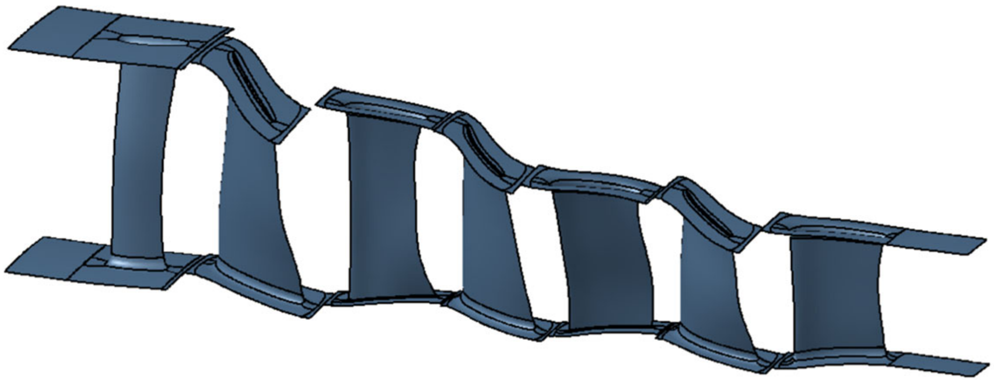

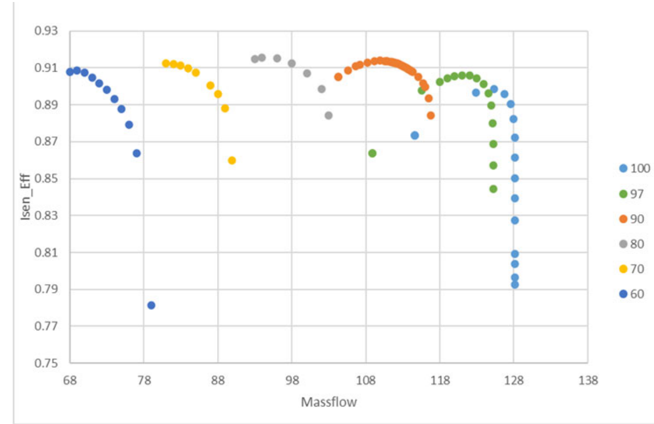

Design and Optimization of a 3-Stage Axial Supercritical CO2 Compressor

Paper #70

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February 28,2024

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8th International sCO_2 Power Cycles Symposium

Outline

- Overview
- Single Stage Background
- Design and Optimization Methodology
- Three-Stage Design
- Future work
- Conclusions

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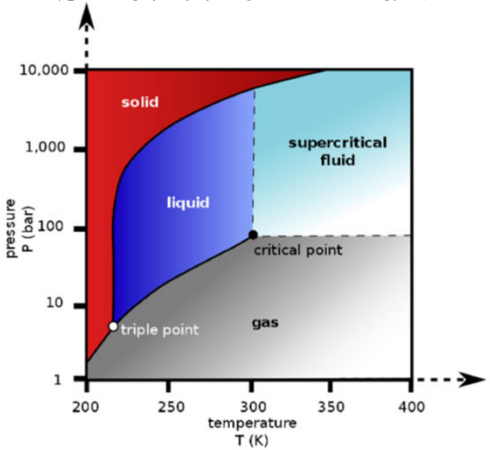
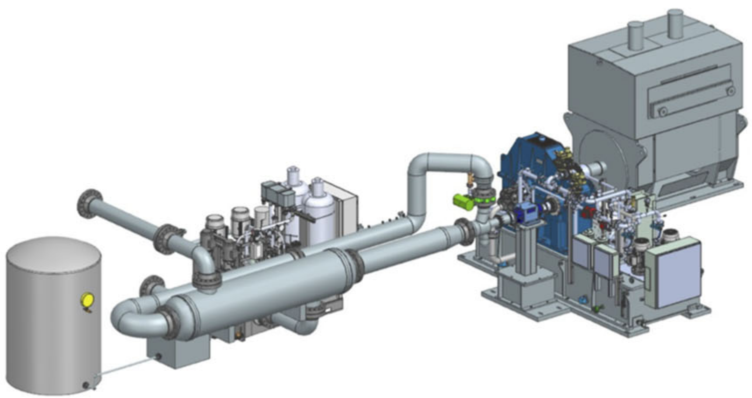
The SCO_2 Axial compressor

- Echogen Pumped Thermal Energy Storage System (PTES) defines compressor requirements
- 9 stage 100 MW SCO_2 compressor design
- Scaled 10 MW first 3-stages of the compressor designed/optimized by UC and to be tested in NDTL's 10MW test cell
- Size: 0.25m in diameter and 15 cm in length



CO_2 Pressure-Temperature Phase Diagram
Above its critical point (304.13K, 7.3773MPa), CO_2 behaves like a supercritical fluid.
(Ben Finney, Mark Jacobs / Wikimedia Commons)



NDTL Supercritical CO_2 Compressor Test Facility

SCO_2

- High thermal efficiency
- Compact physical footprint
- Operational flexibility
- Abundant, low cost, non-toxic

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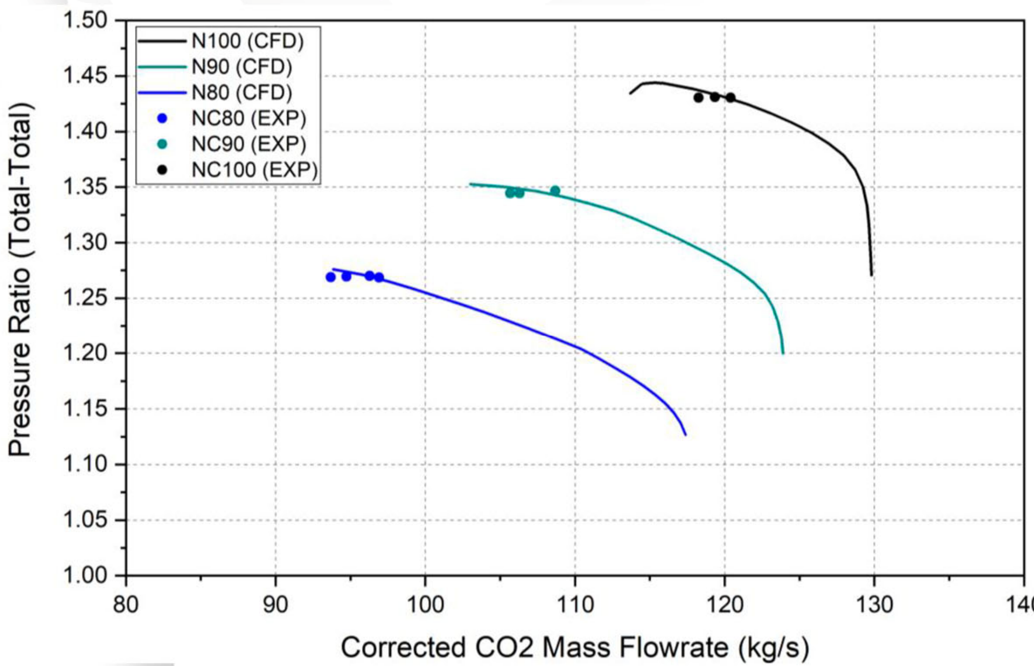
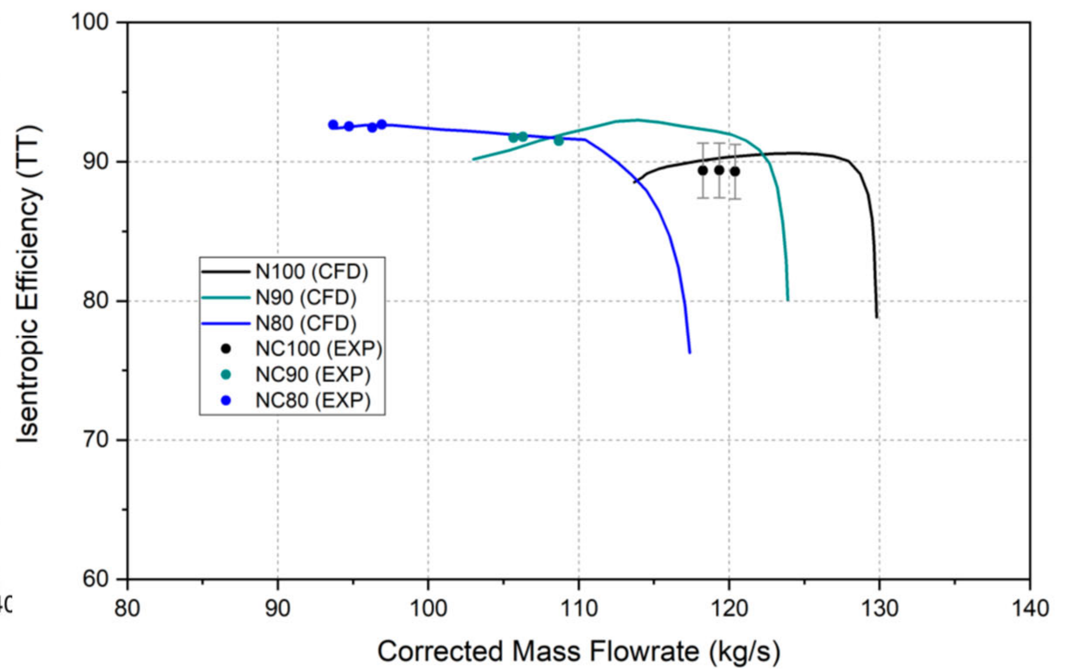
First Stage Results

