TPFL: The Turbomachinery Performance and Flow Research Laboratory, Texas A&M University

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

PIs: M.T. Schobeiri, J.C Han
Department of Mechanical Engineering
Texas A&M University

Research Contract: DE-FOA-0000031
U. S. Department of Energy
National Energy Technology Laboratory

Richard Dennis, National Energy Technology Laboratory
Robin Ames, National Energy Technology Laboratory

Project Awarded 10/01/2009 (36 Month Duration)

$499.969 Total Contract Value ($399,891 DOE)

Content

Introduction

Part I: CFD- Investigations, Endwall Contouring and Filleting

- Overview Existing Cascade Results
- Application to Rotating Turbine Rig, Hub Contour Geometry Variation, Optimization
- Introduction of a New Technology to use a physics based systematic method for Hub Contouring Turbine Blades of any Arbitrary Airfoil Geometry

Part II: Turbine Rig Experimental Investigations

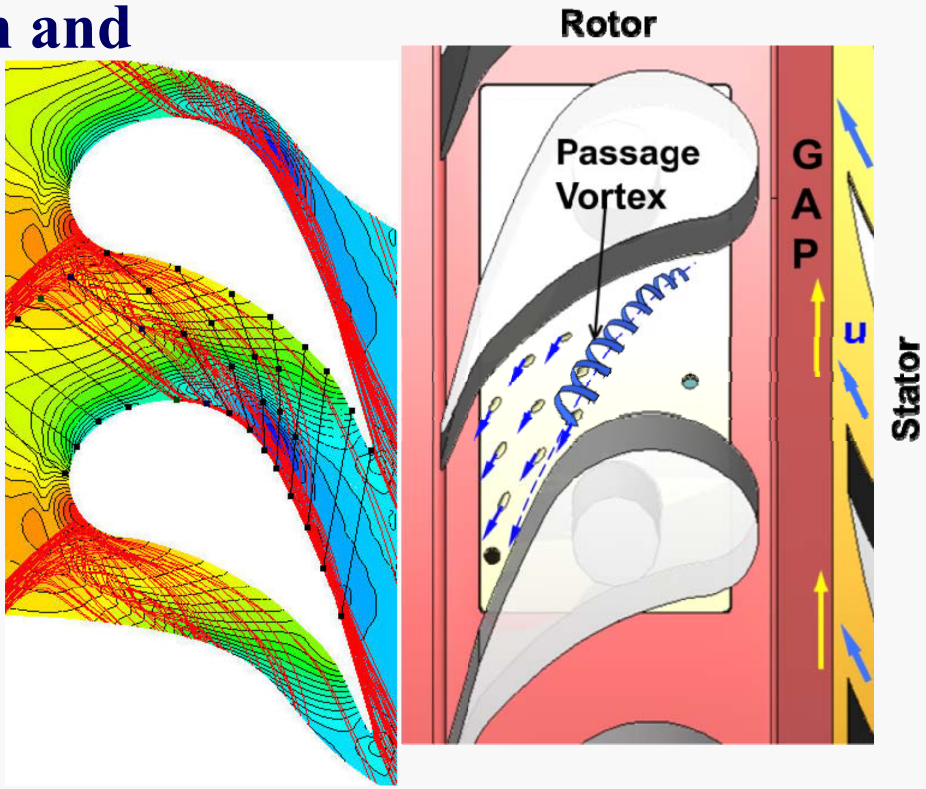
- Preparation of Turbine Rig for Reference Experiments
- Interstage Flow Field Measurements
- Efficiency and Performance

Conclusion

Introduction: Endwall Secondary Flow, 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

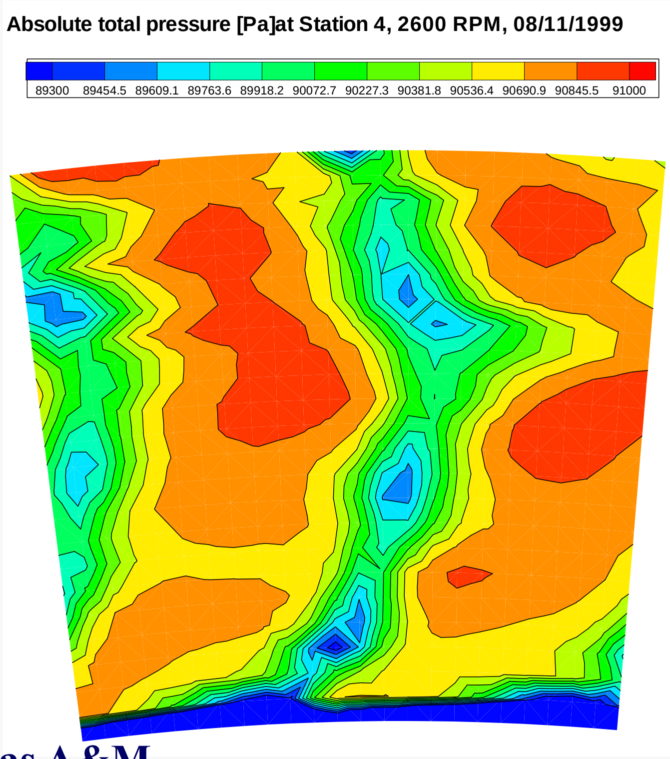


Overview: Secondary Flow Reduction

There are **five methods** of reducing the secondary flow losses at the turbine hub and tip:

1) Blade Special Design:Fully-3D Blades with Compound Lean

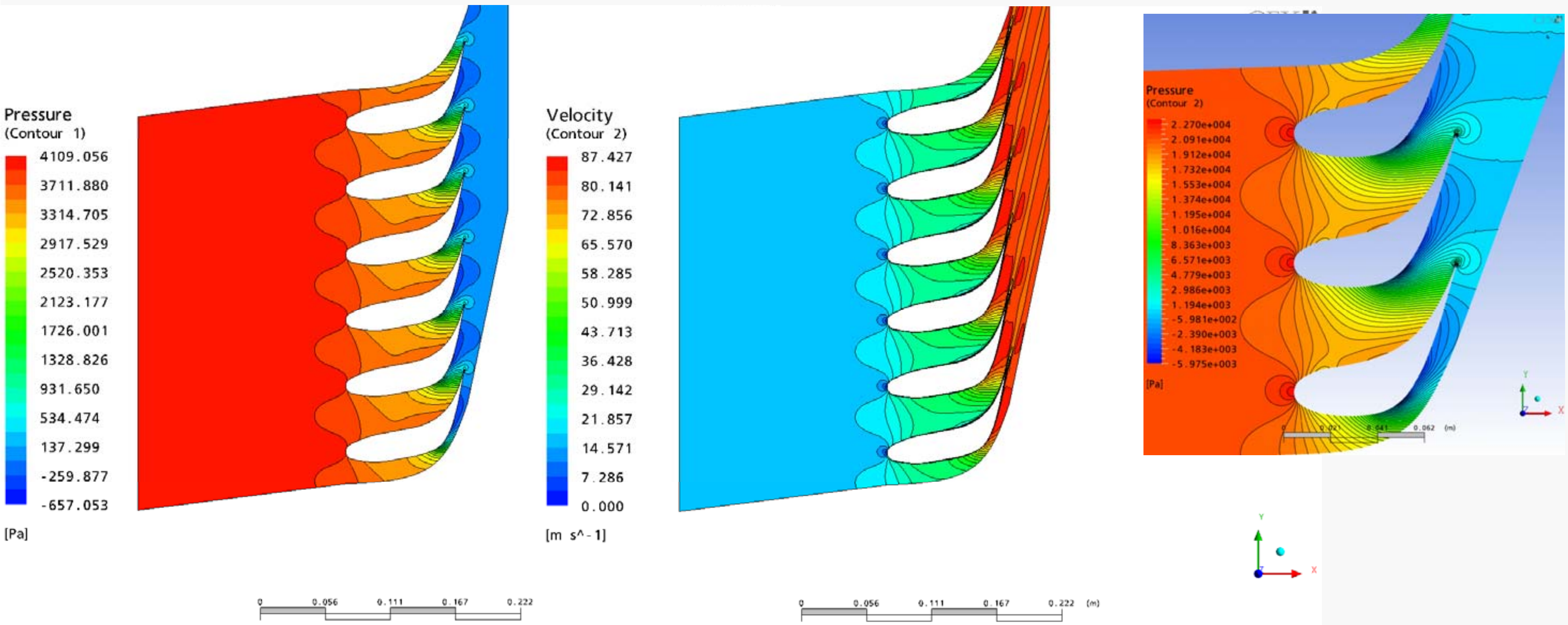
- **Very effective used in advanced HP-Turbines**



HP-Turbine Design: TPFL, Texas A&M

Overview: Secondary Flow Reduction, Special Design

2) Blades are insensitive to incidence change
Turbines operate at off-design conditions:
with incidence change from - 30^o to + 30^o



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

Overview: Secondary Flow Reduction

3) Endwall Contouring (extensive literature review in proposal):

Numerous cascade (mostly CFD) investigations suggest a **substantial reduction of secondary flow loss of 50% and more,** however the effects of rotation such as:

- Boundary layer centrifugation **missing**
- Centrifugal force **missing**
- Coriolis forces **missing**

- **These require Rotating Rig Assessment Tests**
- **Clarification: A substantial reduction (50% or more) in secondary flow loss may result in an efficiency improvement of 0.3-1%**

Overview: Secondary Flow Reduction

4) Leading Edge Filleting:

- Stationary cascade experiments show a reduction of secondary loss coefficient, due to filleting (for details: see Proposal, References).
- Other mainly numerical cascade investigations have shown similar results. These investigations lack features inherent to a **Rotating Turbine Rig:**
  - Centrifugal force, Coriolis forces

These Require Rotating Rig Validation Tests

Overview: Tip Secondary Flow Reduction

5) Rotating Blade Tip Ejection (Year 2 Research)

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.**

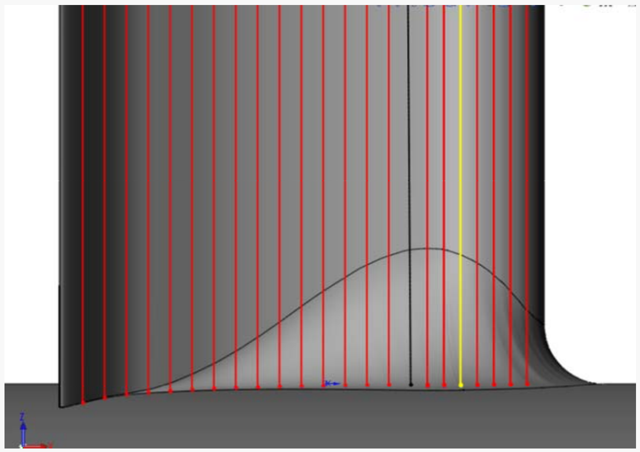
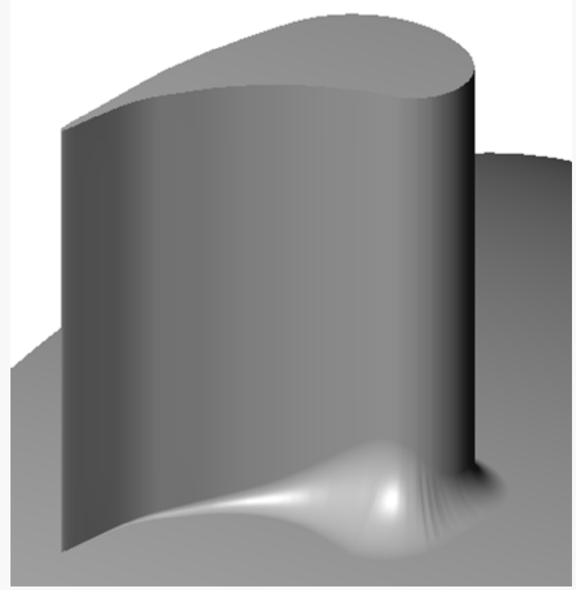
Endwall Contouring Applied to Turbine Rig

The method used in open literature is a *Trial and Error* Approach: (extensive literature review presented in DE-FOA-0000031, 2009)

Approach:

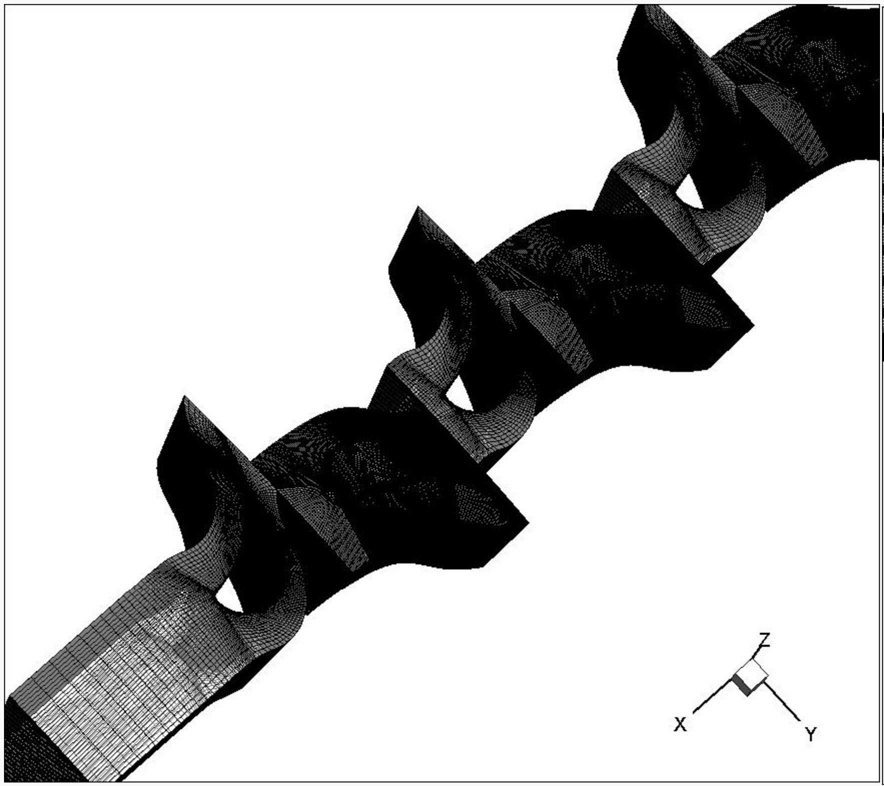
- **Reducing the local area by placing a "hill" on the pressure surface side to increase the velocity, decrease the pressure.**
- **Increasing the local area by placing a "valley" on the suction side to increase the pressure.**
- **Combination of the above**
- **For turbine rig application, extensive verification and rectification** is essential before producing hardware to be tested
- **We numerically simulated numerous cases**
  - **For each individual case several grids were generated to ensure the results were grid insensitive**
  - **Complete flow field, detailed loss and efficiency analyses were performed**
  - **For each single case a parallel computation on A&M Super Computers took about a week**

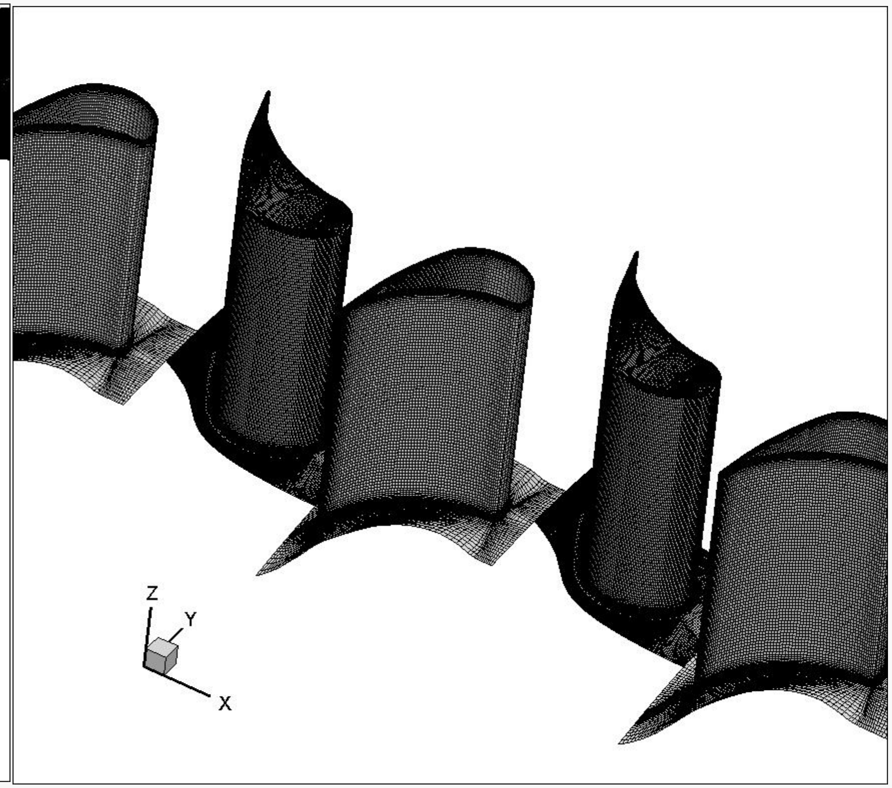
Non-Axisymmetric Endwall Contouring Design

- Several 5th order polynomial were applied to define the variation of contouring height in streamwise direction
- The profile of contouring cross-section is an arc curve which is tangent to both blades and hub.
- 13mm-15%C_{ax} , 13mm-30%C_{ax} , etc.

Endwall Contouring Applied to Turbine Rig

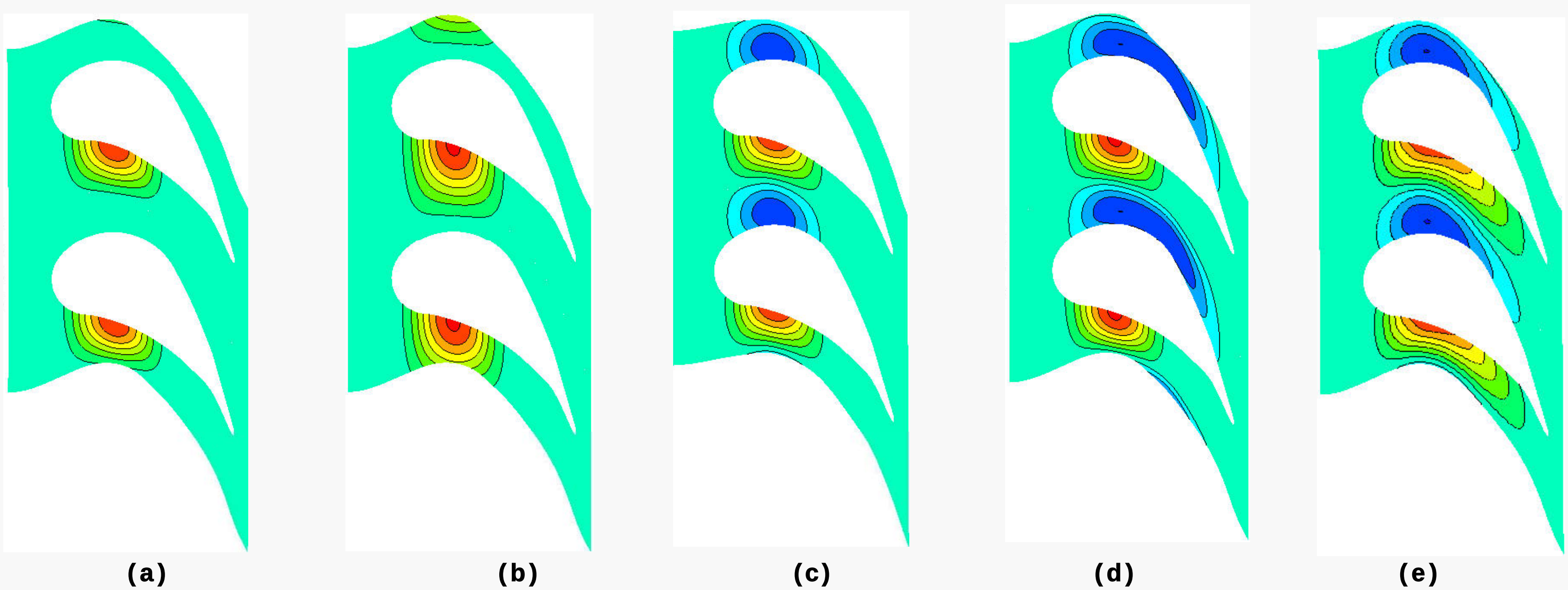




- Rotor mesh has over 2 million elements
- Wall regions use 22 nodes
- The entire model involves over 9 million elements

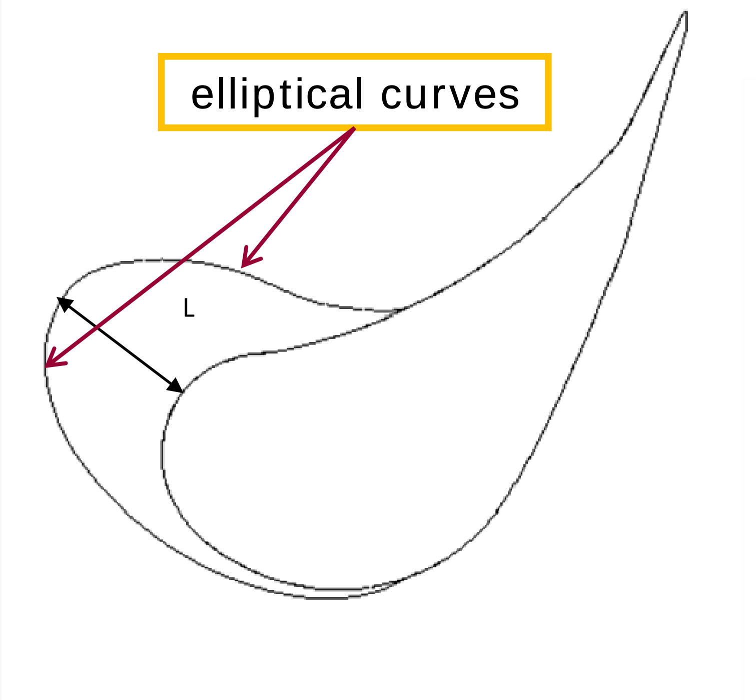
Non-Axisymmetric Endwall Contouring Design

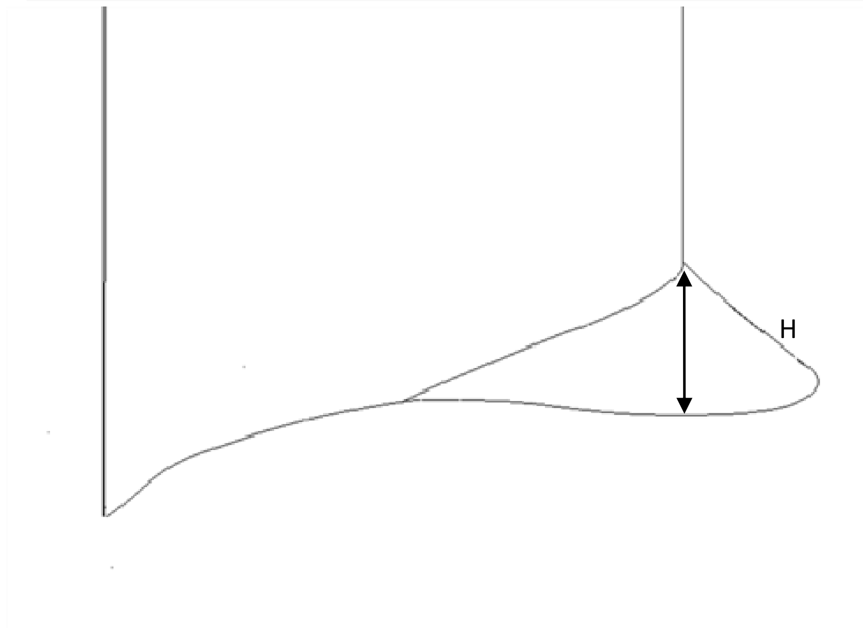
- Contouring: (a) partial positive, (b) extended partial, (c) partial positive-negative, (d) extended positive-negative, (e) full-passage



Contour height based on reference case for: (a) partial positive contouring; (b) extended partial positive contouring, full-passage contouring; (c) partial positive, negative contouring; (d) extended partial positive , negative contouring; (e) full passage contouring

