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The Effect of Impurities in Rich CO_2 Working Fluid on the Power Output of a 10 MW sCO_2 Gas Turbine Power Plant

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sCO_2 Research at Carleton University

- Mechanical and Aerospace Engineering
  - Strong history of research and teaching in gas turbine technology
  - 4th year capstone projects
  - Graduate students
    - Petrusenko (2011) – The development of a high temperature sCO_2 corrosion test rig
    - Parks (2013) – Corrosion of candidate high temperature alloys in sCO_2
    - Wei (2014) – Meanline analysis of radial inflow turbines at design and off-design conditions
    - Daouk (2017) – Performance analysis and modeling of a printed circuit heat exchanger with air and carbon dioxide as working fluids
    - Martel Matos (2017) – Preliminary aerodynamic design of a sCO_2 centrifugal compressor
    - Strang (2018) – Aerodynamic design of a sCO_2 radial inflow turbine using meanline and computational methods
    - Ali (2021) – Health monitoring system for the 10 MW sCO_2 gas turbine power plant
    - Kaur (2021-) – Dynamic modelling of STEP cooling system/Heat exchanger modelling
- Natural Resources Canada (NRCan) – CanmetENERGY
  - R&D in clean fossil fuel technologies
  - Pilot-scale research facility
  - STEP facility support
- Design and development of advanced semi-closed and closed gas turbine cycles

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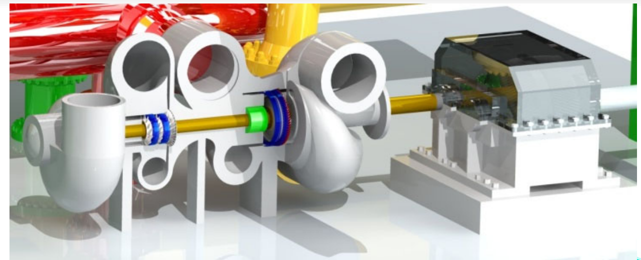
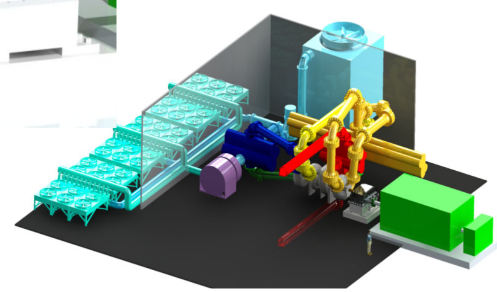
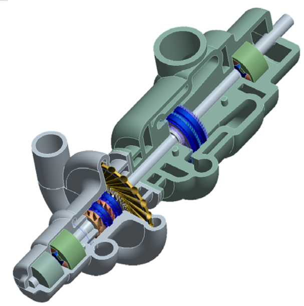
sCO_2 Research at Carleton University

- 2006-11: 100 MW_e plant
- 2011-12: 10 MW_e plant
- 2012-16: 250 kW_{th} pilot-scale, 10 MW_e plant
- 2016-17: hiatus
- 2017-19: 250 kW_{th} pilot-scale, 10 MW_e plant, US DOE STEP Project Support
- 2019-: 100 MW_e plant, turbomachinery scaling (50-300/500 MW_e), US DOE STEP Project Support

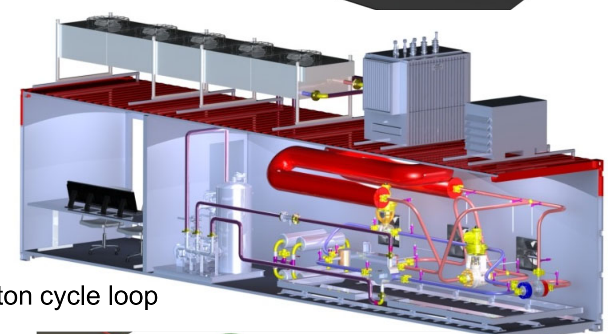




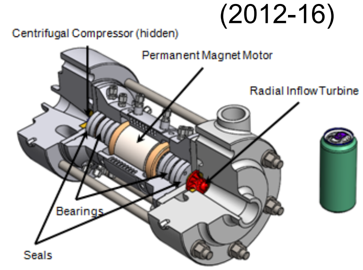
100 MW_e plant (2006-11)

