Aerodynamics and Heat Transfer Studies of Parameters Specific to the IGCC-Requirements: Endwall Contouring, Leading Edge Filleting and Blade Tip Ejection under Rotating Conditions

Year 2 Report, October 2011

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Robin Ames, National Energy Technology Laboratory
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Content

Introduction

Brief Recap of Year 1 Activities, Achievements Endwall Contouring

- Introduction of a new physics based systematic method for endwall contouring turbine blades of any arbitrary airfoil geometry
- Implementation of the method into the second rotor hub of an existing three-stage research turbine

Year 2 Activities, Achievements

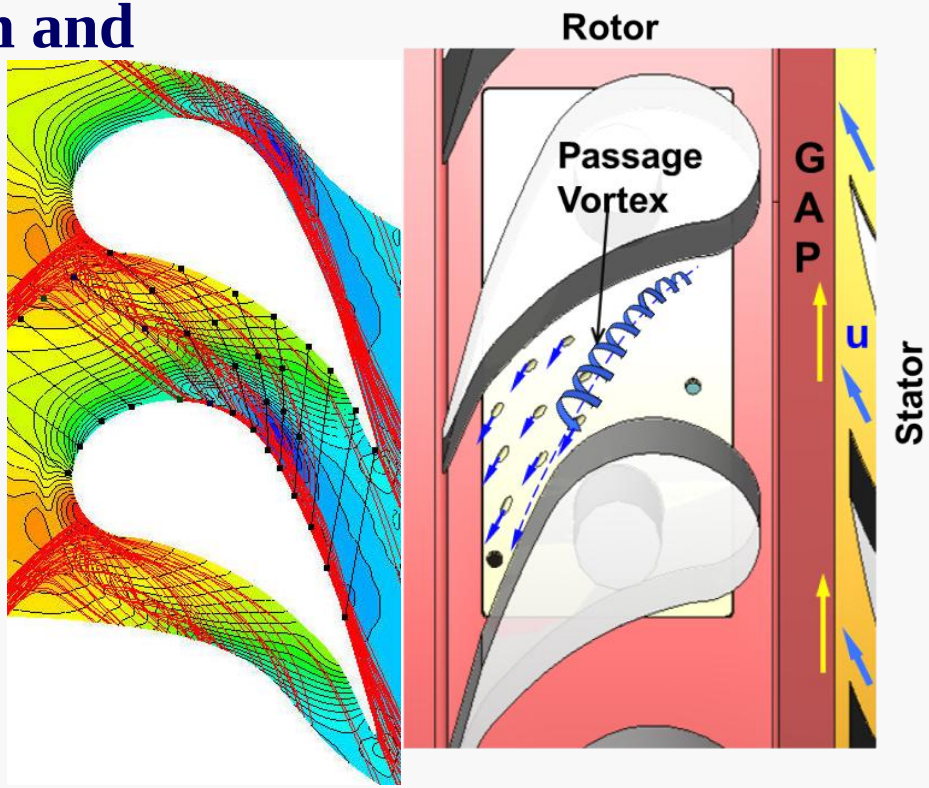
- Implementation of the method into the first rotor hub to investigate the behavior of film effectiveness under the impact of purge flow
- Rotating Blade Tip Ejection (Year 3 Research, proponed)

Conclusion

Introduction: Endwall Secondary Flow Loss Reduction

Pressure difference between suction and pressure side causes:

- Systems of secondary vortices
- Generation of induced drag forces
- Total pressure reduction
- Secondary flow losses
- Efficiency decrease



Secondary Flow Loss Reduction

Effective methods for reducing the secondary flow losses at the turbine hub and tip:

- **Special design:Fully-3D blades with compound lean:**
  Very effective used in advanced HP-Turbines (TPFL-R&D)

- **Specially designed stator blades insensitive to incidence change when turbines operate at off-design conditions with incidence change from - 30° to + 30° (TPFL-R&D)**
- **Endwall contouring (new method introduced by TPFL)**

- **Rotating blade tip ejection (new blade ejection configuration)**
- **Filleting also contributes to secondary flow reduction, but restricted**

Blade Tip Secondary Flow Loss Reduction

Rotating Blade Tip Ejection (Year 2-3 Research)

The new blade tip ejection experiments to counteract the tip clearance vortices are intended to:

- **Reduce the induced drag force by the tip clearance vortices,**
- **Reduce the tip clearance leakage**
- **Reducing the secondary flow loss**
- **Improving the efficiency and**
  - **simultaneously reducing the potential for corrosion, erosion, and deposition on the blade tip.**

Breakthrough Technology, Disclosure of Invention TAMUS 3259

This *Continuous Diffusion Method* introduced by Texas A&M can be applied to HP, IP, and LP turbines and compressors regardless the load coefficient, flow coefficient and degree of reaction

Step-by-Step Instruction:

1) For the reference blade place cylindrical control surface at a radius $R_{hub} + \delta$ with δ as the boundary layer thickness developed by the secondary flow from pressure to suction side, (Fig. A)

2) For the reference blade obtain the pressure distribution close to the hub (about one δ) on the suction side (Fig. B)

3) Find the actual pressure difference Δp_i (Fig. B) and define the target pressure difference $\Delta p_{itarget} > \Delta p_{lim}$ (Fig.B)

Breakthrough Technology, Disclosure of Invention TAMUS 3259

4) Obtain streamlines at the same radial position (next slide Fig. C)

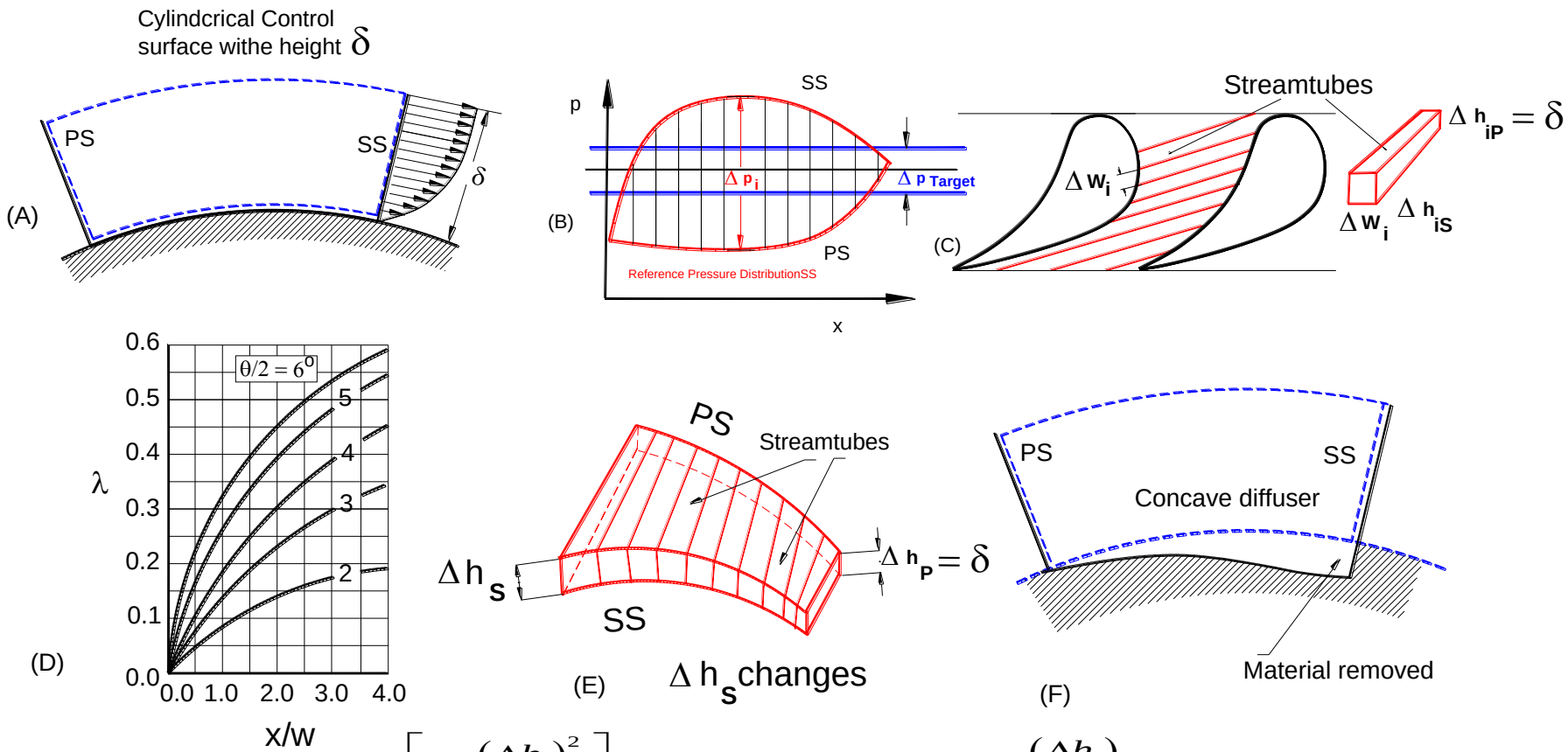
5) Based on the diffuser performance map (next slide Fig. D) construct a diffuser (next slide Fig. E) with the constant $\Delta h_{ip} = \delta$ at the pressure side and variable $\Delta h_{is} > \delta$ on the suction side, follow the pressure recovery diagram to avoid separation!!

6) Design 3-D contour by removing the hub material (next slide Fig. F)

7) Generate a high density grid with for the above design and run CFD with the Menter's SST-turbulence model

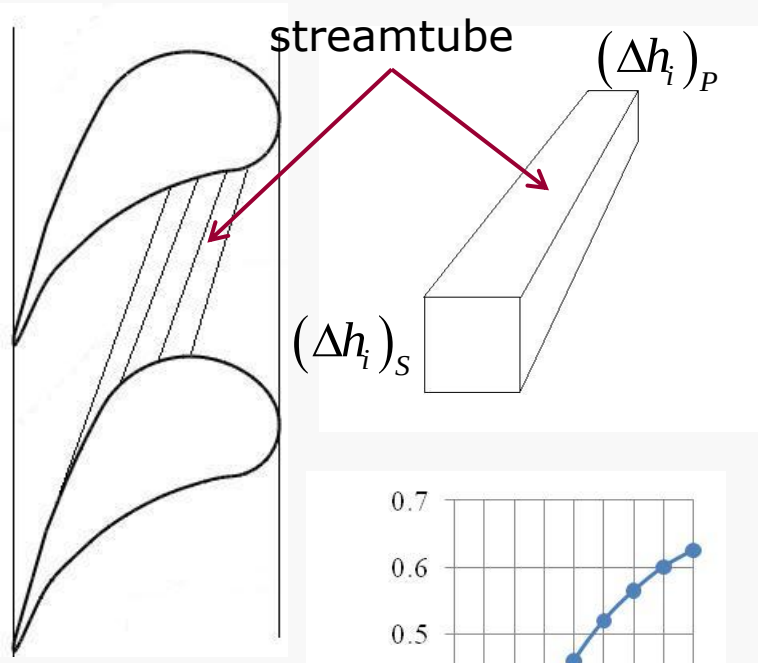
8) Re-evaluate results make changes if necessary

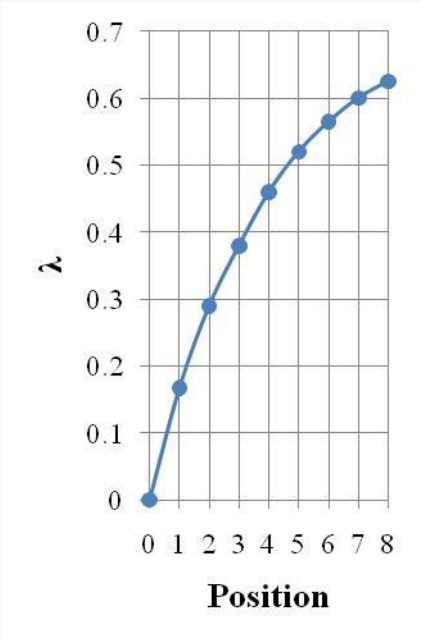
Continuous Diffusion: Summary of the Working Principle



$$\left[1-\frac{(\Delta h_i)_P^2}{(\Delta h_i)_S^2}\right]=\lambda \quad \text{Results in:} \quad (\Delta h_i)_s=\frac{(\Delta h_i)_p}{\sqrt{1-\lambda}}$$

Non-Axisymmetric Endwall Contouring Design-Family





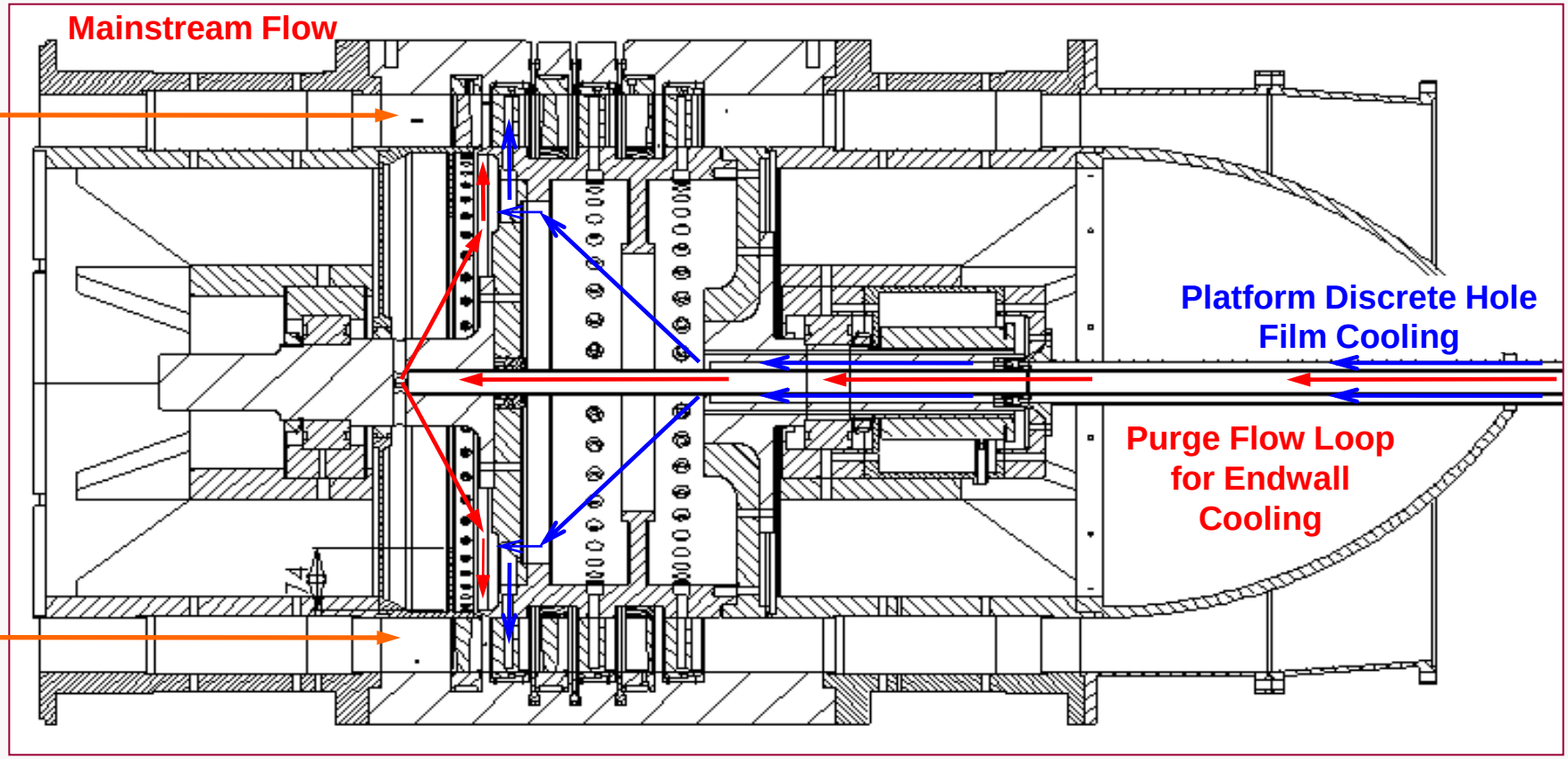
- **Basic idea: decrease the pressure difference as much as possible between pressure surface and suction surface near hub.**
- **With the concept of continuous diffusion, redesign the streamtube as we do for diffuser to increase the pressure against suction side.**
- **Taking into account the diffuser conversion coefficient l, a correlation is derived by M. T. Schobeiri:**

$$\left[1-\frac{(\Delta h_i)_P^2}{(\Delta h_i)_S^2}\right]=\lambda \qquad \text{OR} \qquad (\Delta h_i)_s=\frac{(\Delta h_i)_p}{\sqrt{1-\lambda}}$$

- **Choosing proper $(\Delta h_i)_P$, the variation of $(\Delta h_i)_S$ is obtained and thus the contouring profile is determined.**

TPFL Research Turbine Test Section

New Turbine Rotor with two Independent Coolant Flow Loops, DOE-Project 2006

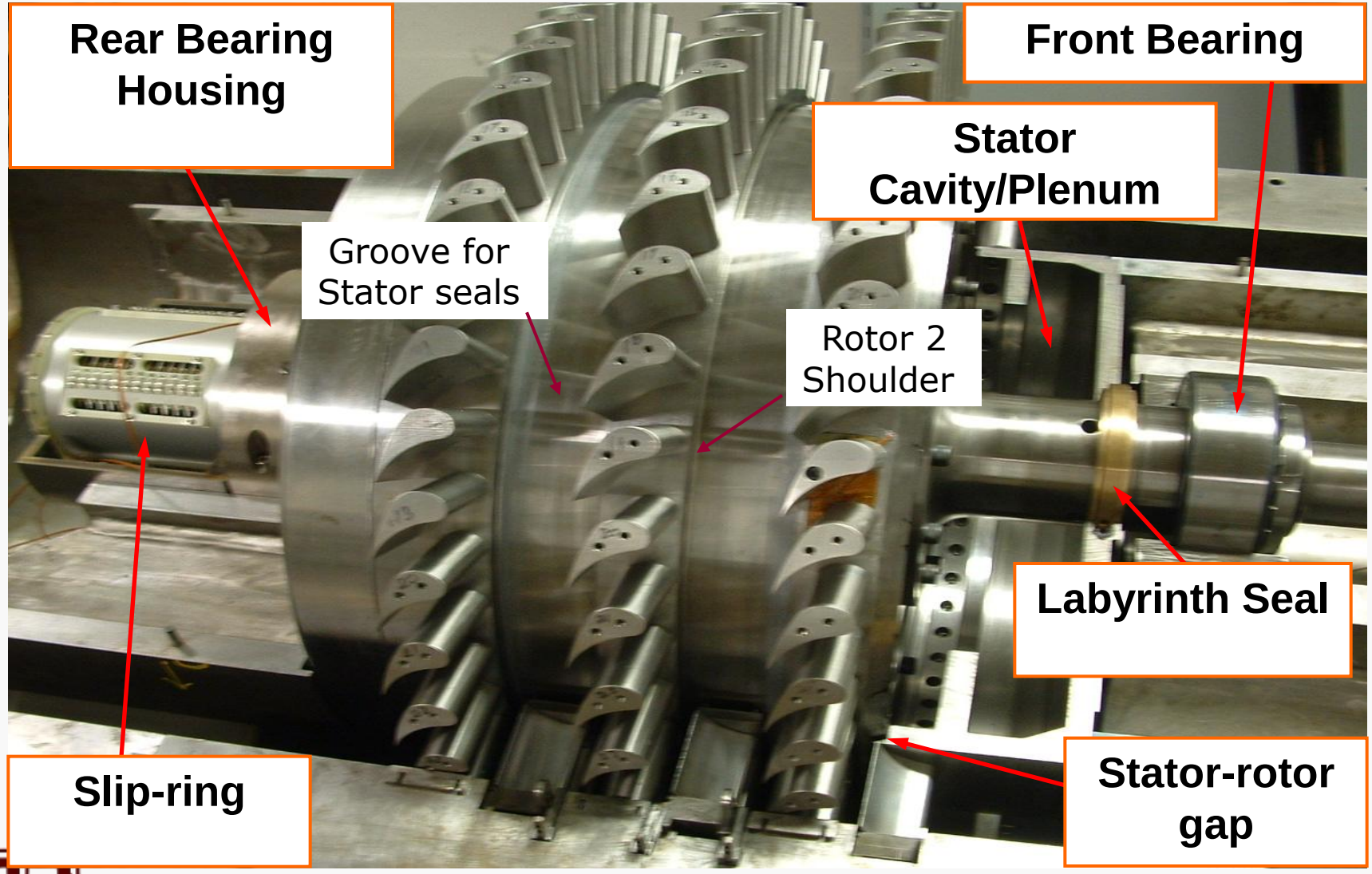


Tow Independent Coolant Loops for Coolant Injection from Stator-Rotor Seal and Downstream Film Cooling Holes

