Modeling the Variation in a sCO2 Compressor’s Map Characteristics Operating Near the Critical Point

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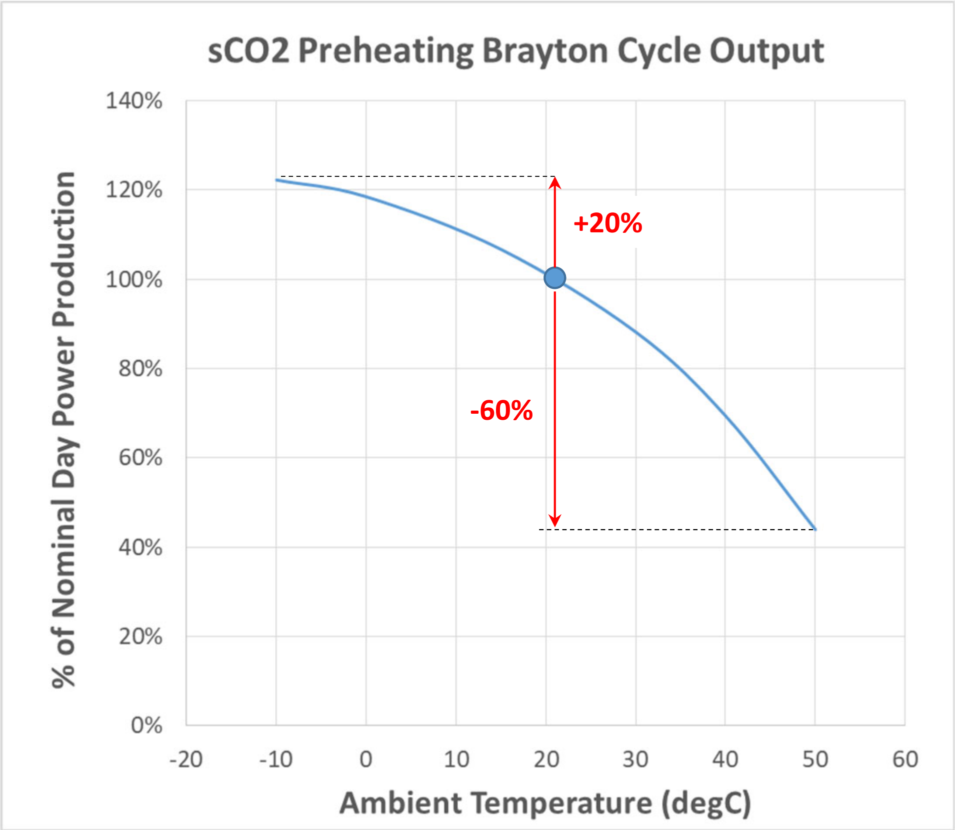
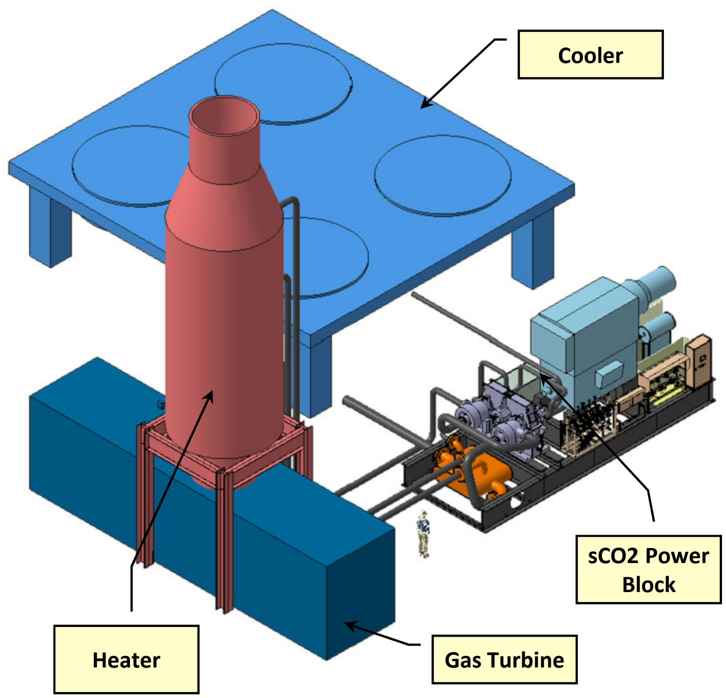
Background

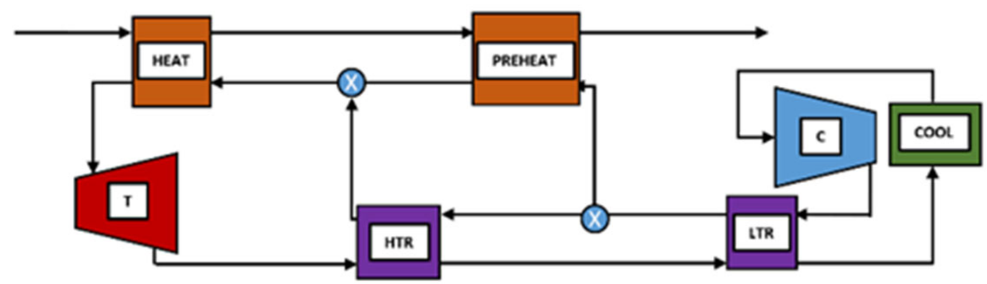
- One of the objectives of an sCO2 power cycle is to maximize the power generation for a given amount of available heat
- For an air cooled cycle the power output varies with ambient conditions
- Ambient temperature typically vary from -10C to +40C
- Compressor inlet temperature may vary from 25C to 50C
  - Below 25C CIT, little additional performance gains are possible
- Gas properties change significantly across this range and compressor performance will change too.
- For a typical waste heat recovery cycle power output may vary from 45% to 120% of the nominal across this range of ambient temperatures