- Detailed Results Presented Thursday 8:30 at this symposium by Jeongseek Kang from Notre Dame Turbomachinery Lab (paper #44)



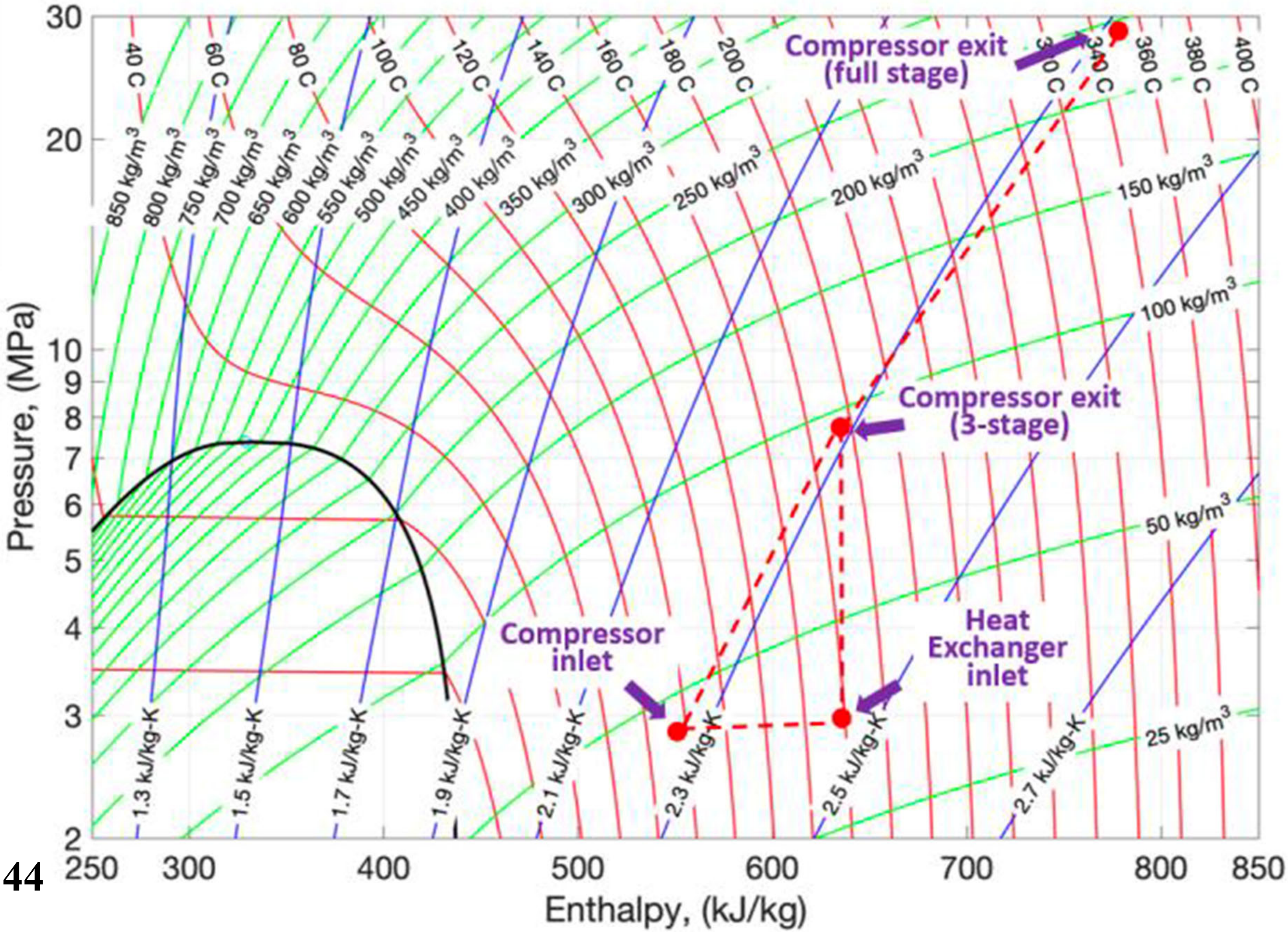


80, 90, and 100% predicted/design speed lines and experimental results

MLC0 Can you increase the size of the solid circles? I caught myself squinting. Are there error bars on the 90% and 100% case?

Mark L Celestina, 2024-02-21T15:58:45.032

Three Stage Design Conditions on p-h diagram



from **2021-sCO2.eu-144**

Axial Compressor Design/Optimization System

- Similar to traditional approach of using meanline – axisymmetric – 3D CFD – static FEM – Campbell diagrams
- Second and Third stage designs completed before first stage test

Details of Design System are Unique and Revolutionary

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Axial Compressor Design

CO_2 Application

- Open Source meanline code Py-C-Des using CO_2 properties in tables from Refprop
- 3D geometry from T-Blade3
  - Parametric
  - Creates sections on surfaces of revolution
  - 2nd derivative of blade meanline plus NACA thickness
  - Lean and Sweep
  - Creates solid model by connecting with ESP

Traditional

- Proprietary meanline code
- Very Simple geometry or proprietary geometry generator
  - Connections to CAD are proprietary or cumbersome

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Axial Compressor Design

CO_2 Application

- No empirical base to start from – design from first principles
- Axisymmetric Solver from MIT mtflow (limited because fixed gamma)
- Builds in Off-Design Range and Operability
- Blade-to-Blade Optimization
  - At design inlet angle and 7-degree incidence
  - Constrains exit angle
  - Solidity is a parameter (chord)
  - Uses OpenMDAO and Mises

Traditional

- Usually, an evolutionary step from a prior design
- Proprietary axisymmetric solver
- Operability improvements from design point changes
- Solidity usually comes from past experience or old test data
- Uses expert designer for blade-to-blade design or simple optimization

Axial Compressor Design

CO_2 Application

- Parametric Optimization in 3D
  - Multi-objective functions include design and off-design efficiency to build in stall margin
  - 3D method has CO_2 tables so multi-blade row simulation accounts for real properties
- Solid model from ESP is used for FEM
  - Static stresses
  - Campbell Diagram
  - Automated hot-to-cold

Traditional

- Expert designer typically makes geometry changes by hand with hand running of simulation
- Solid models from geometry built in CAD by hand or specialized scripts
- Hot to Cold process is proprietary

Axial Compressor Design

CO_2 Application

- Design team is one professor*, 4 graduate students, 2 undergraduates and former student's work to build from
  - does not include build and test provided by NDTL

Traditional

- Design teams are usually in an aero group and separate structures group with information sent in files by hand