***TPFL*: The Turbomachinery Performance and Flow Research Laboratory**
Texas A&M University
M. T. Schobeiri

Project DE-FOA-0000031
October 2011

Endwall Contouring Applied to First and Second Rotor Hub



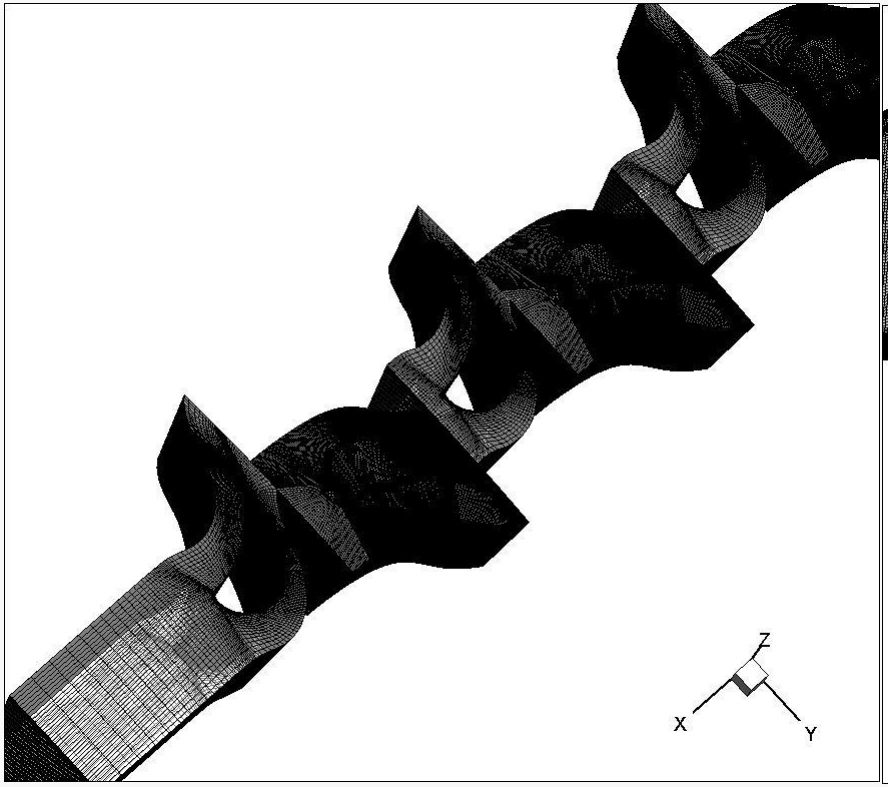
Research Turbine Facility Data

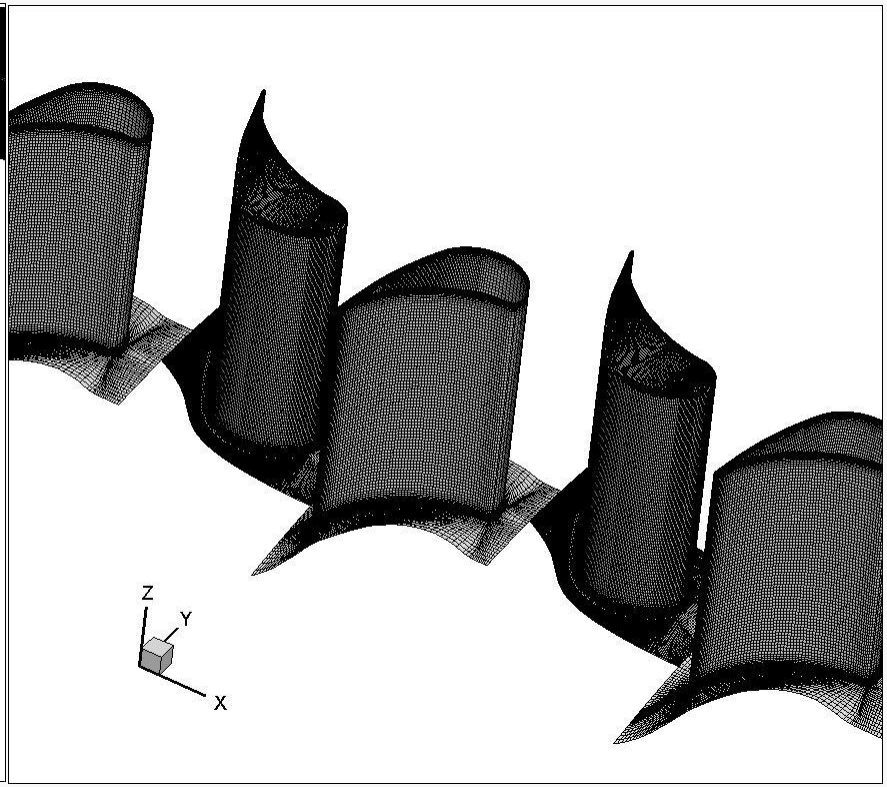
Item	Specifications
Number of Stages	**3**
Tip Diameter	**685.8 mm**
Hub Diameter	**558.8 mm**
Blade Height	**63.5 mm**
Power	**80.0 – 110.0 kW**
Mass Flow	**3.728 kg/s**
Speed Range	**0 – 8000 rpm** **For this particular blading: 0-3000 rpm**
Inlet Pressure (Design Condition)	**101.356 kPa**
Exit Pressure (Design Condition)	**71.708 kPa**
Stator Blade Number	**S1 = 58 S2 = 52 S3 = 56**
Rotor Blade Number	**R1 = 46 R2 = 40 R3 = 44**

Numerical Methodology

- Steady state RANS used, convergence was assessed through monitoring of:
  - Equation RMS and maximum residual values
  - Inlet and exit mass flow
  - Area-averaged pressure and velocity at turbine exit
- Turbulence model
  - Shear Stress Transport (SST) model
  - CFX Automatic wall treatment employed
    - Switches between wall functions to a low-Reynolds number near wall formulation
    - Requires $y^+<2$, and at least near-wall nodes
- Boundary conditions
  - Pt_{in}, Tt_{in}, P_b
  - Fixed rotation speed
  - Adiabatic and non-slip conditions on the wall

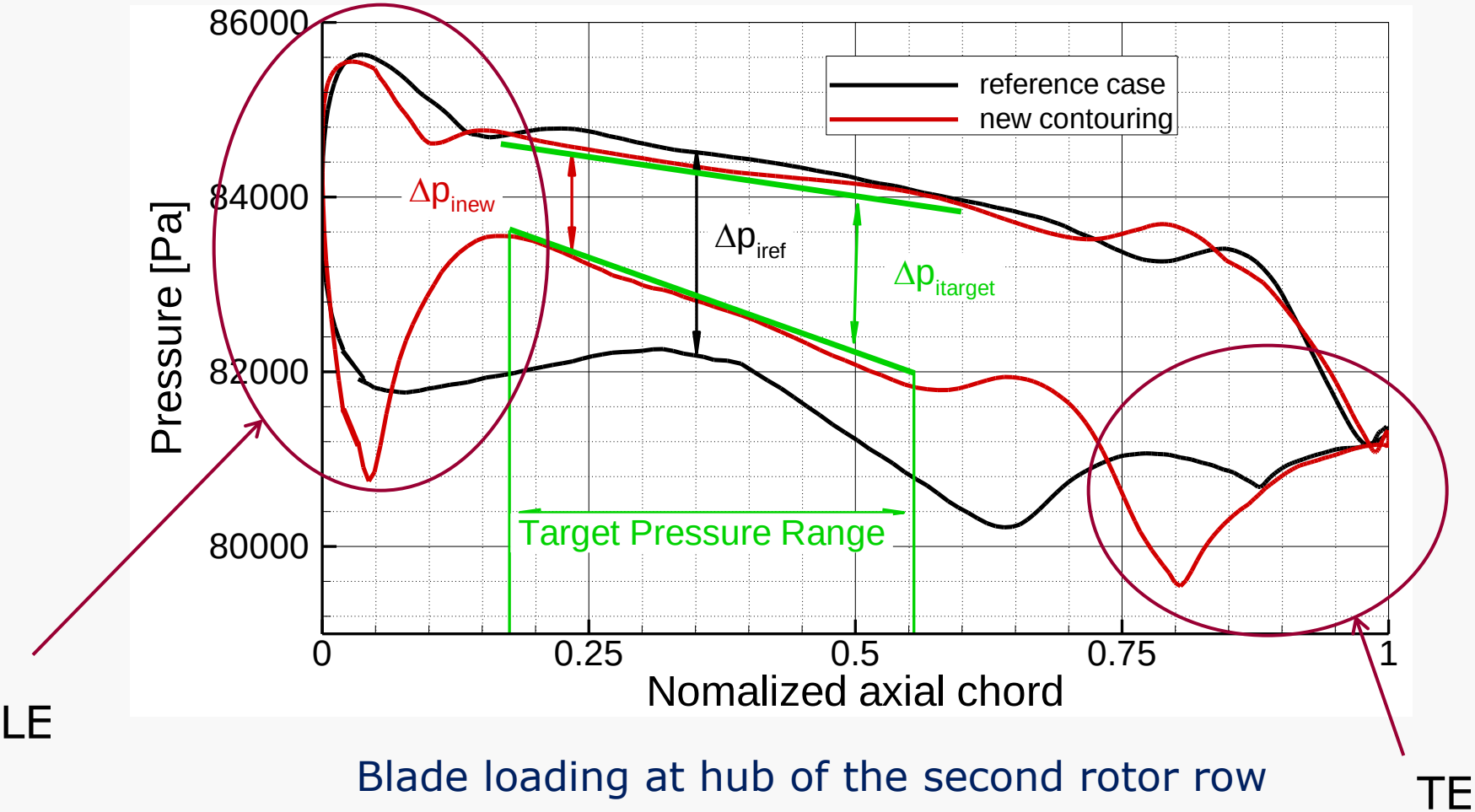
Endwall Contouring Applied to Turbine Rig





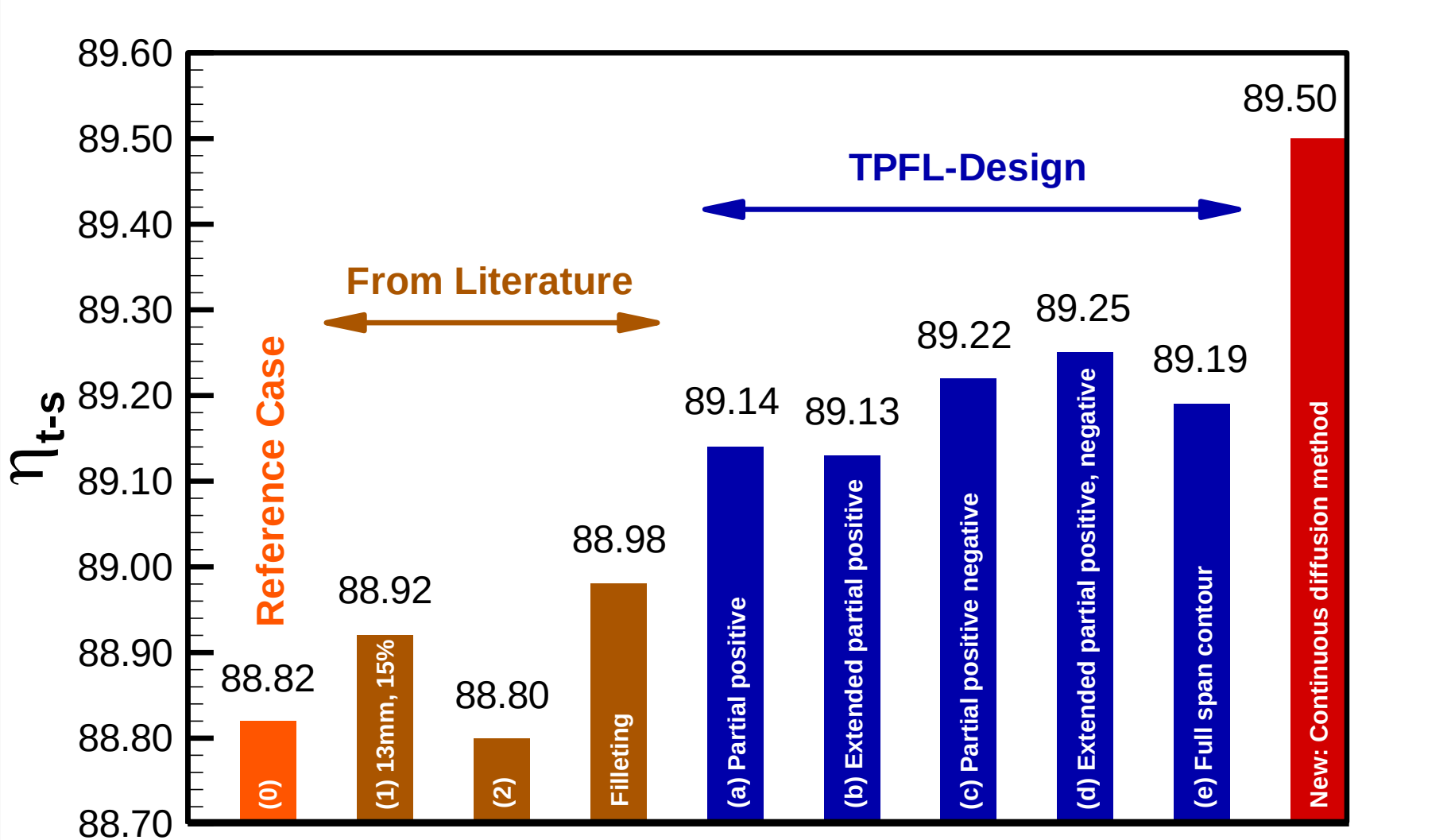
- Extensive grid sensitivity test performed
- Rotor mesh has over 2 million elements
- Wall regions use 22 nodes
- The entire model involves over 9 million elements