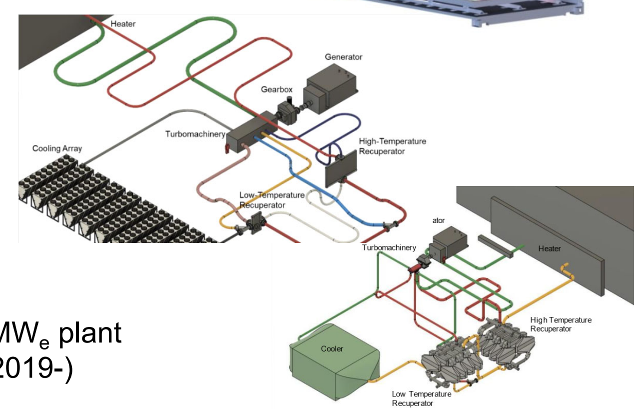


10 MW_e turbomachinery (2011-12)



250 kW_{th} pilot-scale Brayton cycle loop (2012-16)





100 MW_e plant (2019-)

sCO_2 Research at Carleton University – This Work

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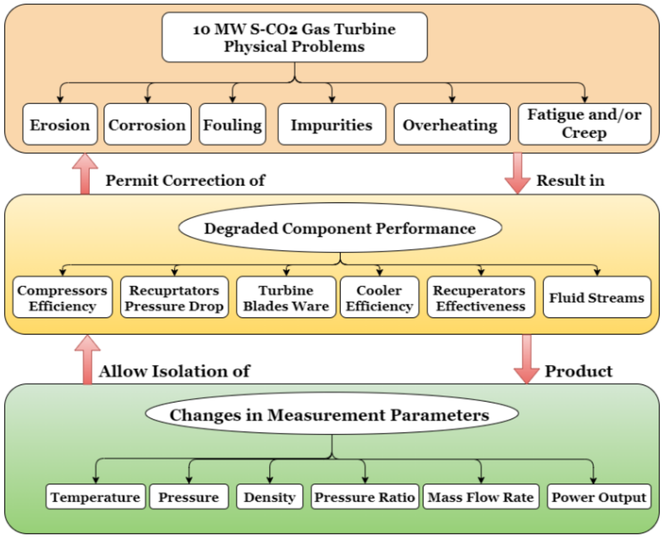
- Health monitoring system for (10 MW_e) sCO_2 power plant
  - Artificial neural network (ANN)
    - Capture effects of impurities and fouling effects on cycle power and efficiency
      - Property prediction
      - Compressor inlet changes on cycle efficiency
      - Effect of impurities on power output
      - Fouling effects
      - Impacts on components and efficiency
  - Other considerations
    - Oil monitoring, vibration monitoring
- 10 MW_e STEP facility/10 MW_e Carleton Design
  - "baseline" for this work



Motivation and Goal

Investigate the effect of the impurities in the rich 99% CO_2 working fluid for 10 MW sCO_2 gas turbine power plant

- **Non-condensable impurities:**
  - **Nitrogen (N_2)**
  - **Oxygen (O_2)**
  - **Carbon monoxide (CO)**
  - **Argon (Ar)**
- **Condensable impurities:**
  - **Sulfur dioxide (SO_2)**

Considering these affected impurities on:

- **Power output (Operation)**
- **Turbomachinery degradation (Design stages)**

Carleton University Brayton Cycle Loop (CUBCL) 10 MW sCO_2 gas turbine

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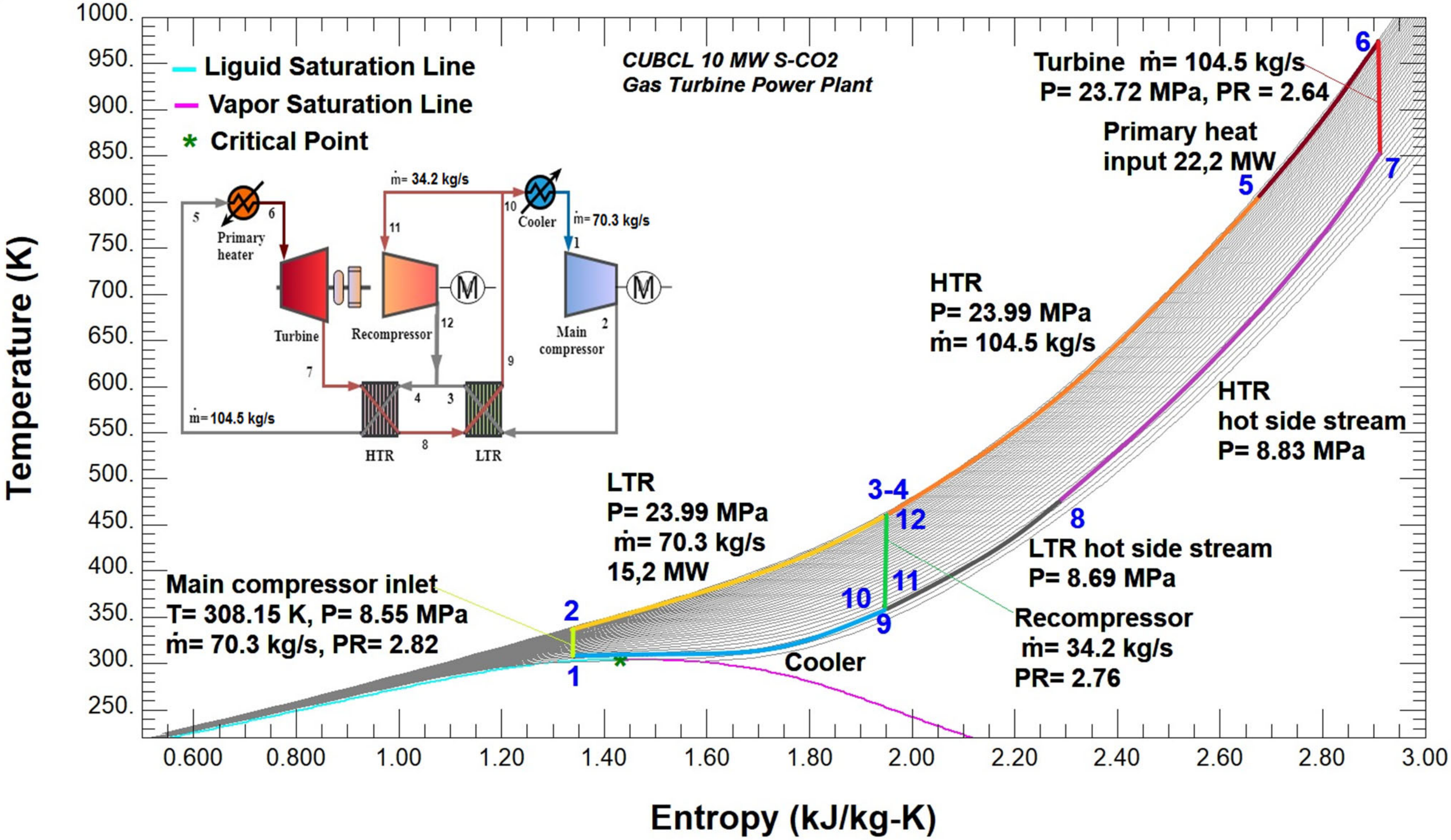

US Department of Energy

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CUBCL 10 MW sCO_2 gas turbine turbomachinery inlet conditions

Turbomachinery	Temperature (K)	Pressure (MPa)	η %
Main compressor	308.15	8.55	82%
Recompressor	361.15	8.69	78%
Turbine	973.15	23.72	85%