Application



- Waste Heat Recovery (WHR) System
- Split-recuperated sCO2 Brayton cycle with pre-heating
- GT engine exhaust providing the heat source
- Exhaust gas temperature of 500C
- ~35MWth of available heat
- 6MWe power generation



Cycle Modeling Goals

- Predict the net (Daily, Monthly, Annual) power production of the sCO2 cycle
- Component performance must be modeled for design and off-design conditions
- Typically a single non-dimensional performance curve is used to characterize the compressors and expanders and similarity laws are applied to estimate off-design performance
- For the expanders this works well since CO2 exhibits near ideal gas characteristics at the turbine operating conditions
- For the compressors this is inadequate since the gas does not behave as a ideally near the critical point.
- An analytic study was conducted to better quantify and model the off-design compressor performance

Baseline Compressor Performance Characterization

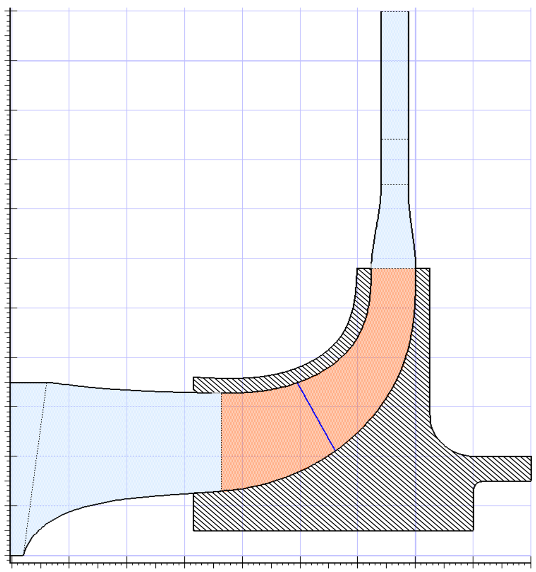
- Head Coeff.
- Flow Coeff.
- Efficiency

$$\psi = \frac{\Delta h}{\left(\frac{1}{2}\right) U_2^{\,2}}$$

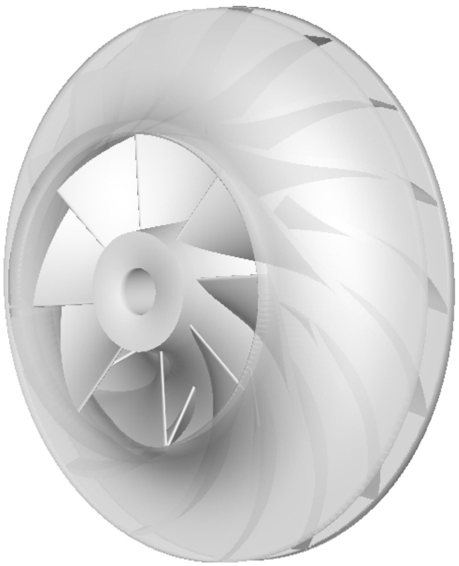
$$\phi = \frac{Q}{\frac{\pi}{4} \times D_2^{\,2} \times U_2}$$