* Now Professor Emeritus

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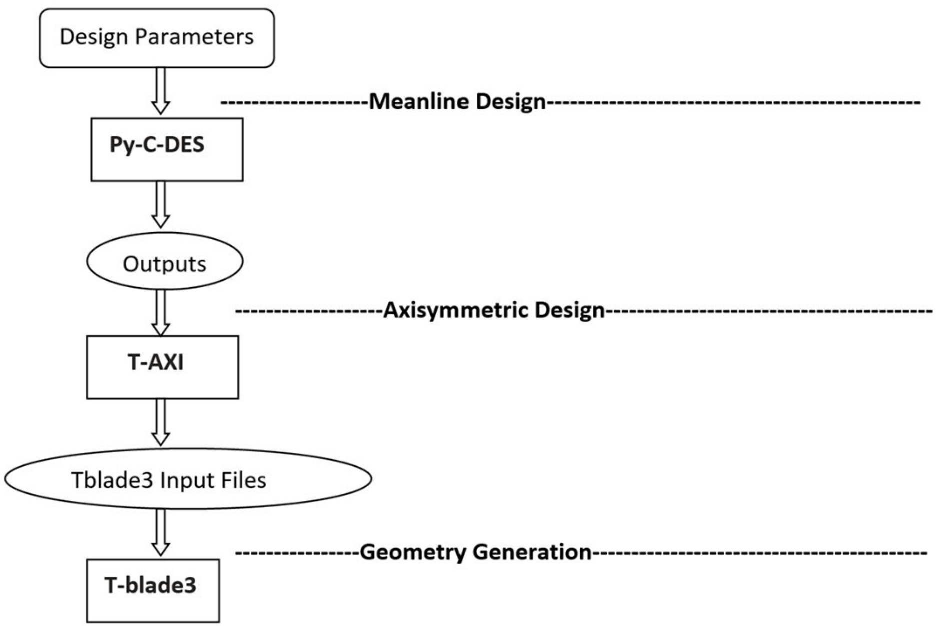
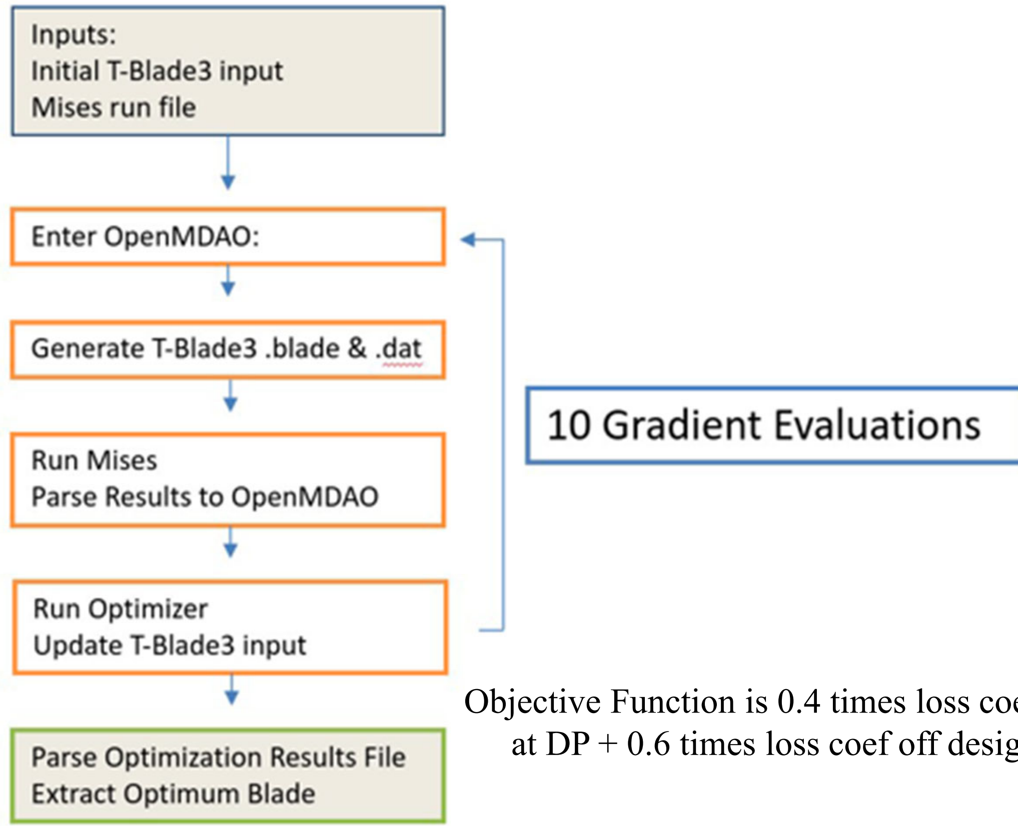
Compressor Design and Optimization