The design point of the main compressor inlet:

- **Mass flow rate ($\dot{m}$) = 70.3 kg/s**
- **Density (ρ) = 619.06 kg/m^3**
- **Pressure ratio (P_2/P_1) = 2.82**

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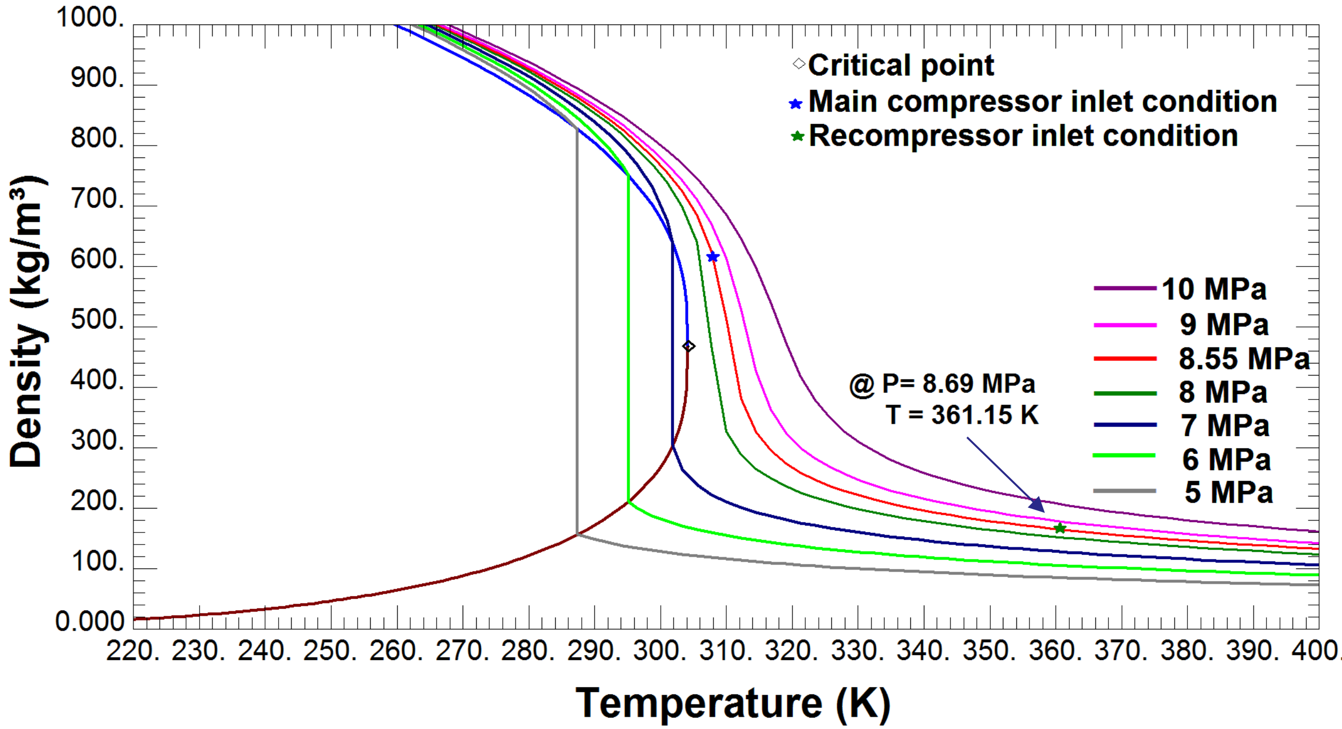
Main and Recompressor Inlet Condition



The pure CO_2 at main compressor inlet at T=308.15 K and P=8.55 MPa has a density of ρ =619.06 kg/ m^3

Methodology

REFPROP Software

Commercial tool from the US National Institute of Standards and Technology (NIST)

Version 10 is used to calculate the CO_2 properties and mixtures

The accurate to within 0.03% of the density near critical point with Maximum error of