Accurate within range prescribed by PTC-10 for ideal gas applications

Compressor Geometry



Stage Layout

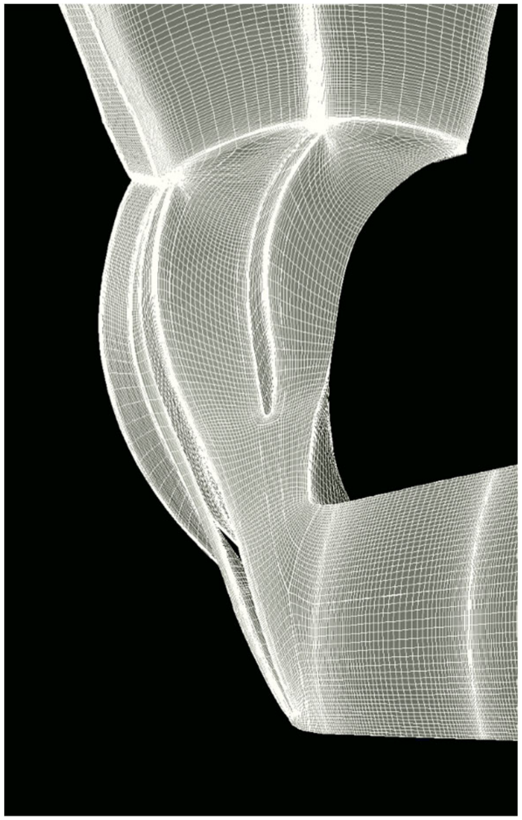


Compressor Wheel

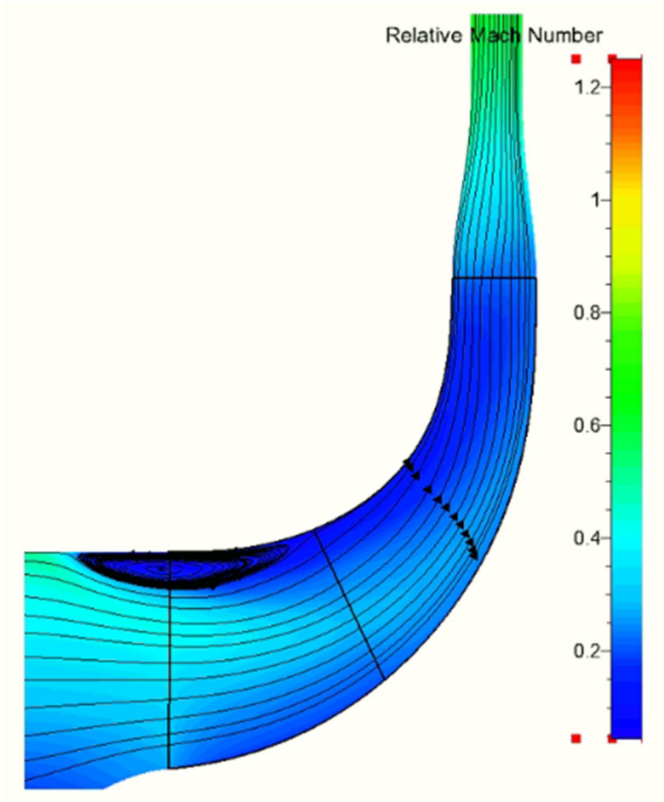
- 1^{st} stage of a 2 stage main compression process
- Centrifugal flow compressor
- Design flow coefficient of 0.064
- Diameter of 135mm
- T_{design}: 32C
- P_{design}: 90BarA
- Power: ~1500kW
- *This same basic impeller has now been built and tested*

CFD Setup

- Solver: NUMECA Fine/Turbo
- The domain consisted of a single blade passage with an axial inlet, the impeller and splitter, and a vaneless diffuser
- Spalart-Allmaras one-equation turbulence model with wall functions.
- Table based fluid properties generated from NIST REFPROP
- Front and back leakage cavities were not included in the CFD analysis.
- A structured hexahedral mesh size of ~1 million cells



