02/22/2022

Supercritical CO_2 Power Cycles Symposium

Radial Compressor Design and Off-Design for Trans-critical CO_2 Operating Conditions

NATIONAL ENERGY TECHNOLOGY LABORATORY

Solutions for Today | Options for Tomorrow

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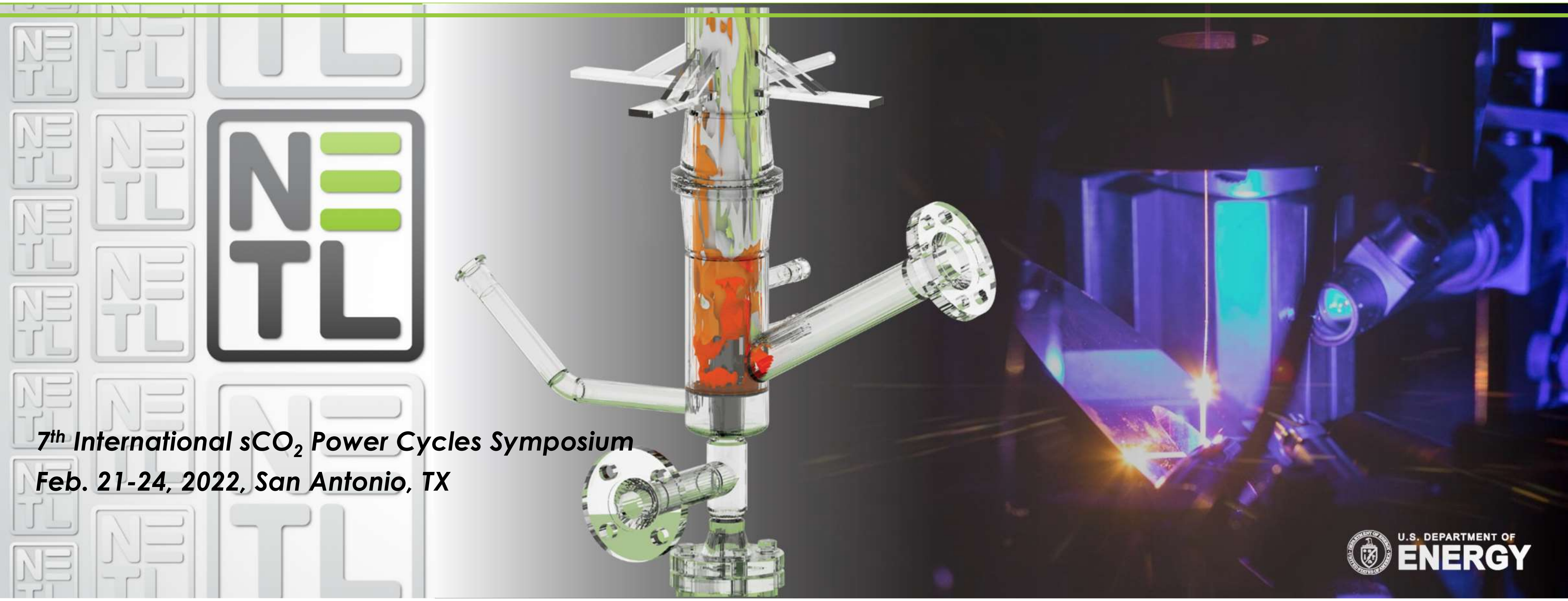


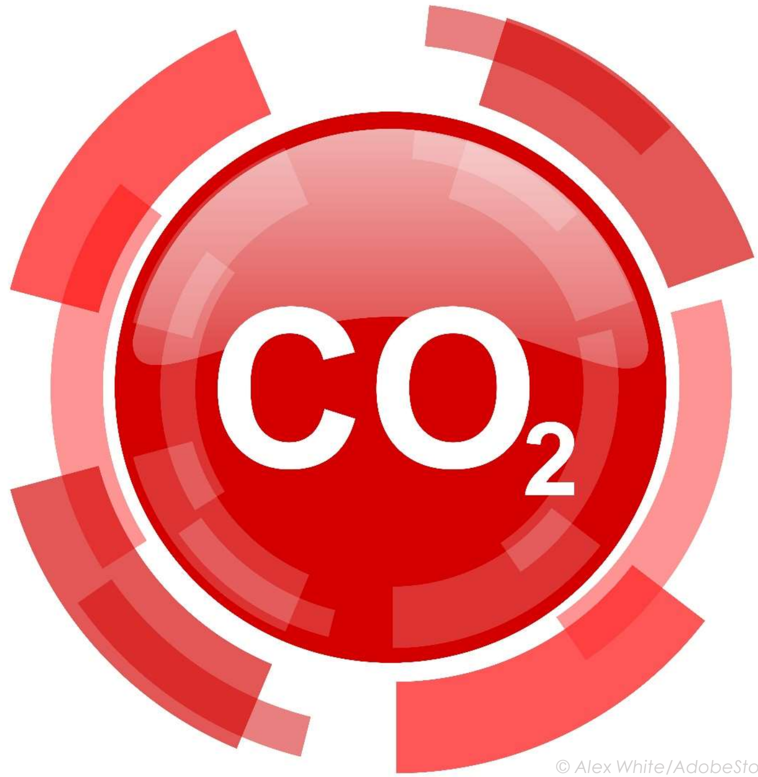
7th International sCO_2 Power Cycles Symposium

Feb. 21-24, 2022, San Antonio, TX

Agenda

NATIONAL ENERGY TECHNOLOGY LABORATORY

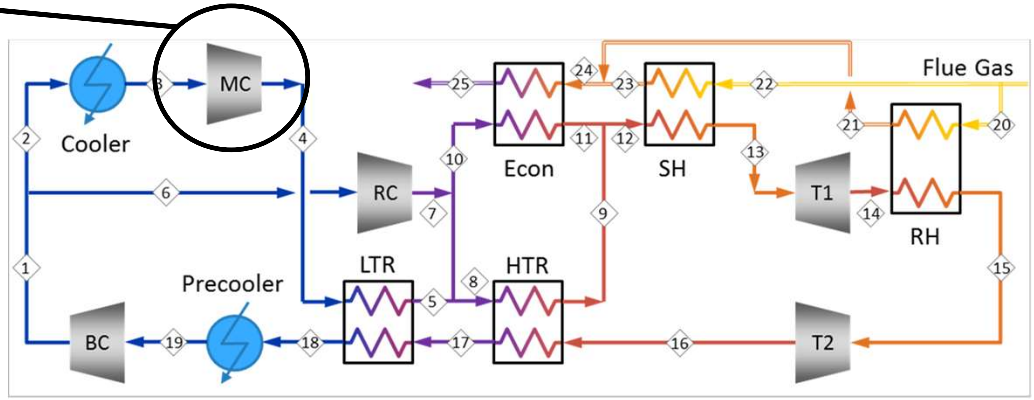
- Background
- Fluid Similarity Method
- Map Scaling
- Validation
- Compressor Design
- Off-Design Maps
- Compressor Design Updates
- Summary and Conclusions



Background

- The main compressor/pump design condition ranges are as follows:

Main-Compressor	Inlet	Exit
Pressure (psia)	887-1200	4096-5980
Temperature (F)	71-94	98-131
Mass Flowrate (lbm/s)	5326-6991	
Volumetric Flowrate (ft^3/s)	134-206	
Density (lbm/ft^3)	37-46	55-58



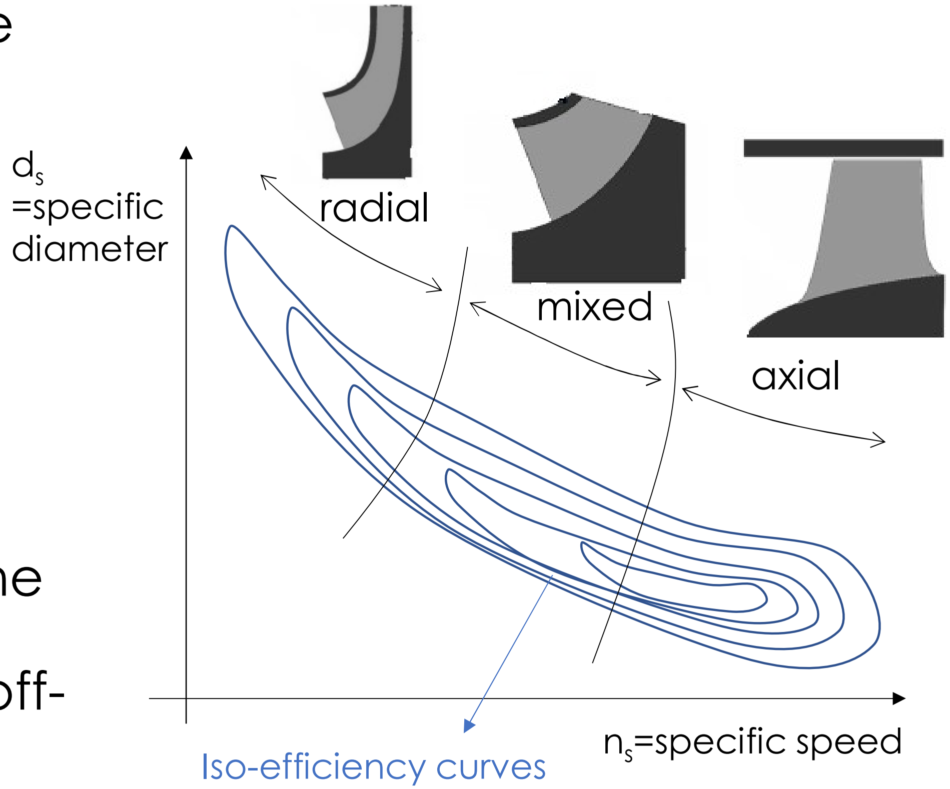
Source: NETL

- The indirect cycle model uses two-stage compressor with intercooling.