0.2% for the working region of the cycle

Results

The density of the working fluid changing dramatically as a function of the total impurity concentration effects the power output

$$\dot{m}_{main-comp} = \rho * A * v$$

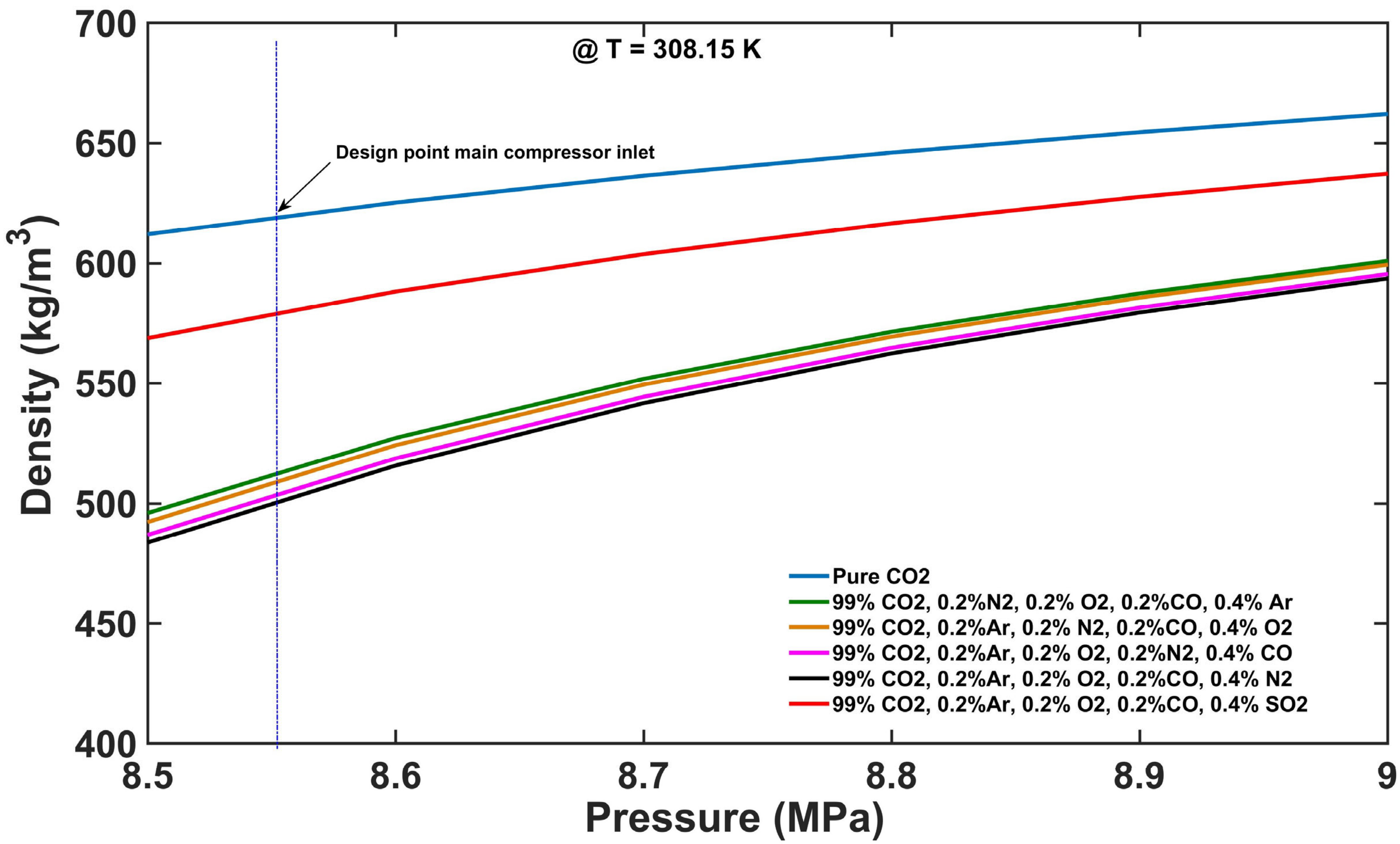
Where $\dot{m}$ mass flow rate, ρ the density and A the cross suction area.

