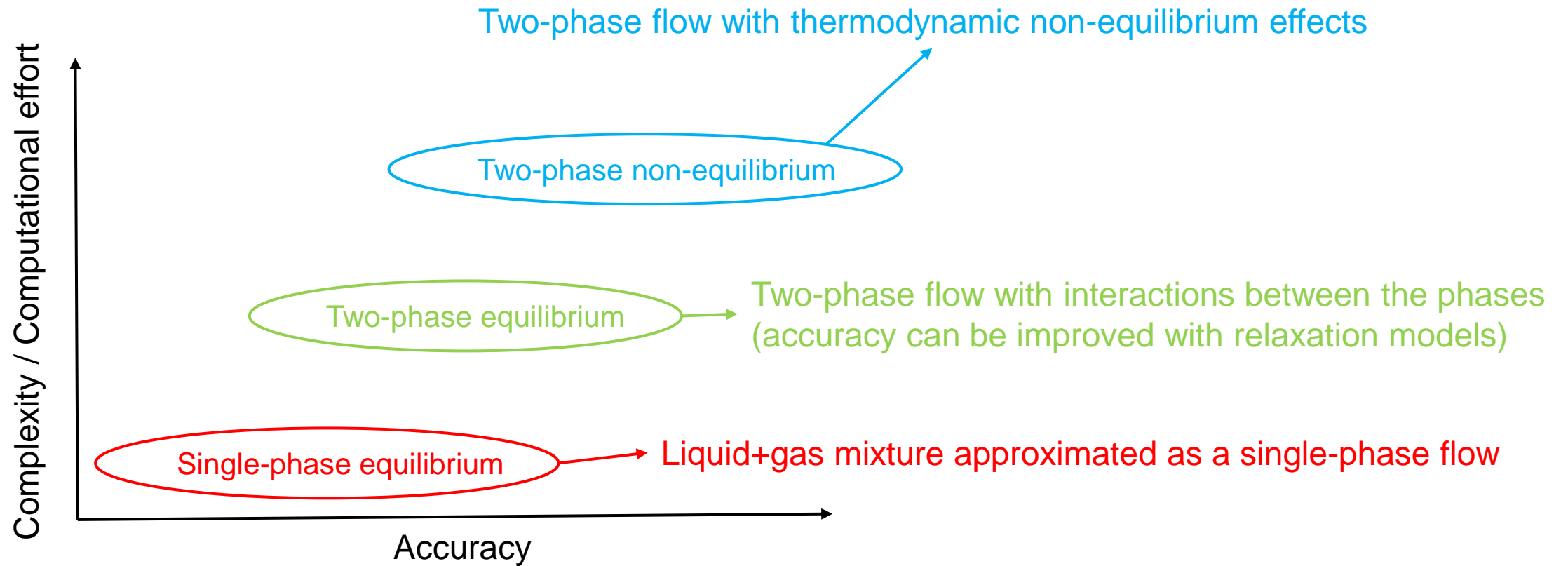


TWO-PHASE CONDENSATION MODELS

- >> Mechanical equilibrium between the gas phase and droplets:
 - >> The phases share the velocity and pressure fields
 - >> It is an excellent approximation if the droplet size is smaller than 10 μm
- >> Thermodynamic equilibrium between the gas phase and droplets:
 - >> The phases share the temperature field (no metastable gas)
 - >> This is only valid near the critical point, where the metastable region is narrow
- >> Two main modeling approaches:
 - >> Homogeneous Equilibrium Models (HEM)
 - Assume both mechanical and thermodynamic equilibrium
 - Does not consider droplet nucleation driven by the chemical potential between phases ($A \rightarrow B \rightarrow C$)
 - >> Homogeneous Non-Equilibrium Models (HNEM)
 - Assume only mechanical equilibrium
 - Droplet nucleation begins within the metastable region, followed by droplet growth ($A \rightarrow B \rightarrow D \rightarrow E$)



TWO-PHASE MODELING APPROACHES COMPARISON



REAL GAS EFFECTS IN DROPLET NUCLEATION

➤ Non-equilibrium condensation models were developed for low-pressure wet steam in the final stage of steam turbines