Background

Deciding on the Compression Method

- A Baije chart is used to determine the compression type.
- The compressor type is dependent on
  - Mass (or volumetric) flowrate to the compressor.
  - Inlet pressure and temperature.
  - Desired compression ratio.
  - Shaft speed.
- The type of the compressor affects the design methodology to be used, performance map generation, and off-design analysis.*



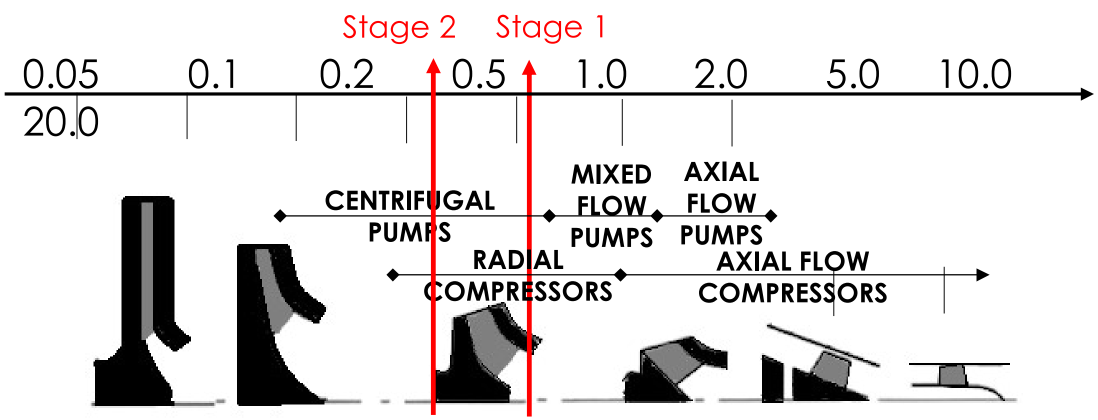
*G. Musgrove, "Preliminary Aerodynamic Design of Centrifugal Compressors for Beginners," in SwRI Webinar Presentations, 2020

Background

Deciding on the Compression Method (continued)

- The calculations are updated with Stage 1 and Stage 2 data from the recent cycle optimization studies.

	$\dot{V}$ (ft³/s)	$\bar{z}$	$T_{t,in}$ (F)	π_c	γ	H (ft.lbf/lbm) (Isentropic Head Coefficient)	n_s (Specific Speed)
Stage 1	135	0.233	71.44	2.484	4.479	5744	1.057
Stage 2	114	0.488	71.44	2.506	2.464	11114	0.6



$$H = \frac{\bar{z}RT_{t,in}}{\gamma - 1/\gamma}\left[\pi_c^{\gamma-1/\gamma} - 1\right]$$

$$n_s = \frac{\omega\sqrt{\dot{V}}}{(H)^{3/4}}$$

Fluid Similarity Method

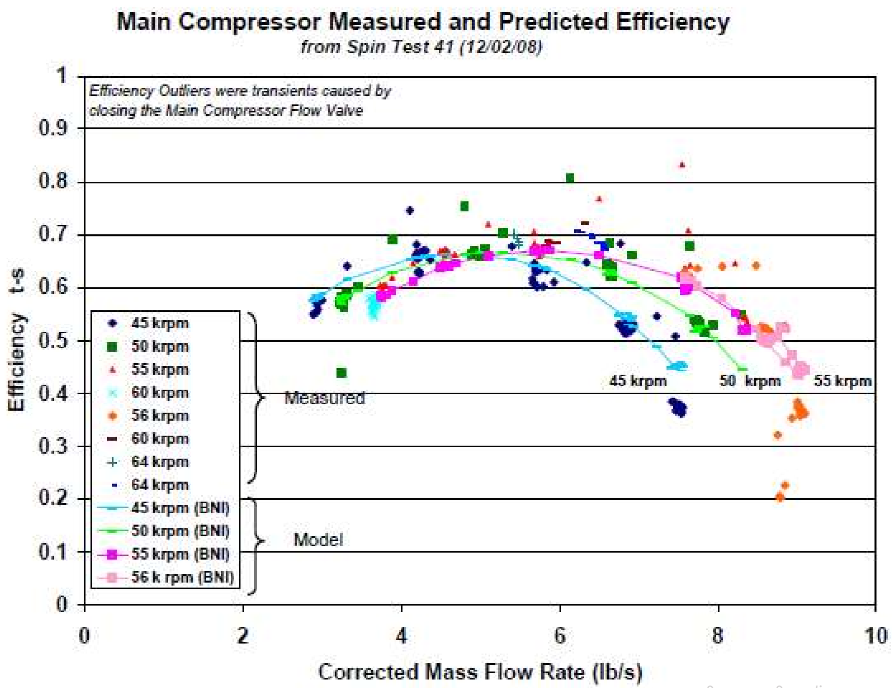
Introduction

- Fluid similarity is frequently used in experiments to replace the actual fluid with an alternate fluid due to availability, safety or cost.
- Fluid similarity can be used in simulations and models for easier modelling (e.g., to use ideal gas models for real gas flows).
- Transcritical operation of the main compressor requires real gas and "calorically imperfect" gas modelling.
- Sandia National Lab's (SNL) compressor is designed using this methodology.

Fluid Similarity Method

Level of Uncertainty of the Method

- SNL compared the measured compressor performance maps to the maps generated by using the fluid similarity method.*
- The design was made with a refrigerant fluid, and performance maps are generated with NASA CCODP code.*
- For the efficiency, the difference between the actual data and model prediction with fluid similarity is within 5%.
- SNL concluded that the fluid similarity approach is applicable and gives results close to actual compressor performance.*



Source: Sandia National Laboratories*

*Wright S.A., Radel R.F., Vernon M.E., Rochau G.E. and Pickard P.S., (2010), "Operation and Analysis of a Supercritical CO_2 Brayton Cycle", Sandia Report, SAND2010-0171, Albuquerque, NM

Fluid Similarity Method

Definition

- The method is analogous to Laplace or Fourier transforms for differential equations.

Mathematics

- If the differential equation meets several requirements, it can be represented in either Laplace or Fourier domains.
- In the Laplace or Fourier domains, the equation is linear, and the solutions are simple.
- The solution of the transformed equation is then converted back to the real domain to obtain the actual solution.

$$\frac{d^2y}{dt^2} - 5\frac{dy}{dt} + 6y = 0$$
$$y'(0) = 2 \;\; y(0) = 2$$

$\mathcal{L}$

$$s^2Y(s) - 5sY(s) + 6Y(s) - 2s + 2 - 10 = 0$$

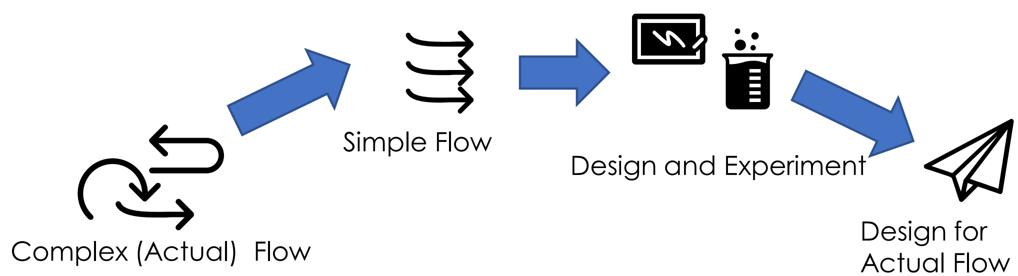
$$Y(s) = \frac{4}{s-2} + \frac{-2}{s-3}$$