$$P_{el} = \dot{m}(h_6 - h_7)_t - \dot{m}(h_2 - h_1)_{main-comp} - \dot{m}(h_{12} - h_{11})_{re-comp}$$

Where P_{el} is electrical power and h the enthalpy

Results

Density reduction at the main compressor inlet at different concentrations



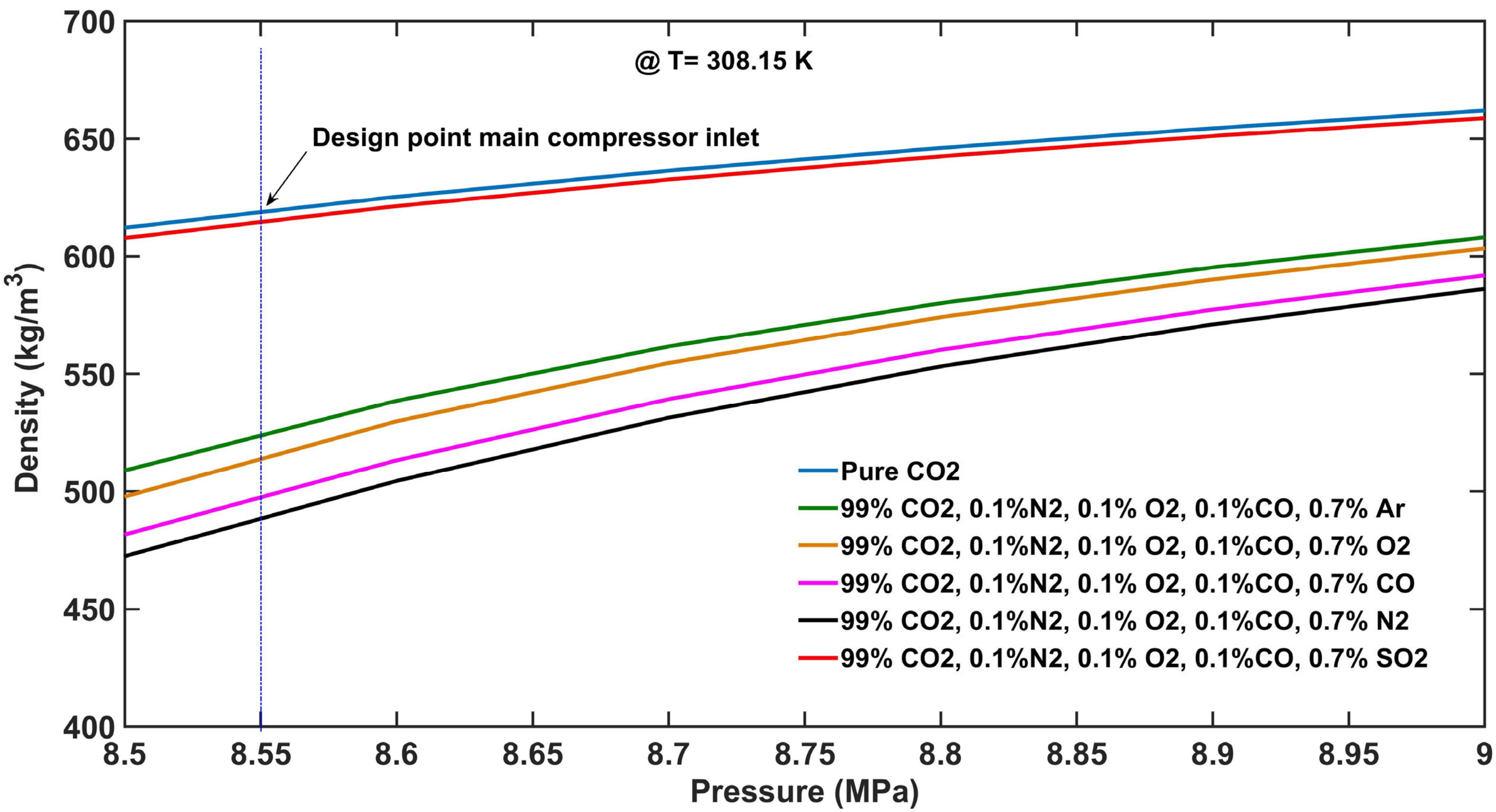
Results

Shows the degree of power loss due to impurities at different concentrations in rich 99%CO_2 working fluid