Blade Loading of Second Rotor

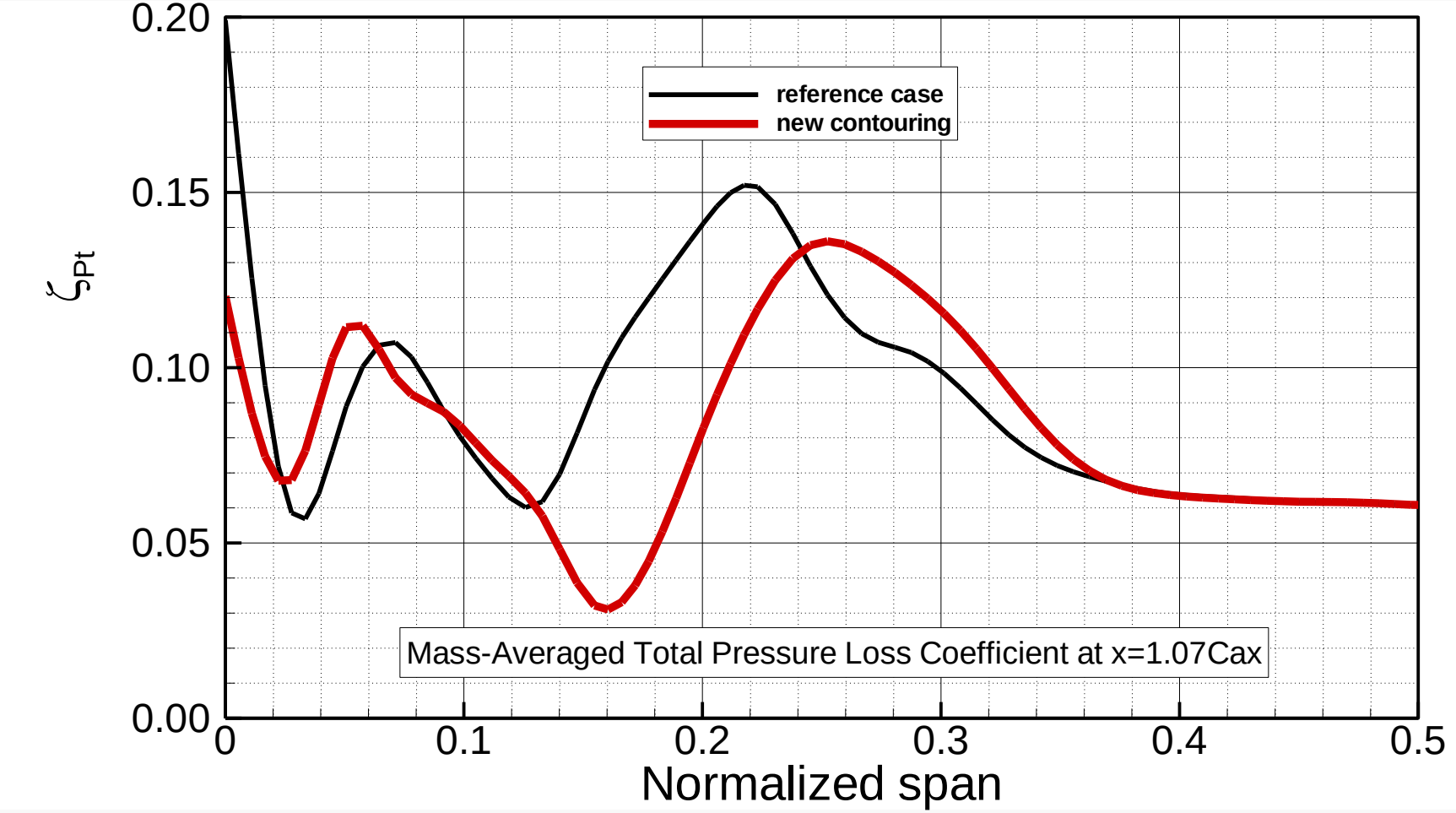


Blade loading at hub of the second rotor row

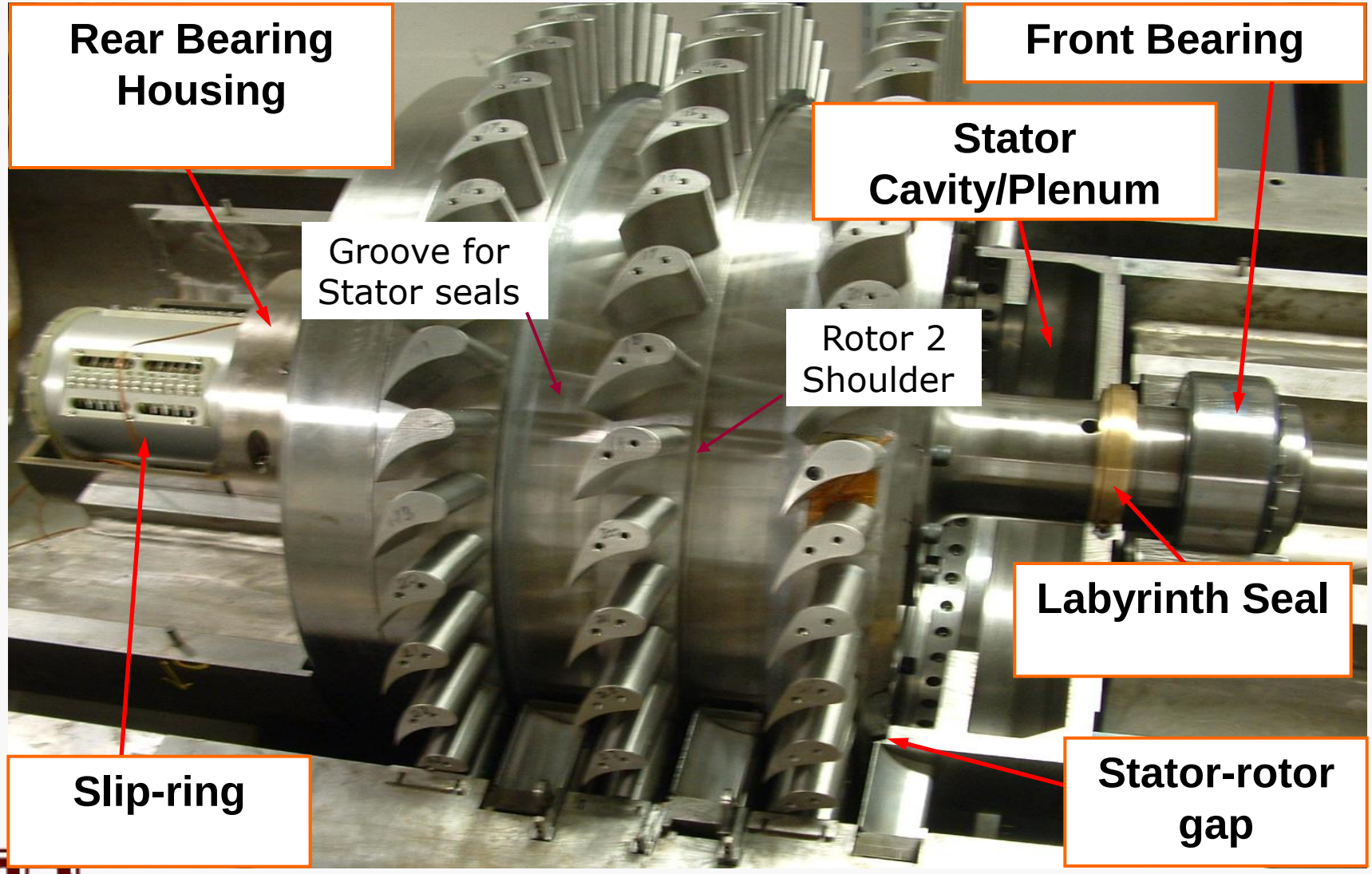
Total-Static Efficiency for Second Rotor



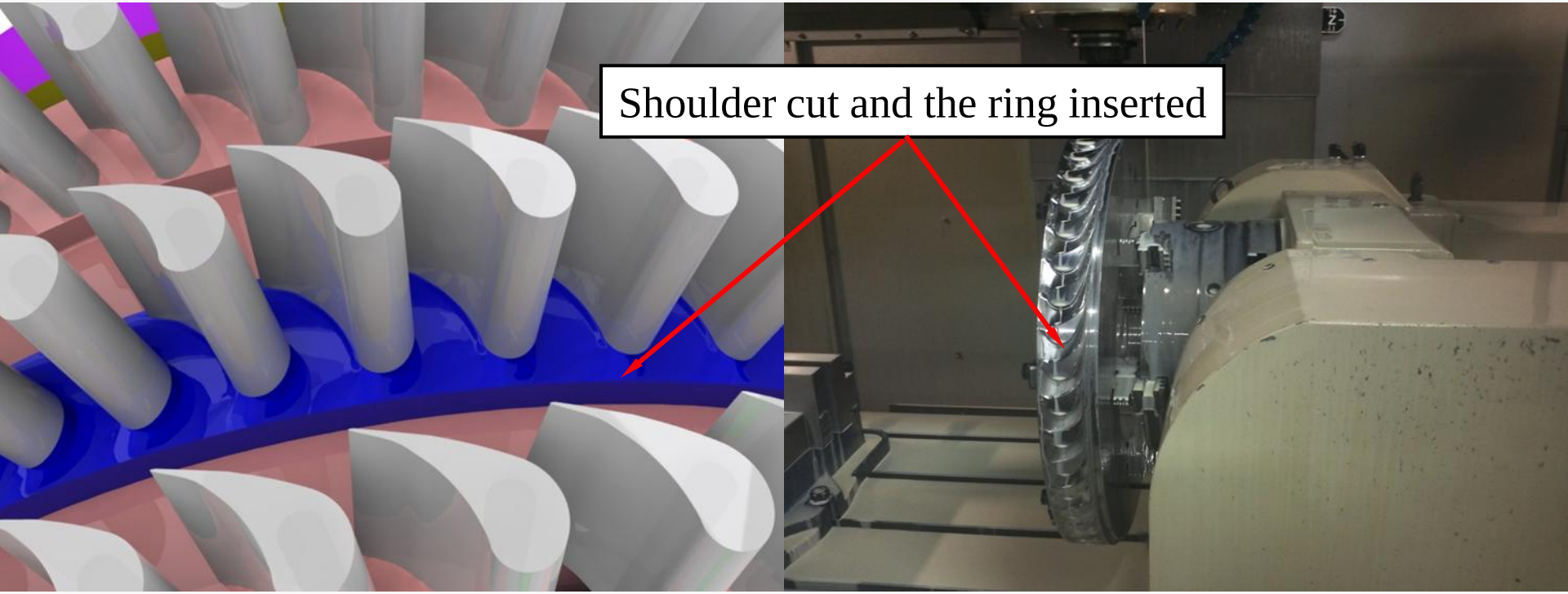
Total Pressure Loss Coefficient for Second Rotor



Endwall Contouring Applied to First and Second Rotor Hub



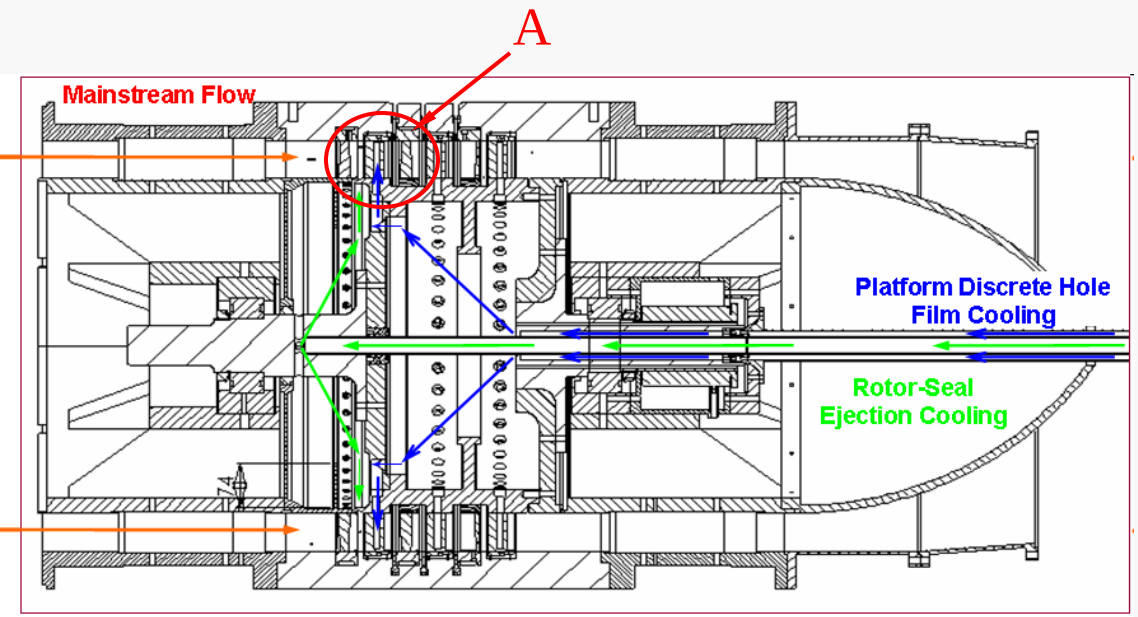
Manufacturing of Non-Axisymmetric Endwall Contouring



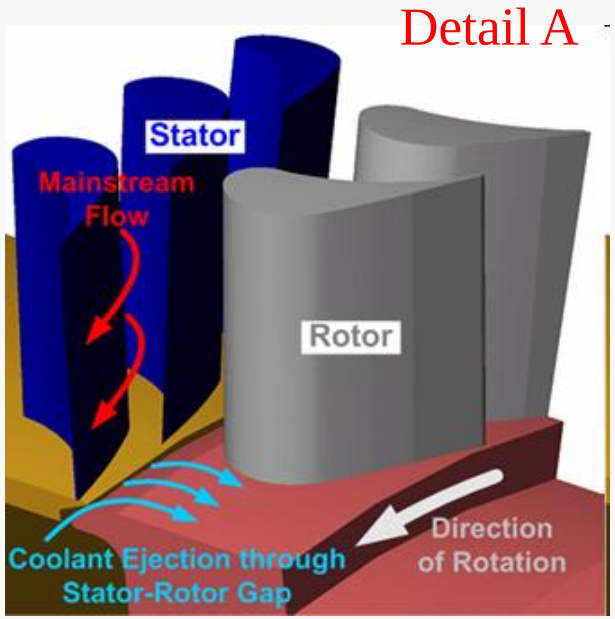
- **The rotor hub shoulder had to be removed and replaced by a ring that extends upstream (left).**
- **The ring with the endwall contouring cut on a CNC machine**

Effects of Purge Flow, Endwall Contouring

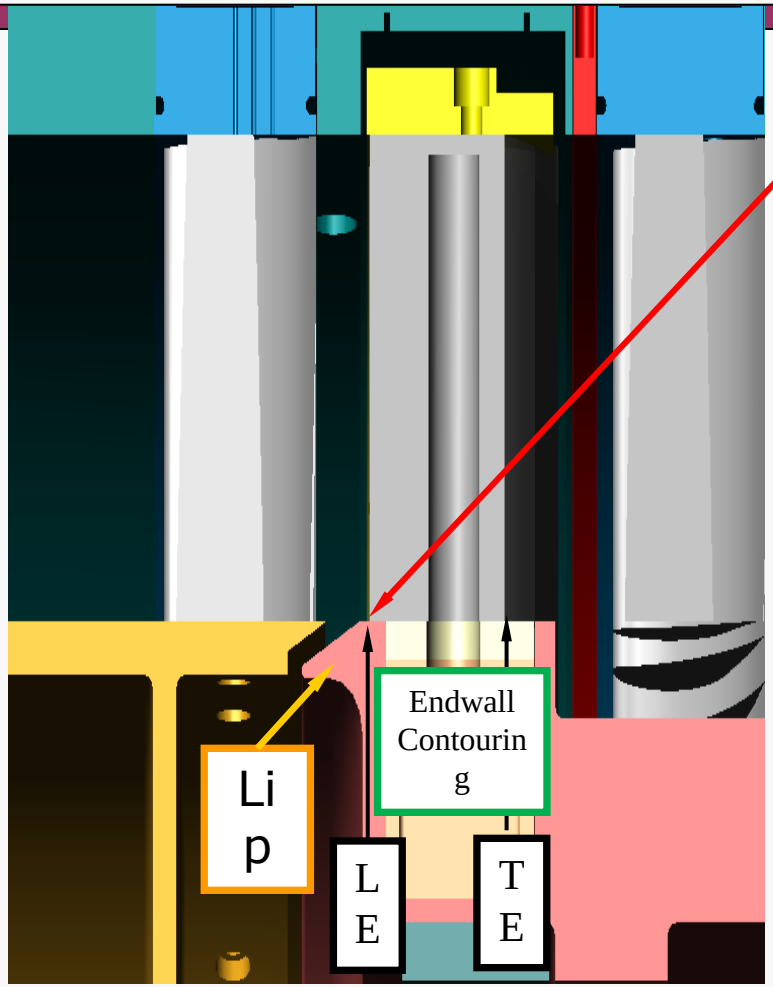
To investigate the combined effects of purge flow and endwall contouring on heat transfer, the endwall of the first rotor row had to be designed considering hardware constraints.



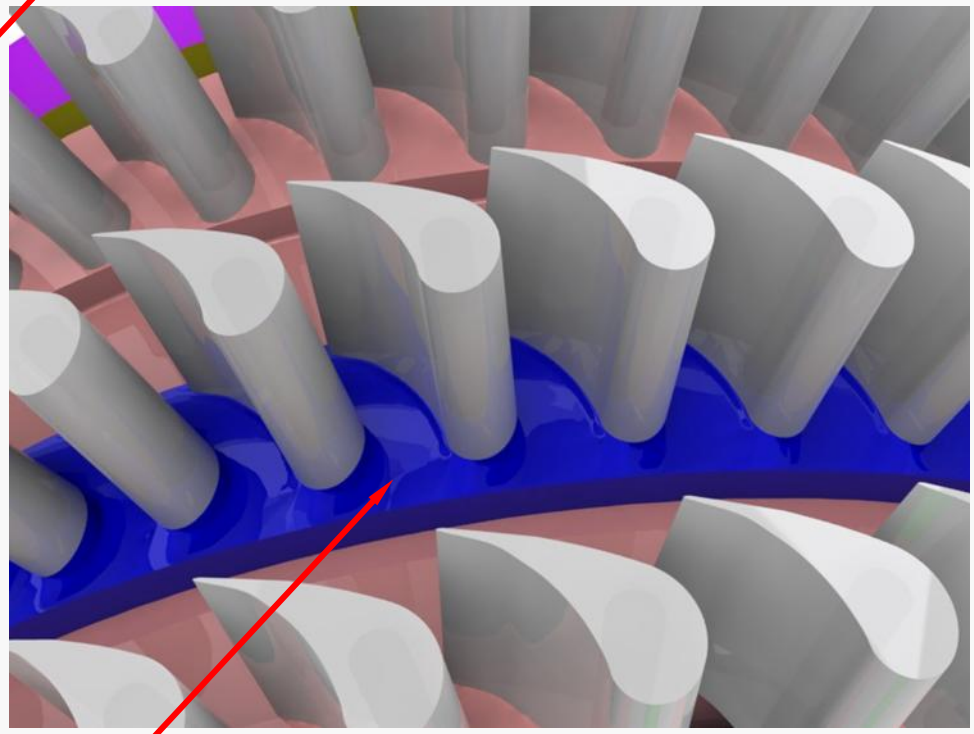
Tow Independent Coolant Loops for Coolant Injection from Stator-Rotor Seal and Downstream Film Cooling Holes



Endwall Contouring Design for First Rotor



No space for upstream extension of first rotor

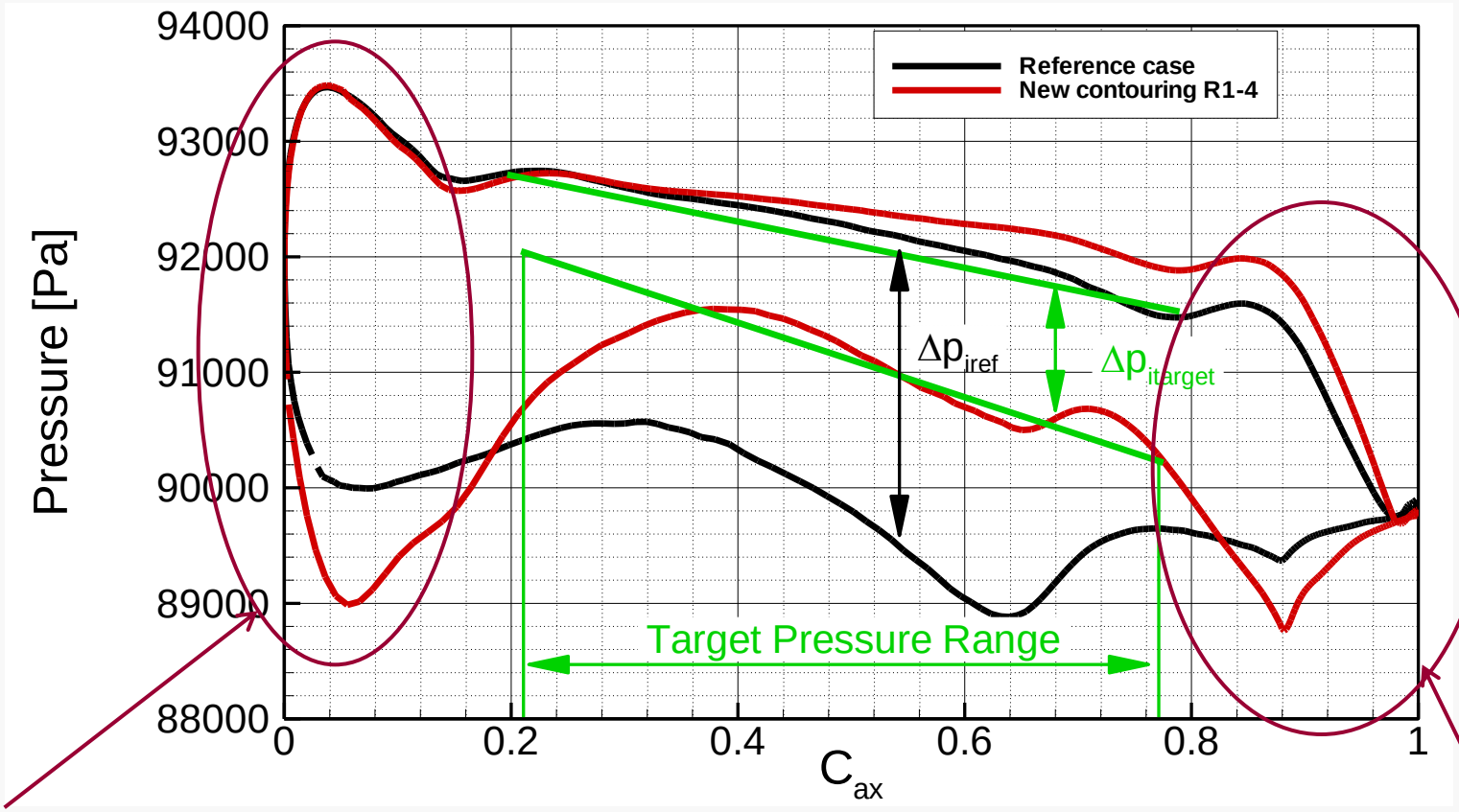


2nd rotor ring extended upstream

- **Endwall contouring for first rotor is constrained between LE, TE due to the existence of ejection slot lip .**

Pressure Distribution at the Hub for First Rotor

Target pressure $\Delta p_{itarget} = 0.5\Delta_{iref}$ but because of the LE-constraint, it cannot be extended beyond the slot lip.