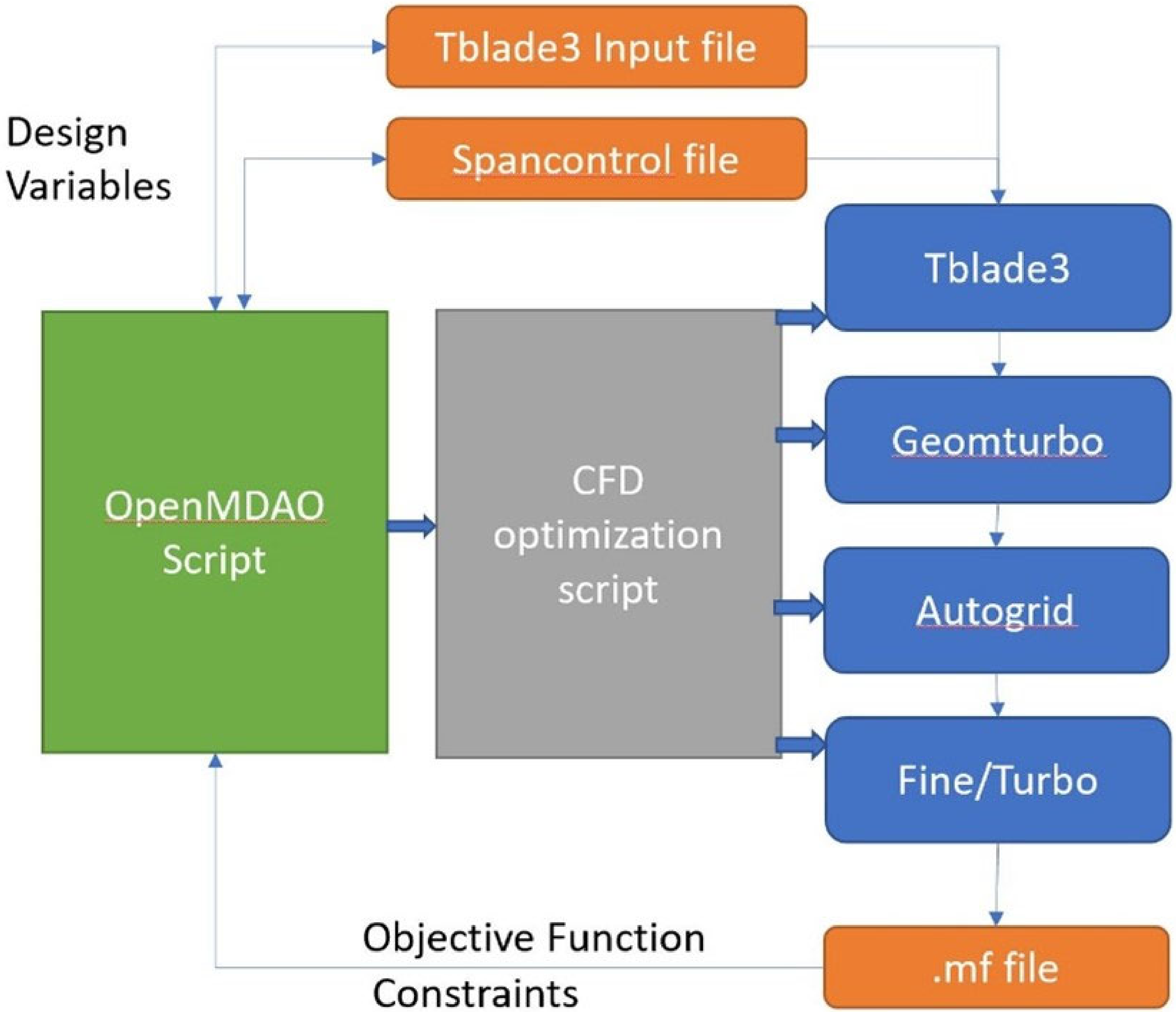


Meanline and axisymmetric design



Objective Function is 0.4 times loss coef at DP + 0.6 times loss coef off design

Blade-to-Blade Optimization Flowchart



3D Optimization Flown Chart

No constraints used for this application

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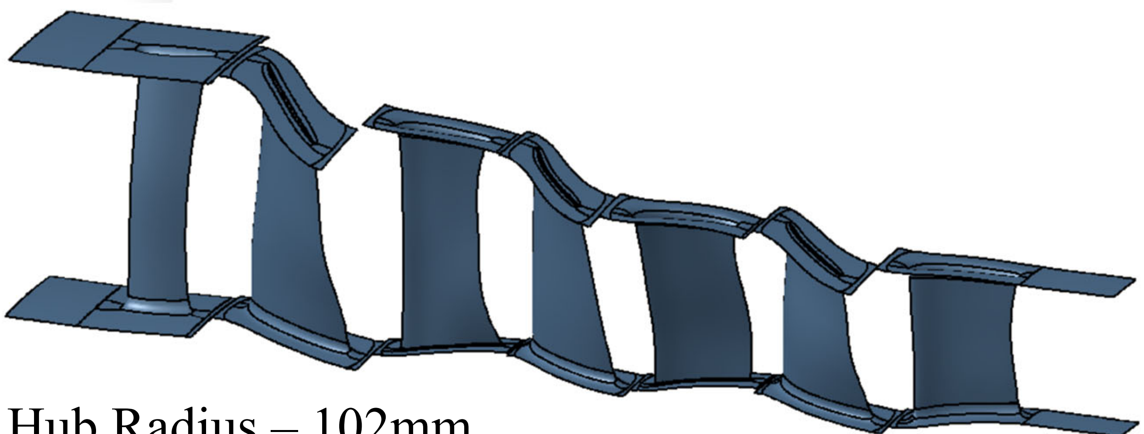
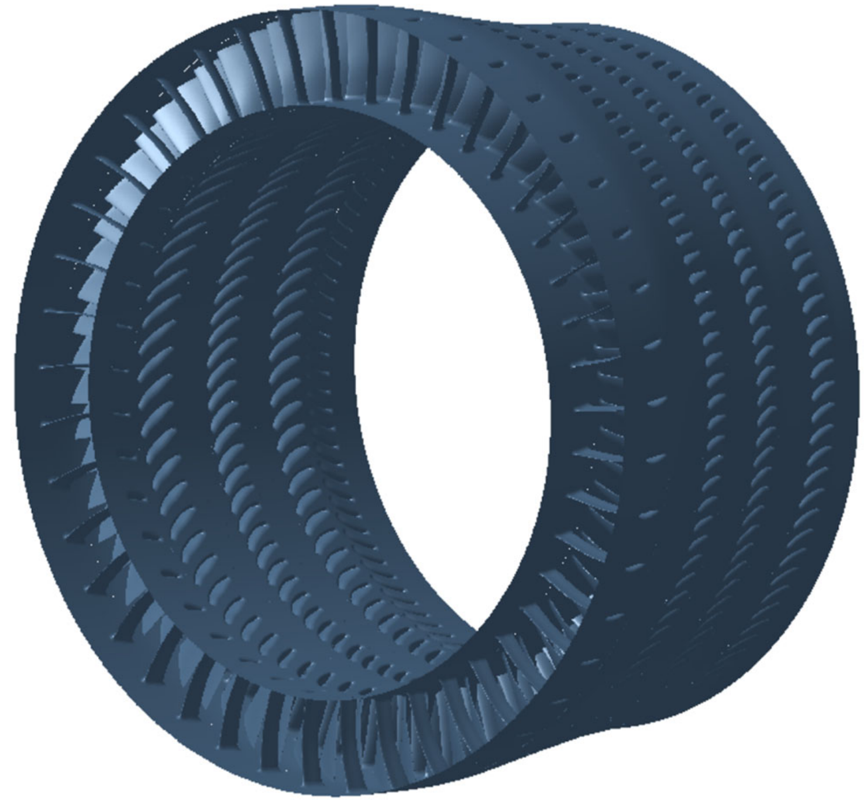
Three Stage Design

Row	Tip Radius_LE (mm)	Hub Fillet (mm)	Tip Gap (mm)	Tip Fillet (mm)	Blade Count
IGV	134.79	1.6	-	1.6	43
R1	134.22	1.6	0.201	-	69
S1	131.56	1.6	-	1.6	114
R2	128.62	1.6	0.192	-	88
S2	126.24	1.6	-	1.6	112
R3	123.59	1.6	0.186	-	83
S3	122.09	1.6	-	1.6	101