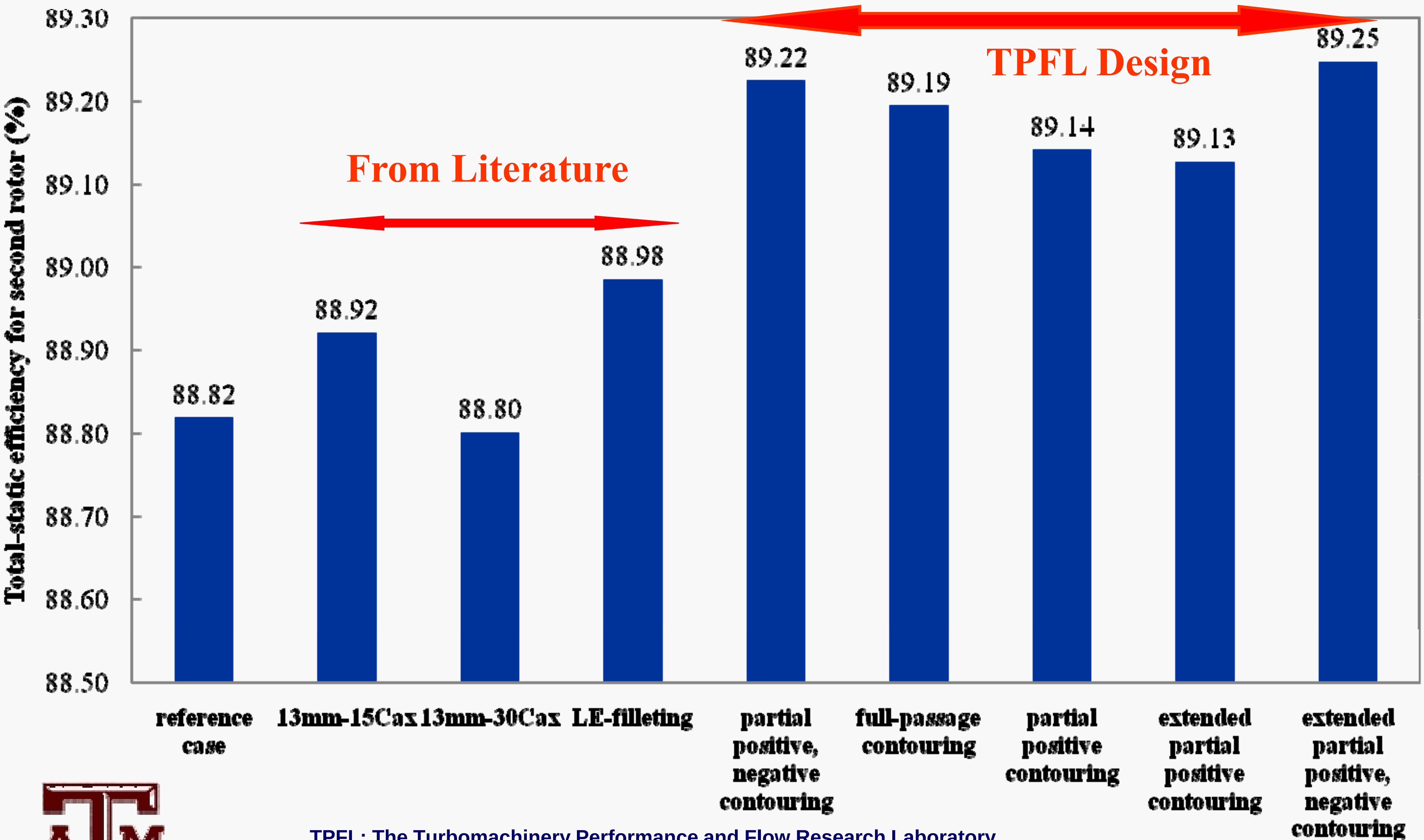
Leading-edge Filleting Design





- **The filleting shape is following linear function and the outer shape is limited by elliptical curves.**
- **The filleting extends along the stagnation line.**

Efficiency Comparison



From Trial and Error to a Physics Based Systematic Approach

The trial and error approach has proven to be:

- **Ineffective for designing efficient endwall contours**
- **As shown, the efficiencies were inconsistent throughout**
- **The results were inconclusive to be generalized and transferable to different turbine blade types**
- **Most importantly, it does not allow to generate a design guideline for the industry, a major objective of this project**
- **A hardware design based on this approach did not seem to deliver any substantial, physics based result that we can offer to the industry with clear conscience**

➢ **These facts caused the PI to abandon this trial and error approach altogether and to introduce a completely new and physics based technology**

Breakthrough Technology, Disclosure of Invention TAMUS 3259

This *Continuous Diffusion Technology* introduced by M.T. Schobeiri 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)

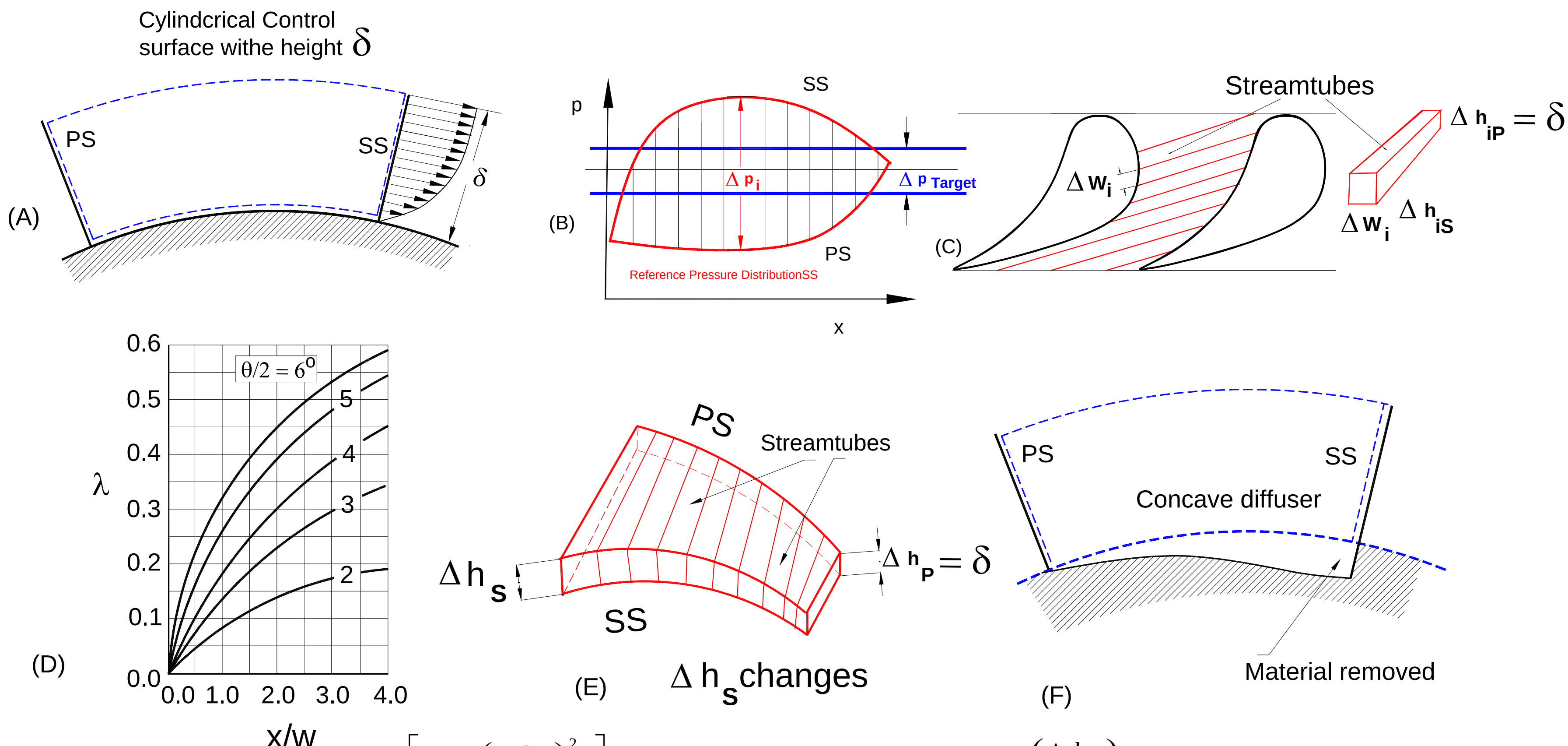
3) Find the actual pressure difference Δp_i (Fig. B) and define the target pressure difference $\Delta p_{itarget} > \Delta p_{lim}$ (Fig.B)

Continuous Diffusion Technology

Step-by-Step Instruction Continued:

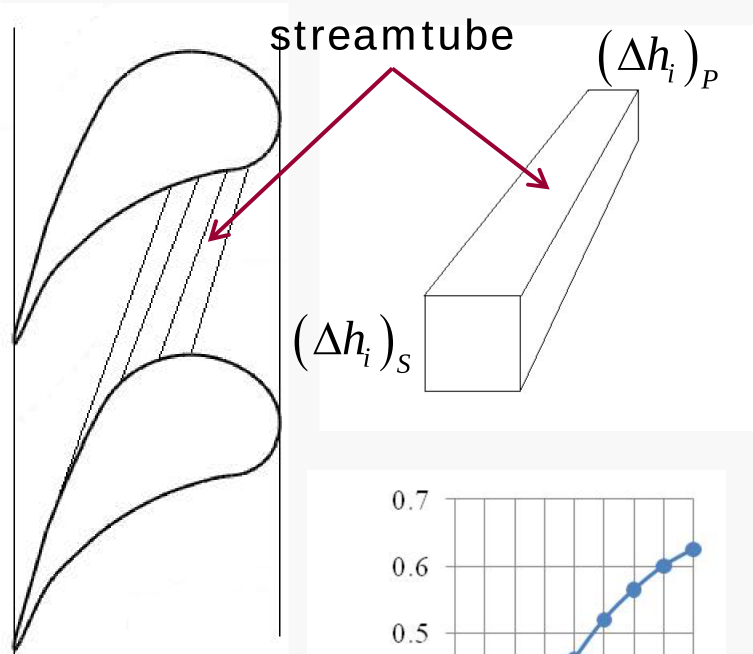
4) Obtain streamlines at the same radial position (next slide Fig. C)
5) Based on the diffuser performance map (next slide Fig. D) construct a diffuser (next slide Fig. E) with the constant $\Delta h_{ip} = \delta$ at the pressure side and variable Δh_{is} o> δ on the suction side, follow the pressure 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

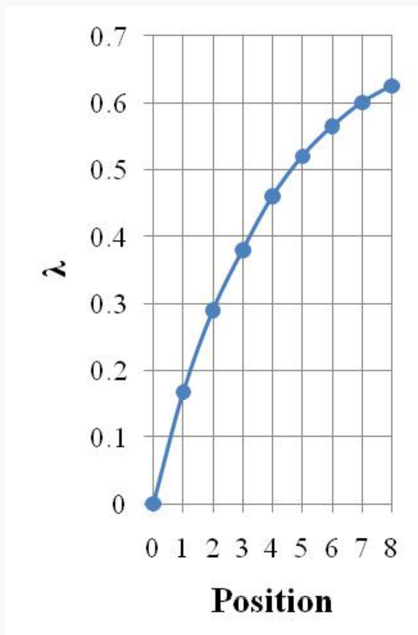
Continuous Diffusion: Summary of the Working Principle



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

Non-Axisymmetric Endwall Contouring Design-Family 3





- **Basic idea: decrease the pressure difference as much as possible between pressure surface and suction surface near hub.**
- **Starting from Bernoulli equation and following the streamlines close to the hub, assume several streamtubes extending from pressure side to suction side.**
- **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 λ, 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.**

Continues Diffusion, Hub Contouring: Preliminary Example

In the following slides, we present:

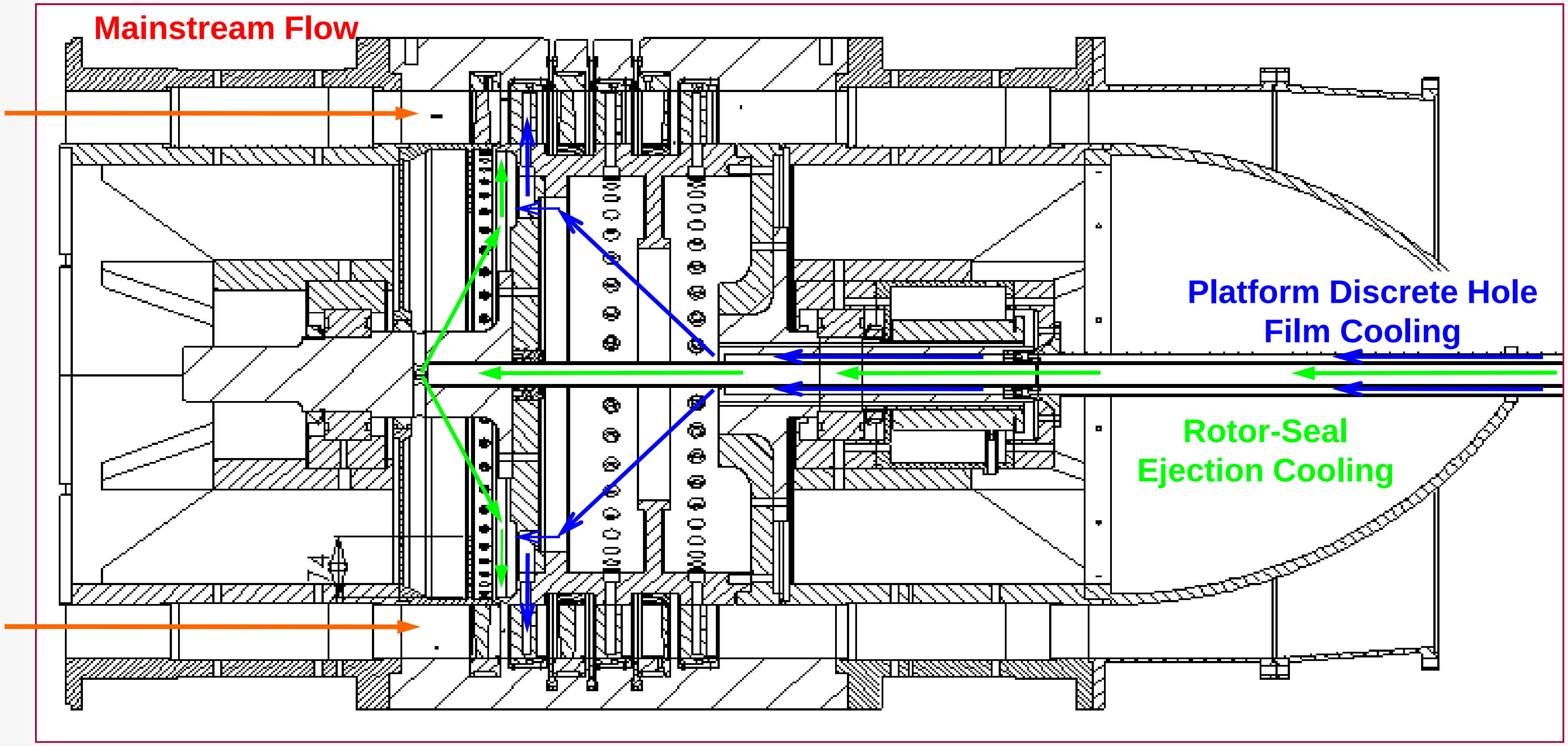
- A preliminary example that executes the steps described previously.
- This example is the very first attempt, thus refining and further improvement is underway.
- The example applied the Continuous Diffusion Technology to the second rotor row of the three-stage TPFL Research Turbine
- Complete flow field, performance and efficiency data are presented.
- The turbine data follows