$\mathcal{L}^{-1}$

$$y(t) = 4e^{2t} - 2e^{3t}$$

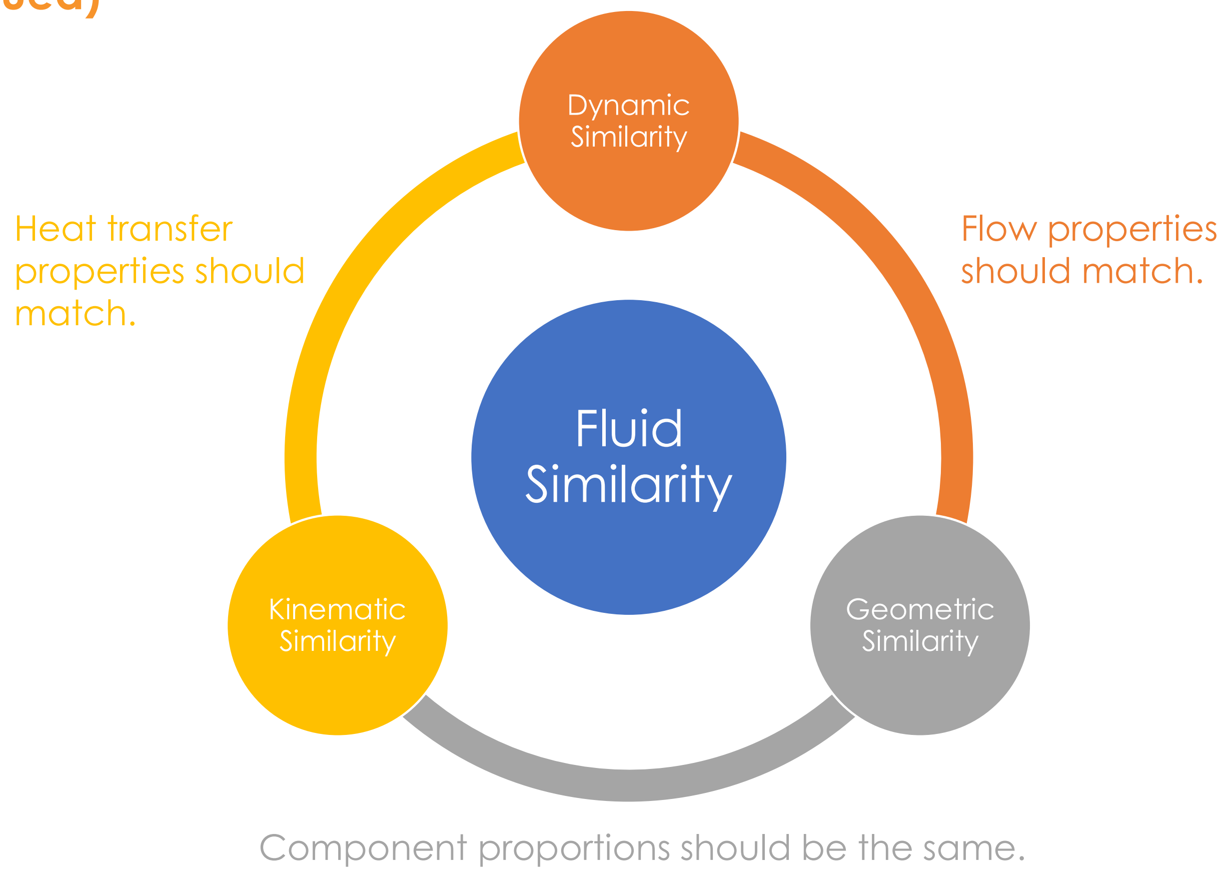
Fluid Dynamics

- If the actual fluid meets several conditions, the flow can be represented with another fluid.
- The "similar fluid" is both an ideal and calorically perfect gas, for which modelling is easier and well known.
- The solution obtained with the "similar fluid" is transformed back by scaling laws to obtain the solution for the actual fluid.



Fluid Similarity Method

Definition (continued)



Fluid Similarity Method

Finding Similar Fluids for sCO_2

- The similar fluid should have the same following properties as the actual fluid. *,**
  - Reynolds Number
    In order to have equivalent flowrate that would yield identical inlet and exit flow angles with actual flow. This will partially satisfy geometrical similarity.

$$Re_D = \frac{\rho V D}{\mu}$$

Density (ρ), Flow Speed (V), Dynamic Viscosity (μ)

  - Prandtl Number Behavior
    In order to have similar heat transfer scheme with the actual flow. Ensures same heat transfer boundary layer behavior.

$$Pr = \nu / \alpha$$

Kinematic Viscosity (ν), Thermal Diffusivity (α)

*Nichols K.E., "How to Select Turbomachinery for your Application", Barbera-Nichols Inc.
**Munson B.R., Young D.F. and Okiishi T.H., (2006), "Fundamentals of Fluid Mechanics", 5th Edition (International), John Wiley and Sons Inc., pp. 371-389

Fluid Similarity Method

Finding Similar Fluids for sCO_2 (continued)

- A study by University of Pisa* researched several fluids for replacing supercritical CO_2 with an alternate fluid for experimental setups.
- The research was made amongst various fluids that have properties tabulated in well known databases such as REFPROP.
- Prandtl number behavior of various fluids is analyzed in the study.
- The following fluids were identified as the best candidates to be similar to sCO_2.
  - Ammonia (NH_3).
  - Air.
  - Freon/Refrigerant 23 (CHF_3).
  - Water (H_2O).

*Pucciarelli A. and Ambrosini W., (2020), "A Successful General Fluid-to-Fluid Similarity Theory for Heat Transfer at Supercritical Pressure", International Journal of Mass and Heat Transfer, Vol.159, 120152, Elsevier Inc.

Fluid Similarity Method

Finding Similar Fluids for sCO_2 (continued)

- Main Compressor inlet flow Reynolds number is calculated for Stage 1 and Stage 2.
- The volumetric flowrate should be equal for both fluids to ensure the flow velocities are equivalent.
- REFPROP* is used for the candidate fluids to find the matching flow conditions with sCO_2.
- At the matched Reynolds number, the similar fluid should be:
  - Ideal gas.
  - Calorically perfect gas.
  - In gas or supercritical phase.
- Water and ammonia are eliminated due to their being liquid and non-ideal at the matched conditions.

*NIST REFPROP v10

Fluid Similarity Method

Finding Similar Fluids for sCO_2 (continued)

	sCO_2	Air	CHF_3 (Freon)
Pressure [psia]	887	3550	5510
Temperature [F]	71.44	22	260
Compressibility Factor	0.144	1.03	0.95
Sp. Heat Ratio	4.479	1.197	1.56
Density [lbm/ft^3]	47.285	19.249	54.291
Mass Flowrate [lbm/s]	6383	2599	7329
Volumetric Flowrate [ft^3/s]	135	135	135
Reynolds Number	65.7E6	65.7E6	65.7E6

- Air mass flowrate at matched conditions is significantly different due to the difference in density.
- Using air as the similar fluid would cause significant geometrical differences (scaling would be problematic).

- Freon mass flowrate at matched conditions is close to sCO_2; designed geometry will be "similar."
- The density of Freon is very close to that of sCO_2, making scaling of the maps easier and less error prone.

Fluid Similarity Method

Turbomachinery Design Similarity

- Reynolds number matching satisfies dynamic similarity only.
- To have kinematic similarity, the following design specs of the compressor should be matched with the similar fluid:*
  - Head Coefficient

    Ensures that the forces and pressures acting on the turbo component will be similar to the actual flow.
  - Specific Speed

    Ensures that the flow coefficient and velocity triangles of the compressor design made for similar fluid will be similar to the actual flow.
- If the above two criteria are satisfied, then the geometric similarity is also assured.*

Nichols K.E., "How to Select Turbomachinery for your Application", Barbera-Nichols Inc.

Fluid Similarity Method

Turbomachinery Design Similarity (continued)

- For the "Freon compressor," the following should be the same as the "sCO_2 compressor" to satisfy kinematic similarity:
  - Shaft Speed.
  - Volumetric Flowrate.
- Equivalent compressor pressure ratio can be found by equating the head coefficients for two flow cases:

$$\frac{\bar{z}RT_{t,in}}{\gamma-1/\gamma}\left[\pi_c^{\gamma-1/\gamma}-1\right] = H = \frac{\bar{z}^{*}R^{*}T^{*}_{t,in}}{\gamma^{*}-1/\gamma^{*}}\left[\pi_{c*}^{\gamma*-1/\gamma*}-1\right]$$

$$\frac{\omega\sqrt{\dot{V}}}{(H)^{3/4}} = n_s = \frac{\omega^{*}\sqrt{\dot{V}^{*}}}{(H)^{3/4}}$$

sCO_2 Freon

Map Scaling

Affinity Laws

- Turbomachinery scaling is used frequently for performance map scaling of similar compressors and pumps.
- If the two pumps or compressors are geometrically close in terms of design, then the performance map of one machine can be used to estimate the performance of the other one.
- Scaling laws can be used to scale different fluid operation cases.
- Affinity Laws are used to scale the pressure ratio, isentropic efficiency, or head coefficient.
- In this context, the scaling laws are used to scale the maps from the Freon compressor to sCO_2 compressor.