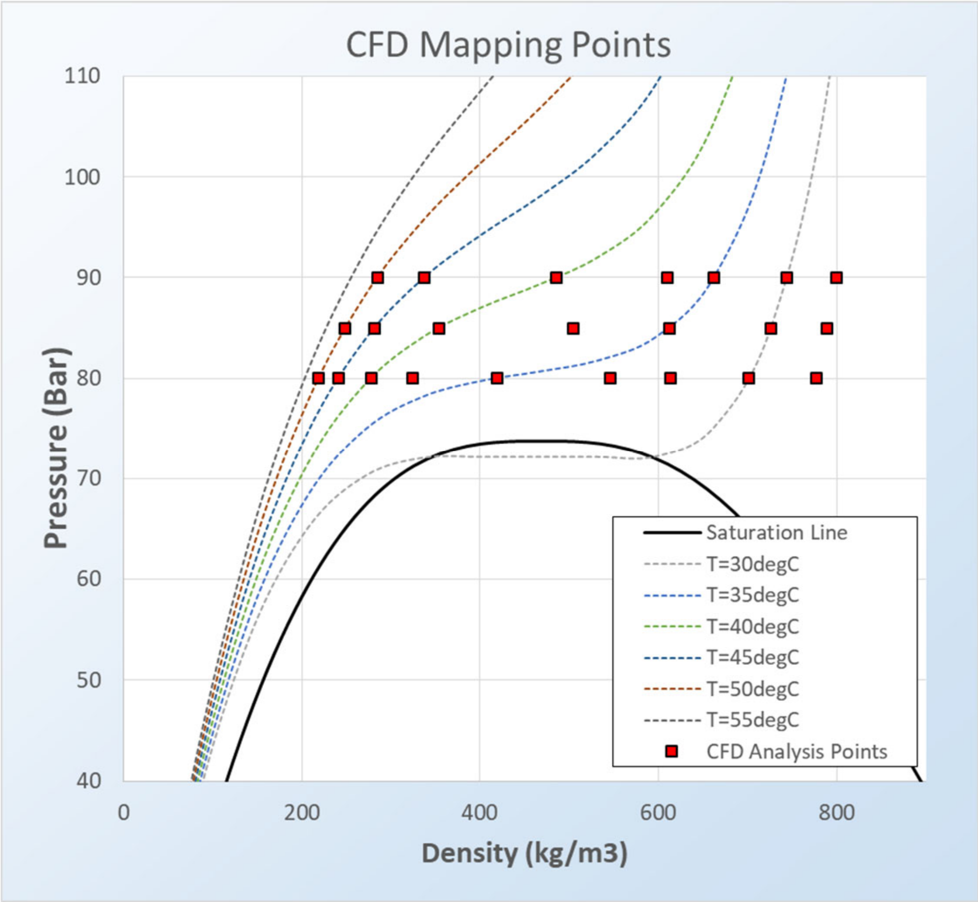
Mesh



Solution

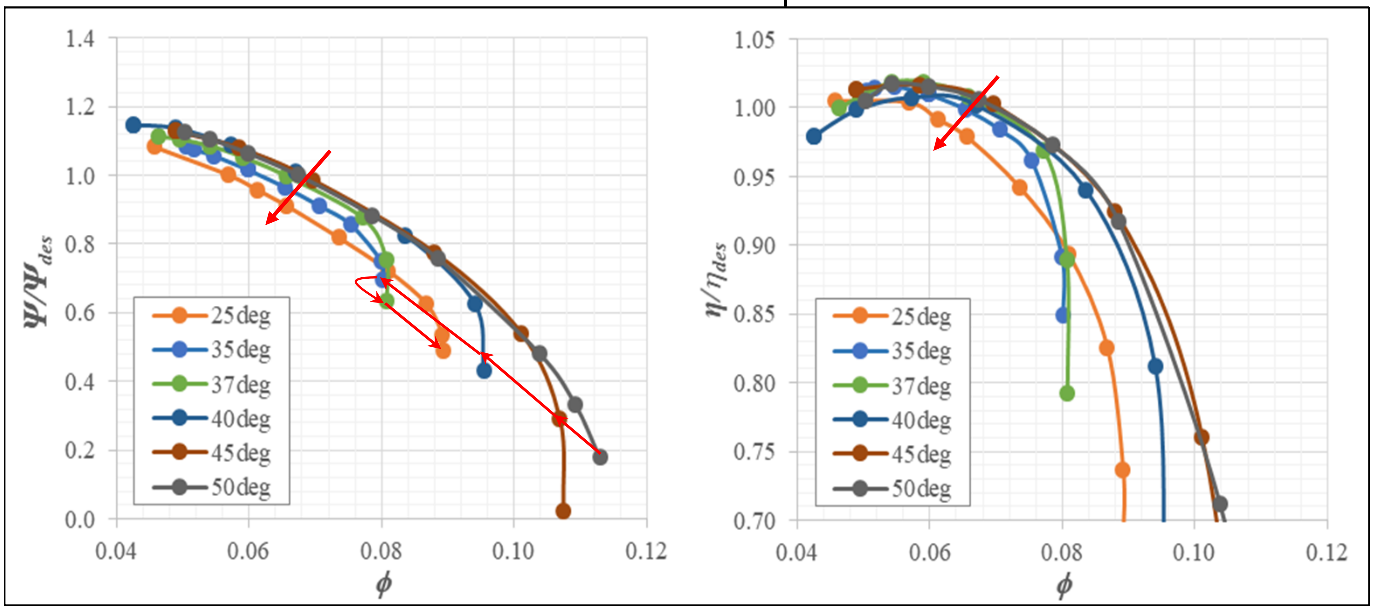
CFD Analysis Points

- The CFD analysis was completed for three different inlet pressures,
  - 80, 85 and 90barA
- Multiple different inlet temperatures
  - 25 to 50°C
  - To cover potential off-design operating conditions
- Stall point was defined where there was no further rise in head with reduction in flow, or when a stable numerical solution was not achievable
- Choke was defined as the flow rate where there was no increase in flow with a reduction in back-pressure



CFD Results

85BarA Maps



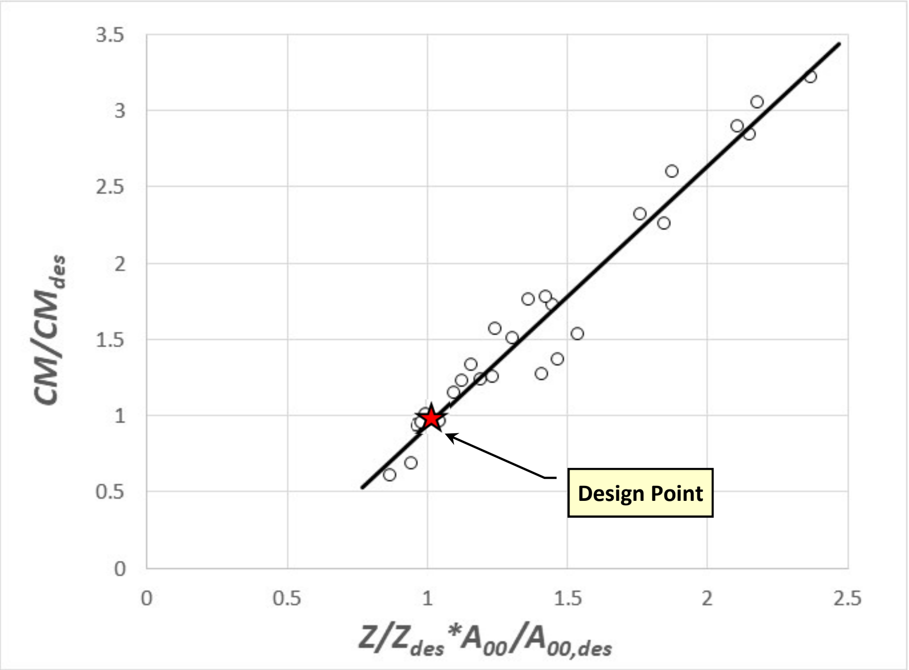
- Compressor map calculated for each operating point
- The choke flow rate is the highest at 50°C and decreases as the temperature approaches the critical temperature.
- The minimum choke flow rate occurs at an inlet temperature of 37°C and as the temperature is further reduced, the choke flow rate increases again

Choke Flow Model

- The variation in choke margin was observed to be strongly dependent on two parameters
  - The sonic velocity, a00, of the gas at the specific inlet condition analyzed
  - The compressibility factor, z.
- A reduction in either the sonic velocity or the compressibility resulted in a reduced choke margin
- Choke occurs when the velocity of the bulk flow at the throat matches the speed of sound

$$M = \frac{c_{throat}}{a_{00}}$$

- A reduction in the speed of sound will result in choke at a lower throat velocity
- A reduction in compressibility factor results in higher throat velocities
- Care should be taken to select a design point that avoids potential choke at off-design operating conditions.