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**

TPFL Research Turbine Test Section

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



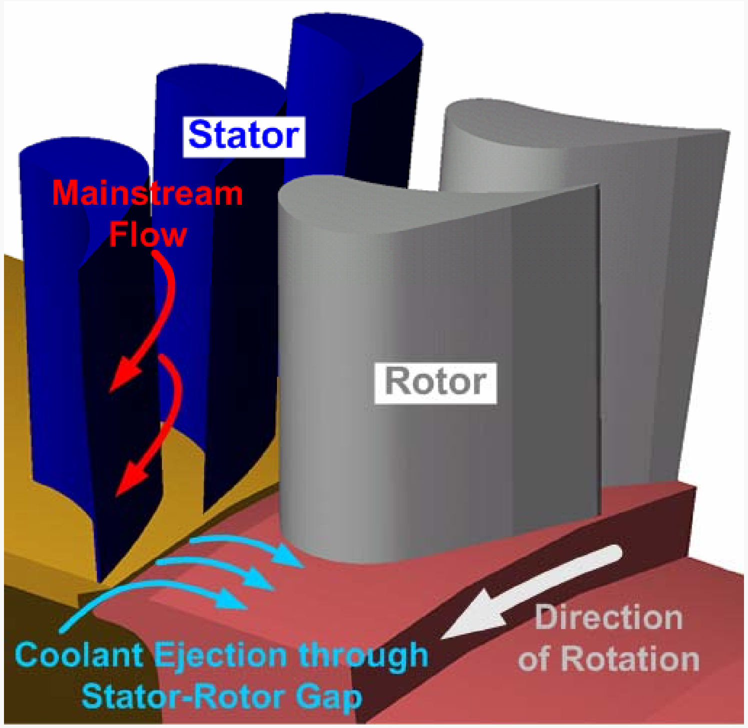
Tow Independent Coolant Loops for Coolant Injection from Stator-Rotor Seal and Downstream Film Cooling Holes

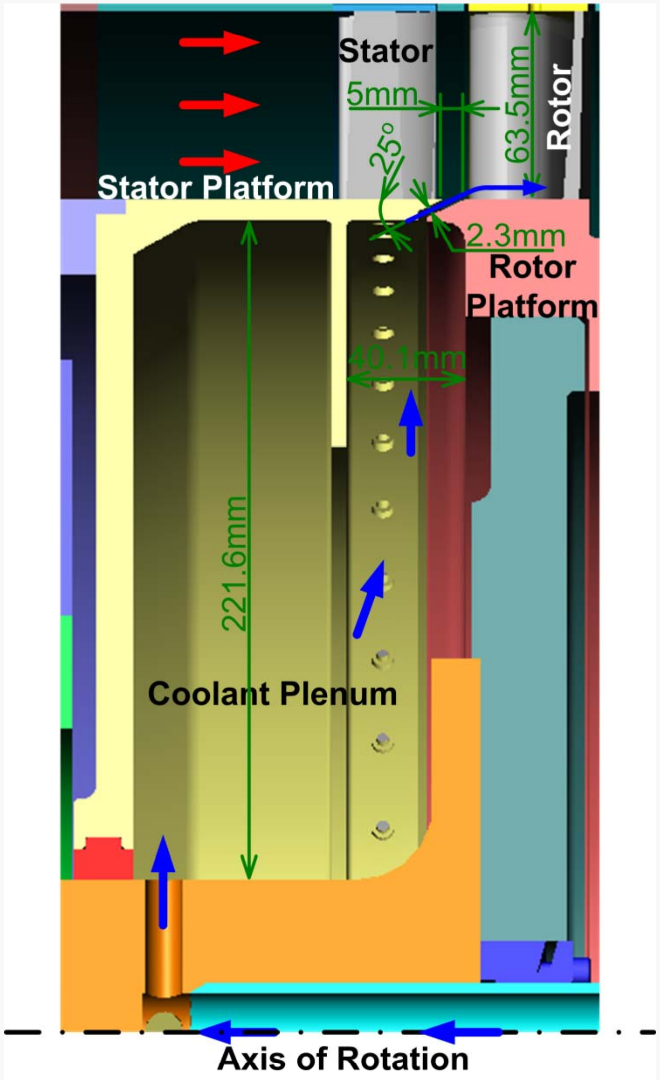
***TPFL*: The Turbomachinery Performance and Flow Research Laboratory**
Texas A&M University
M. T. Schobeiri

Project DE-FOA-0000031
October 2009

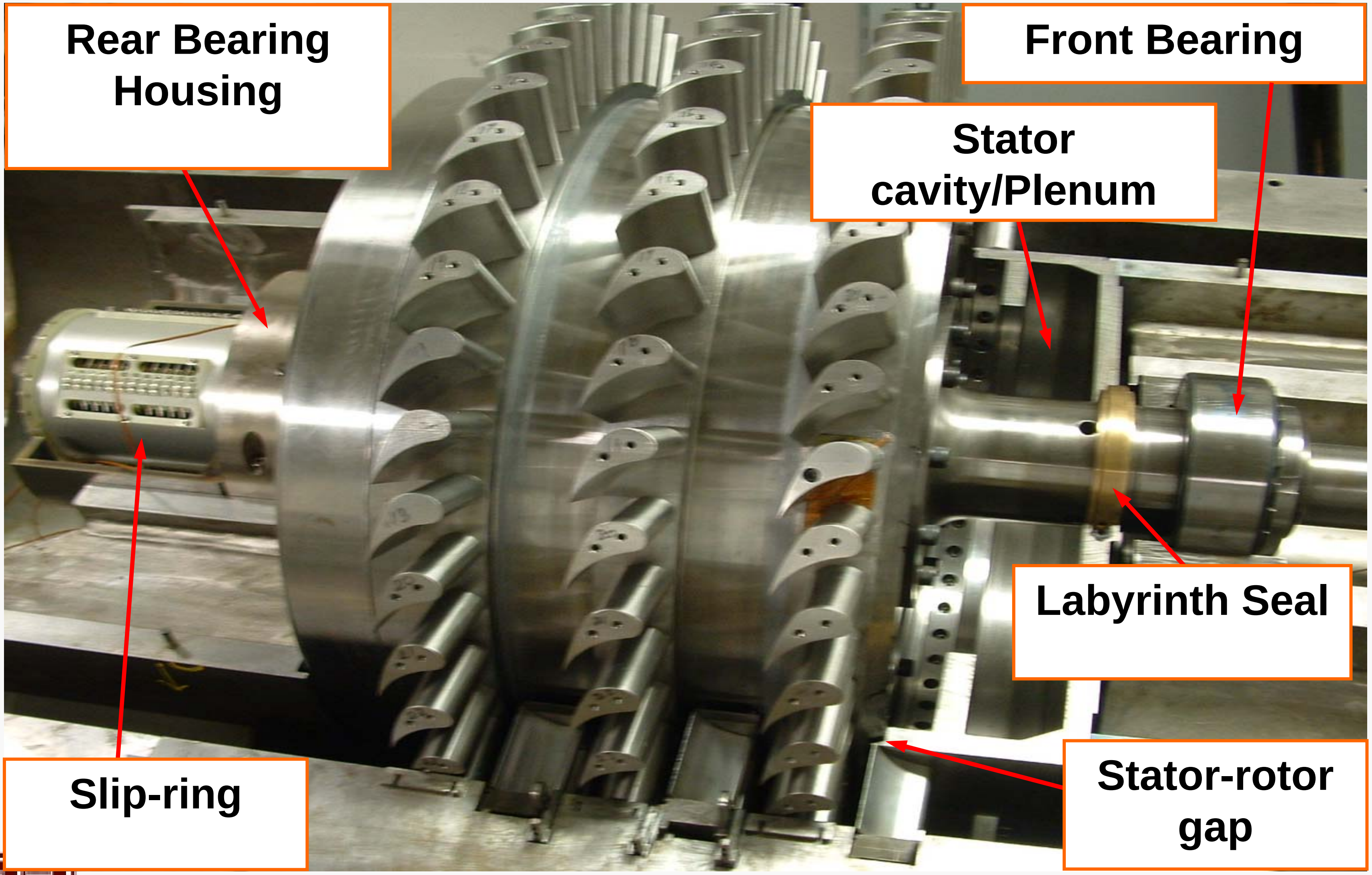
Cooling Loop Details

- Cross sectional view of the slot upstream of the 1st rotor stage
- Coolant enters the plenum through the hollow shaft and exits the slot at 25º to the horizontal.