Component	Density kg/m³	$\dot{m}_{main\_comp}$ kg/s	Cycle η %	Power loses %
Pure CO_2	619.06	70.3	47.9	0
99% CO_2, 0.2%Ar, 0.2% O_2, 0.2% CO, 0.4% N_2	500.46	56.8	40.7	7.1
99% CO_2, 0.2%Ar, 0.2% O_2, 0.2% N_2, 0.4% CO	503.59	57.1	40.9	6.9
99% CO_2, 0.2%Ar, 0.2% N_2, 0.2% CO, 0.4% O_2	509.10	57.8	41.3	6.6
99% CO_2, 0.2%N_2, 0.2% O_2, 0.2% CO, 0.4% Ar	512.49	58.1	41.5	6.4
99% CO_2, 0.2%Ar, 0.2% O_2, 0.2% CO, 0.4% SO_2	579.16	65.7	45.5	2.4

Results

Density reduction at the main compressor inlet at different concentrations



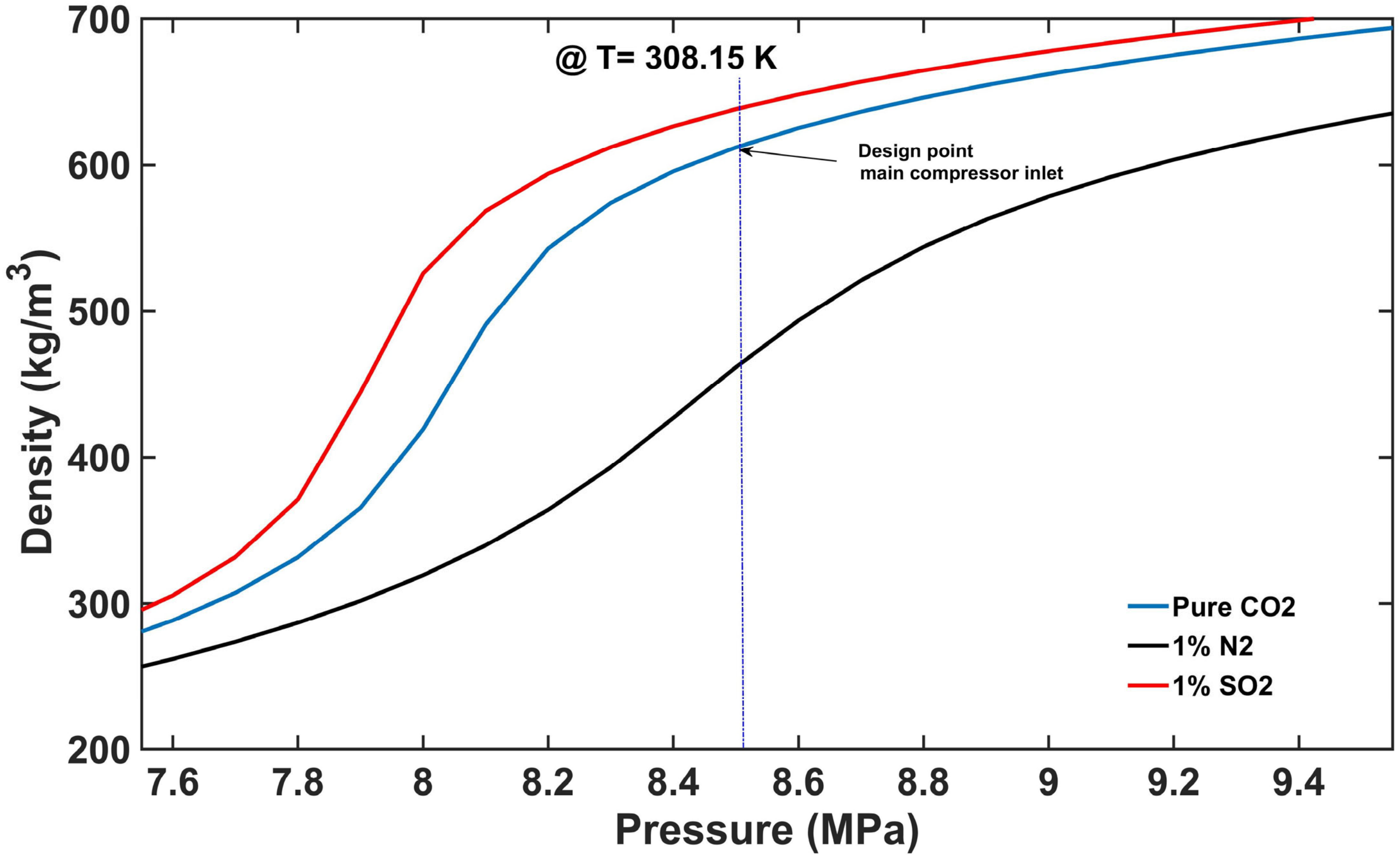
Results

Shows the degree of power loss due to impurities at different concentrations in rich 99%CO_2 working fluid

Component	Density kg/m^3	$\dot{m}_{main\text{-}comp}$ (kg/s)	Cycle η %	Power loses %
Pure CO_2	619.06	70.3	47.9	0.0
99% CO_2, 0.1%Ar, 0.1% O_2, 0.1%CO, 0.7% N_2	488.99	55.5	40.1	7.8
99% CO_2, 0.1%Ar, 0.1% O_2, 0.1%N_2, 0.7% CO	498.14	56.5	40.6	7.3
99% CO_2, 0.1%Ar, 0.1% N_2, 0.1%CO, 0.7% O_2	514.77	58.4	41.6	6.3
99% CO_2, 0.1%N_2, 0.1% O_2, 0.1%CO, 0.7% Ar	524.7	59.5	42.2	5.7
99% CO_2, 0.1%Ar, 0.1% O_2, 0.1%CO, 0.7% SO_2	614.87	69.8	47.7	0.2

Results

The effect of SO_2 and N_2 concentrations of 1% on the density of rich 99% CO_2 working fluid



Results