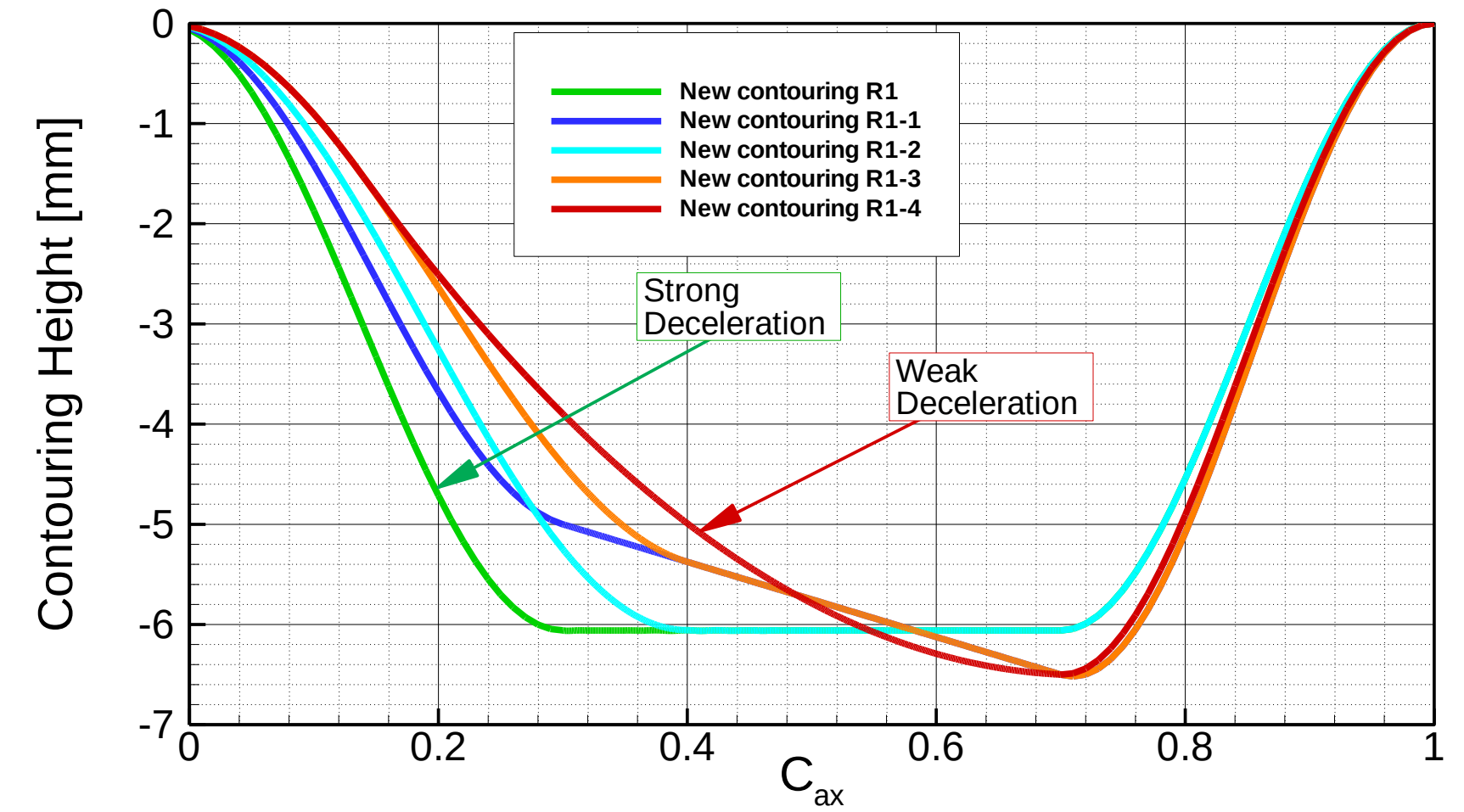


LE

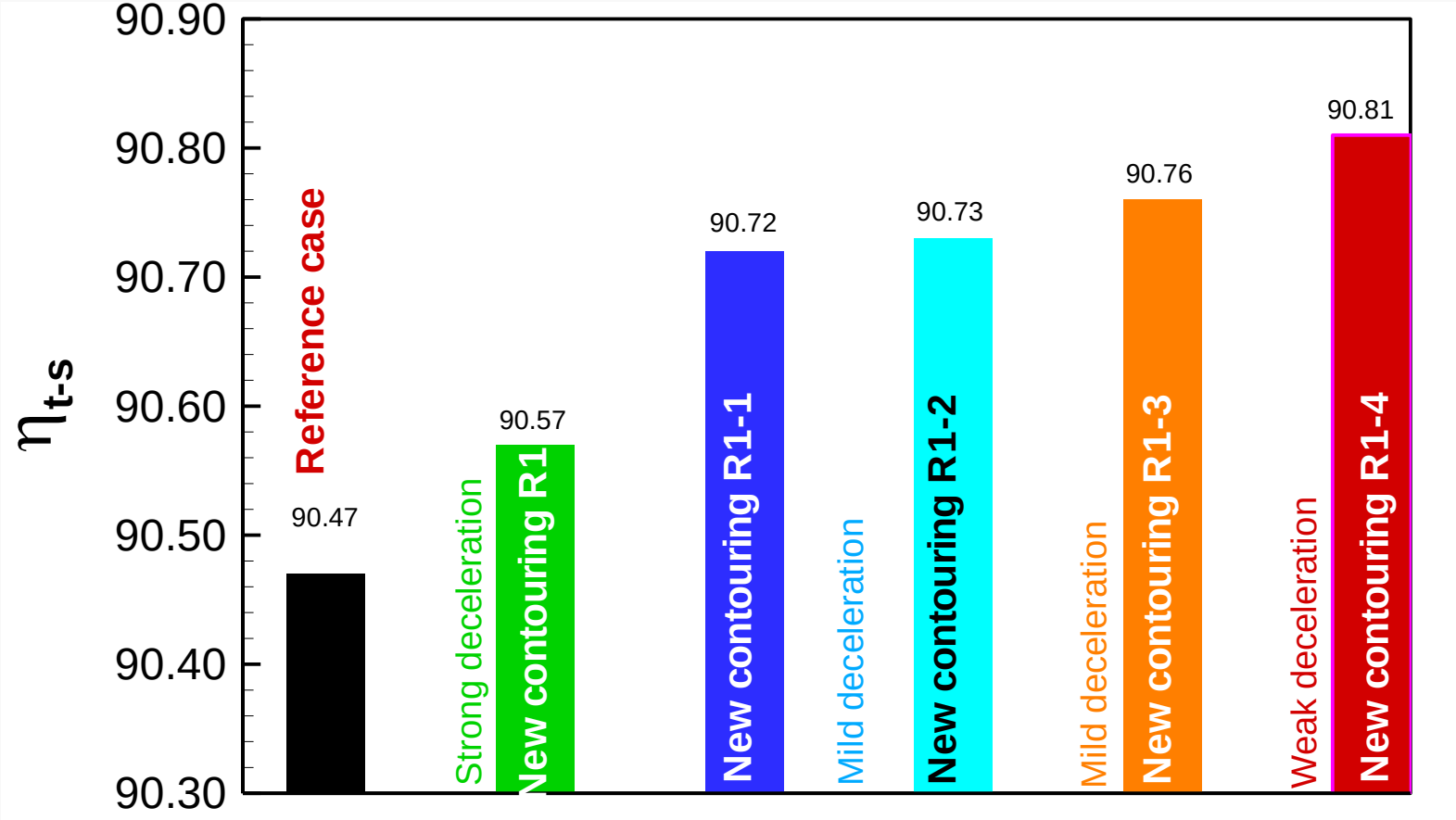
TE

Contouring Height in Streamwise Direction for First Rotor

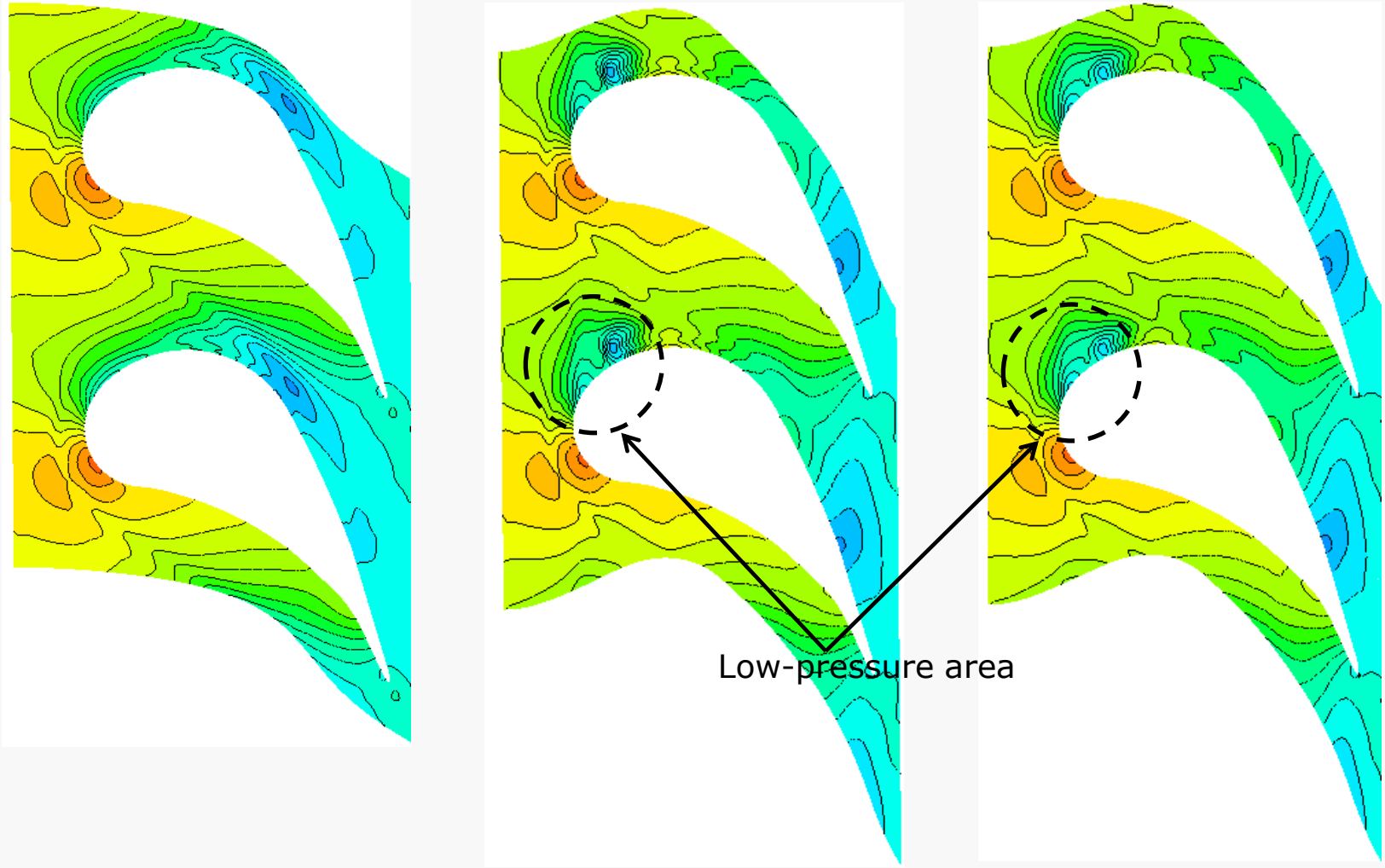
Sensitivity study: Variation of Deceleration Parameter



Impact of Deceleration Rate on Efficiency for First Rotor

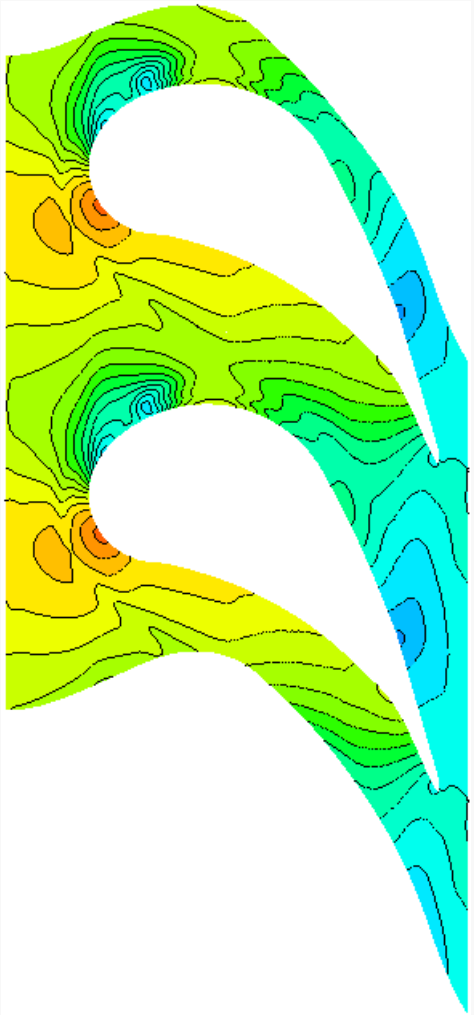


Pressure Distribution at Hub for First Rotor

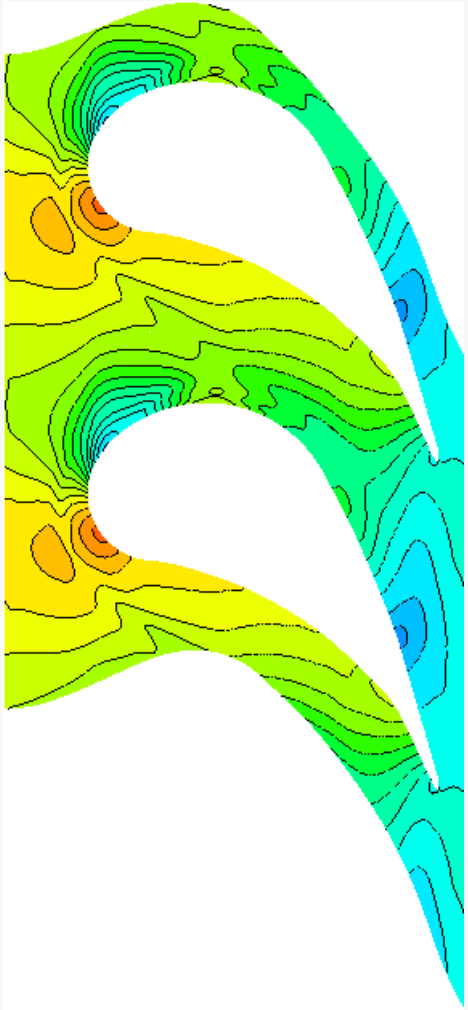


Reference case | New contouring R1 | New contouring R1-1

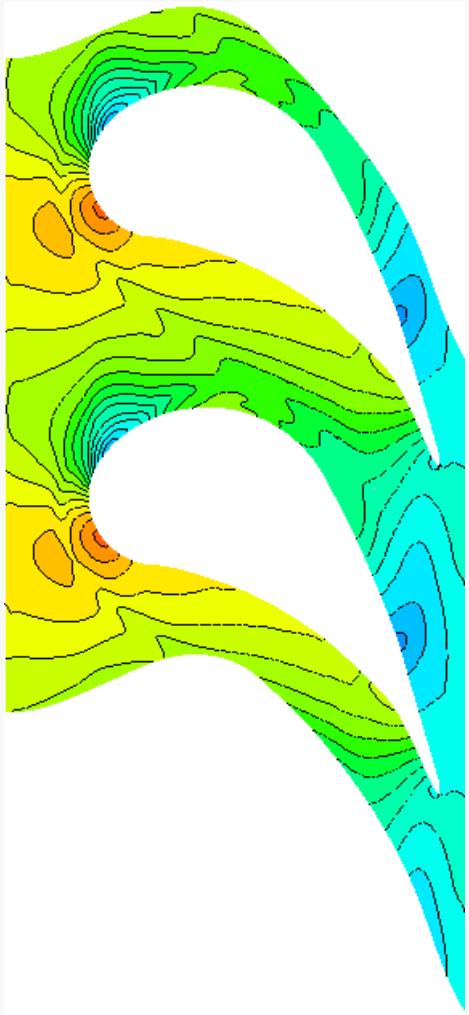
Pressure Distribution at Hub for First Rotor