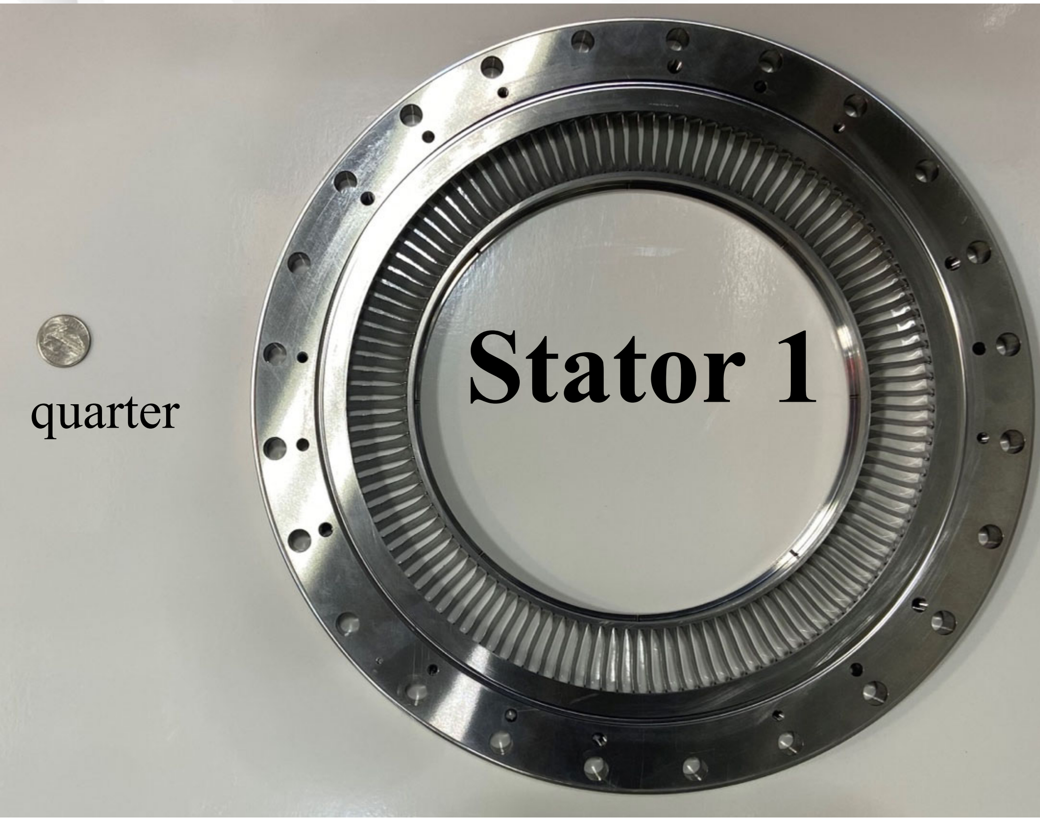
Hub Radius – 102mm



Three Stage Hardware

Rotor 1

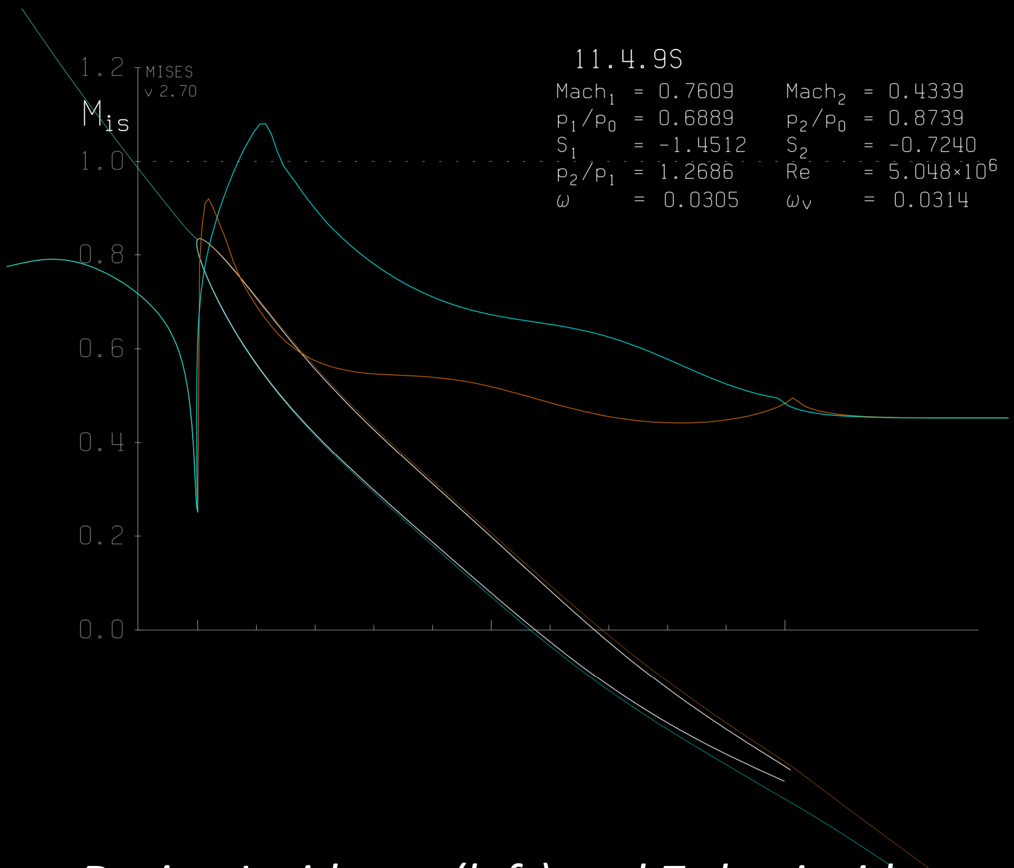
Hardware

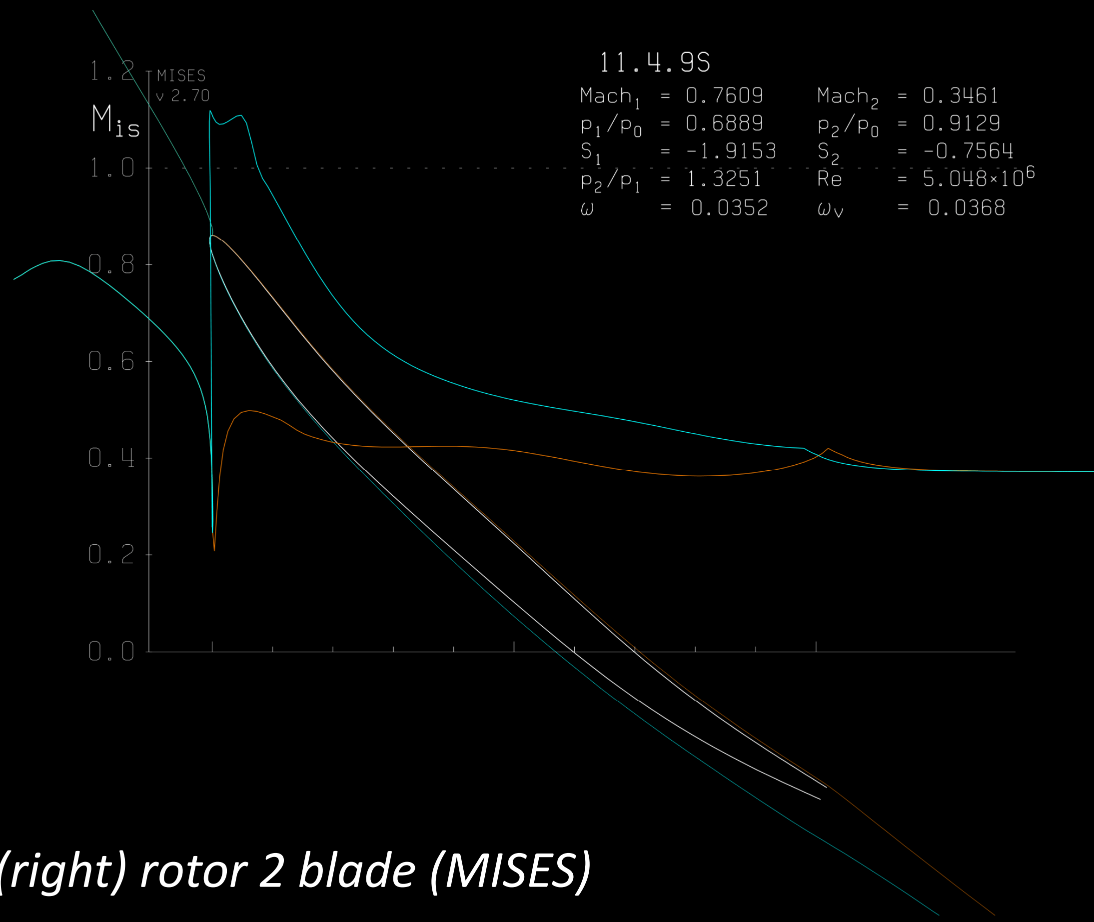


Rotor 2

Rotor 3

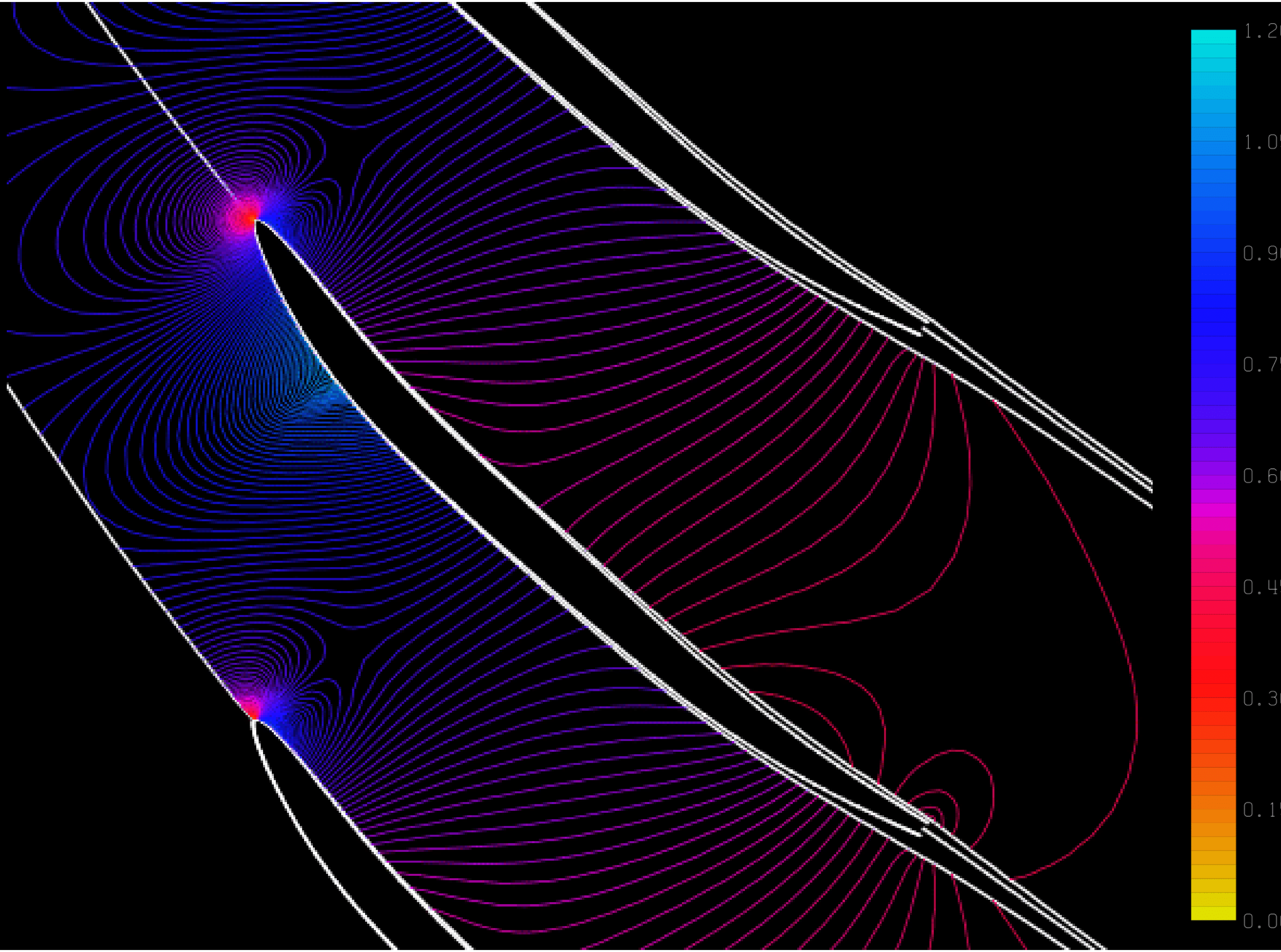
MISES (Quasi-3D Optimized Results)