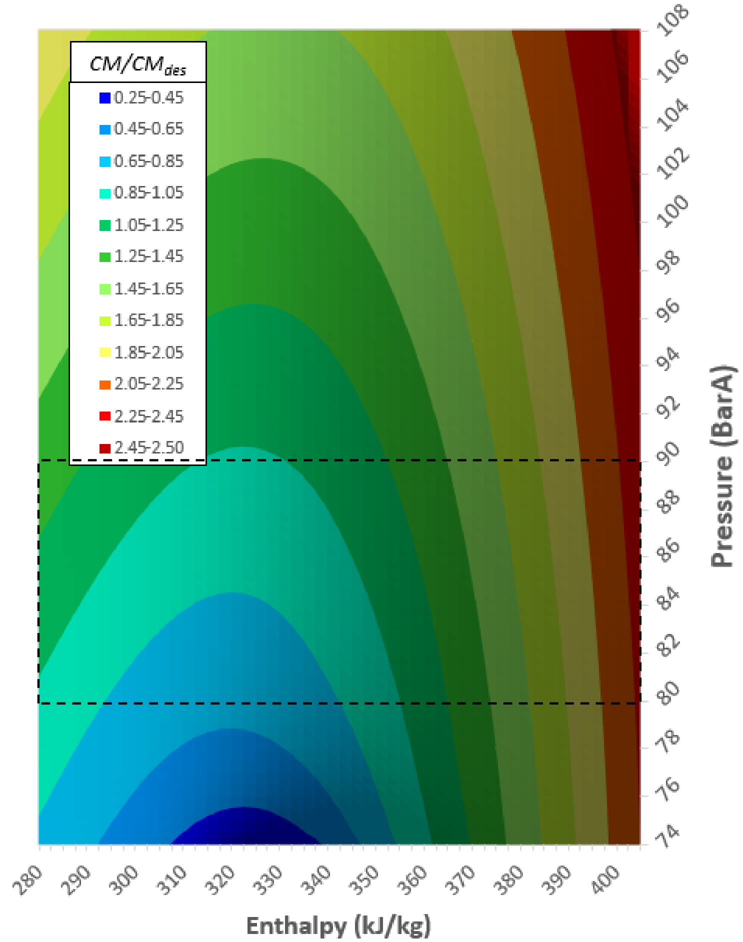


$CM = (Q_{choke} - Q_{design})/Q_{design}$

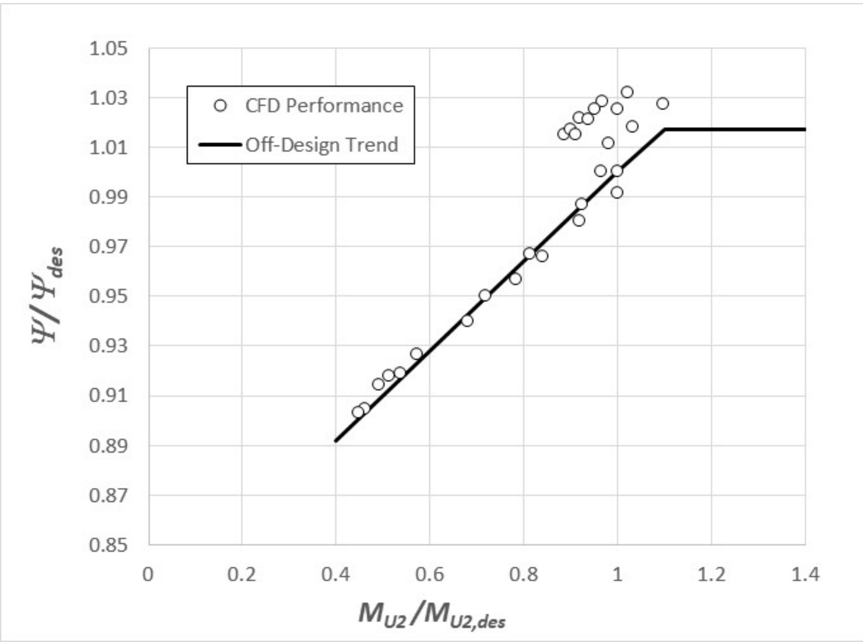
Across the 25C and 10barA range of inlet conditions evaluated the Mach # can change by 60%

Off-Design Performance Trends

- The model variation of the compressor choke margin over a range of inlet conditions is shown.
- With the lowest choke margin is predicted near the critical point and increases as the inlet condition moves further from the critical point.
- The plot also shows that the choke margin is much more sensitive to changes in inlet temperature than pressure.
- As the inlet condition approaches the critical point significant uncertainly develops in the steady, single phase, CFD used in this study.