New contouring R1-2

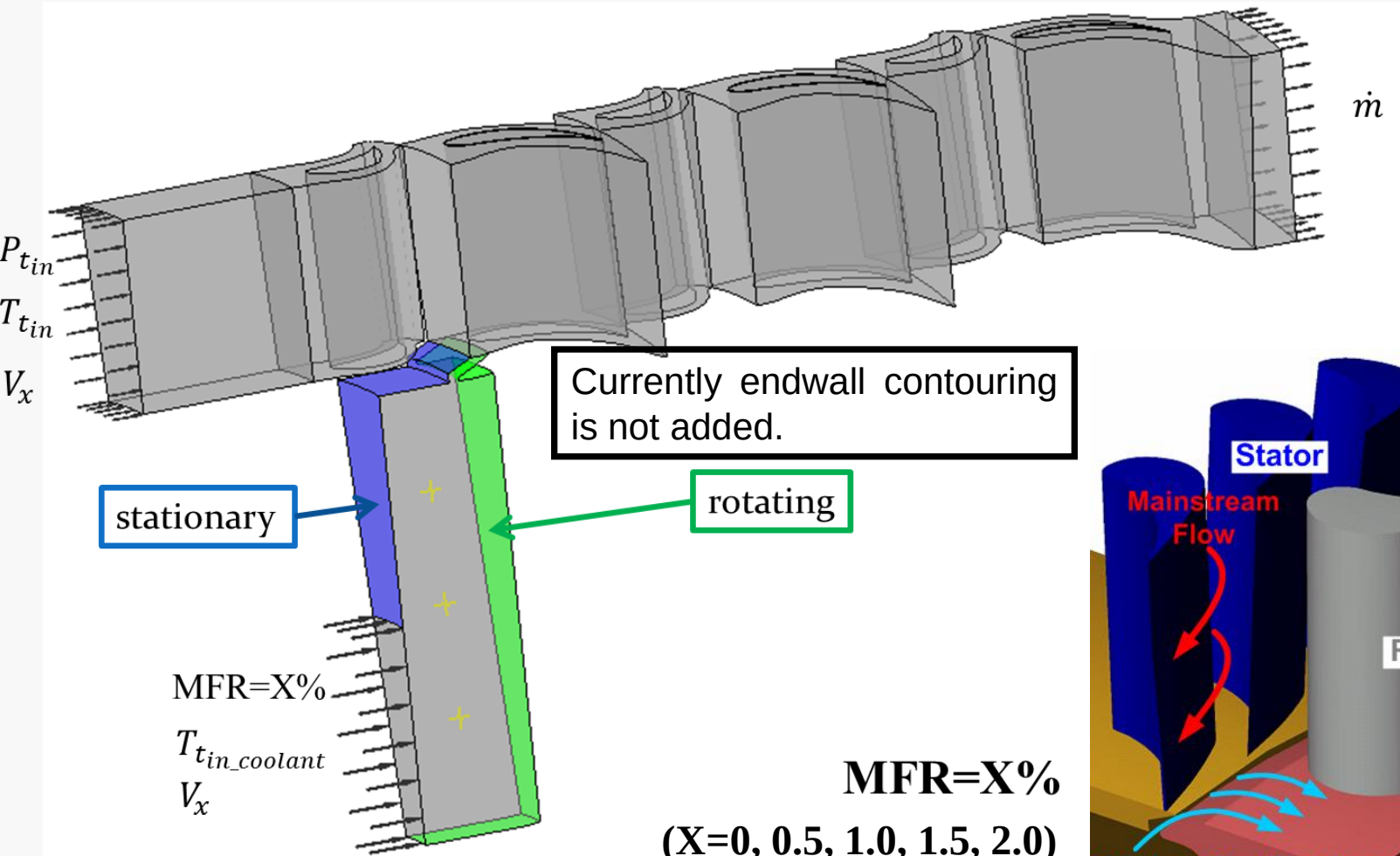


New contouring R1-3



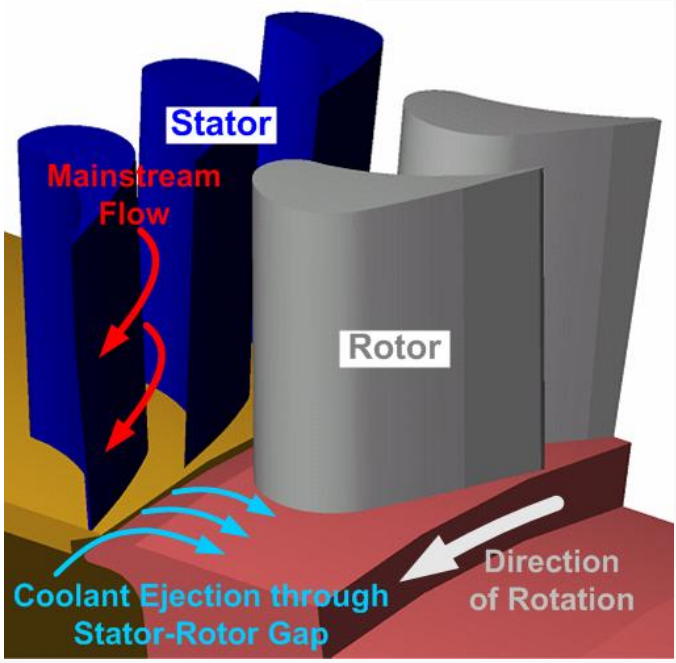
New contouring R1-4

Numerical Simulation with Purge Flow Ejection

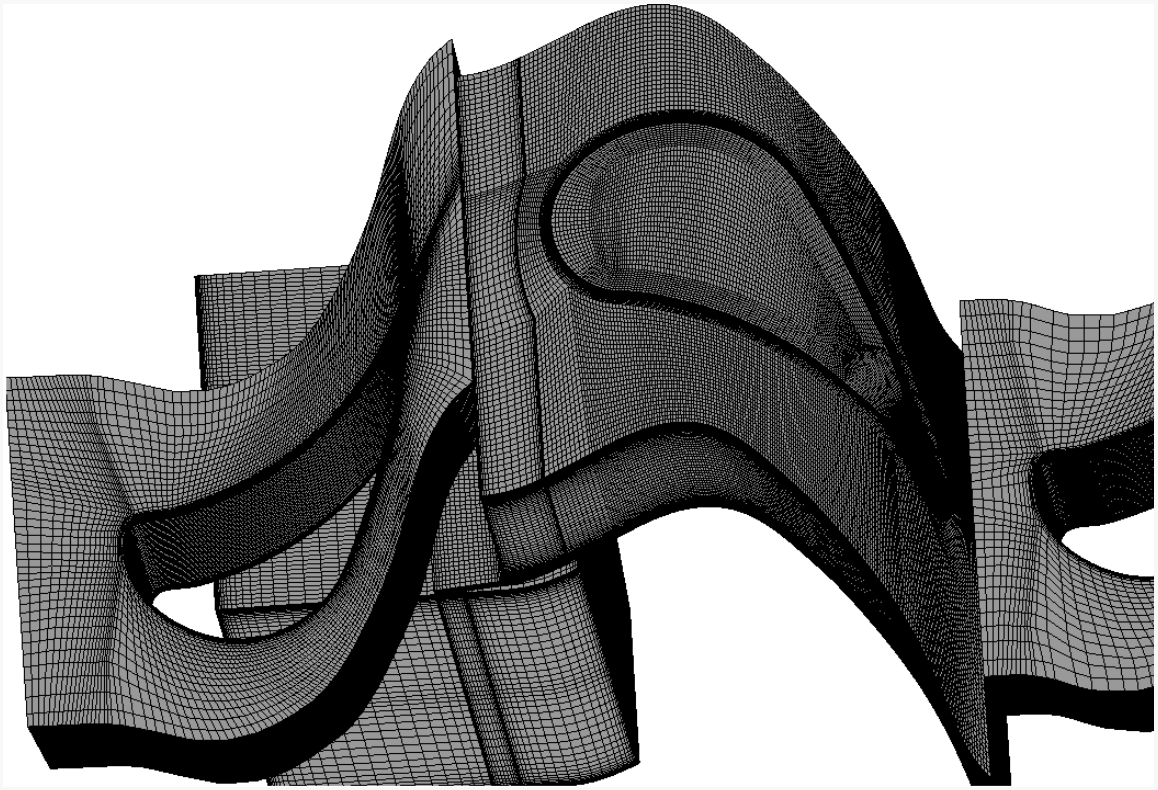


MFR=X%

(X=0, 0.5, 1.0, 1.5, 2.0)



Design of the blades with ejection holes

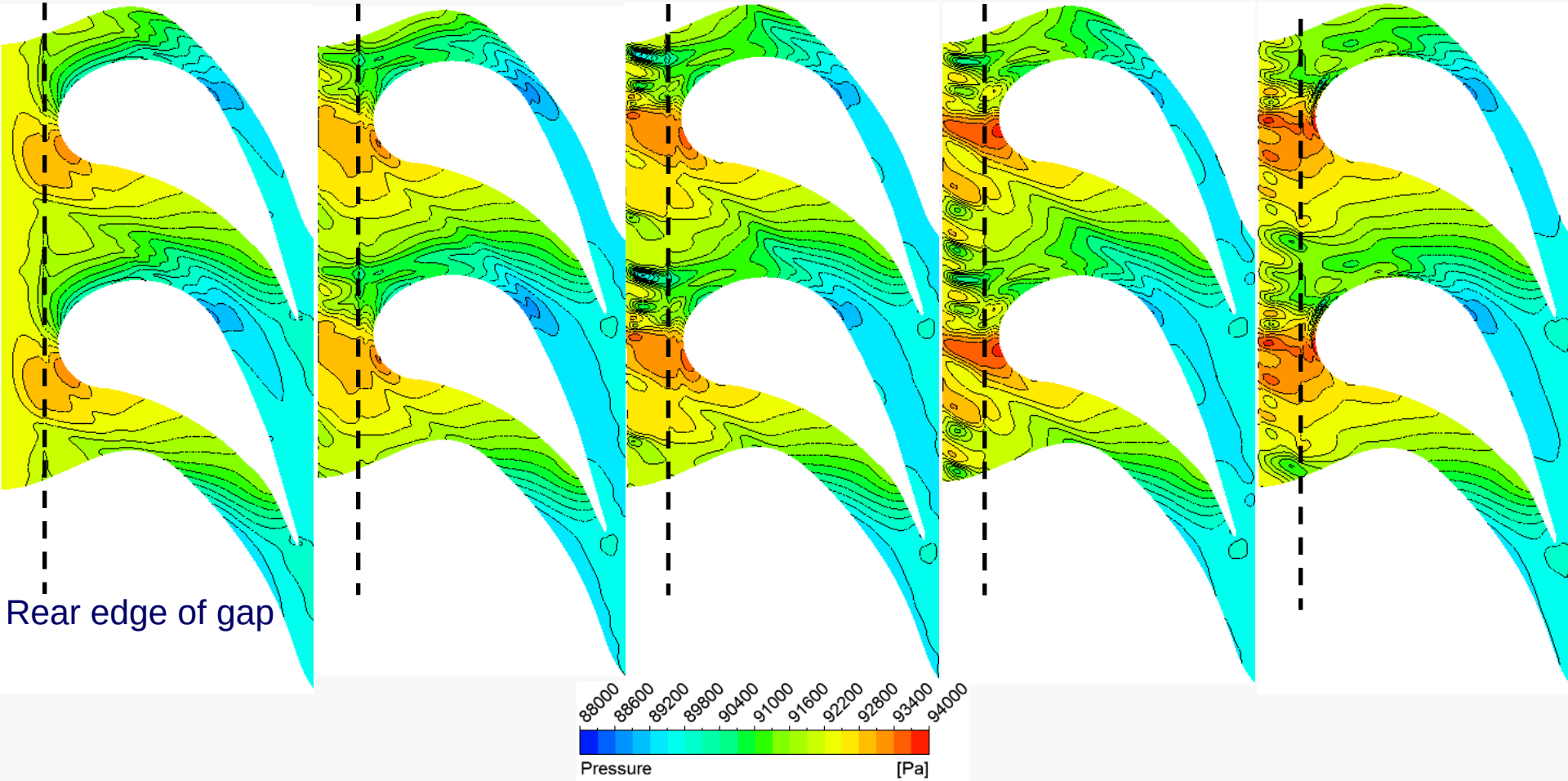


Effect of Purge Flow on Pressure and Temperature Distribution

Physics of purge flow ejection:

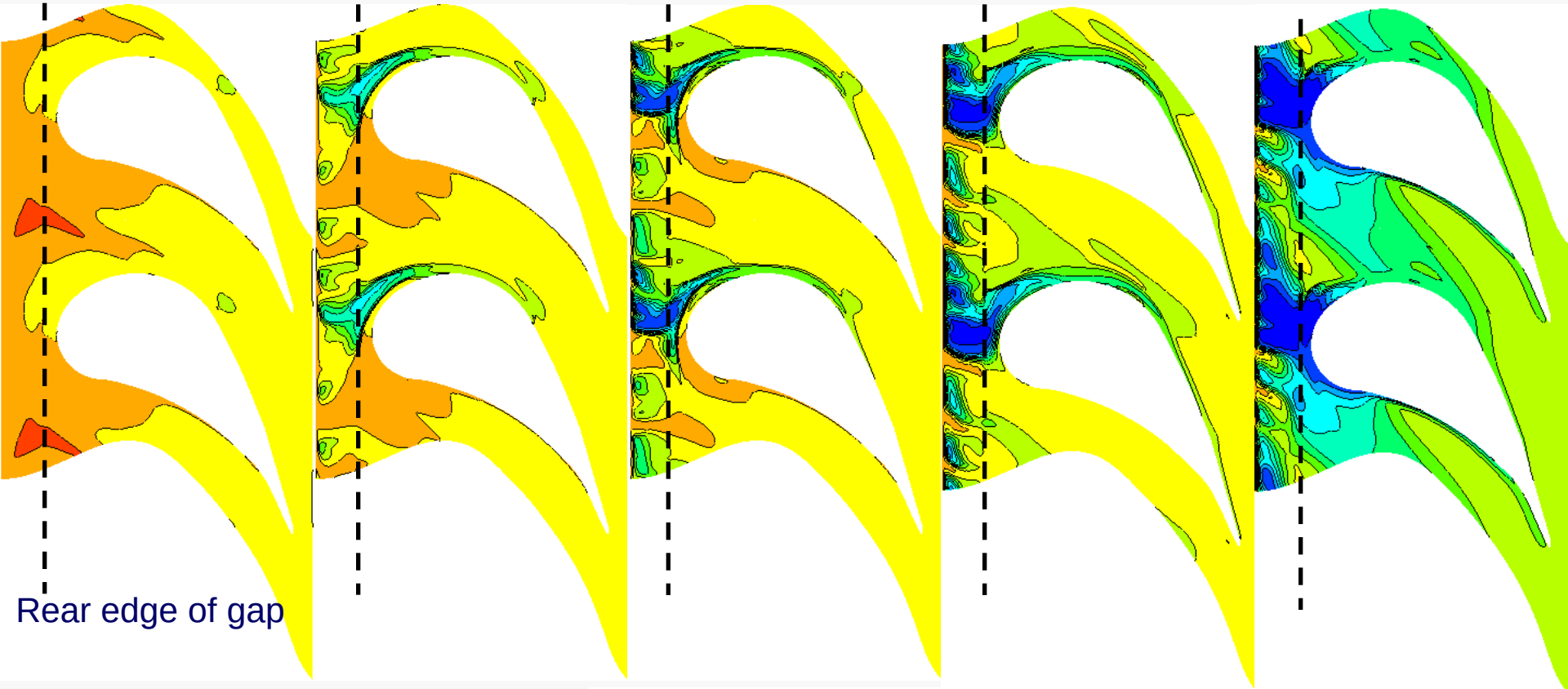
- At MFR = 0, due to rotation and centrifugation of the boundary layer, fluid discharges from the cavity leaving behind a temporary "vacuum" within the cavity.
- Fluid particles tend to eject toward the suction side of the blades.
- After the vacuum level has reached a certain threshold it breaks down, fluid from the main stream flows back, filling the cavity and the periodic process of emptying and re-filling starts all over again.
- This periodic unsteady process cannot be captured by steady Reynolds averaged Navier-Stokes (RANS) code. The unsteady version, URANS, must be used.

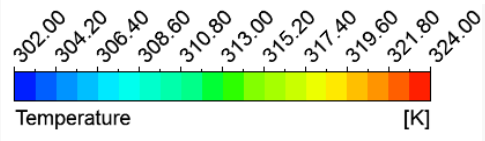
Pressure Distribution Contour at 0% Span



MFR=0% MFR=0.5% MFR=1.0% MFR=1.5% MFR=2.0%

Temperature Distribution Contour at 0% Span





MFR=0% MFR=0.5% MFR=1.0% MFR=1.5% MFR=2.0%

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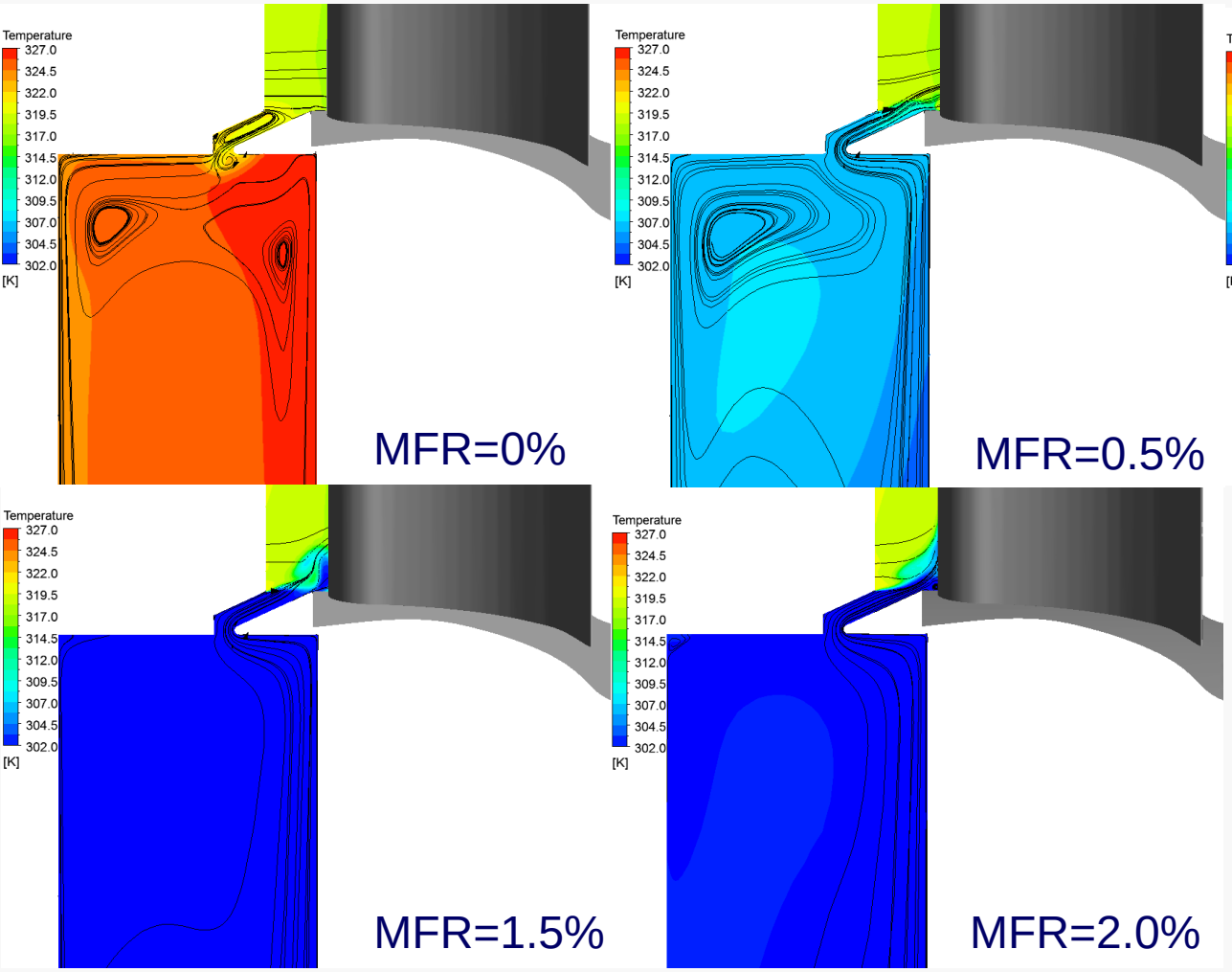
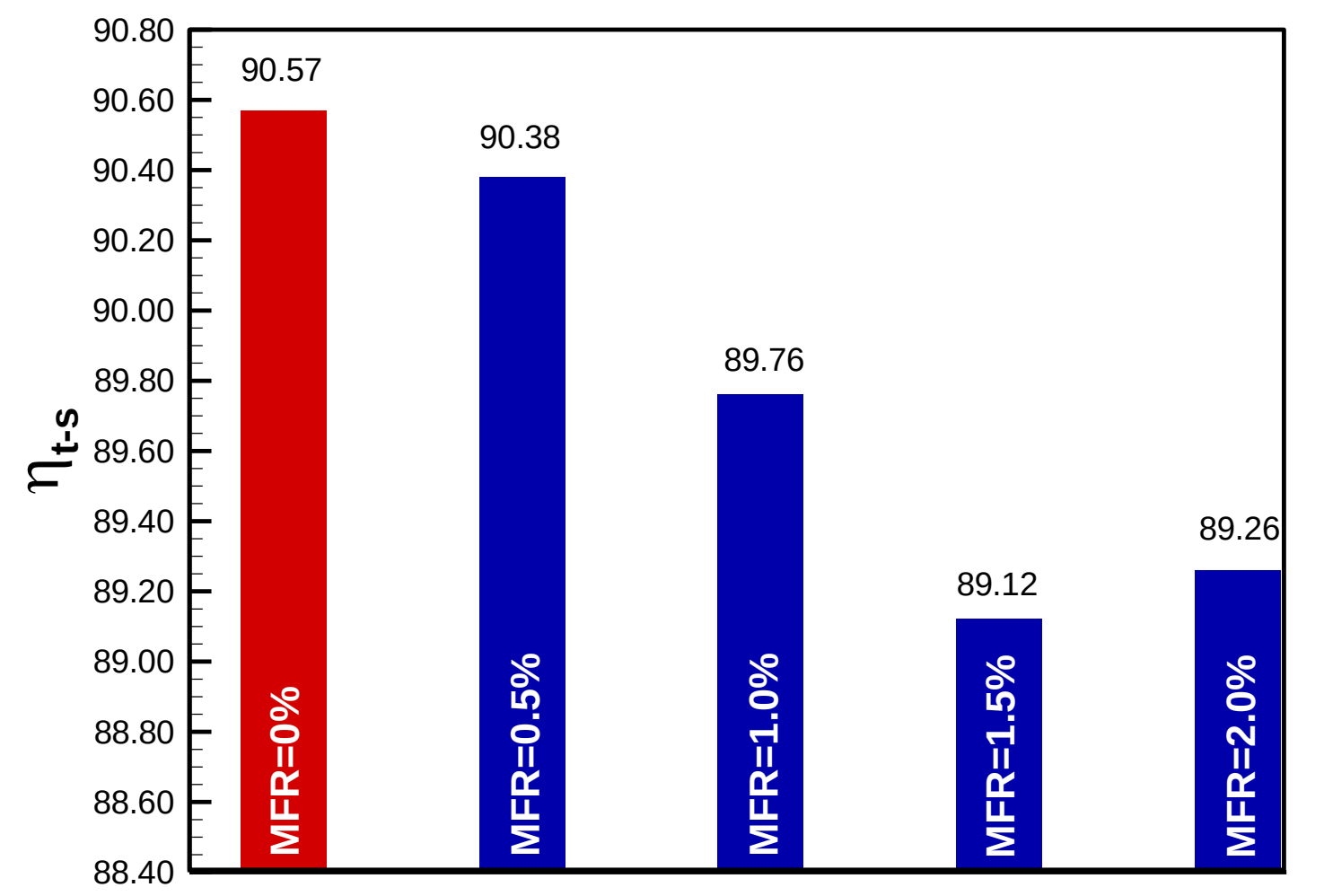
Temperature Distribution and Streamlines at Suction Side