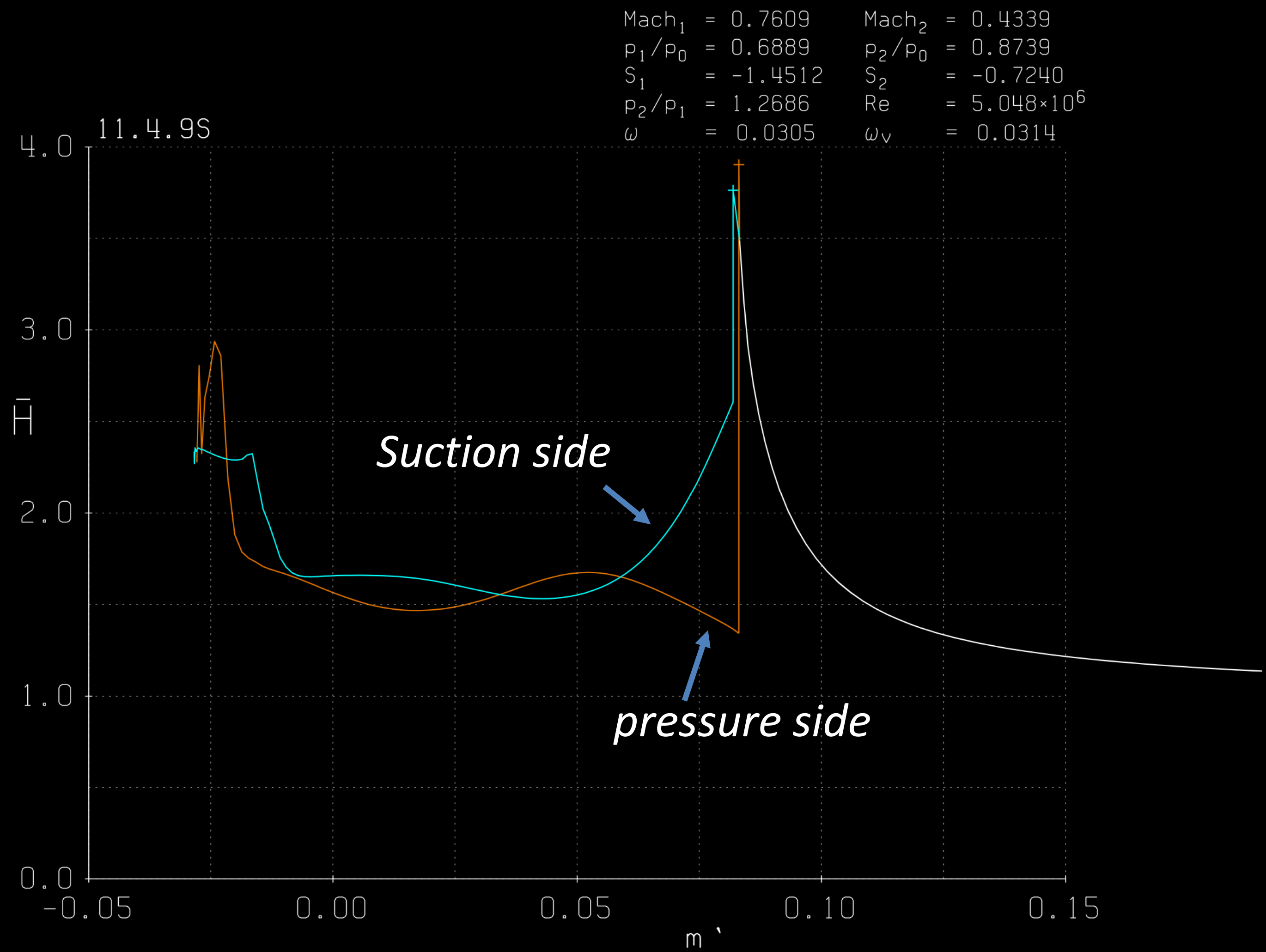


Design Incidence (left) and 7-deg incidence (right) rotor 2 blade (MISES)

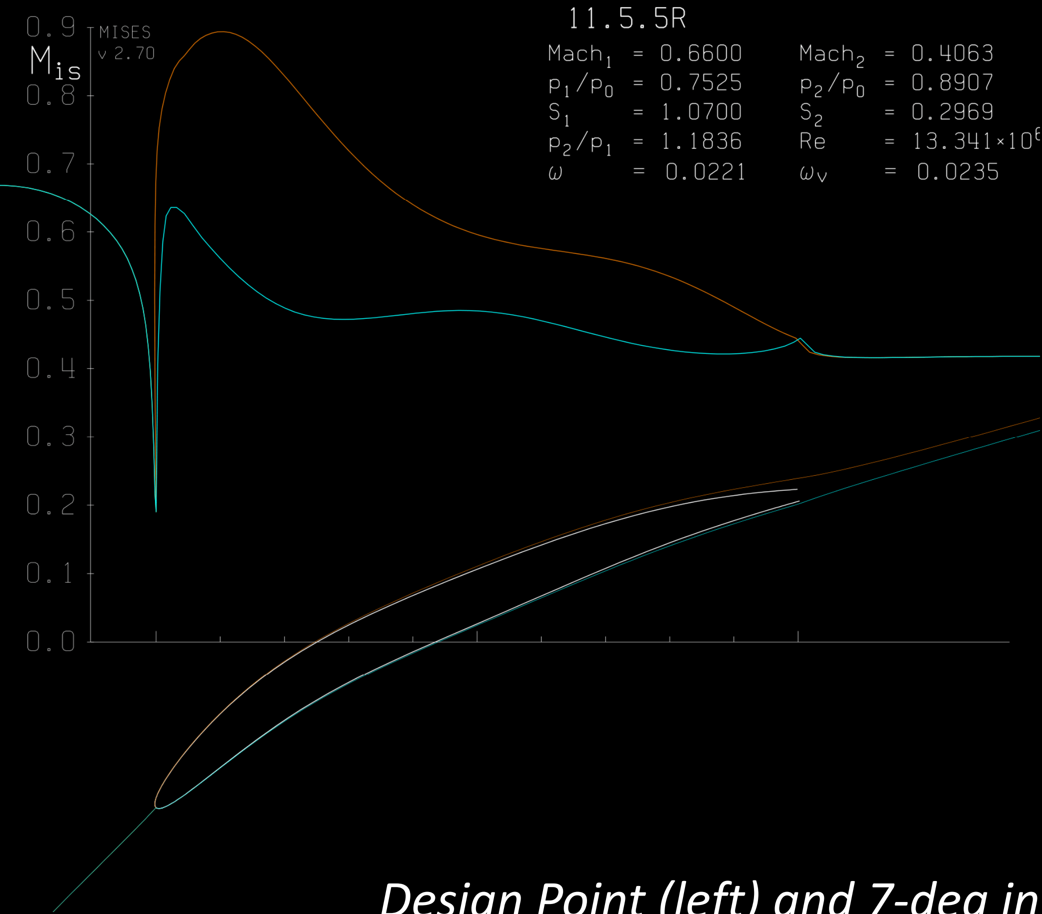
Rotor 2 Mach Contours at Design Incidence

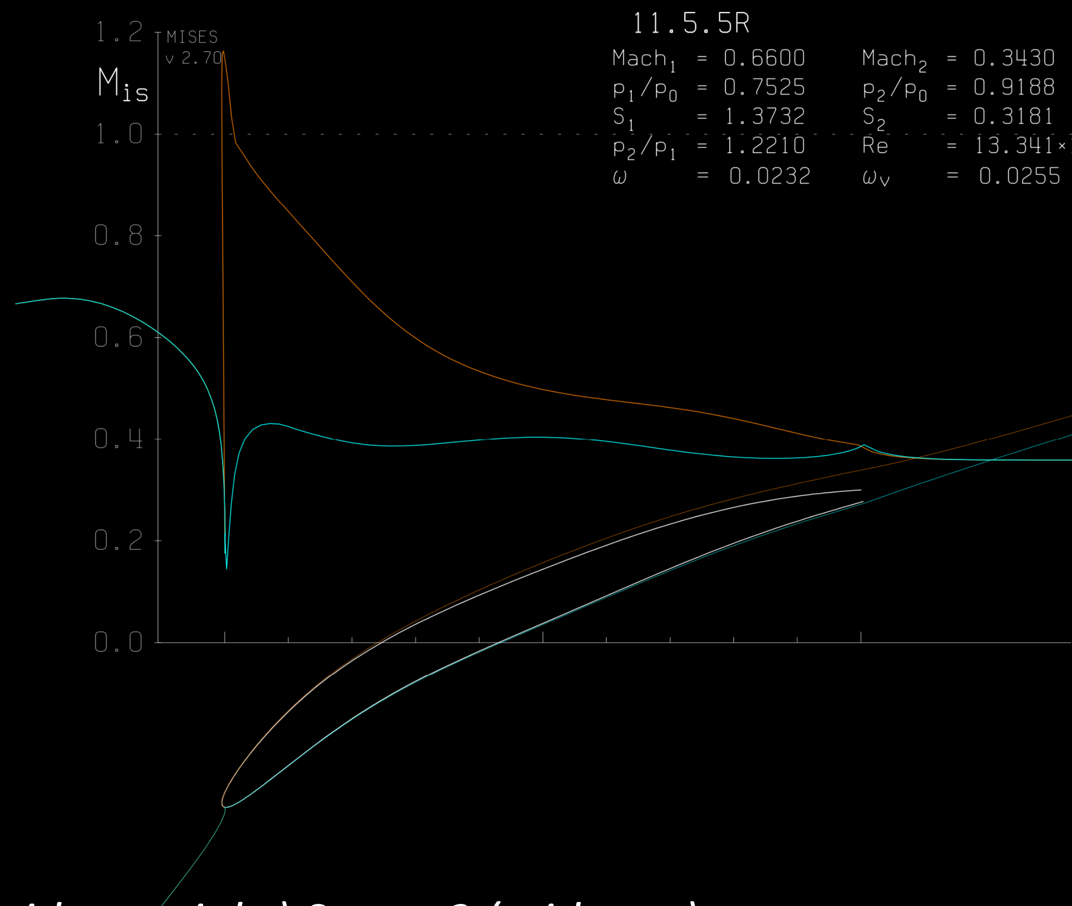


Rotor 2 Shape Factor at Design Incidence



MISES (Quasi-3D Optimized Results)





Design Point (left) and 7-deg incidence right) Stator 2 (midspan)