Map Scaling

Pressure Ratio Scaling

- The head coefficient of the sCO_2 compressor will be equal to the Freon compressor (from fluid similarity principles).*
- Pressure ratio scaling formula is then found by using the above principle as follows:

$$\pi_c = \left\{1 + \frac{z_{CHF_3}\gamma_{CHF_3}R_{CHF_3}T_{CHF_3}}{z_{CO_2}\gamma_{CO_2}R_{CO_2}T_{CO_2}} \frac{\gamma_{CO_2-1}}{\gamma_{CHF_3-1}} \left[\pi_C^{*\,(\gamma_{CHF_3}-1)/\gamma_{CHF_3}} - 1\right]\right\}$$

- The formula is used for each point in the Freon compressor pressure ratio (π_C^*) vs. mass flowrate map curve.
- The mass flowrate for sCO_2 is scaled using the density ratio of two fluids.

Nichols K.E., "How to Select Turbomachinery for your Application", Barbera-Nichols Inc.

Map Scaling

Isentropic Efficiency Scaling

- The isentropic efficiency is scaled by using the following formula*:

$$\frac{1-\eta_{CHF_3}}{1-\eta_{CO_2}} = \left(\frac{d_{2,CO_2}}{d_{2,CHF_3}}\right)^n$$

- Although geometrically "similar", the impeller diameter (d_2) of the Freon compressor is not exactly equal to sCO_2 compressor.
- The wheel speed of the two compressors are proportional to the diameter ratio.
- The wheel speed equation is used to calculate the diameter ratio in the scaling formula

$$\left\{\frac{h_{t1}\left(\pi_c^{(\gamma-1)/\gamma e_c}-1\right)}{\varepsilon}\right\}_{CO_2} = \frac{d_{2,CHF_3}}{d_{2,CO_2}}\left\{\frac{h_{t1}\left(\pi_c^{(\gamma-1)/\gamma e_c}-1\right)}{\varepsilon}\right\}_{CHF_3}$$

- The coefficient "n" is calculated for each stage separately. It is calculated by using the efficiency scaling formula at the design point.

Nichols K.E., "How to Select Turbomachinery for your Application", Barbera-Nichols Inc.

Validation

Validation of the Proposed Methodology

- Although the fluid similarity method has been used and validated by SNL, there are some variations in the application of the method in this study—mainly in the map scaling.
- The compressor design by SNL was used in the method validation procedure.
- The inlet flow analysis showed that the similar fluid for this compressor should be "air."
- The in-house compressor design code was used to design the compressor for similar fluid conditions.

Validation

Compressor Design Procedure

- The scaling formulas are then used for scaling the air compressor dimensions to the sCO_2 compressor.
- The scaled compressor dimensions are then compared to the SNL compressor design.
- Per the fluid similarity laws, the flow angles should be the same for both the air and sCO_2 cases.

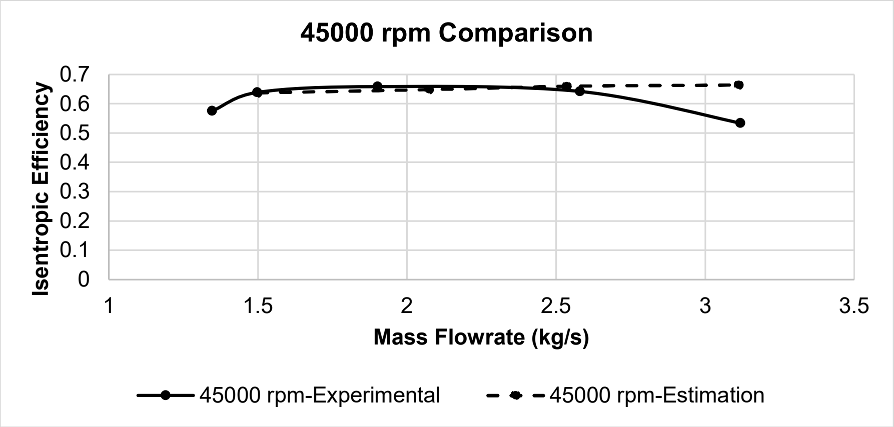
Parameter	Current Study		SNL*
Flow	Air	sCO_2	sCO_2
Impeller Diameter, d_2	0.068 m	0.048 m	0.051 m
Impeller Length, L	0.03 m	0.02 m	0.02 m
Inlet Tip Diameter, R_{1t}	0.01 m	0.008 m	0.009 m
Impeller Inlet Angle, β_1	57^0	57^0	50^0
Impeller Exit Angle, β_2	49^0	49^0	50^0
Throat Diameter, b_2	0.001 m	0.0007 m	0.0008 m
Exit Flow Angle, a_3	72.6^0	72.6^0	71.5^0
Number of Blades	13	13	12

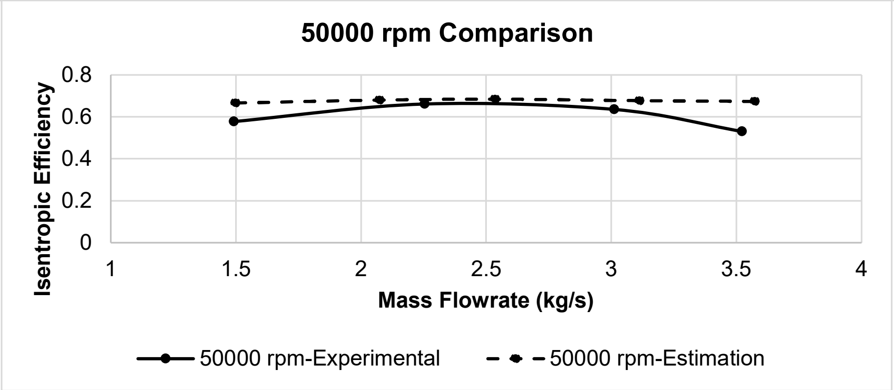
Wright S.A., Radel R.F., Vernon M.E., Rochau G.E. and Pickard P.S., (2010), "Operation and Analysis of a Supercritical CO_2 Brayton Cycle", Sandia Report, SAND2010-0171, Albuquerque, NM

Validation

Map Scaling Methods

- NASA CCODP Code was used with the air compressor design parameters.
- The performance maps for the pressure ratio and isentropic efficiency were generated for the air compressor.
- The performance maps are then scaled to sCO_2 per the previously described methodology.
- Experimental off-design data of the SNL compressor for isentropic efficiency at various shaft speeds are used in map scaling validation.





Compressor Design

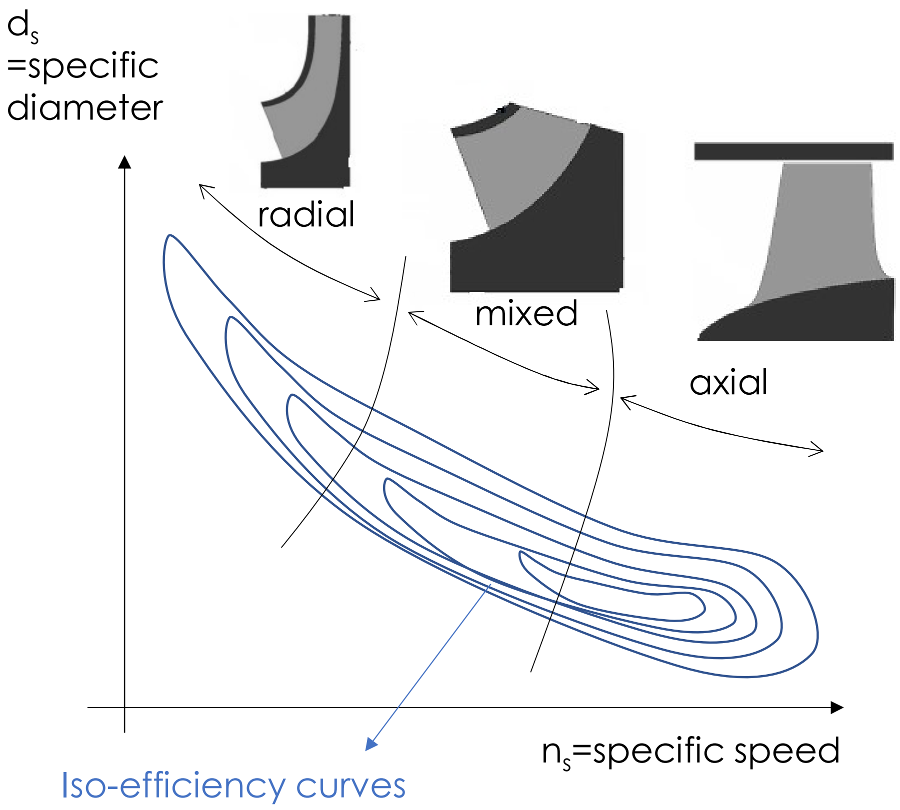
Design Methodology

- Freon compressor is designed at the matched Reynolds number conditions with sCO_2.
- The in-house design code was used to design the compressor stages by using mean-line design principles.
- Freon thermodynamic properties are used in the design code.
- No changes to design equations made; Freon is an ideal and calorically perfect gas.
- A feasible design was made using centrifugal compressor industry design practices and a Baije chart.

Compressor Design

Design Methodology (continued)

- Baije chart is used initially to find initial design parameters such as slip factor, shaft speed, and specific diameter.
- Shaft speed is important; it affects all the design parameters.
- Two options are identified for compressor design shaft speed.
  - Fixed at 3600 rpm (advantageous for turbine coupling).
  - High rpm (higher efficiency).