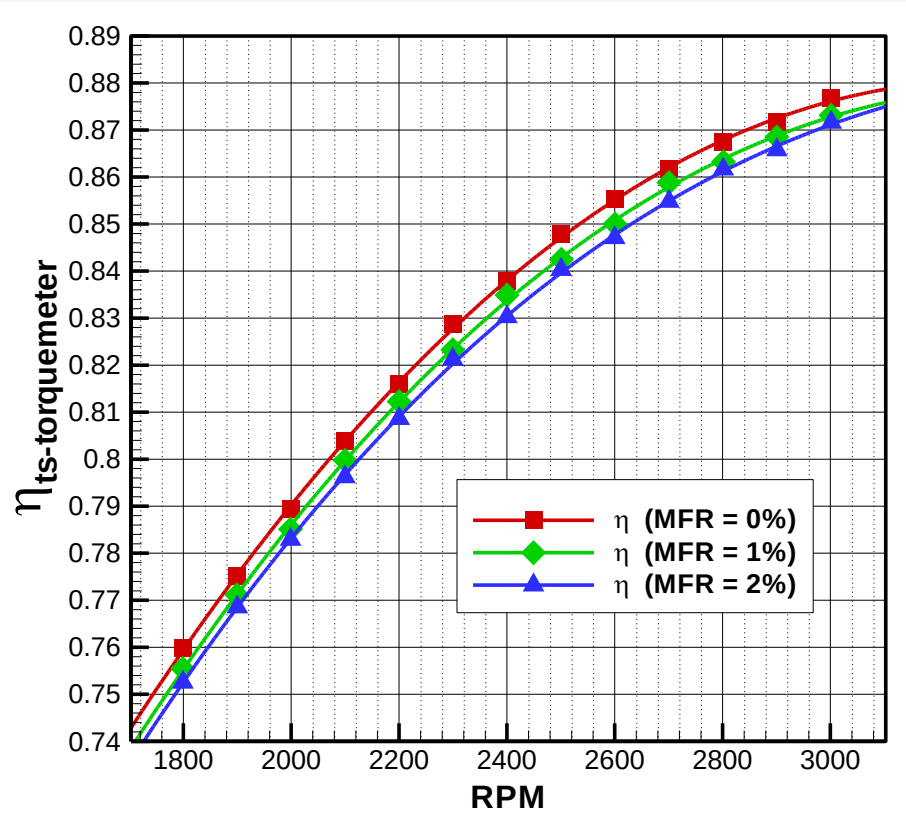


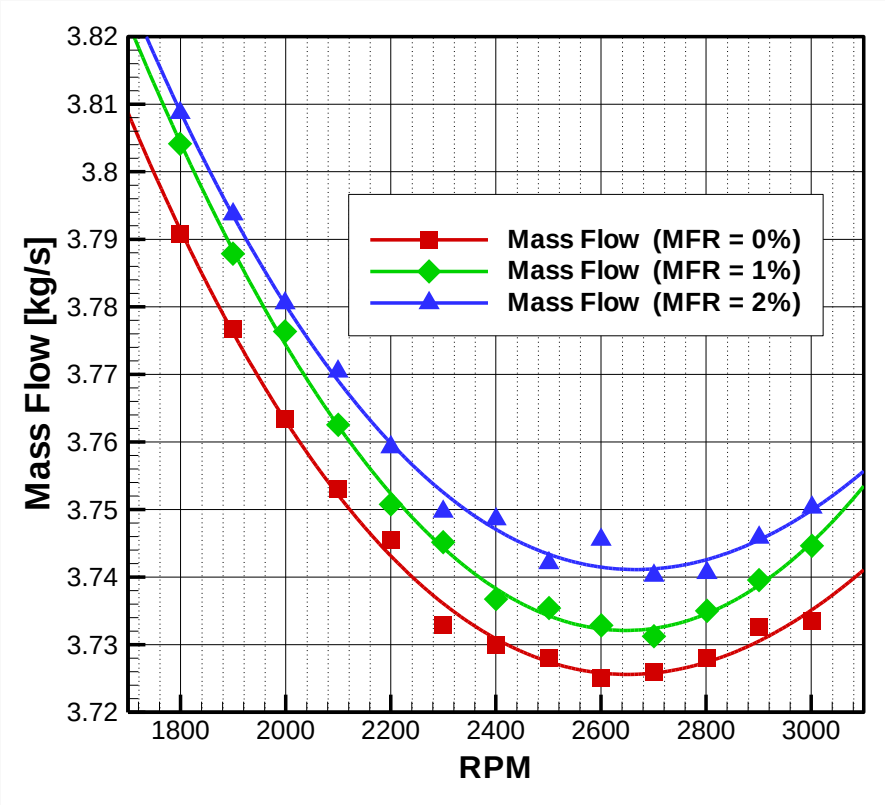
- Purge flow tends to eject from suction side.
- Apparently, more coolant eject to mainstream as MFR increases.
- Different flow patterns were observed with different MFRs.

Effect of MFR on Rotor Efficiency RANS Calculation



Effect of MFR on Rotor Efficiency, Experiment





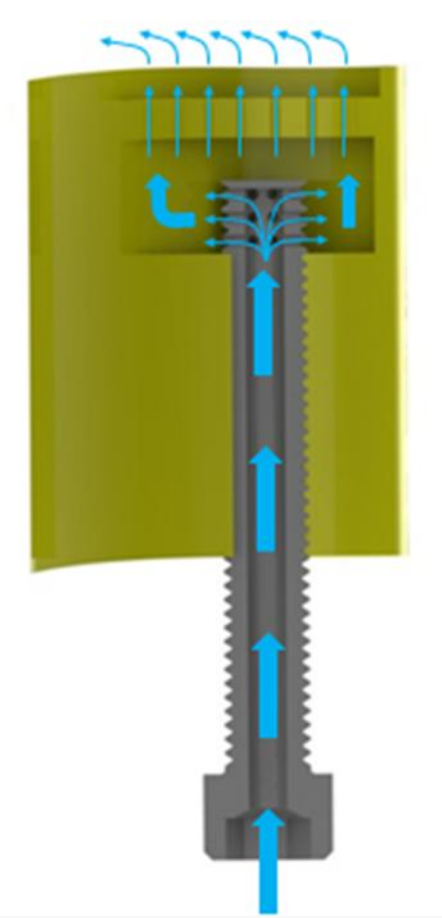
Blade Tip Secondary Flow Reduction, Tip Ejection

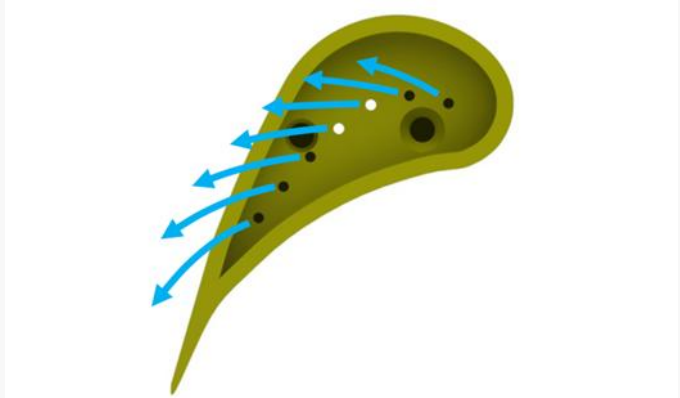
Rotating Blade Tip Ejection (was scheduled for Year 3, preponed)

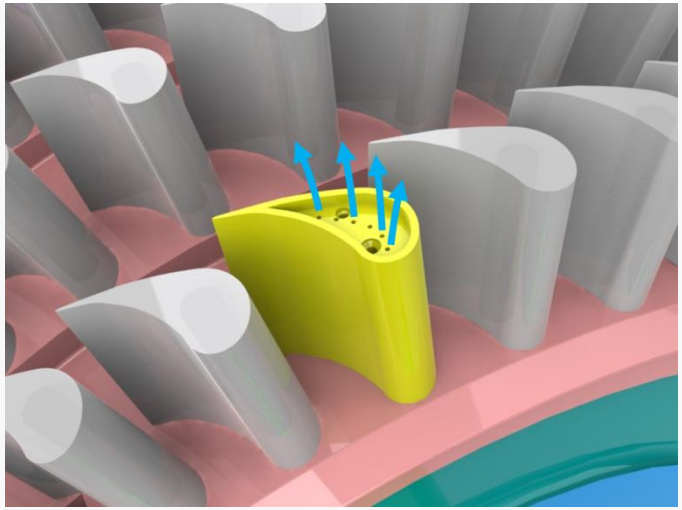
The proposed blade tip ejection experiments to counteract the tip clearance vortex are intended to:

- **Reduce the induced drag force by the tip clearance vortices,**
- **Reduce the tip clearance leakage,**
  - **improving the efficiency and**
  - **simultaneously reducing the potential for corrosion, erosion, and deposition on the blade tip.**

Film Cooling with Ejection Holes at Blade Tip

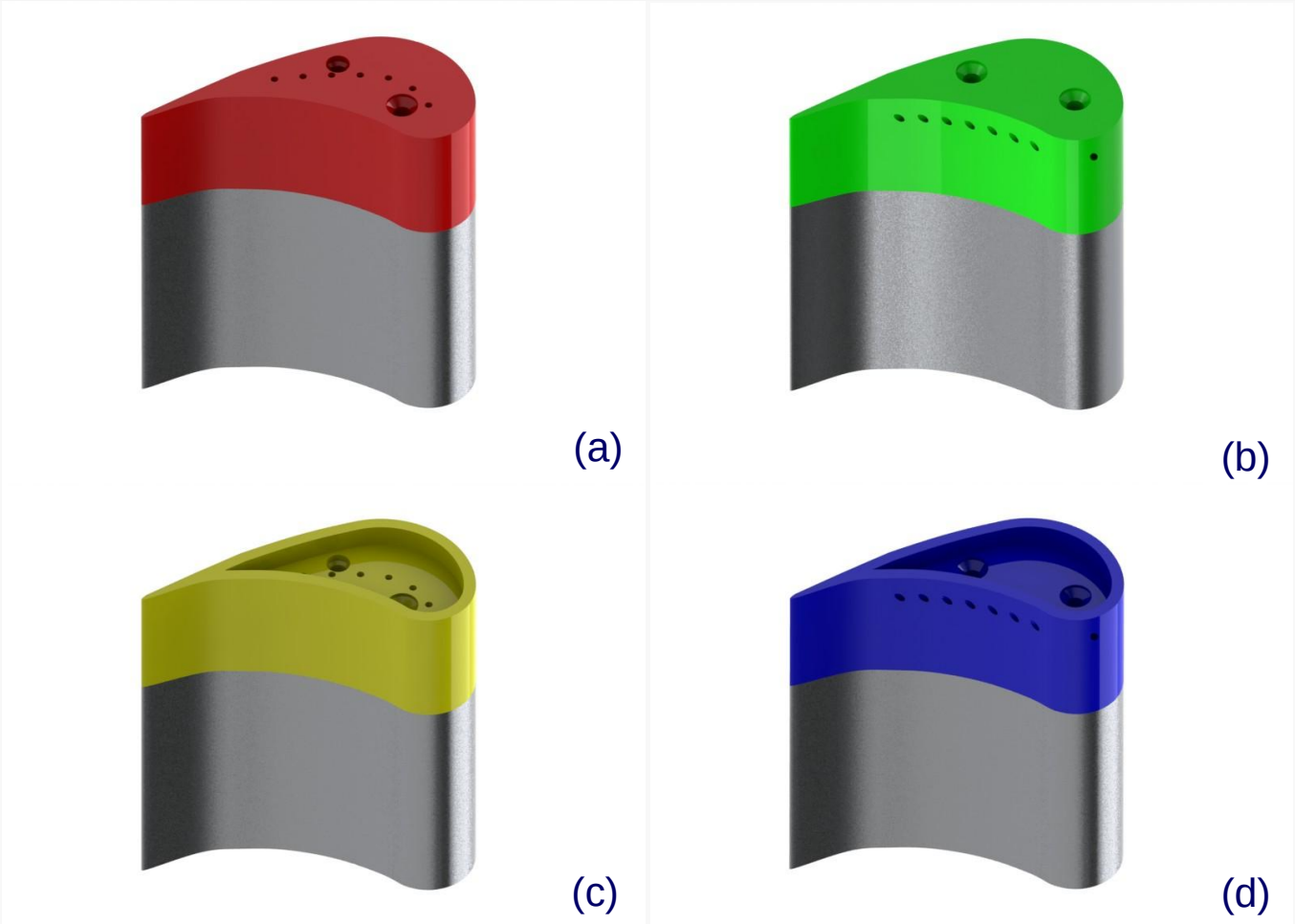






The coolant flow is injected from the bottom of the bolt and then diffuses into the plenum through radially distributed holes near bolt tip. Finally the coolant flow is ejected through the cooling holes.

Design of Blades with Ejection Holes



Rotor blades with four different cooling configurations: (a) ejection from tip, (b) ejection from pressure side near the tip, (c) ejection from tip with squealer, (d) ejection from pressure side near the tip with squealer.

Design of Blades with Ejection Holes

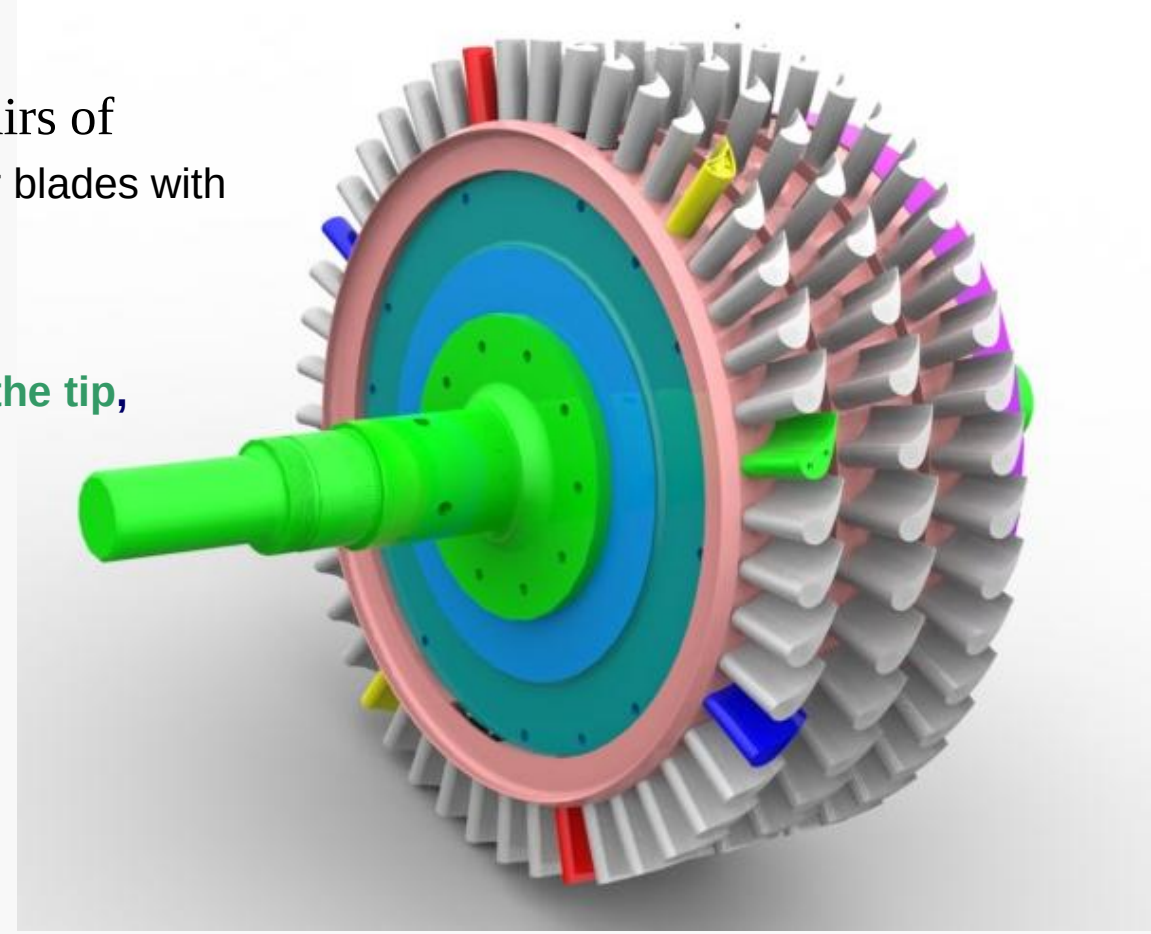
Diametrical arrangement of four pairs of blades with tip ejection holes. Rotor blades with four different cooling configurations:

(a) ejection from flat tip,

(b) ejection from pressure side near the tip,

(c) ejection from tip with squealer,

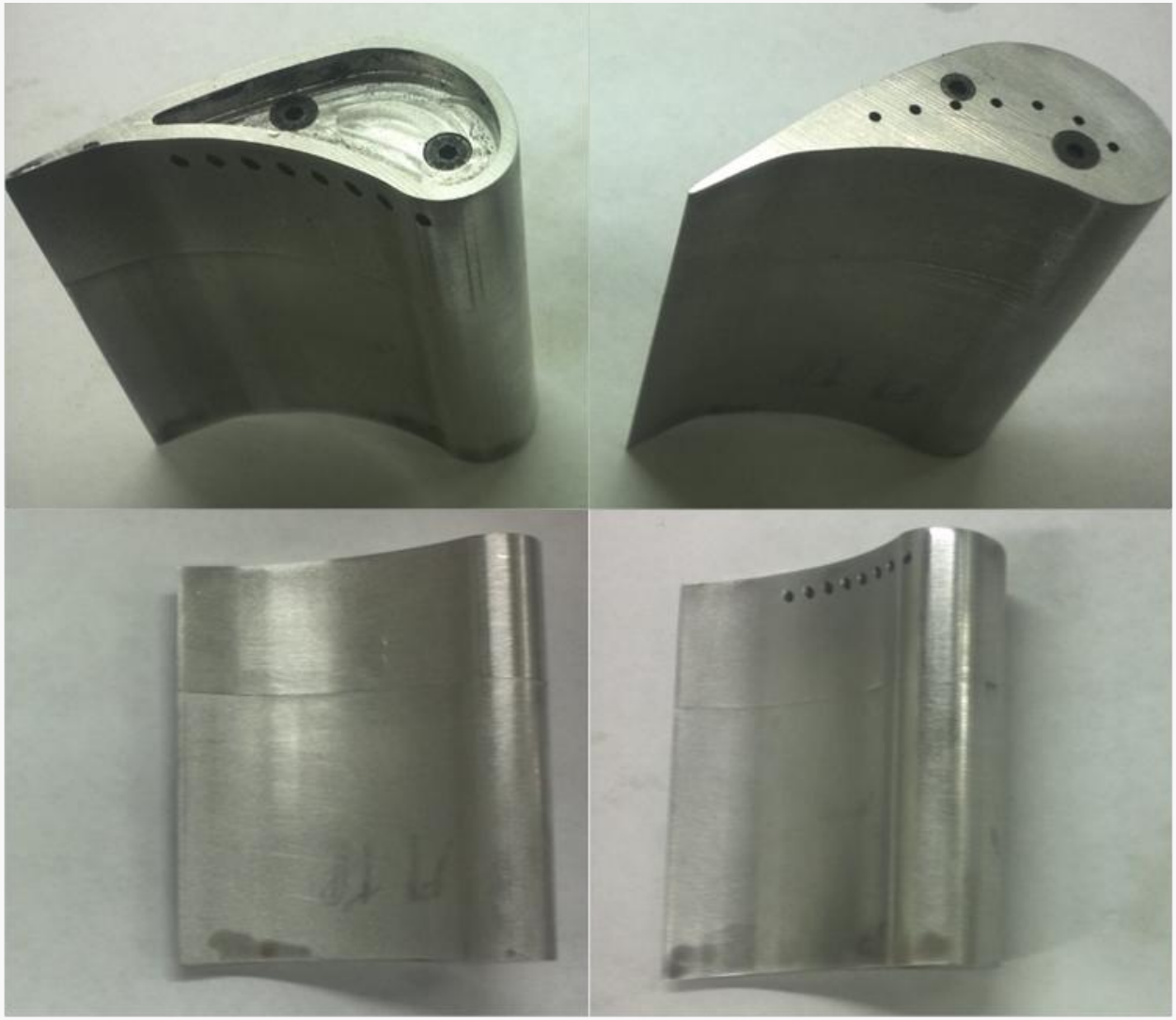
(d) ejection from pressure side near the tip with squealer.



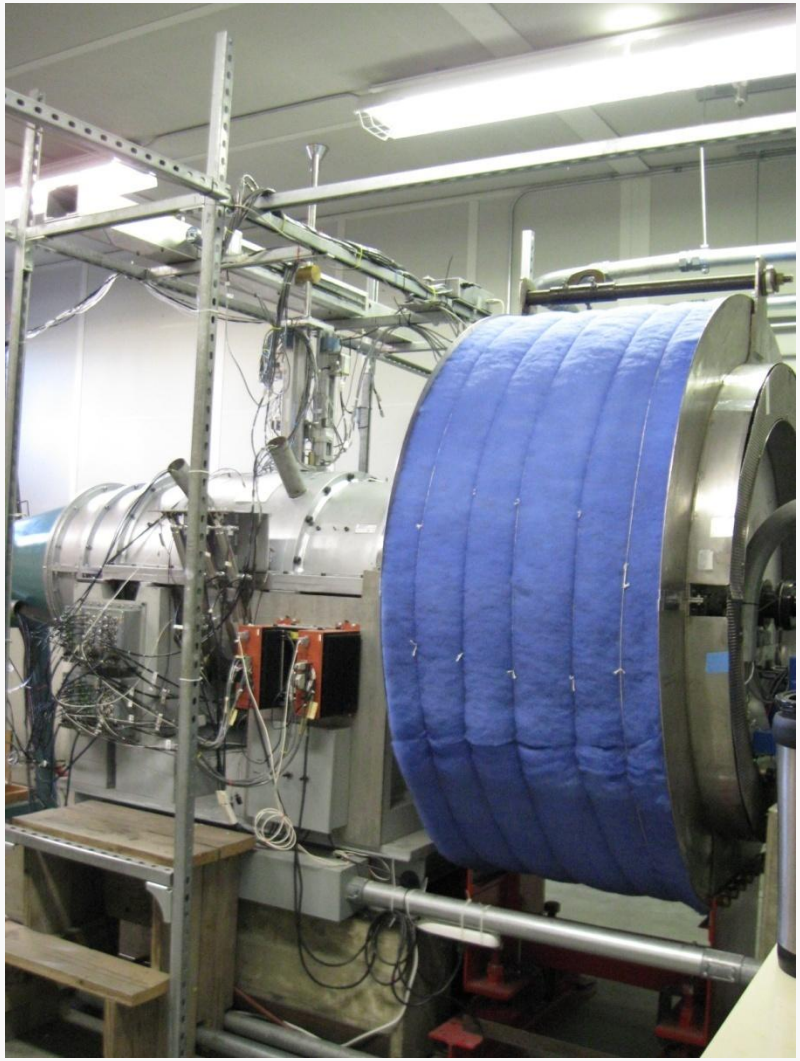
Design of the blades with ejection holes

Stage of manufacturing the blades with ejection holes

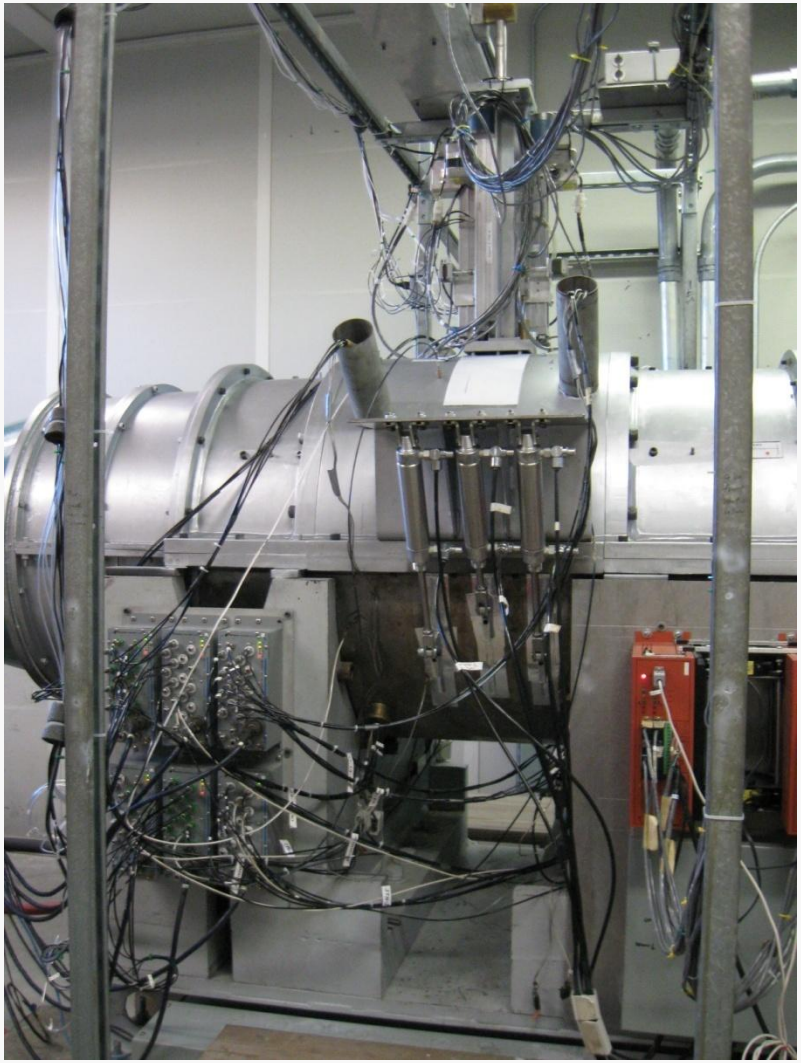
Manufacturing of the blades with ejection holes



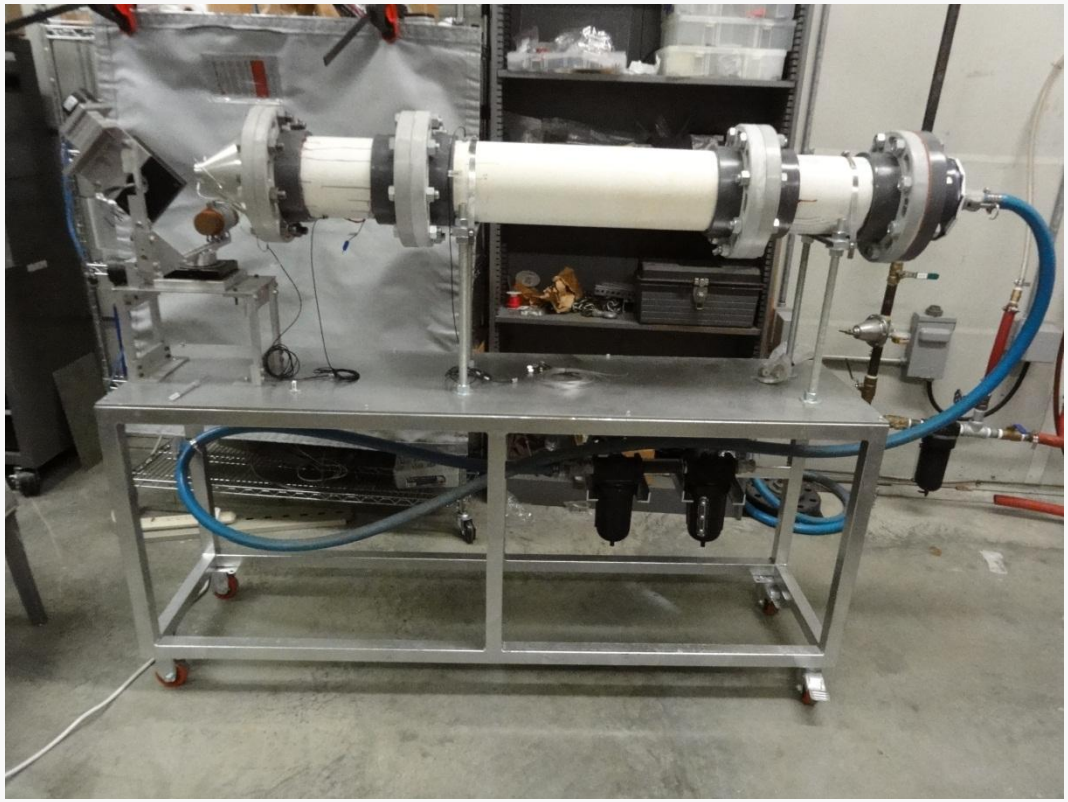
TPFL Three-Stage Research Turbine Facility



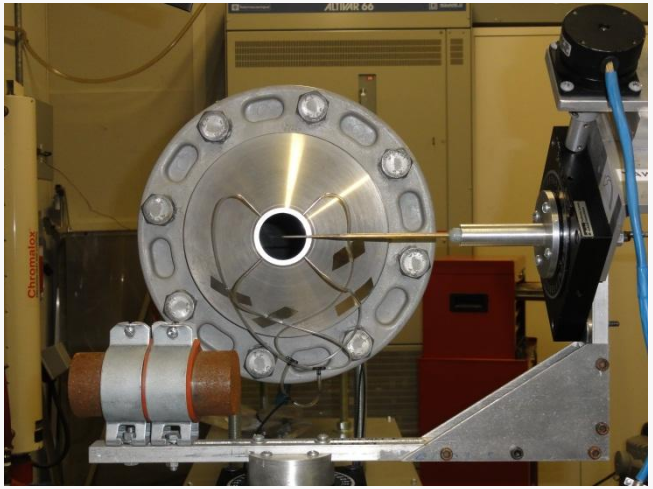
TPFL Three-Stage Research Turbine Facility



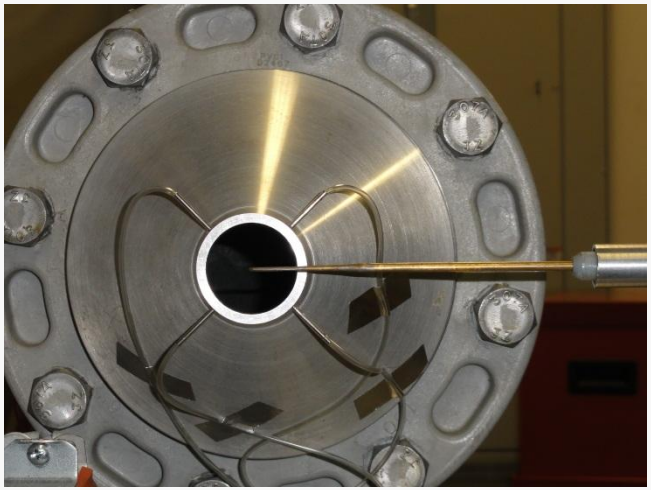
TPFL Calibration Facility



TPFL 5 Hole Probe Calibration Facility



Turn Table for Probe Alignment



Probe Tip and Flow Alignment

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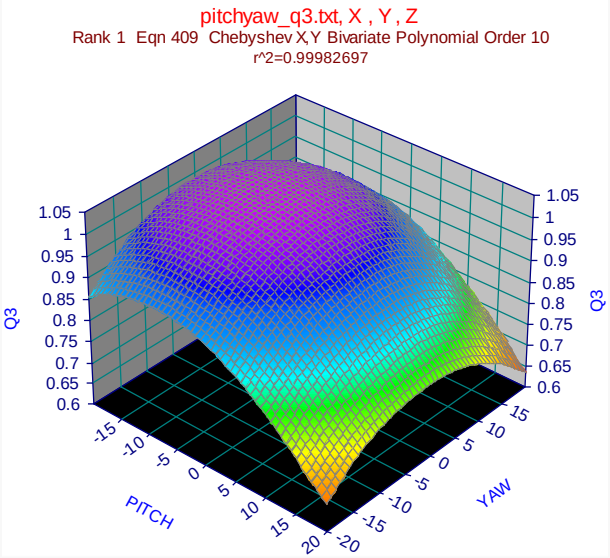
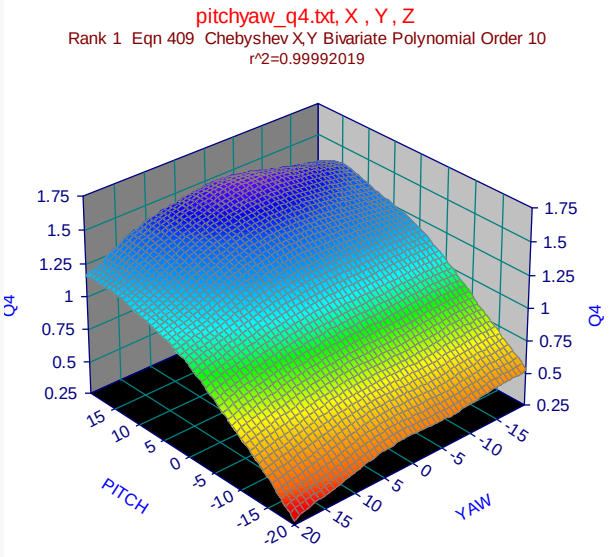
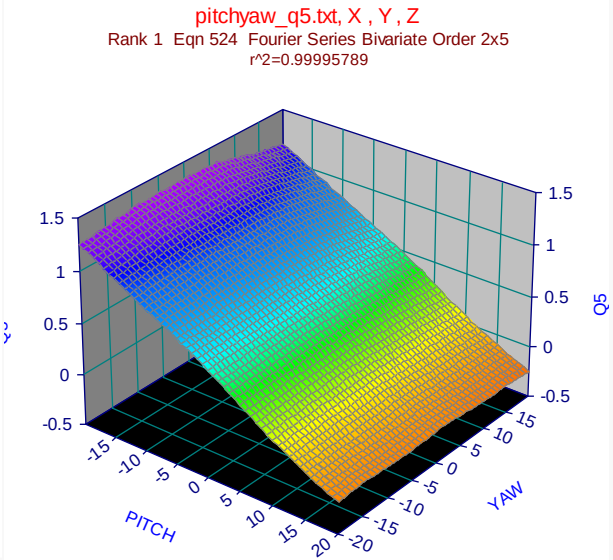
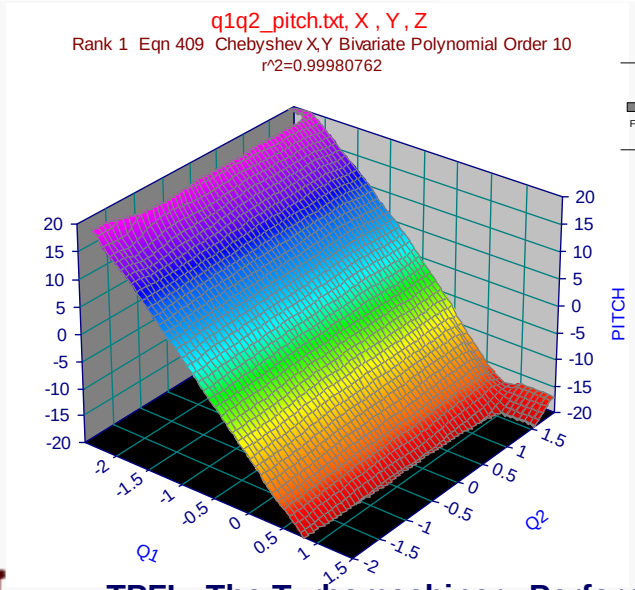
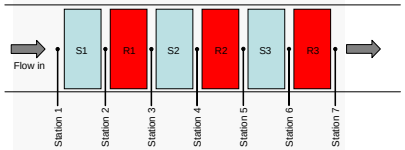
Calibration Precision Examples: Results, Station 4