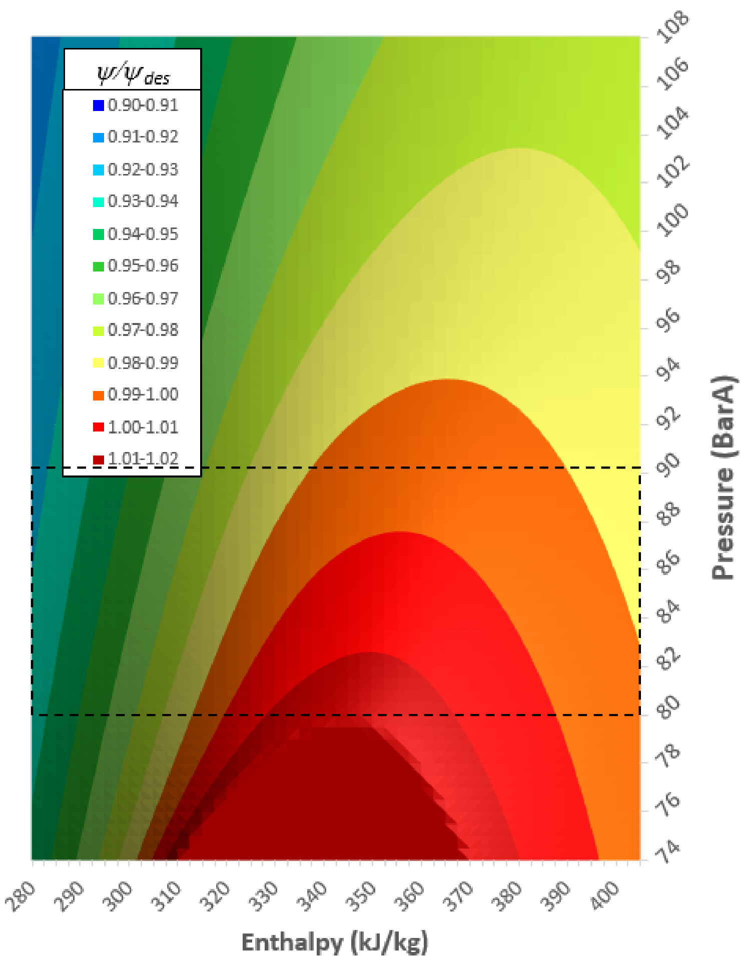
Off-Design Head Model



- **A 10% variation in head is expected in the off-design space**

- The variation in head coefficient is predicted to be directly proportional to the Machine Mach number, M_{U2}.
- A near linear relationship between the magnitude of the head coefficient at the design flow and the ratio of M_{U2} at the specified inlet condition to M_{U2} at the design condition.
- In the absence of any evaluations above a $M_{U2}/M_{U2,des}$ of 1.1, the off-design model assumed a constant head coefficient at machine Mach numbers greater than 1.1.
- It would be expected that at some higher Mach number that the head would begin to fall.

Model Compressor Head Coeff.



- The head coefficient is expected to be a maximum as the nominal inlet conditions approach the critical point.
- The most rapid fall-off in head coefficient is predicted at low pressure moving toward colder inlet conditions
- As the inlet condition approaches the critical point significant uncertainly develops in the steady, single phase, CFD used in this study.