➤ Ideal gas assumption

➤ Droplets behave differently in low-pressure or high-pressure flows (rarefaction)

➤ Real gas effects must be considered during droplet nucleation

➤ Critical radius for droplet formation:

$$\blacksquare r_{real}^* = \frac{2\sigma}{z_v \rho_l R T_v \ln(S) - p \left(1 - \frac{1}{S}\right)}$$

$$\blacksquare r_{ideal}^* = \frac{2\sigma}{\rho_l R T_v \ln(S)}$$

➤ Flow rarefaction affects droplet growth

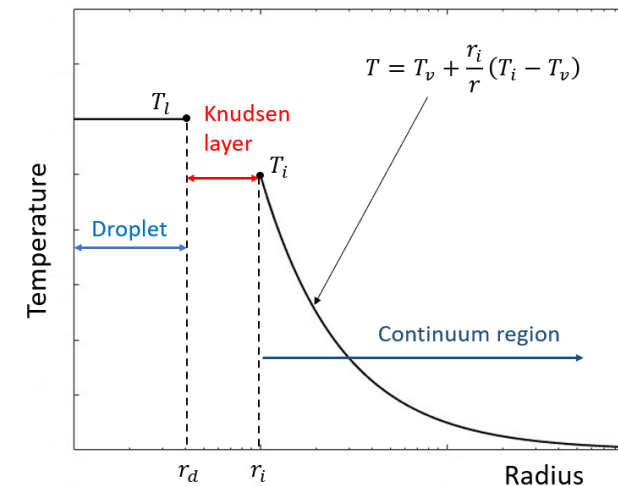
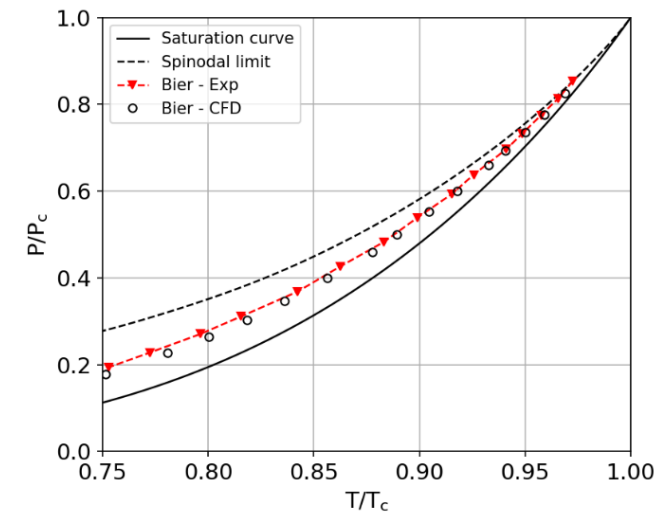
➤ Interphase heat and mass transfer depends on Knudsen number

▪ Low-pressure steam: $1 < Kn < 10$ (fewer collisions between droplets and gas molecules)

▪ High-pressure steam: $0.02 < Kn < 0.1$

▪ Near-critical CO₂: $0.01 < Kn < 0.02$ (many collisions)

CO₂ condensation onset in metastable state



CHALLENGES AND RESEARCH OPPORTUNITIES



- ▶▶ Advanced heat exchanger design
 - ▶▶ Large fluid properties variations near the **pseudo-critical line**
 - ▶▶ Conventional thermal design techniques are either not applicable or inaccurate
- ▶▶ Turbomachinery optimization
 - ▶▶ Large amount of research for steam turbines and gas turbines, but not directly applicable to sCO₂
 - ▶▶ **Real gas effects** and possibility of **condensation** near the critical point
- ▶▶ Development of accurate numerical models for sCO₂ flows
 - ▶▶ Multiphase flows in **equilibrium** or **non-equilibrium** conditions
- ▶▶ Experimental validation
 - ▶▶ Recently tested a **printed circuit heat exchanger** within the sCO₂ test rig (DESOLINATION)
 - ▶▶ Measurements in sCO₂ test facility to capture near-critical phenomena and validate numerical models



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