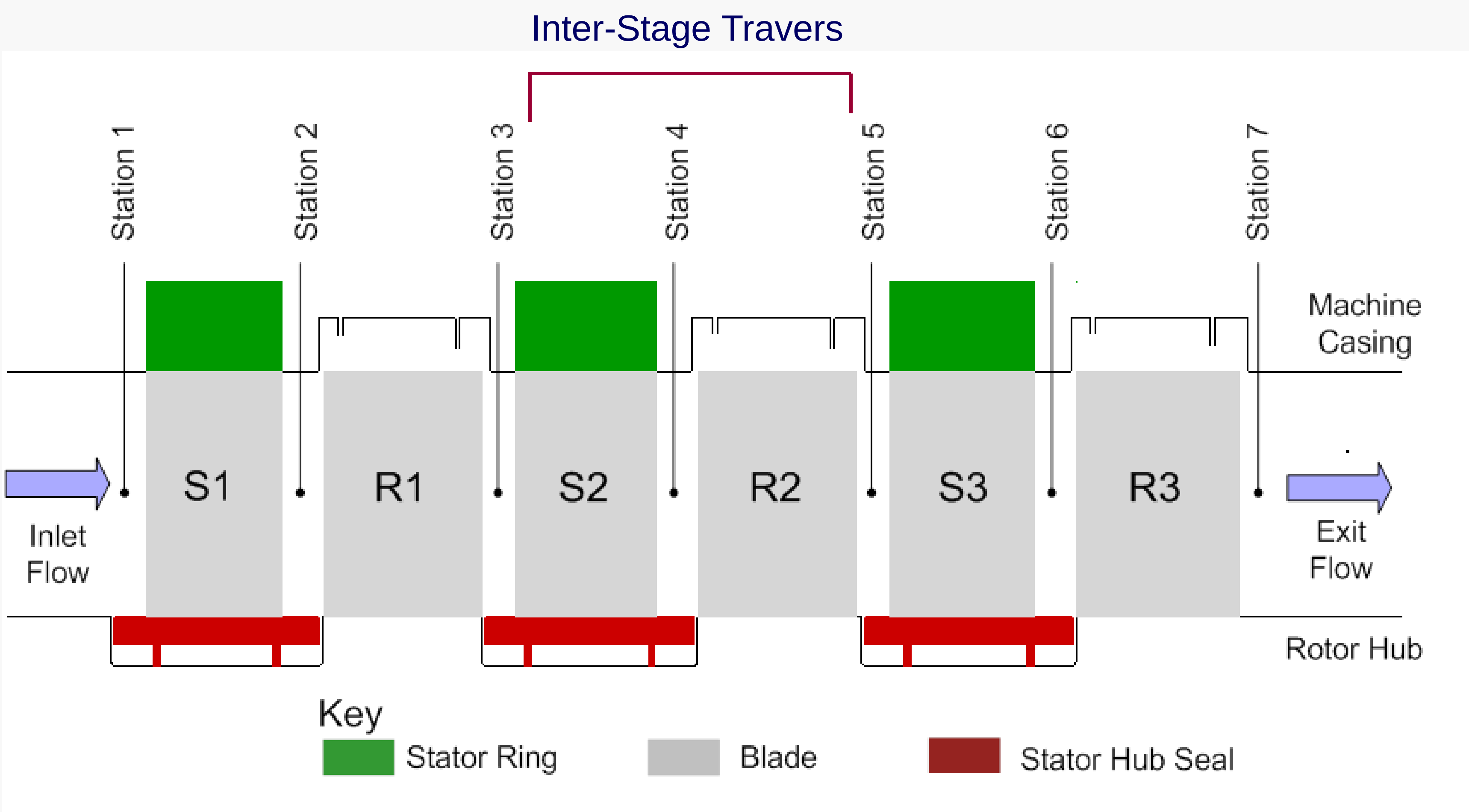




Rotor Blade Channel Endwall contouring



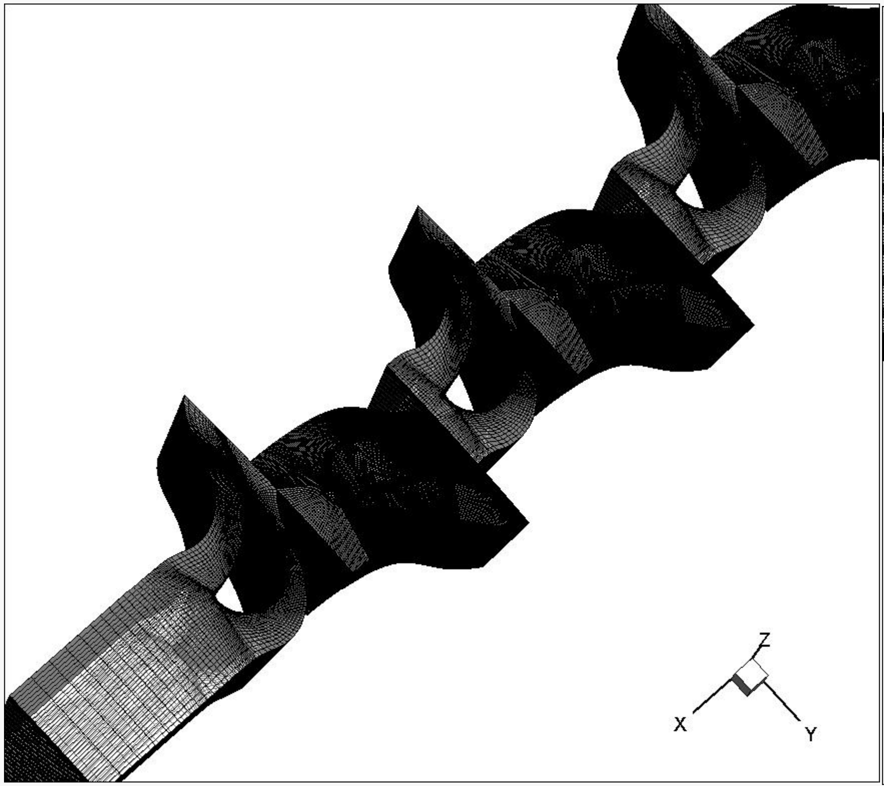
Numerical Simulation of the Three-Stage Turbine Rig

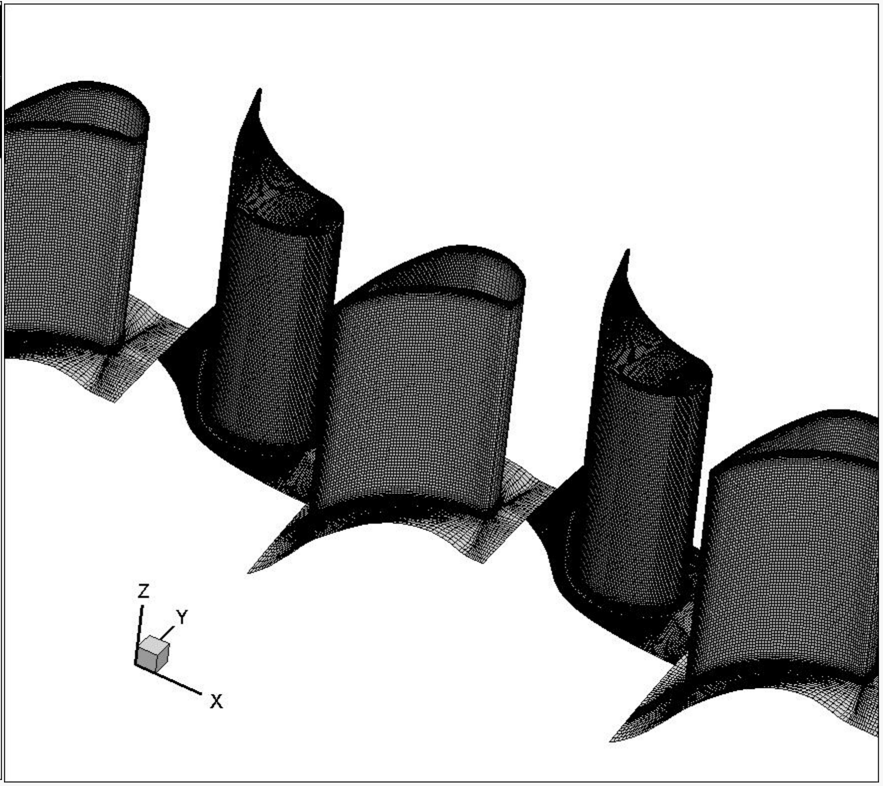


Numerical Methodology

- Steady state models 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

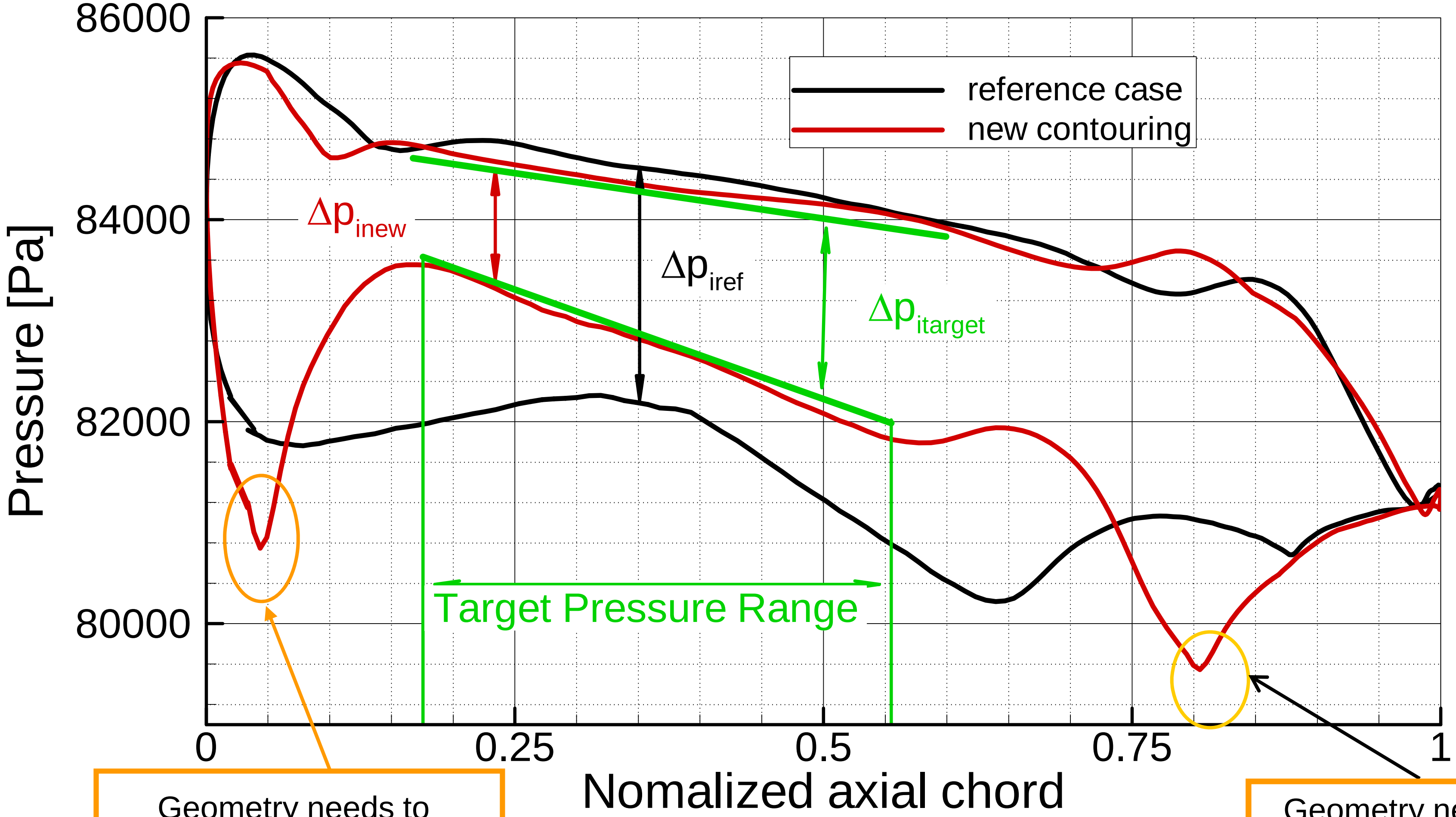
Numerical Simulation Mesh





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

Blade Loading of Second Rotor



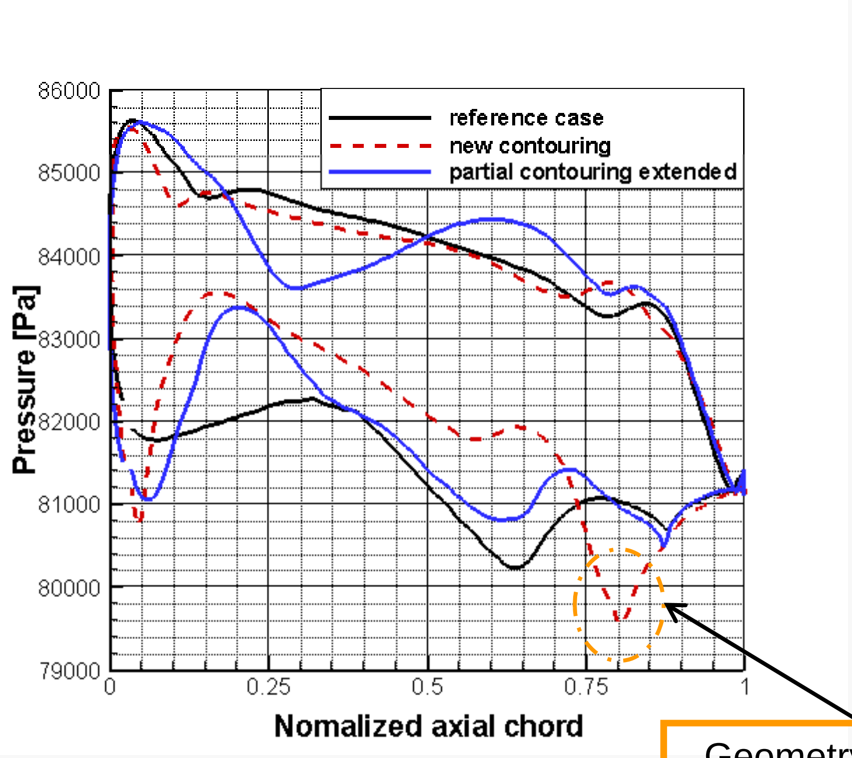
Geometry needs to be further optimized

Geometry needs to be further optimized.

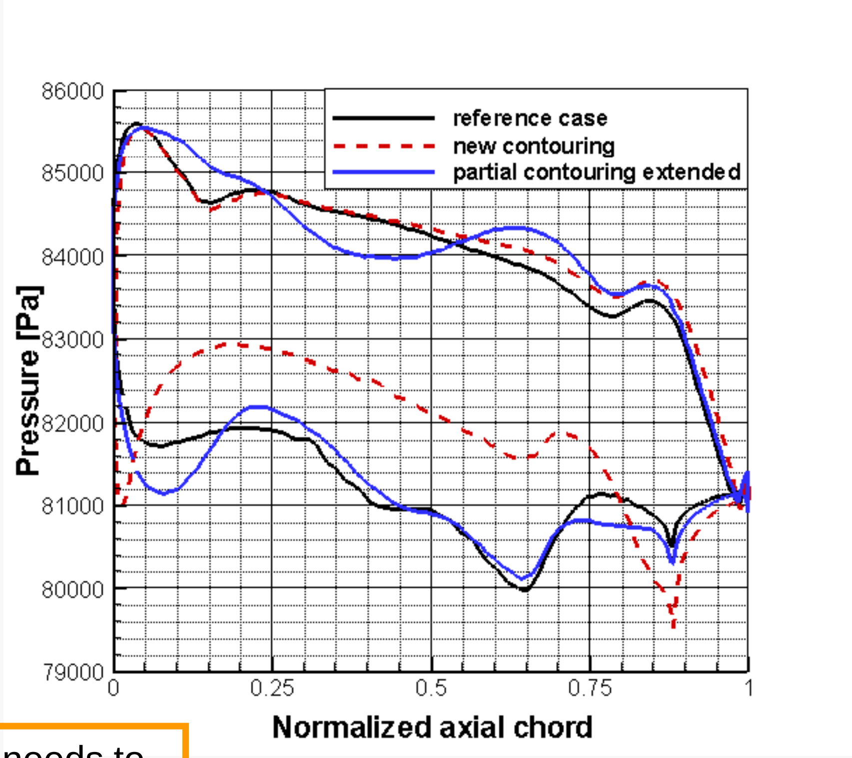
Blade Loading at Hub

Blade Loading of Second Rotor

- **Pressure distribution at two different span locations**



Geometry needs to be further optimized.