Constrain to exit flow angle at the design incidence

CFD Details

Solver : Fine/Turbo

BC's inlet : PT at inlet, TT = 371.15K

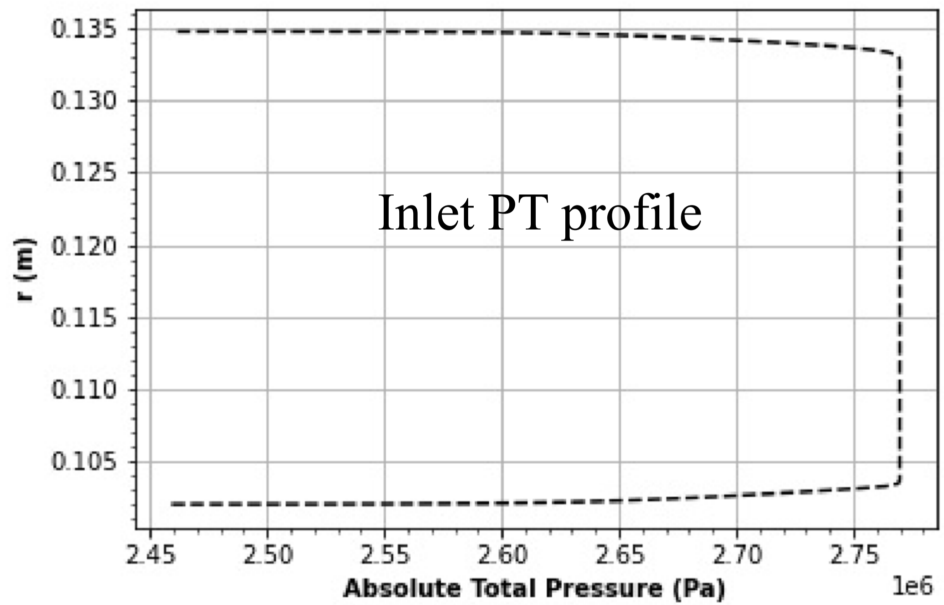
BC's outlet: Ps at exit, M = 0.47

Turbulence : Spalart-Allmaras (SA)

Mixing Plane

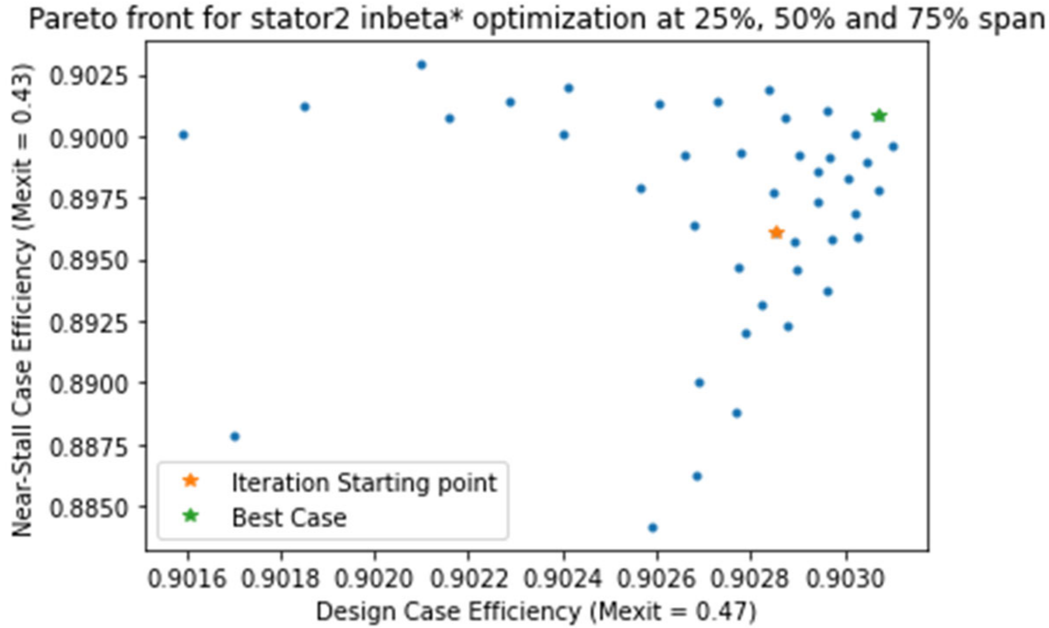
RPM = 19800

Row	Spanwise Points	No. of Grid Points
IGV	193	3.82 million
R1	289	9.9 million
S1	193	8.6 million
R2	305	11 million
S2	193	8 million
R3	305	10 million
S3	193	8 million
Total Grid Points		60 million
First Cell Width		1.2×10^{-7} m



3D Optimization

- Driver – Genetic (OpenMDAO)
- Population size – 50
- Crossover – 0.1
- Mutation – 0.01



Objective Functions are a Design Point Efficiency and an Off Design Efficiency (closer to stall)

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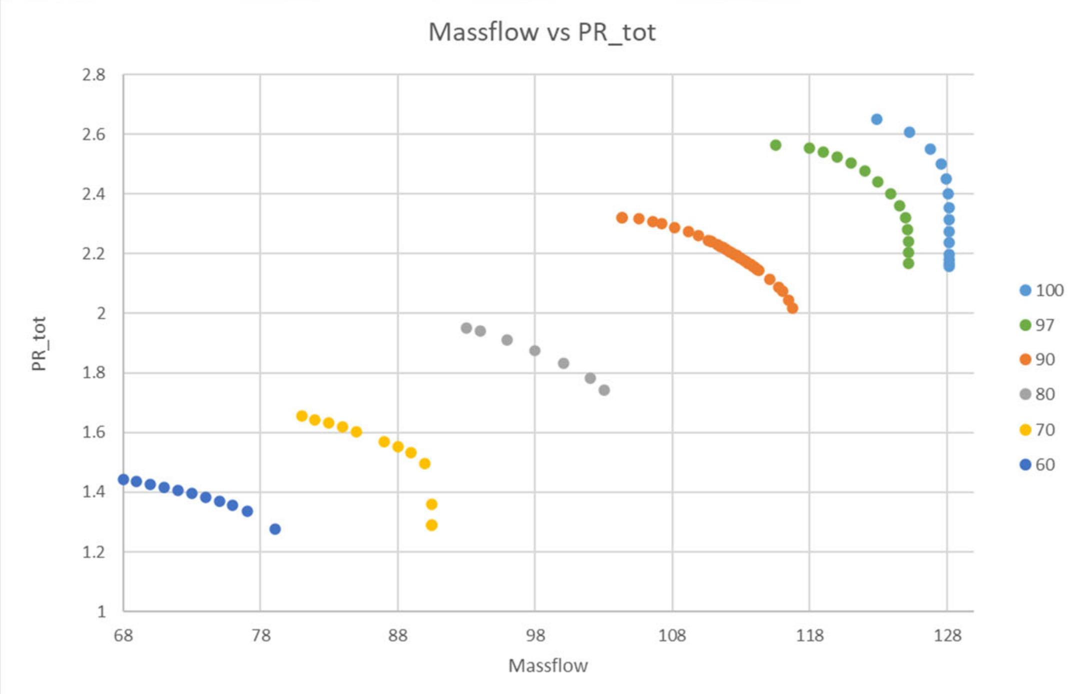
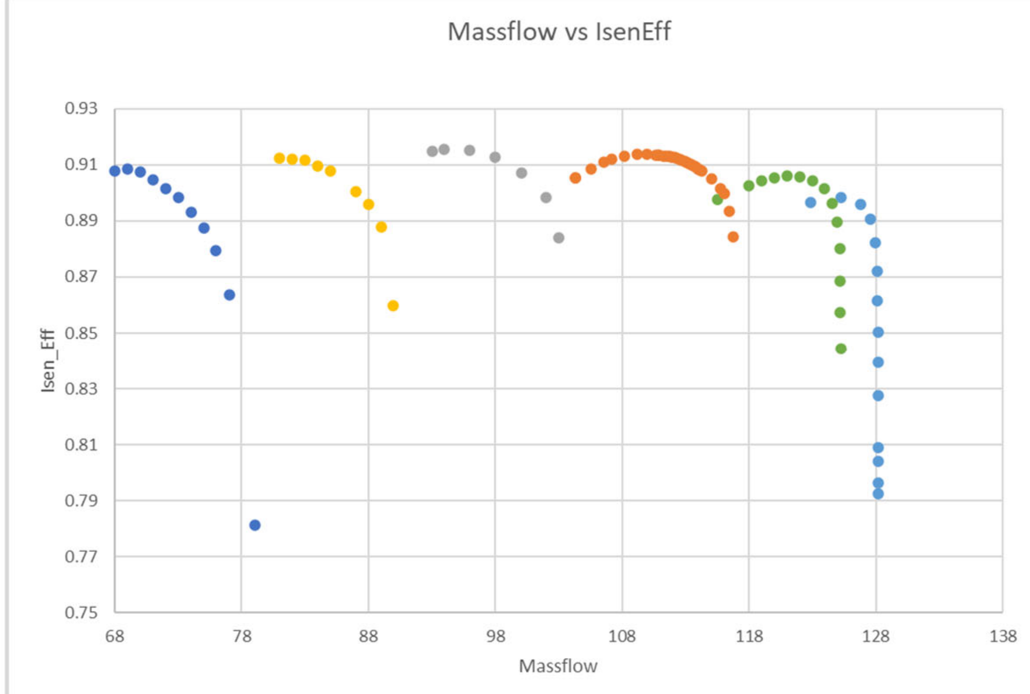
Performance Maps for Final Design