Compressor Design

Radial Compressor Design Options

For Highest Efficiency (average)

- Rotational speed: 16500 rpm
- Impeller Length: 15.5”
- Slip Factor: 0.8
- Polytropic Efficiency: 0.84–0.87
- 2-stage compressor with intercooler (1 stage + Intercooling + 1 Stage)

For Keeping Shaft Speed at 3600 rpm (average)

- Rotational speed: 3600 rpm
- Impeller Length: 31.5”
- Slip Factor: 0.85
- Polytropic Efficiency: 0.8–0.83
- 6-stage compressor with intercooler (3 stages + Intercooling + 3 stages)

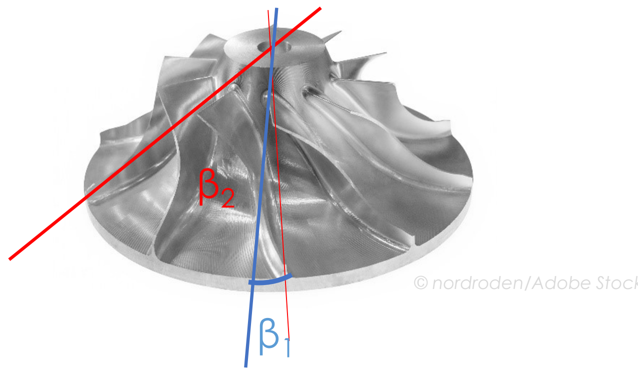
Compressor Design

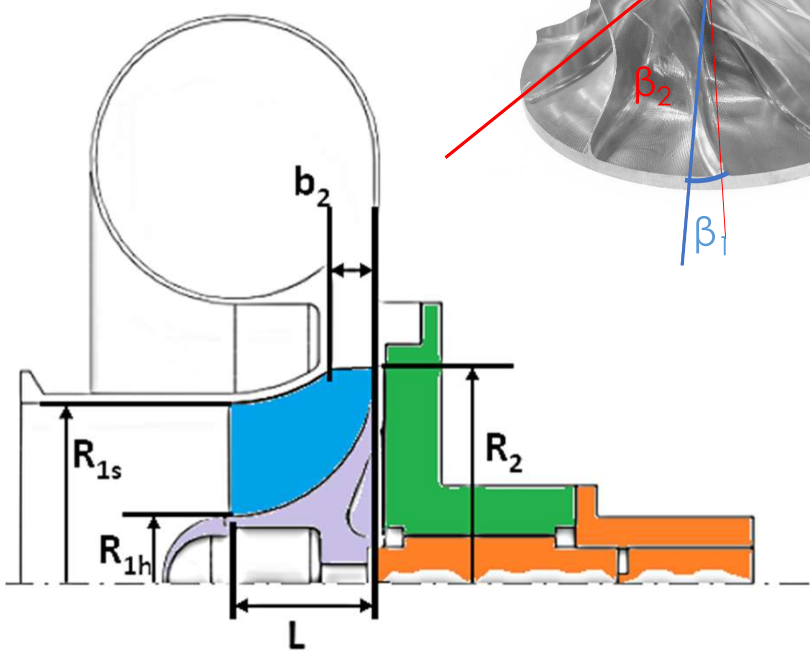
Applied Design Standards

- Several design standards from SwRI tutorials, Aungiers, Wiesner et al., and Walsch et al. are adapted.
- Some design criteria used:
  - Mean Inlet Mach Number = 0.4-0.6
  - Impeller Backsweep Angle < 40^0
  - Inducer hub-to-tip ratio= 0.35-0.5
  - Exit flow speed < 500 m/s
  - Impeller Diameter < 0.8m [a manufacturability limit]
  - Exit Flow Mach Number < 0.2
  - Slip Factor= 0.8-0.95

Compressor Design

Stage 1 Design

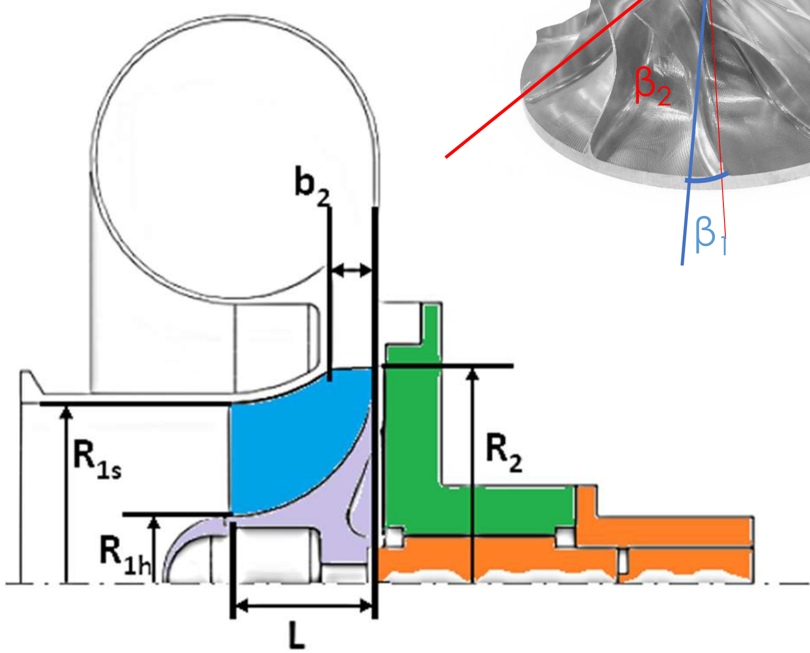


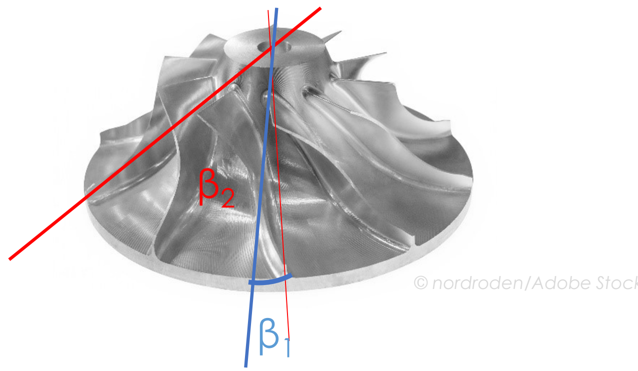


Parameter	Value
Inlet Hub Diameter, R_{1h}	2.64”
Inlet Tip Diameter, R_{1s}	5.28”
Impeller Radius, R_2	7.81”
Blade Length, L	4.8”
Impeller Inlet Angle, β_1	38^0
Impeller Exit Angle, β_2	32^0
Slip Factor	0.81
Number of Impeller Blades	9
Throat Diameter, b_2	0.46”
Pressure Ratio	1.445
Isentropic Efficiency	0.78
Flow Coefficient	0.09

Compressor Design

Stage 2 Design





Parameter	Value
Inlet Hub Diameter, R_{1h}	2.39"
Inlet Tip Diameter, R_{1s}	4.79"
Impeller Radius, R_2	9.72"
Blade Length, L	8"
Impeller Inlet Angle, β_1	37^0
Impeller Exit Angle, β_2	28^0
Slip Factor	0.86
Number of Impeller Blades	15
Throat Diameter, b_2	0.22"
Pressure Ratio	2.013
Isentropic Efficiency	0.85
Flow Coefficient	0.04