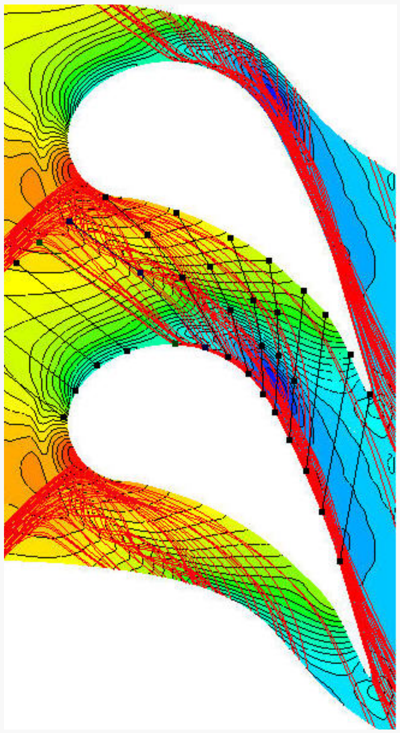


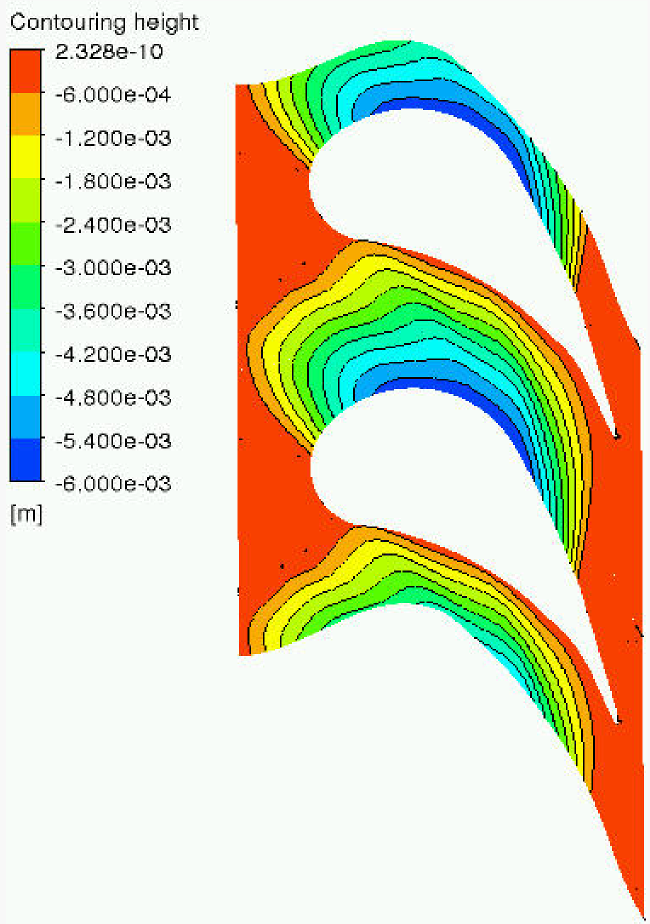
Blade Loading at Hub

Blade Loading at 2% Span
Rad distance from hub
1.3 mm

Continuous Diffusion Technology Applied to Endwall sign

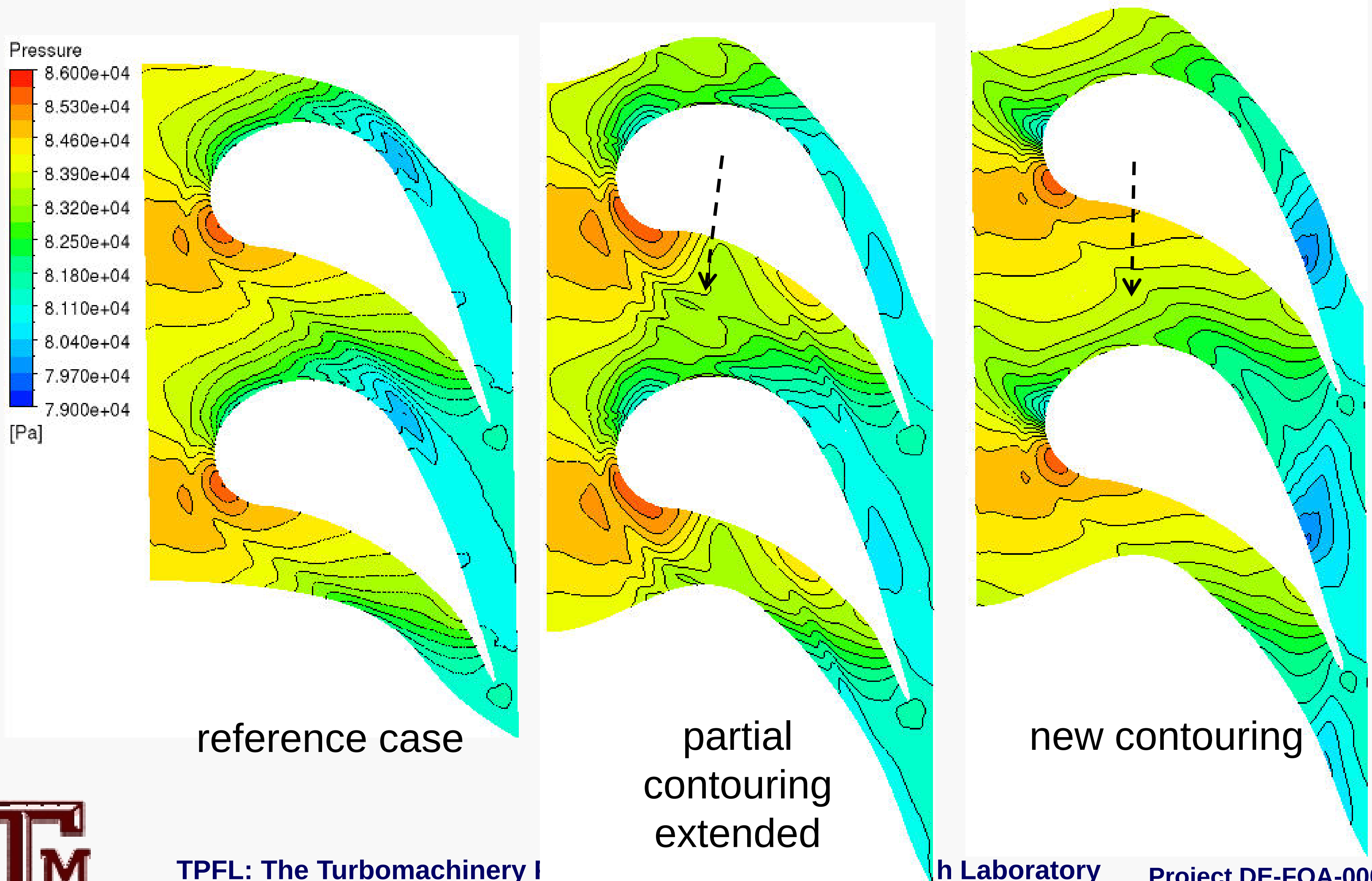
- **The design of contouring considers both the direction of streamlines and pressure gradient near hub. Currently there is no positive portion.**