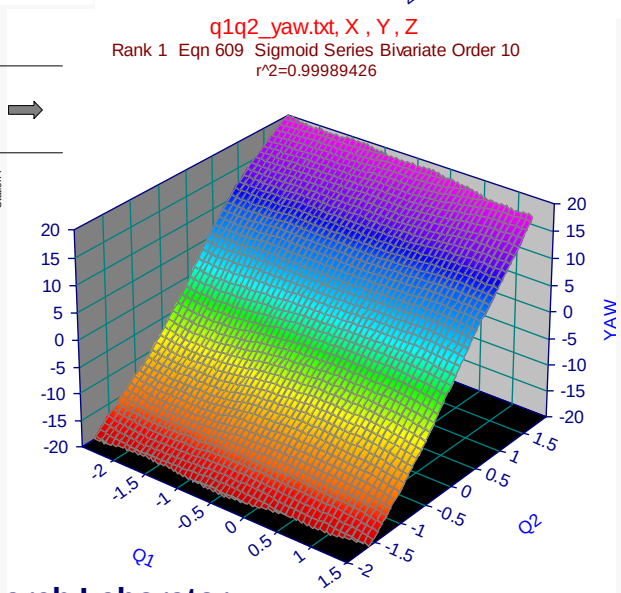












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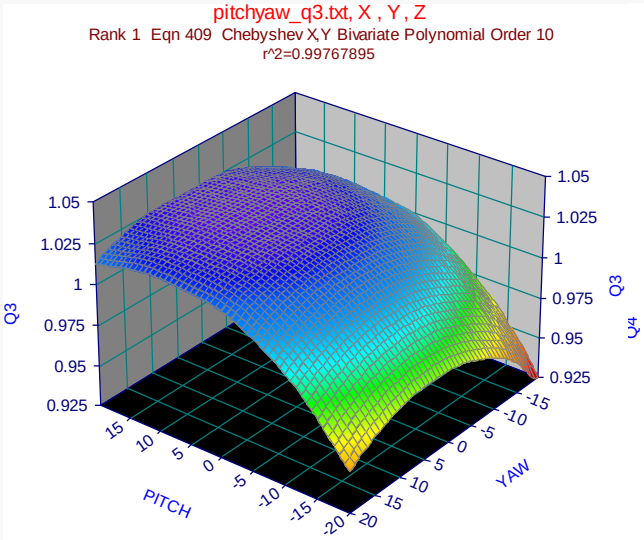
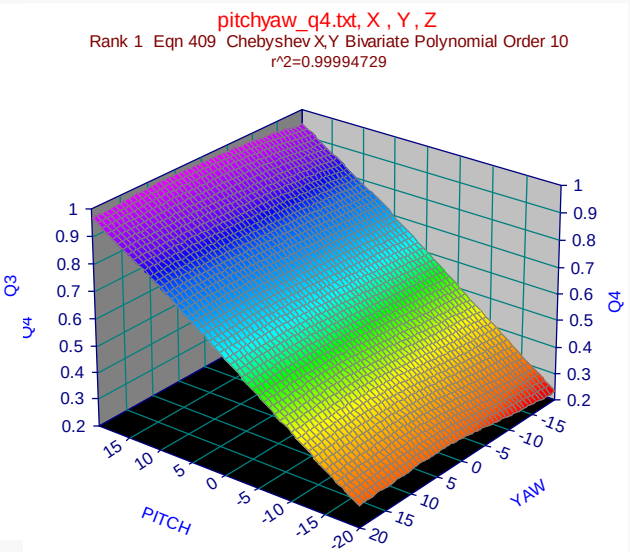
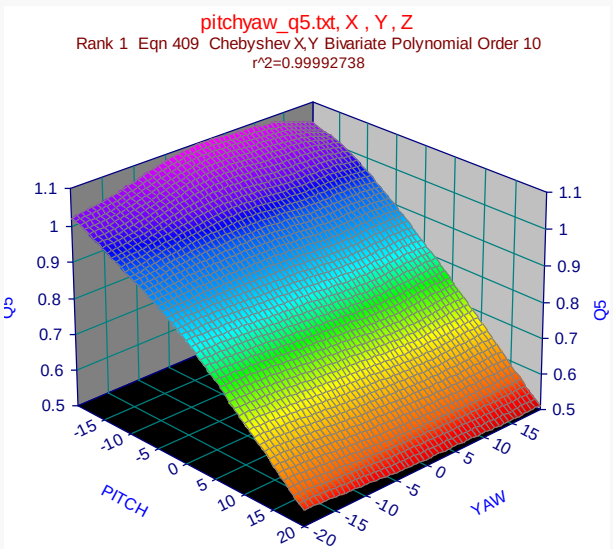
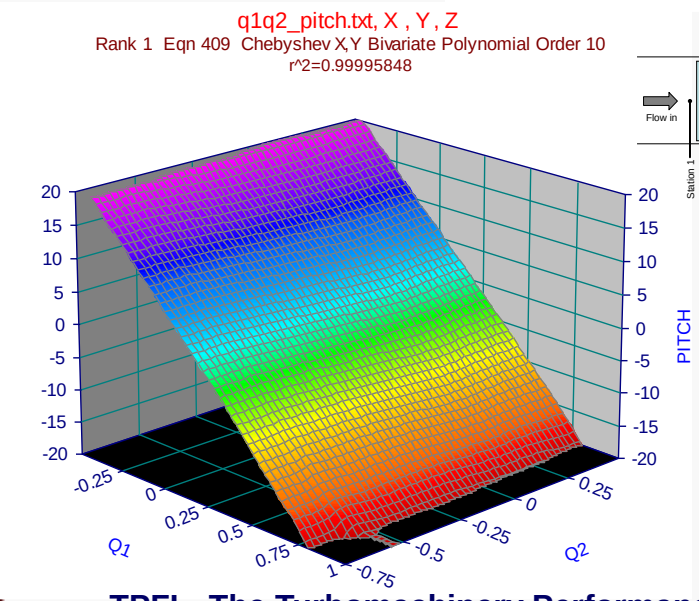
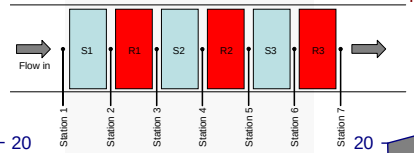
Calibration Results, Station 5

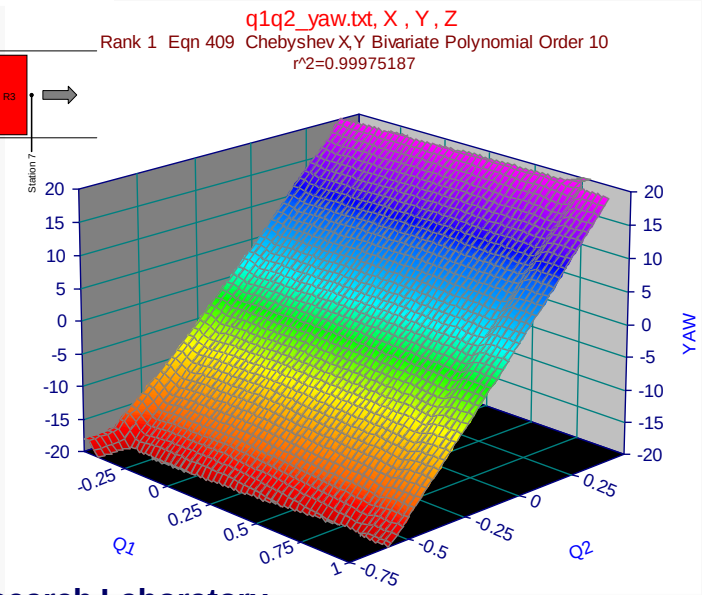












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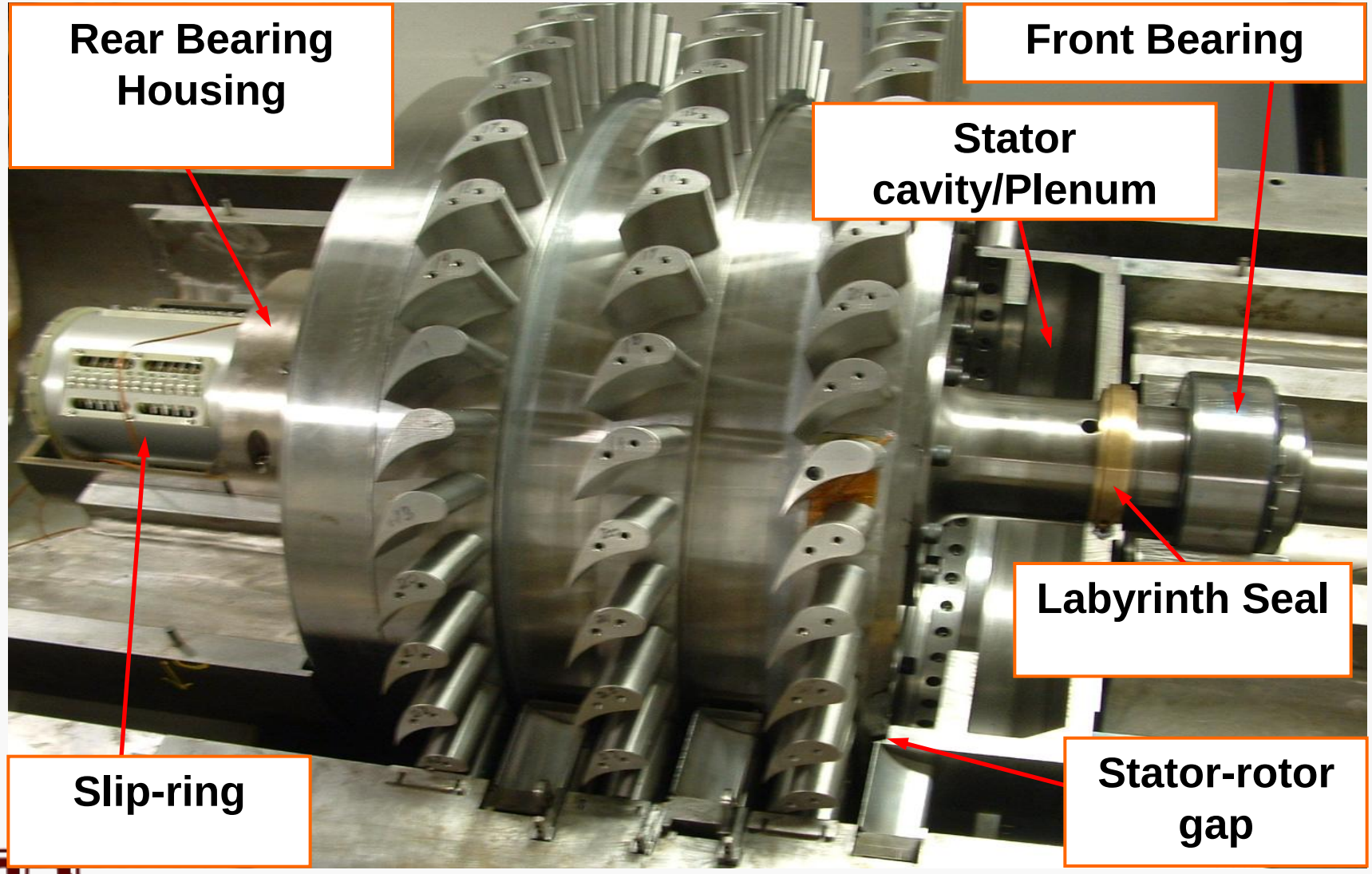
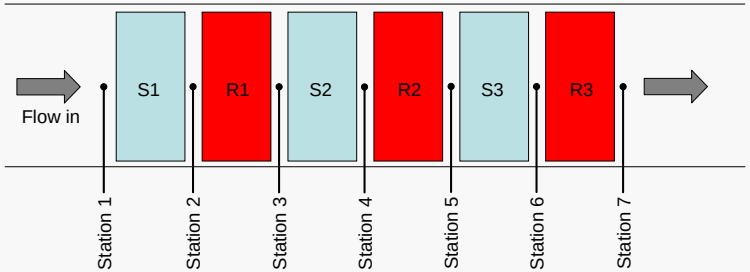
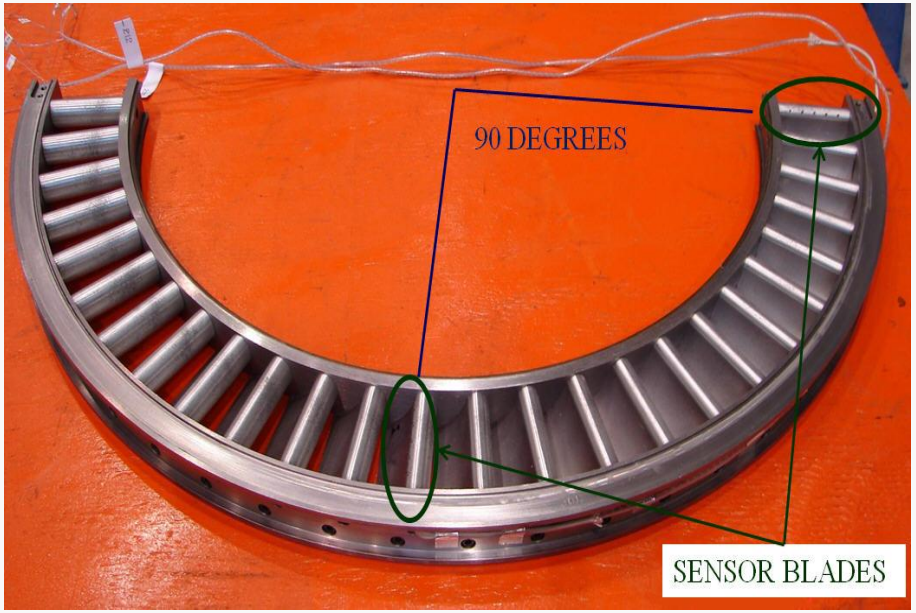
Experimental Facility: New Turbine Rotor Features

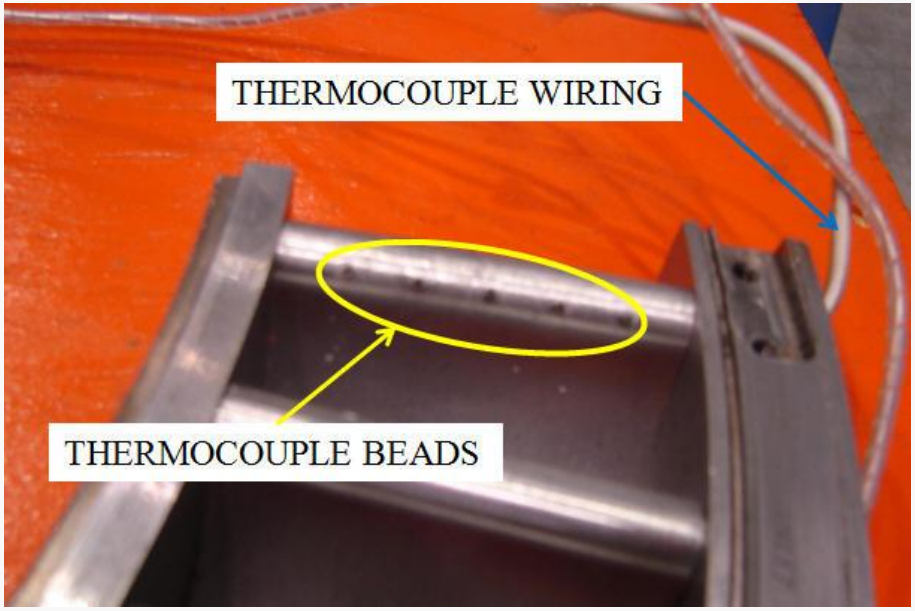


Experimental Facility, Inter-stage Temperature Measurement

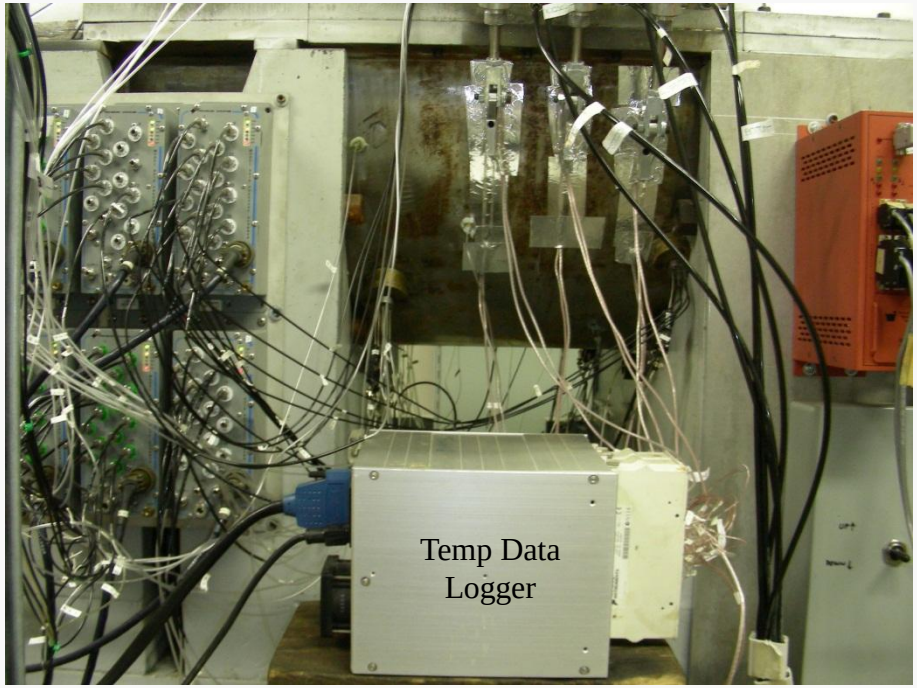
Each stator row from three stages were instrumented with five precision thermocouples in radial direction.







Experimental Facility, Inter-stage Temperature Measurement



Conclusions

- The new endwall contouring method is able to significantly reduce the pressure difference between the pressure and suction surface near hub, which is the primary driving force of endwall secondary flow.
- Applying the method to the second rotor row of an existing three-stage turbine with six rows, an increase of 0.68% in efficiency has been achieved. Applying the same method to all six rows will result in an efficiency increase of 2.5%
- Large leading-edge filleting can significantly reduce the generation of horseshoe vortex and thus weaken the intensity of passage vortex. However, filleting is not able to improve pressure distribution near hub. Also the limited gap between stator and rotor blades dictated by the optimum aerodynamic design may not allow its application.
- The combination of a moderate leading-edge filleting with the new endwall contouring technology may further decrease the secondary flow losses close to hub and therefore considerably enhance the performance of turbines.

Conclusions (continued)

- Due to the existence of the circumferential ejection slot for purge flow, the contouring for thw first rotor could not be extended upstream. As a result, an efficiency increase close to 0.4% was gained for first rotor.
- Starting with the reference turbine, the purge mass flow ratio (MFR) was varied from 0% to 2.0%. While the cooling effect increases, with increasing MFR, the turbine efficiency decreases as expected, which is due to the enhanced mixing process between the coolant ejection and the main stream and accordingly more aerodynamic losses are generated.
- The reference turbine has undergone critical efficiency, performance and interstage tests.
- Turbine rig prepared for the planned comprehensive interstage aerodynamics, efficiency and performance and heat transfer experiments proposed for endwall contouring .
- .

Conclusions (continued)

- The endwall contouring for first rotor could not be extended upstream due to the existence of the circumferential ejection slot for purge flow. As a result, an efficiency increase close to 0.4% was gained for first rotor.
- Starting with the (non-contoured) reference turbine, the purge mass flow ratio (MFR) was varied from 0% to 2.0% with an increment of 0.5%. While the cooling effect in terms of temperature reduction increases, with increasing MFR, the turbine efficiency decreases as expected, which is due to the enhanced mixing process between the coolant ejection and the main stream and accordingly more aerodynamic losses are generated.
- The reference turbine has undergone critical efficiency, performance and interstage tests.

Conclusions Turbine Rig Experiments, Year 3 Work

Current State of the Rotor:

- **Second rotor ring with endwall contouring is completed.**
- **All four pairs of blades with four different ejection hole geometry completed.**
- **Endwall contouring is being machined in first rotor hub.**
- **After completion of the manufacturing and installation of all blade, the rotor will be balanced and returned to Texas A&M.**
- **Comprehensive interstage aerodynamics, efficiency, performance and heat transfer experiments will be completed as outlined in the proposal.**

Thanks for Your Time and Attention.