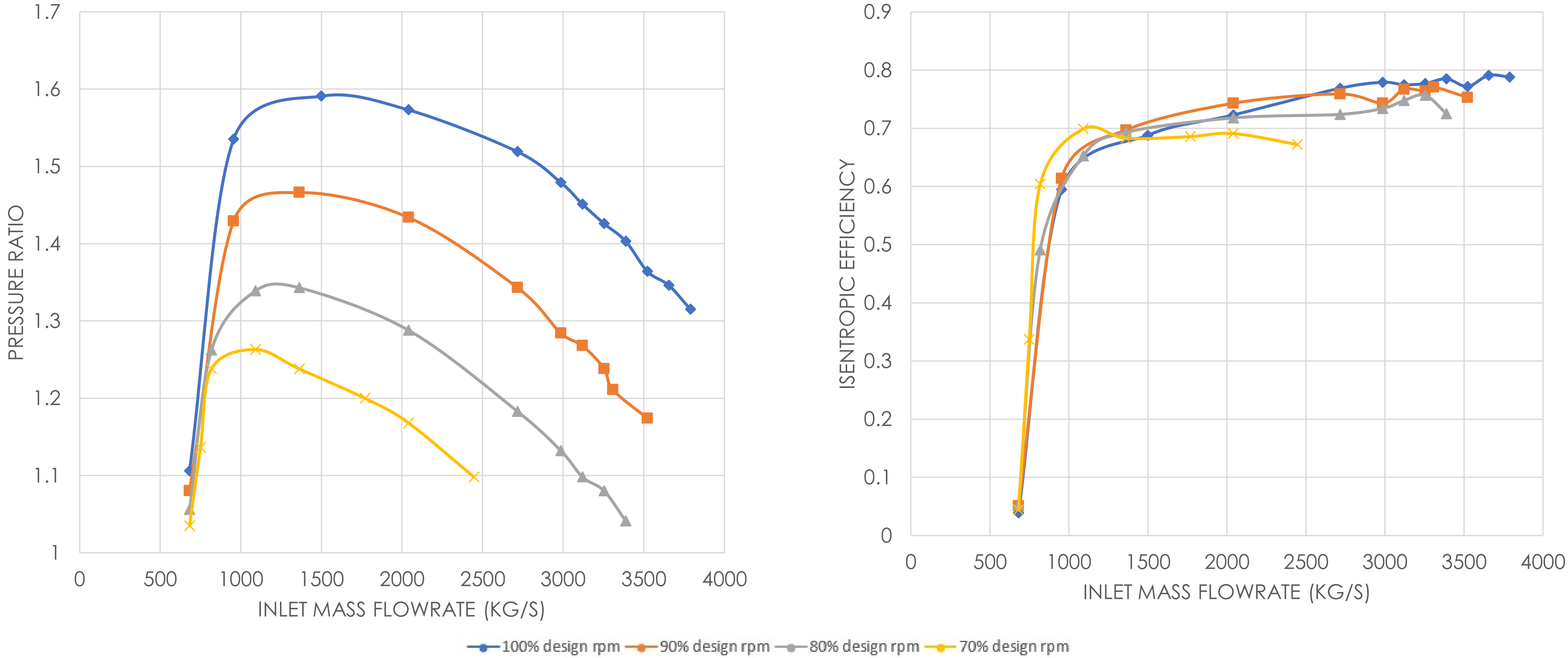
Off-Design Maps

Methodology

- NASA CCODP code is used to generate the off-design maps for the Freon compressor.
- No changes in the performance map calculation are made; Freon is an ideal and calorically perfect gas.
- Maps are generated for four different speeds:
  - 100% Speed (16500 rpm)-Design Speed.
  - 90% Speed (14850 rpm).
  - 80% Speed (13200 rpm).
  - 70% Speed (11550 rpm).
- Maps for pressure ratio and isentropic efficiency are generated.