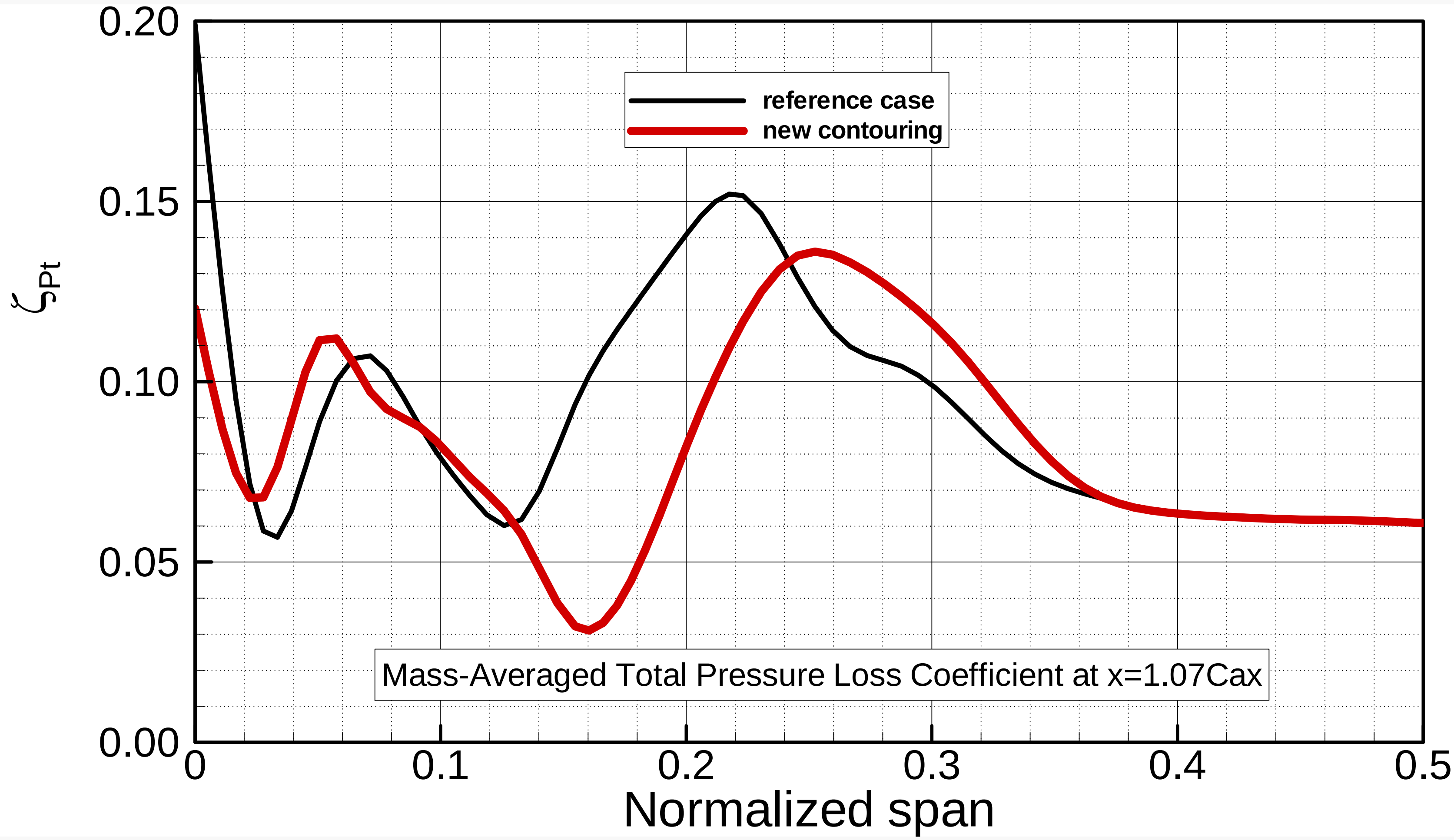


Pressure Distribution at Hub

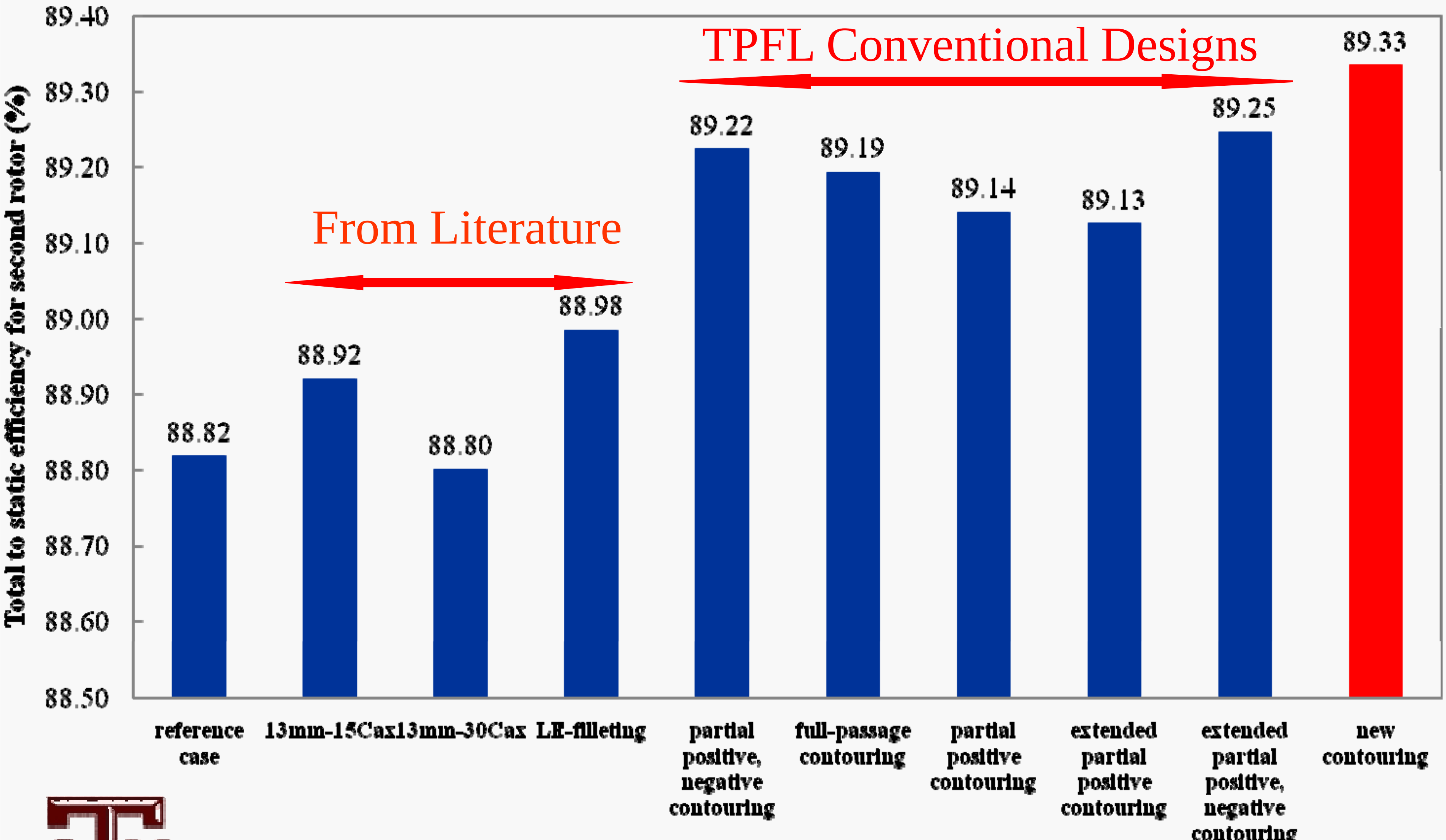
- **Comparison of pressure distributions**



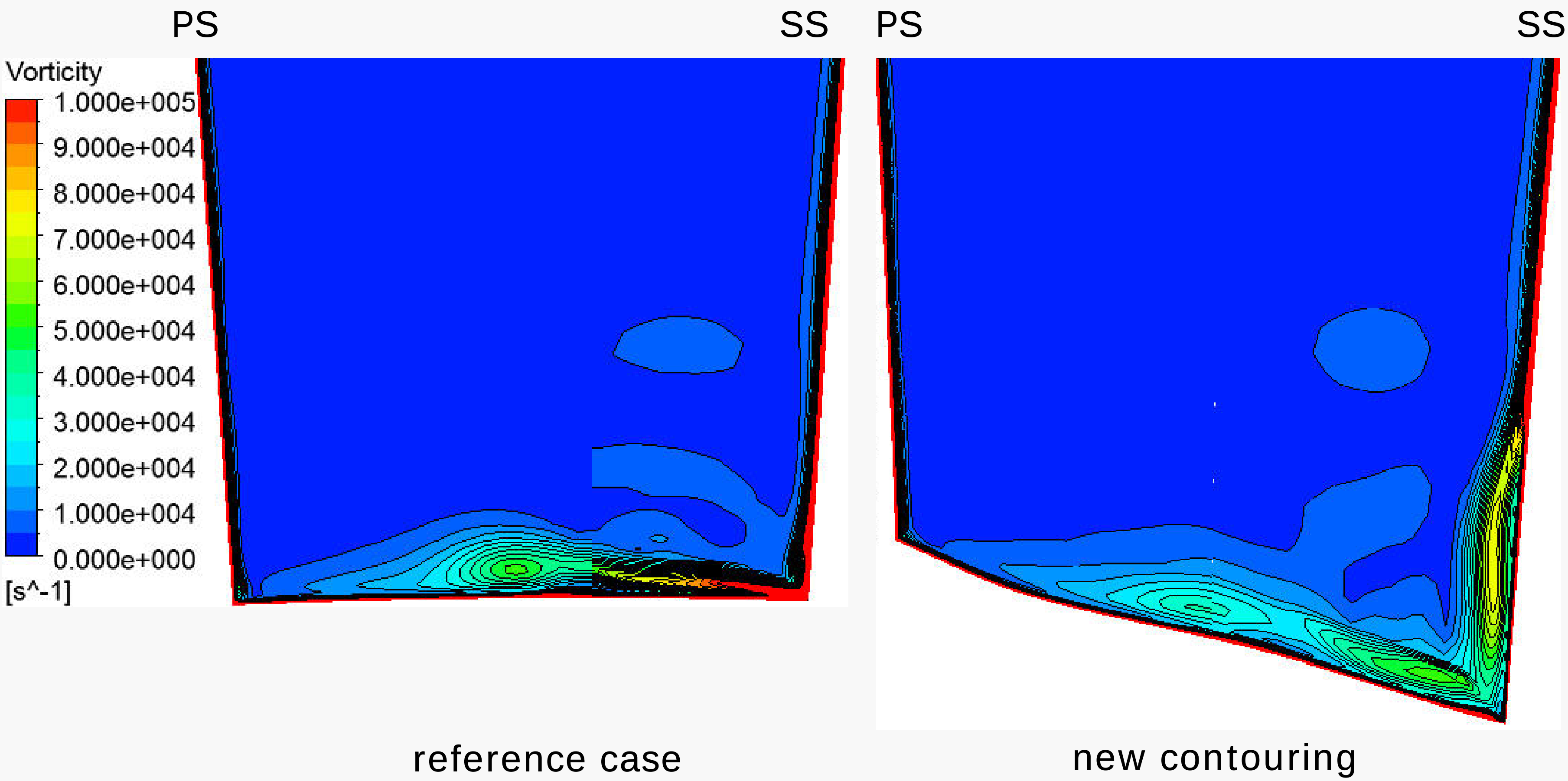
Total Pressure Loss Coefficient for Second Rotor



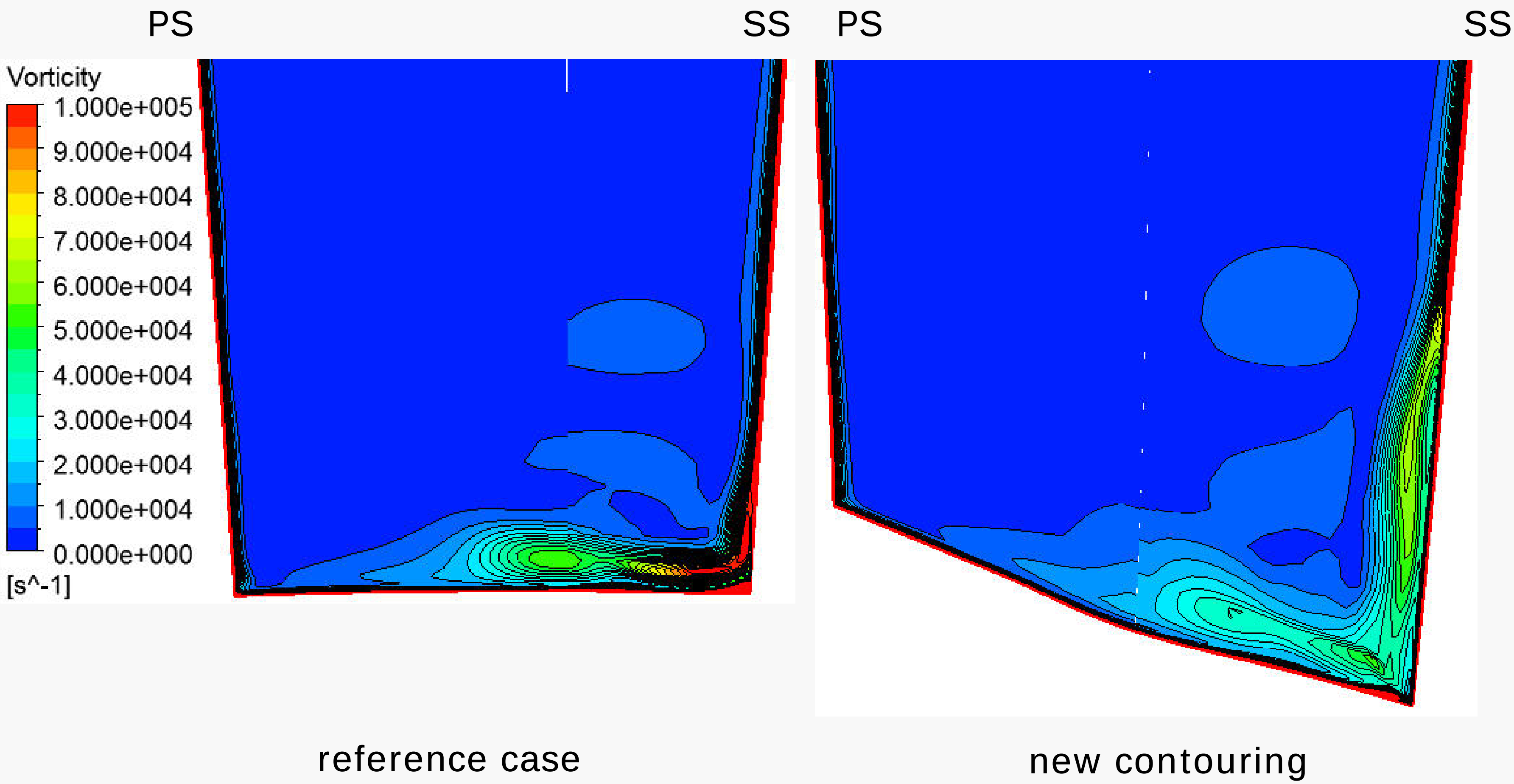
Efficiency bars



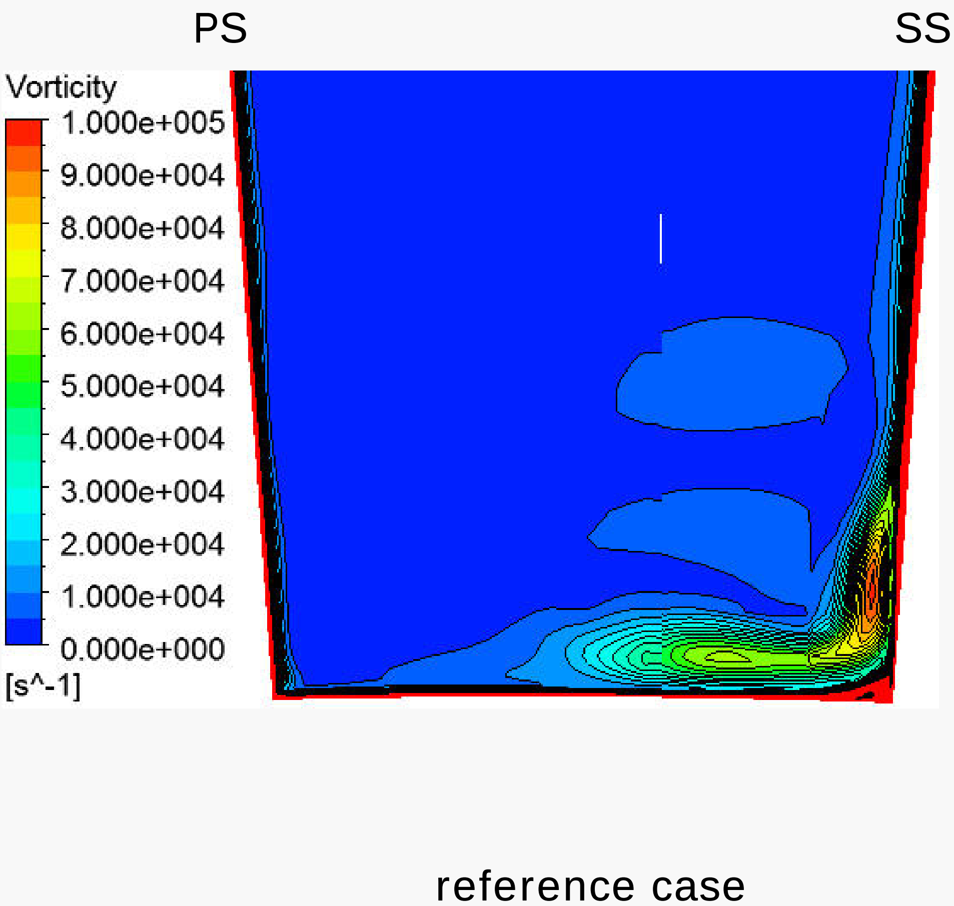
Vorticity Distribution at $x=0.30C_{ax}$ within Second Rotor