At 100% speed, design point efficiency is 89.85%, PT ratio of 2.61, and mass-flow rate of 125.86 kg/sec

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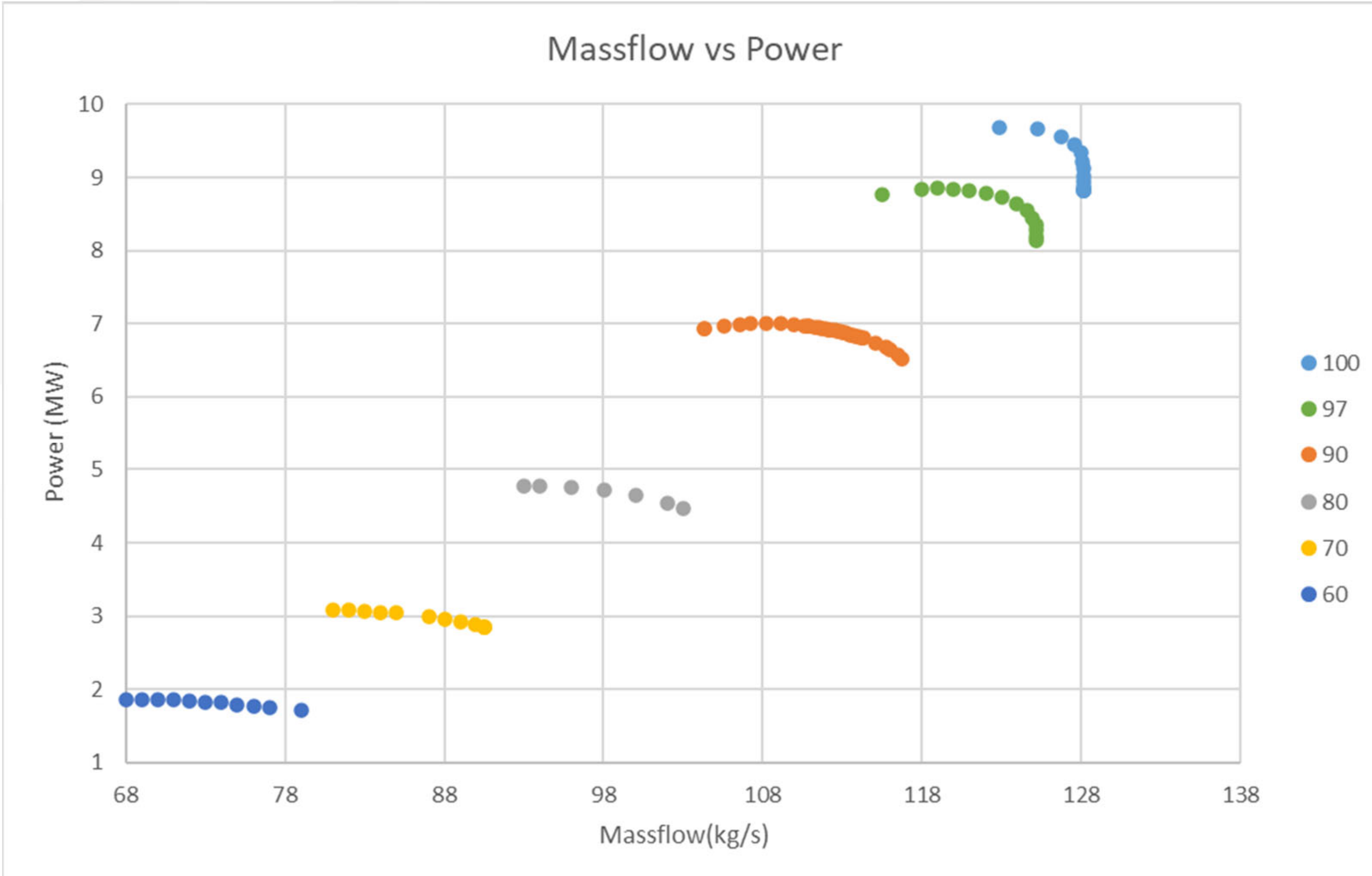
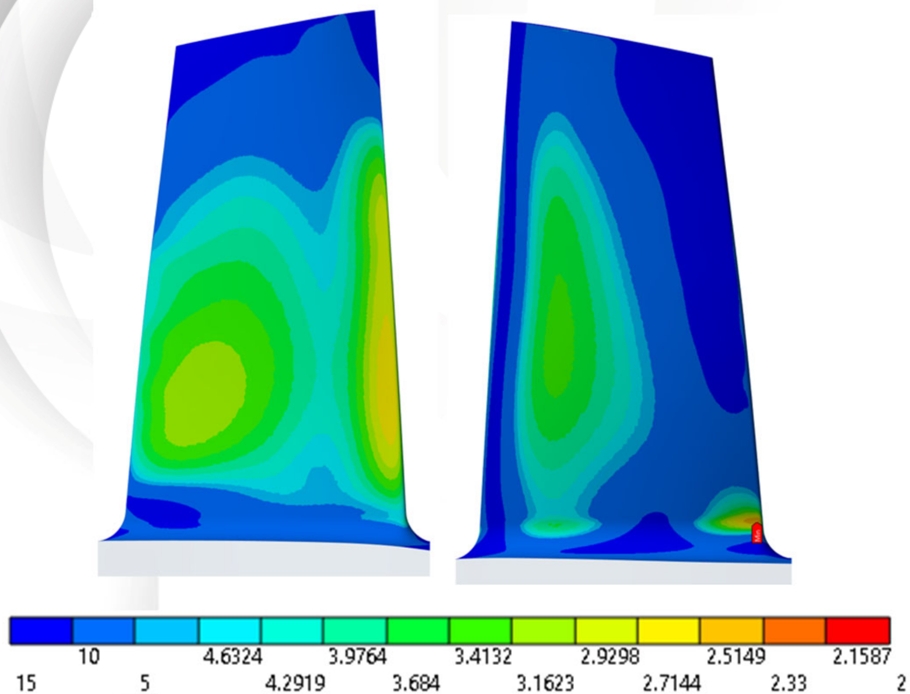
Power for Final Design

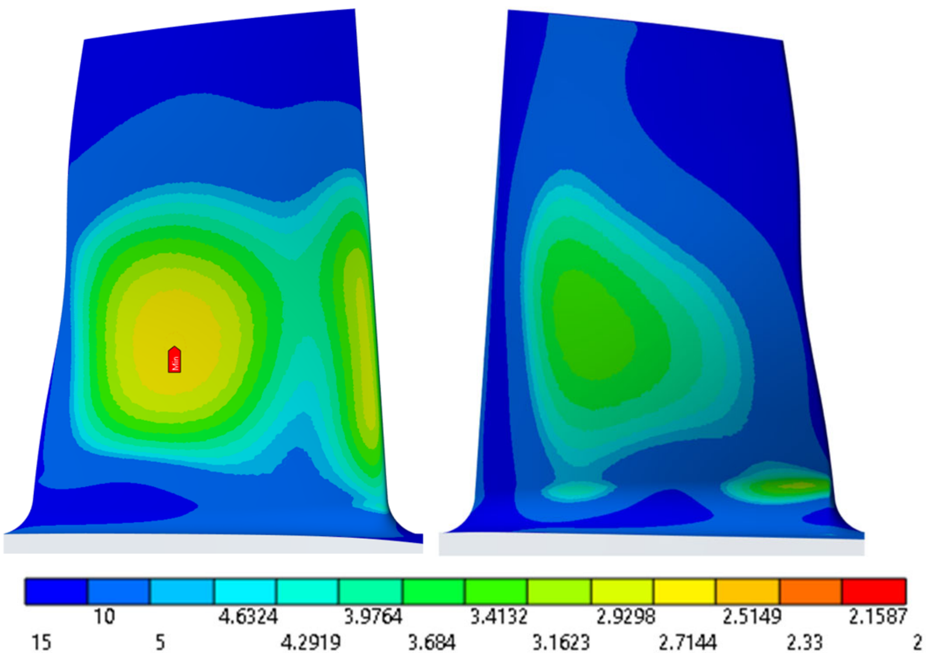


At 100% speed, and design inlet total pressure, the power is 9.52 MW.
This does not include lost power with bearings and motor efficiency.

Safety Factor Contours



R2 safety factor contour on pressure side (left) and suction side (right).



R3 safety factor contour on pressure side (left) and suction side (right).

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Conclusions

- Revolutionary Design/Optimization Approach has been used for a detailed design of an axial CO_2 compressor
- Safety factors exceeding 2 for the second and third stage rotors using static structural analysis
- The final design is predicted to have an adiabatic efficiency of 89.9% and total pressure ratio of 2.61
- The 3-stage rig has been run in air and CO_2 at 30% speed. High speed testing is expected in March

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