Off-Design Efficiency Model

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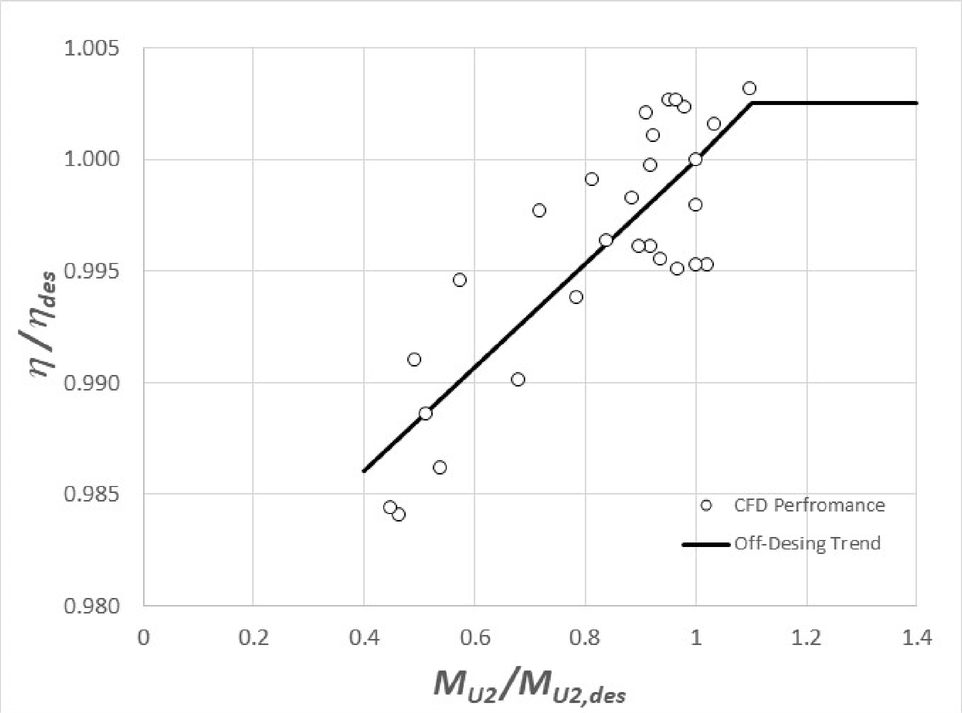
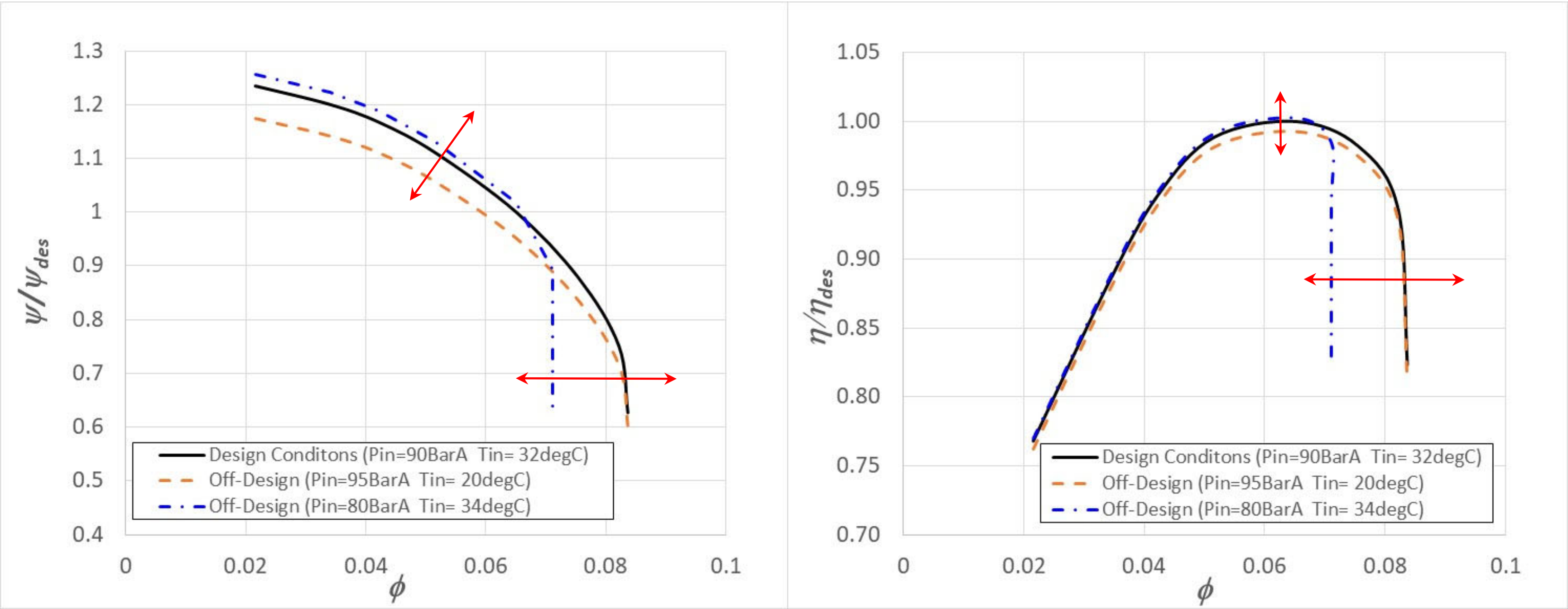
- Efficiency is much less sensitive to changes in inlet condition than head coefficient
- A review of the trend in changes to peak efficiency found that the efficiency is related to machine Mach number in a similar form to that of head coefficient.
- For off-design modelling, a linear trend with machine Mach number was assumed until $M_{U2}/M_{U2,des} = 1.1$.
- CFD analysis assumed a single phase gas, so the effect of any phase change in the stage would not be captured.
- It would be expected that at some higher Mach number that the efficiency would begin to fall as shock losses begin to develop.