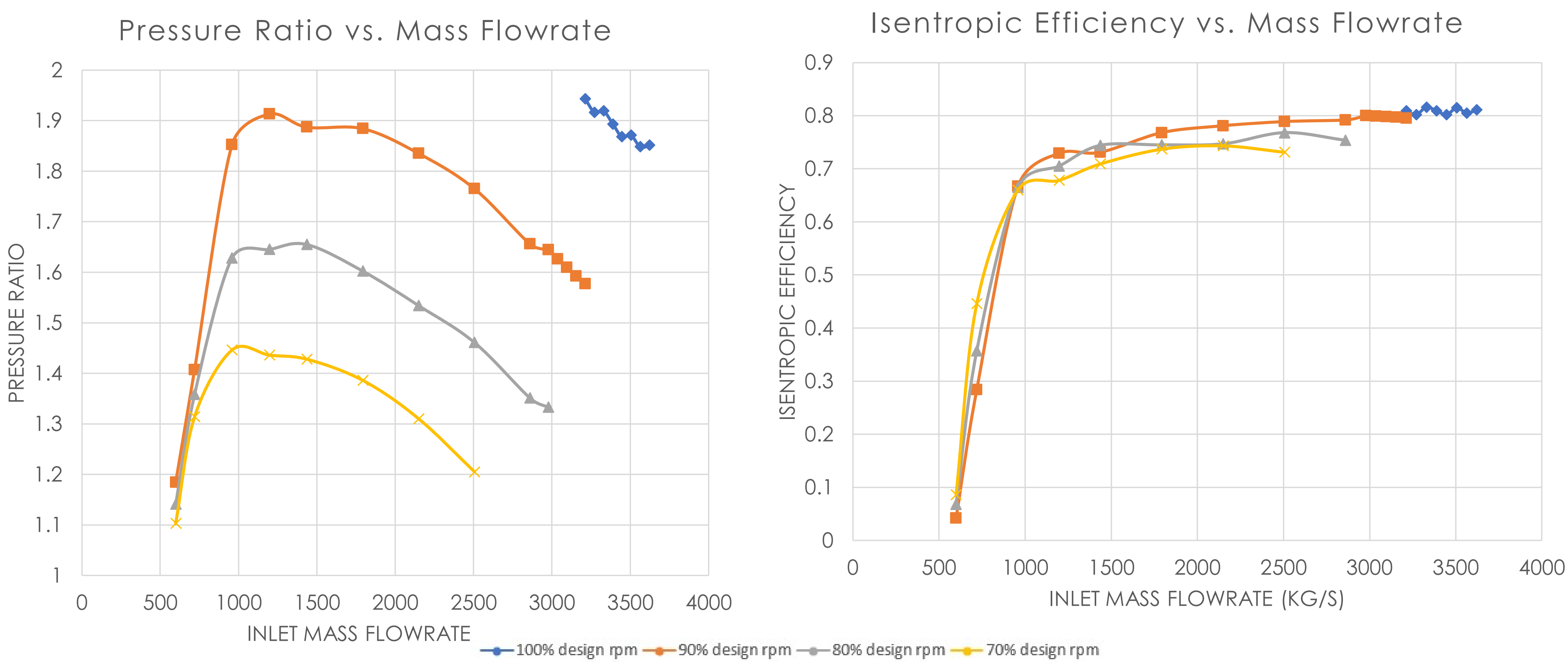
Off-Design Maps

Stage 1



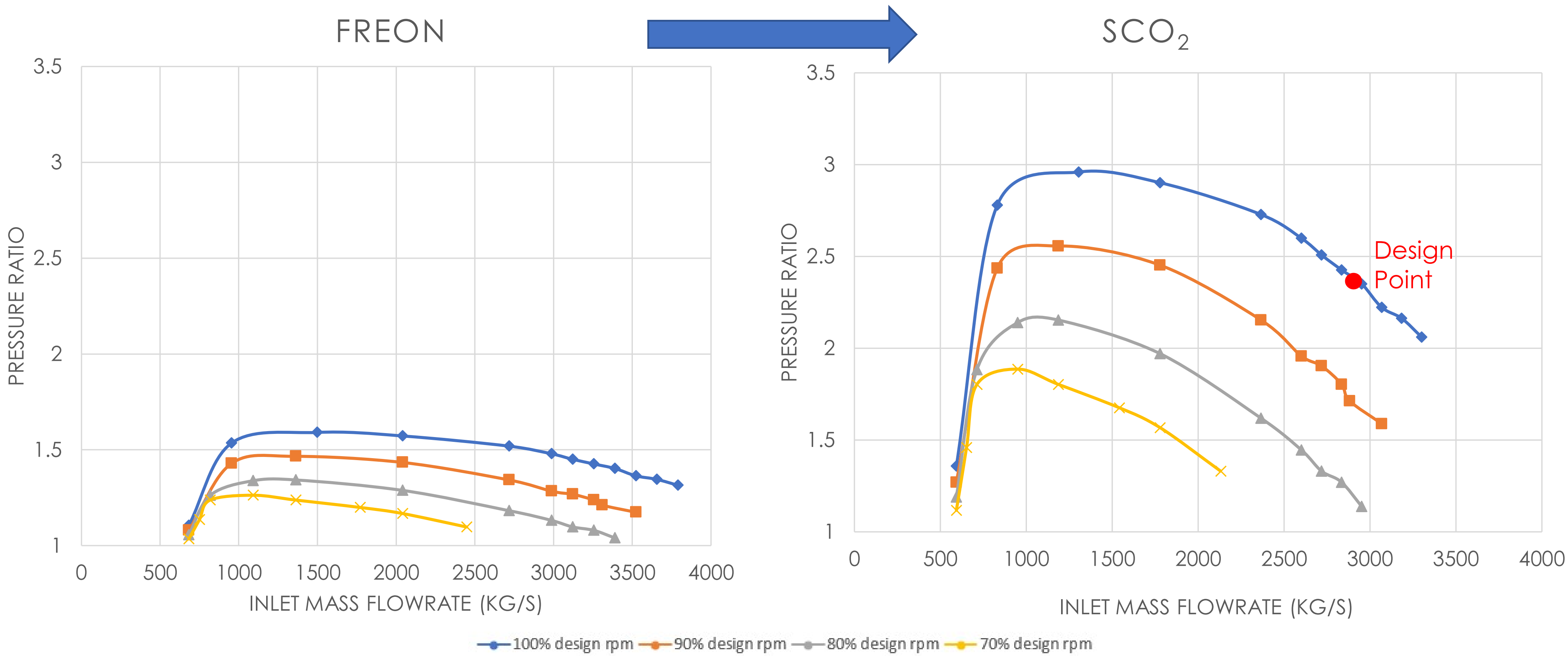
Off-Design Maps

Stage 2



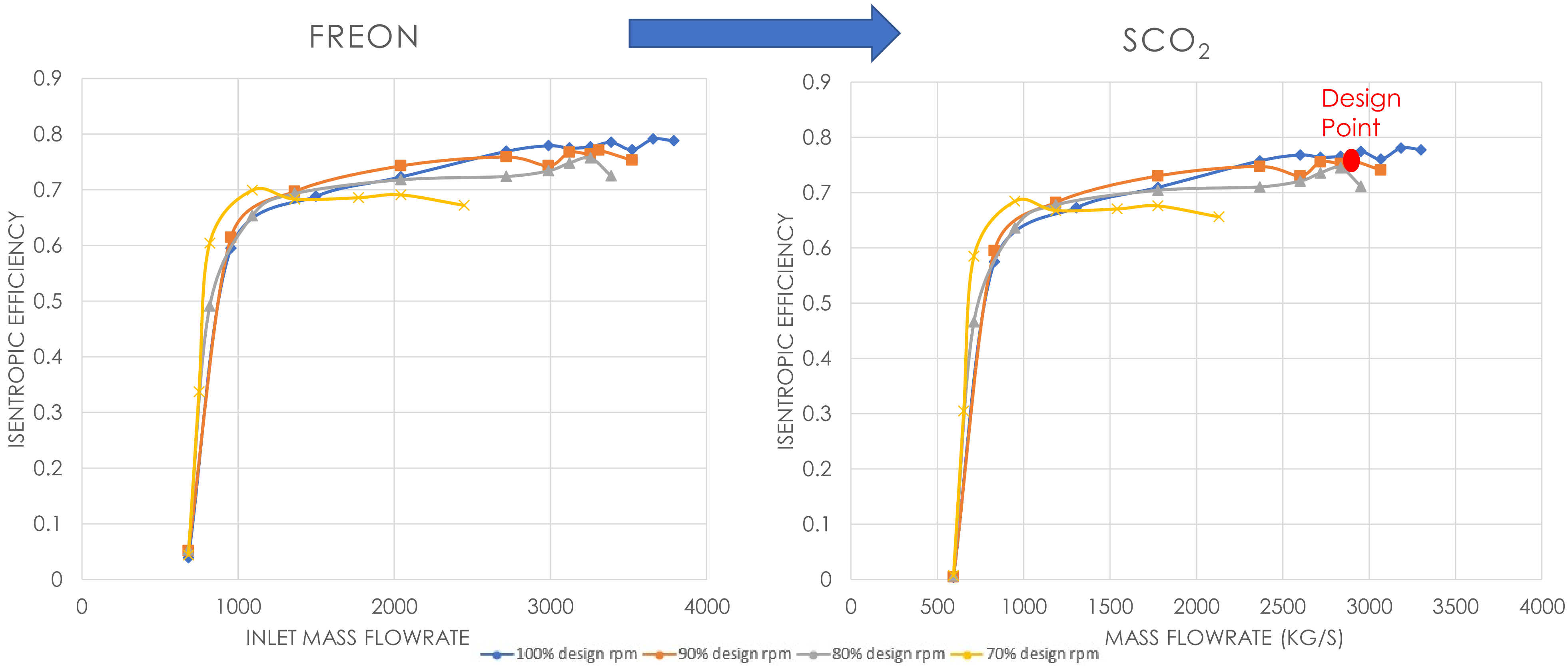
Off-Design Maps

Pressure Ratio Scaling



Off-Design Maps

Isentropic Efficiency Scaling



Off-Design Maps

General Comments

- Map shapes for the pressure ratio are similar to centrifugal pump maps; wide-parabolic curves.
- Similarity to pump maps is expected per Baije analysis.
- Stage 2 operational range is too narrow due to high impeller design exit Mach number (at 0.9).
- Higher impeller design Mach number increases design efficiency but reduces the operational range.
- Stage 2 will be re-designed. Two options exist for Stage 2:
  - Divide Stage 2 into two stages: reduces pressure ratio and the impeller Mach number.
  - Run Stage 2 at lower rpm: requires integrally geared compressor design (second stage will not be on the same shaft with first).

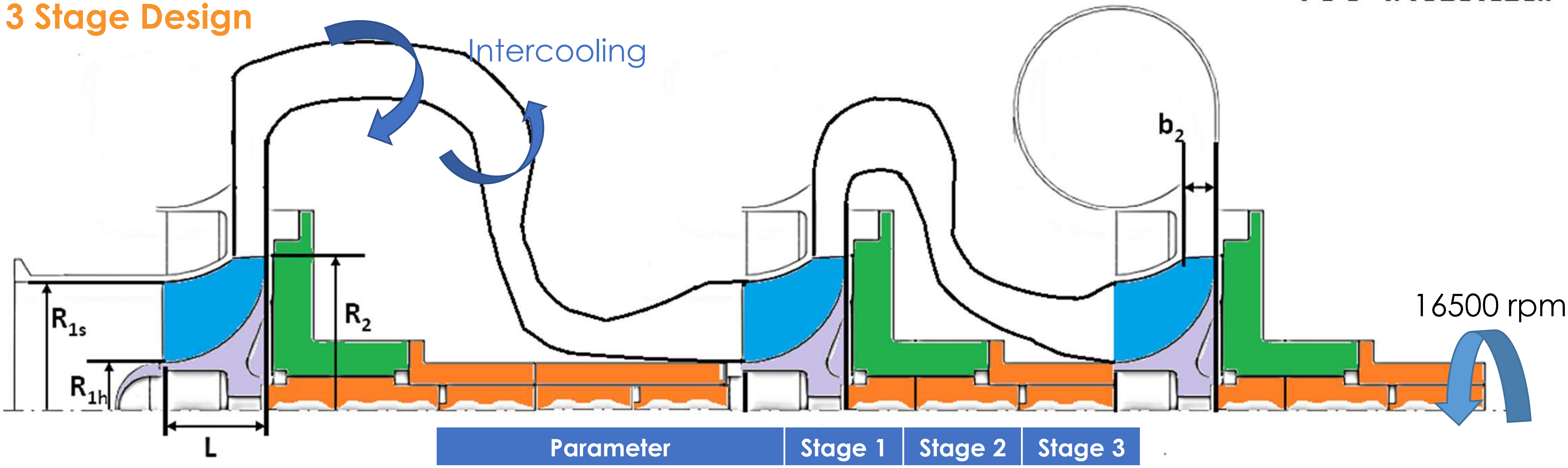
Compressor Design Updates

Re-Design of Second Stage

- Second stage of two stage design had a narrow operational range due to high impeller exit Mach number.
- Second stage of the previous design is divided into two stages with each having the same pressure ratio.
- Shaft speed is the same for all stages (16500 rpm).
- Intercooling is applied between Stages 1 and 2 only.
- Fluid similarity method is used to design and run off-design analysis for each stage.
- Off-design maps are scaled to sCO_2 with the same method used in Stage 1.