The effects of SO_2 and N_2 concentrations of 1% on the density and over all cycle efficiency of rich 99% CO_2

Component	Density kg/m^3	$\dot{m}_{main\_comp}$ kg/s	Cycle η %
Pure CO_2	619.06	70.3	47.9
99% CO_2, 1% N_2	478.11	54.2	39.4
99% CO_2, 1% SO_2	642.56	72.9	49.4

Conclusions

Analysing the effect of impurities of the working fluid would beneficial the 10 MW sCO_2 gas turbine designers and operators.

- **Non-condensable impurities:**
- The present of impurities N_2, O_2, CO and Ar in the working fluid effected the turbine performance
- N2 is found as an affective impure on the power output
- A mixture of 99% CO_2 and 1% N_2 caused maximum density reduction almost 23% and reduced the cycle efficiency to 8.5%.
- **Condensable species:**
- Concentration of 1% of Sulfur dioxide in 99% CO_2 would:
- Increase the density by 23.5 kg/m^3
- and the power output up to 1.4%
- An increase in SO_2 concentration in supercritical CO_2 region rapidly degrades turbomachinery's component by corrosion.
- Understanding the concentration of impurities is vital to avoiding corrosion-related damage and improving the efficiency
- **Other considerations:**
- Effect on cycle operation – shift in operation points
- Cycle performance, temperatures

Thank you

Questions