Corrected Maps

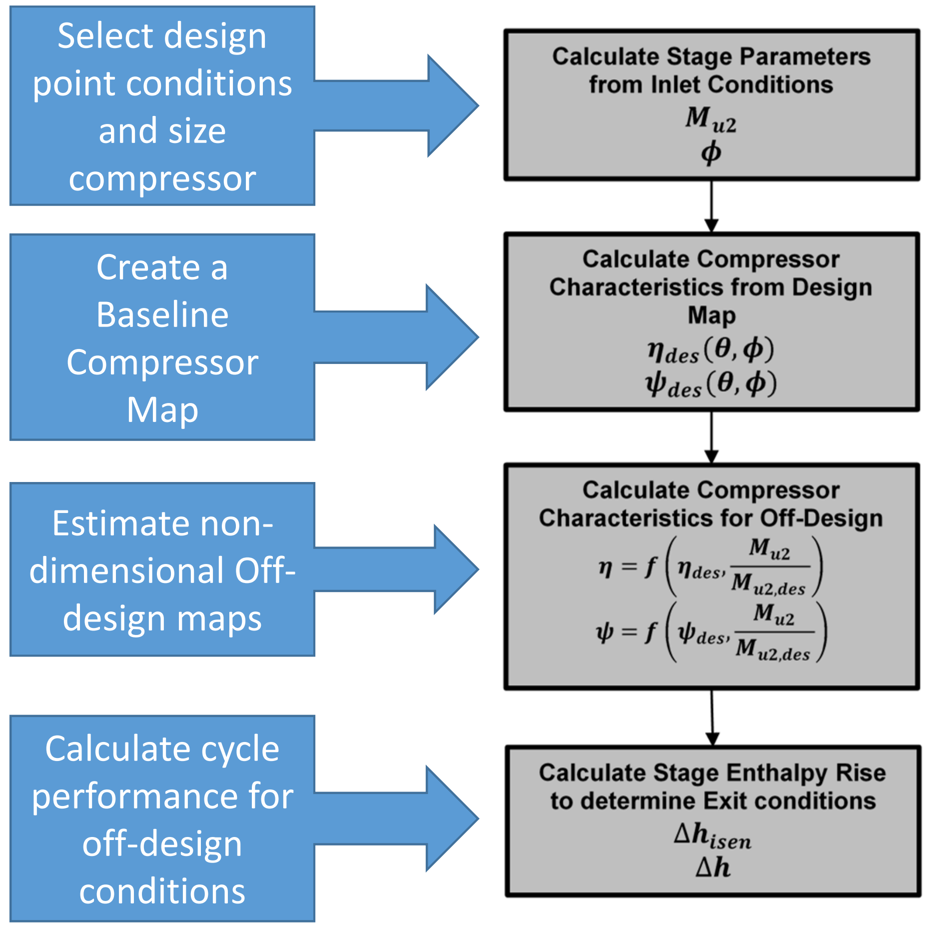


- Using the models presented above, the nominal design point map can be adjusted to correct the head, efficiency and choke flow rates

Cycle Modeling

- Cycle modeling completed with Numerical Propulsion System Simulation (NPSS)
- All the components of the cycle were modeled

- Available heat was varied based on GT operating characteristic
- The annual power generation was modeled with an assumed variation in the ambient conditions based on historical weather trends.
- A range of potential design sizing points was evaluated
- The optimal design point was identified as the compressor sizing that resulted in the maximum annual power generation



$$\Delta h_{isen} = \psi U^2$$

$$\Delta h = \frac{\Delta h_{isen}}{\eta}$$

Model Accuracy

- The 6MWe Brayton cycle performance was evaluated at 5 different off-design conditions.
- The cycle performance was calculated both based on a fixed compressor map, and from the corrected maps generated using the models to adjust for changes in inlet conditions
- Across just an 8deg C variation in inlet temperature, a 3.4% error in power prediction would be expected without correcting for change in compressor performance.
- This only accounted for steady state cycle performance, the effects on transient cycle performance would need to be evaluated with a dynamic cycle model.
- The models could also be used to improve estimation of performance further off-design at start-up or shut down scenarios.

Off-Design Operating Point	**1**	**2**	**3**	**4**	**5**
CIT (C)	26	28	30	32	34
CIP (bar)	76	77	78	79	80
Enthalpy (kJ/kg)	269	277	286	299	321
Output Power Prediction Error (%)	3.43	3.04	2.46	1.64	0.38

206kW error is performance prediction for a 6MWe cycle

Conclusions

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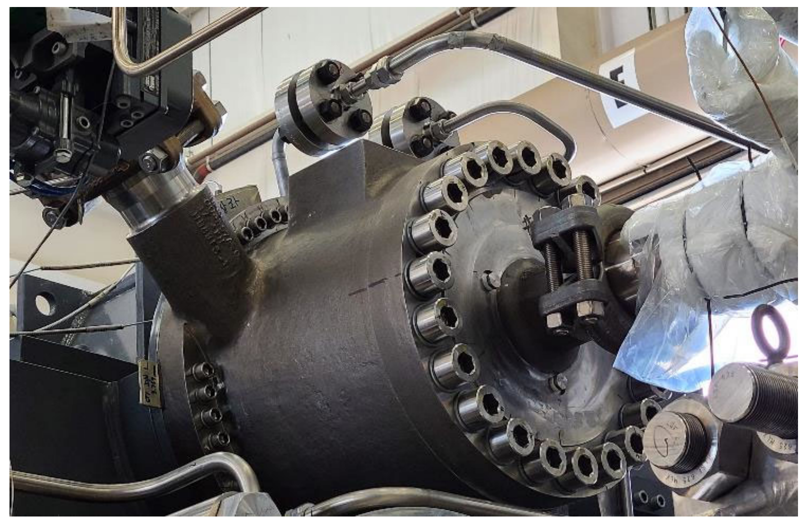
- Variability in gas properties have a significant effect on the performance of a centrifugal compressor operating near the critical point in a sCO2 power cycle.
- The three main deviations seen in the compressor performance curves are predicted:
  1. A strong variation in the choke margin relative to the compressibility factor and inlet speed of sound.
  2. A decrease in the head coeff. As machine Mach number is reduced
  3. A decrease in the efficiency at low machine Mach number
- Across a range of typical inlet temperatures, the variation in head coefficient is expected to be about ±5% while the variation in stage efficiency is ±1.5%.
- These variations in head and efficiency will have a potentially significant effect on the performance of the cycle and should be considered when evaluating overall power generation.
- The variability in choke margin must be well understood as it is important in evaluating the transient performance and operability of the cycle.
- It is recommended to size the inlet of the compressor to avoid choke at any potential operating conditions.

Future Work

- Expand the scope of the modeling to cover operating conditions closer to the saturation line
- Improve the CFD modeling to evaluate potential multiphase flow development
- As the compressor has been tested, compare the CFD based models to actual test results



Thank You