Compressor Design Updates

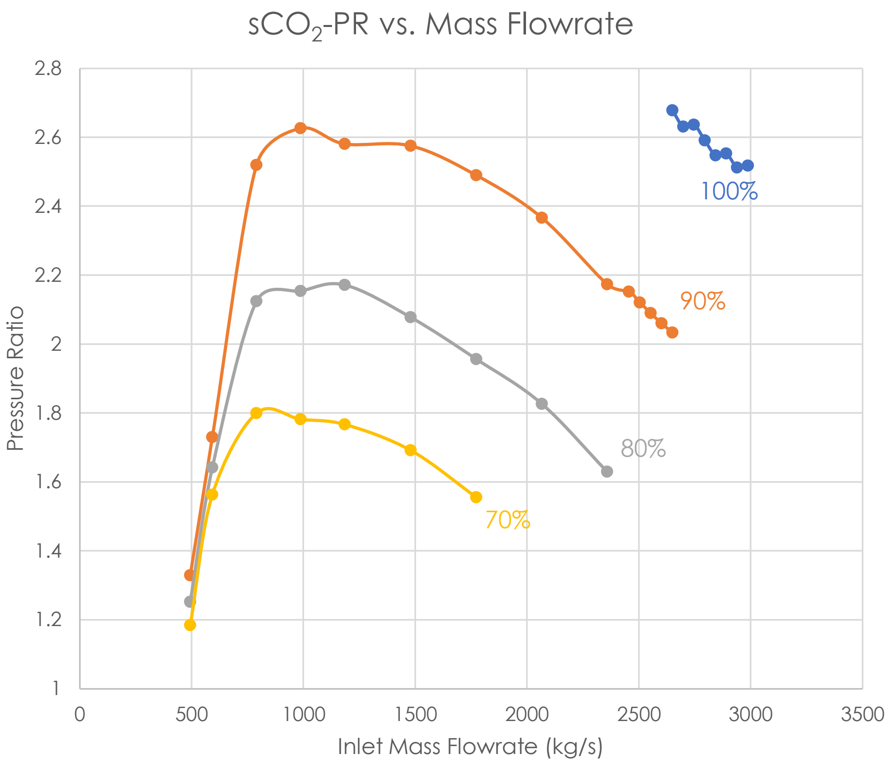
3 Stage Design

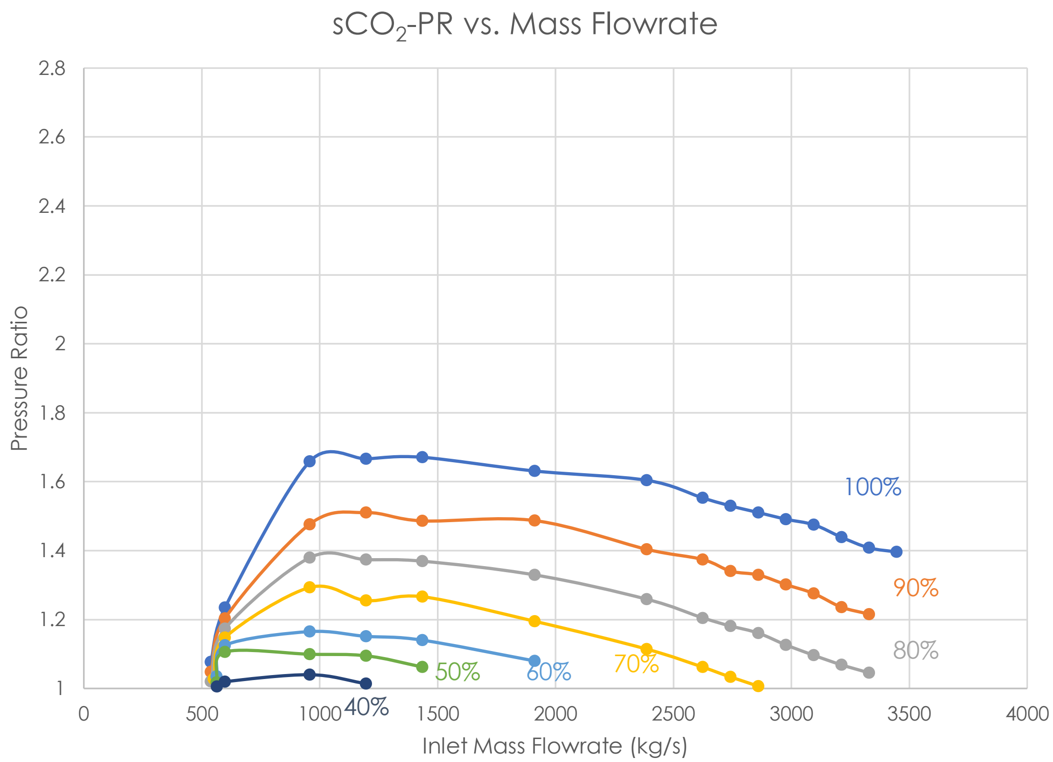


Parameter	Stage 1	Stage 2	Stage 3
Inlet Hub Diameter, R_{1h}	2.64"	2.39"	2.46"
Inlet Tip Diameter, R_{1s}	5.28"	4.79"	4.91"
Impeller Radius, R_2	7.81"	6.57"	7.32"
Blade Length, L	4.8"	3.9"	4.7"
Throat Diameter, b_2	0.46"	0.52"	0.39"
Number of Blades	9	9	13
Pressure Ratio (sCO_2 Equivalent)	2.5	1.583	1.583

Compressor Design Updates

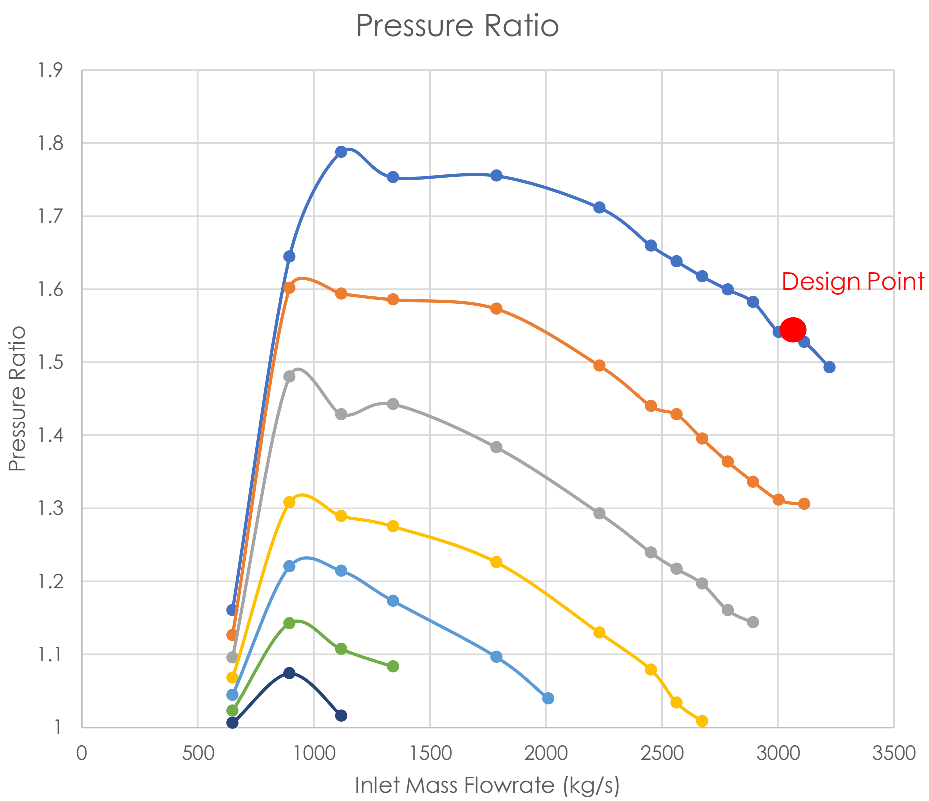
Off-Design Maps – Stage 2

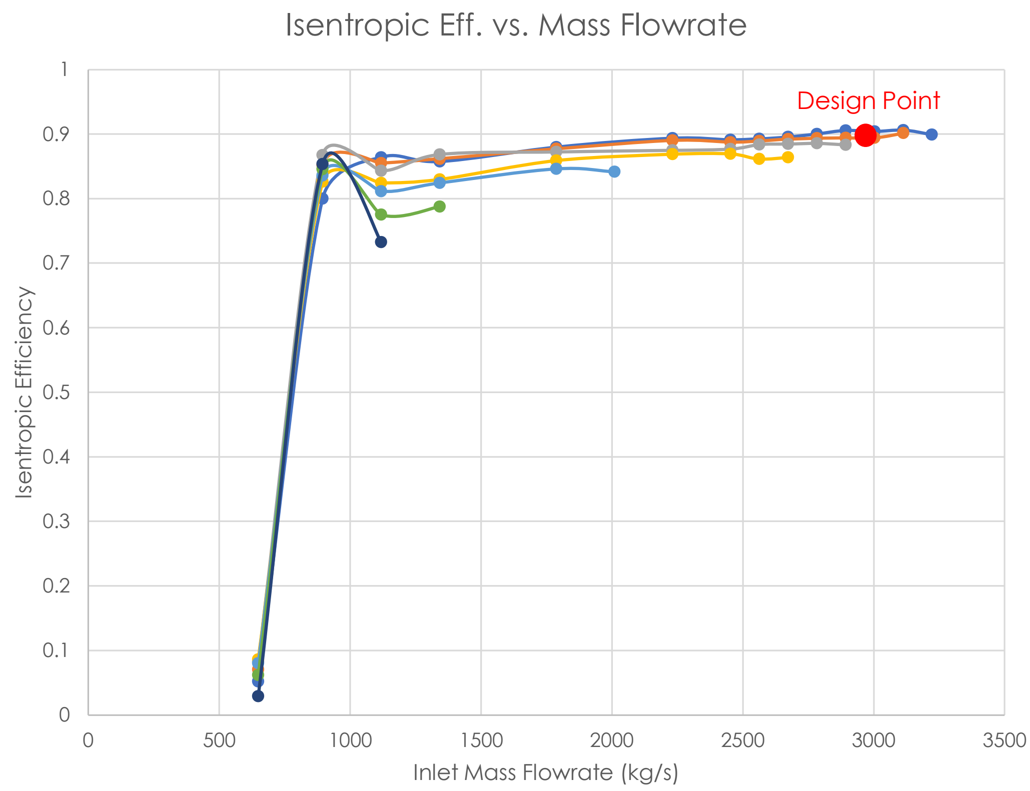




Compressor Design Updates

Off-Design Maps – Stage 3





Summary and Conclusions

- The fluid similarity method is used to design and generate performance maps for the indirect cycle main compressor.
- For the main compressor flow conditions, Freon is the “similar” fluid for the analysis, which is both an ideal and calorically perfect gas.
- NASA CCODP code is used to generate performance maps for the Freon compressor design.
- Maps showed centrifugal pump-like characteristics for the pressure ratio and efficiency.
- The maps are scaled for sCO_2 application.
- Scaled map data are used to develop Aspen Plus compressor models for each stage.

Disclaimer

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Questions/ Comments

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