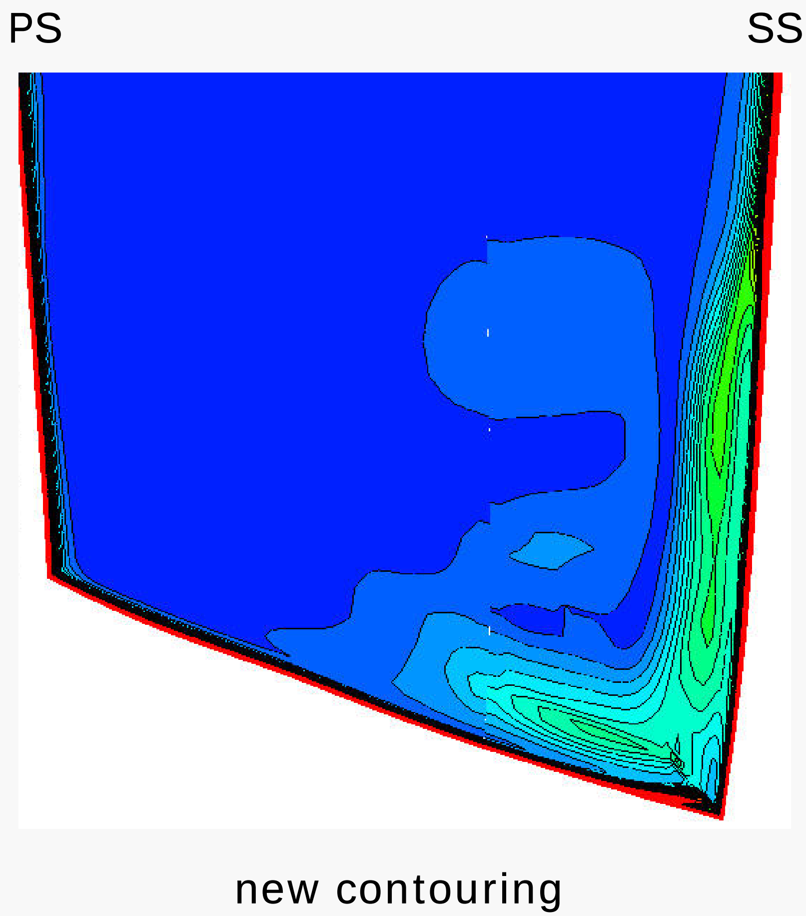


Vorticity Distribution at $x=0.42C_{ax}$ within Second Rotor

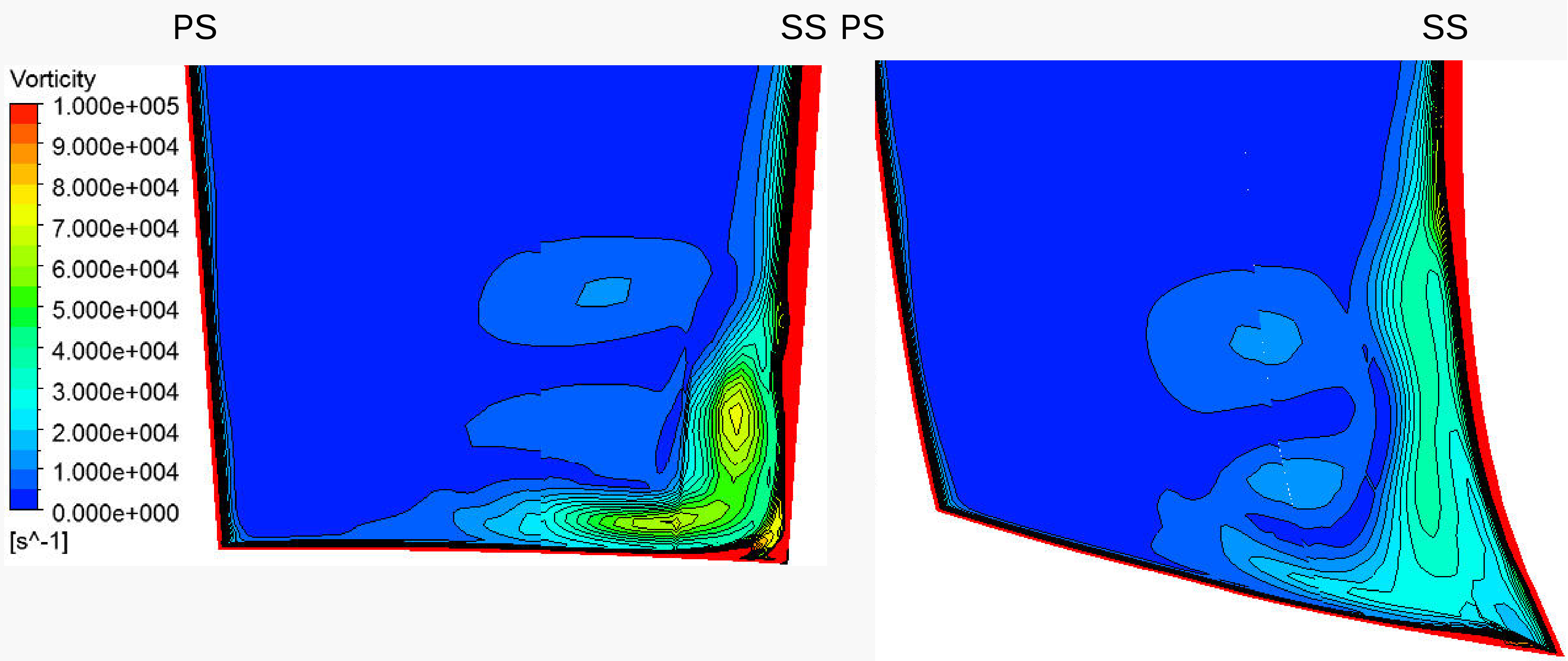


Vorticity Distribution at $x=0.55C_{ax}$ within Second Rotor





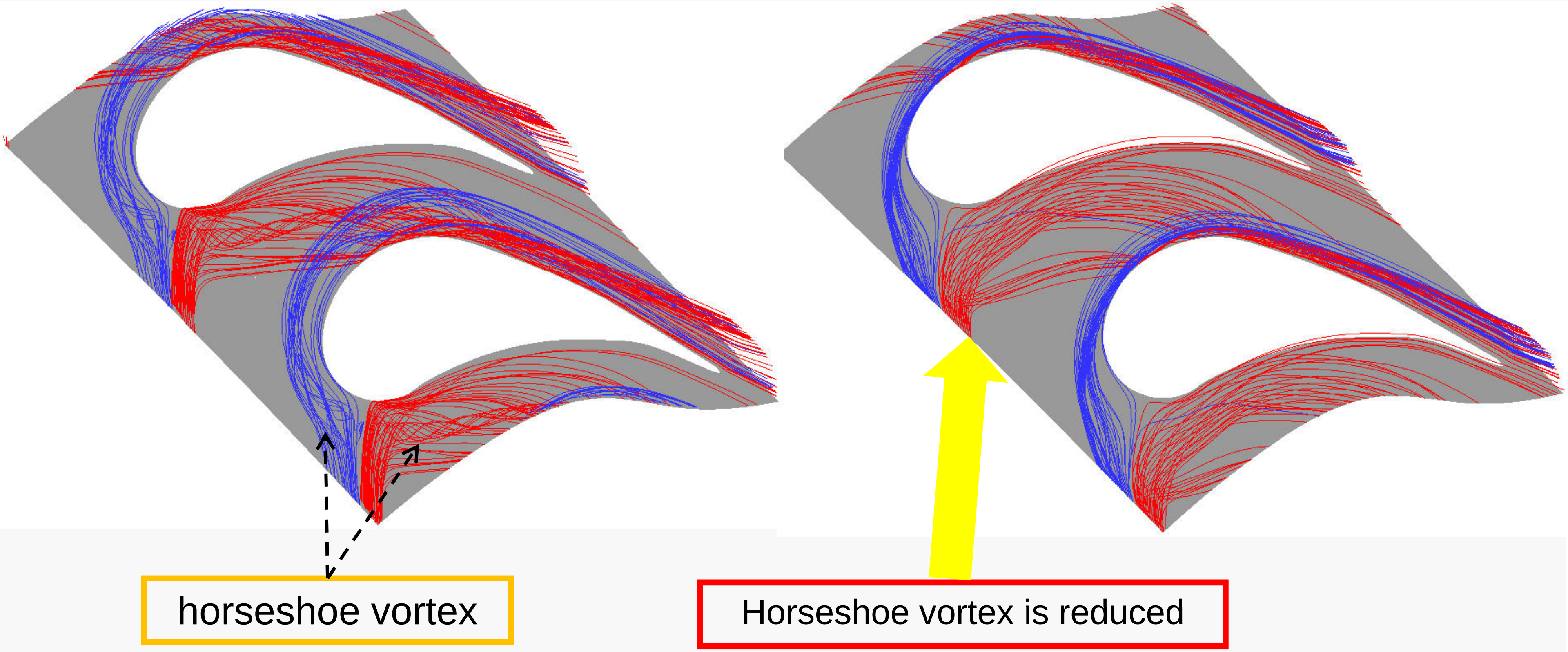
Vorticity Distribution at $x=0.69C_{ax}$ within Second Rotor



reference case

new contouring

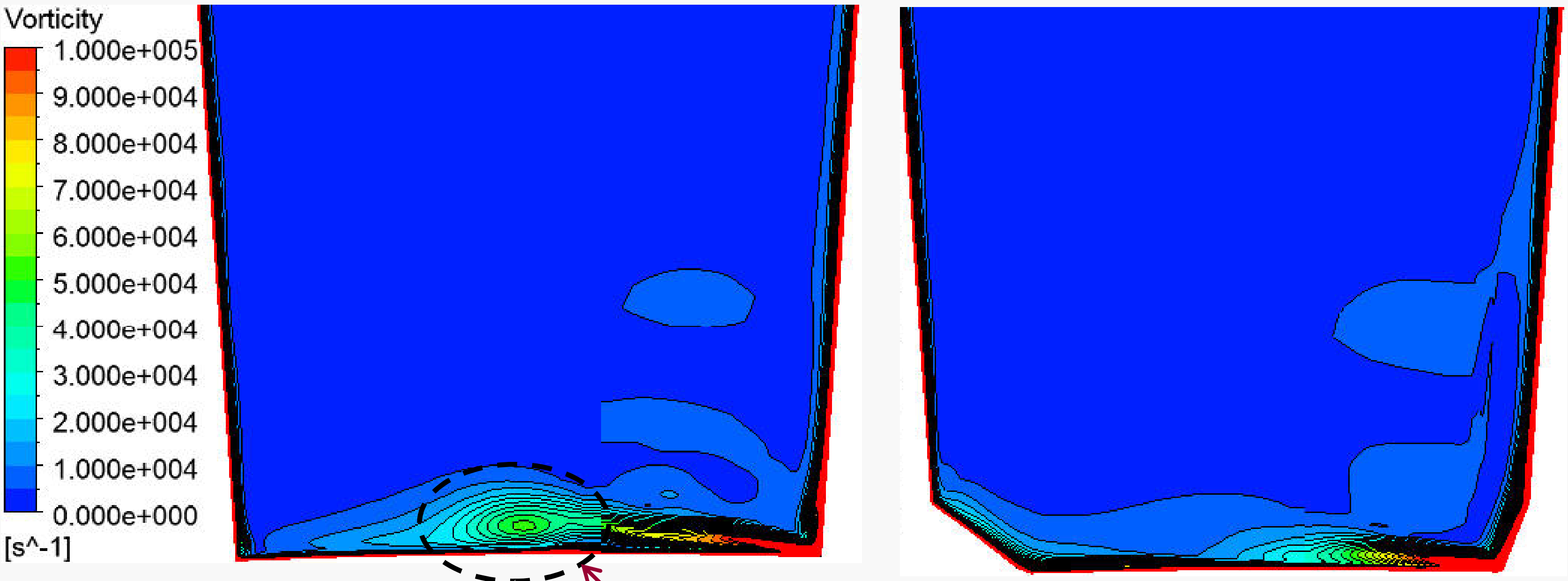
Effect of Leading-Edge Filleting



reference case

LE-filleting

Effect of Leading-Edge Filleting



High-vorticity region due to pressure side leg of horseshoe vortex.

Vorticity distribution at $x=0.30C_{ax}$ within second rotor: reference case (left); LE-filleting (right)

Part II: Experimental Research

Year 1 Experimental task includes:

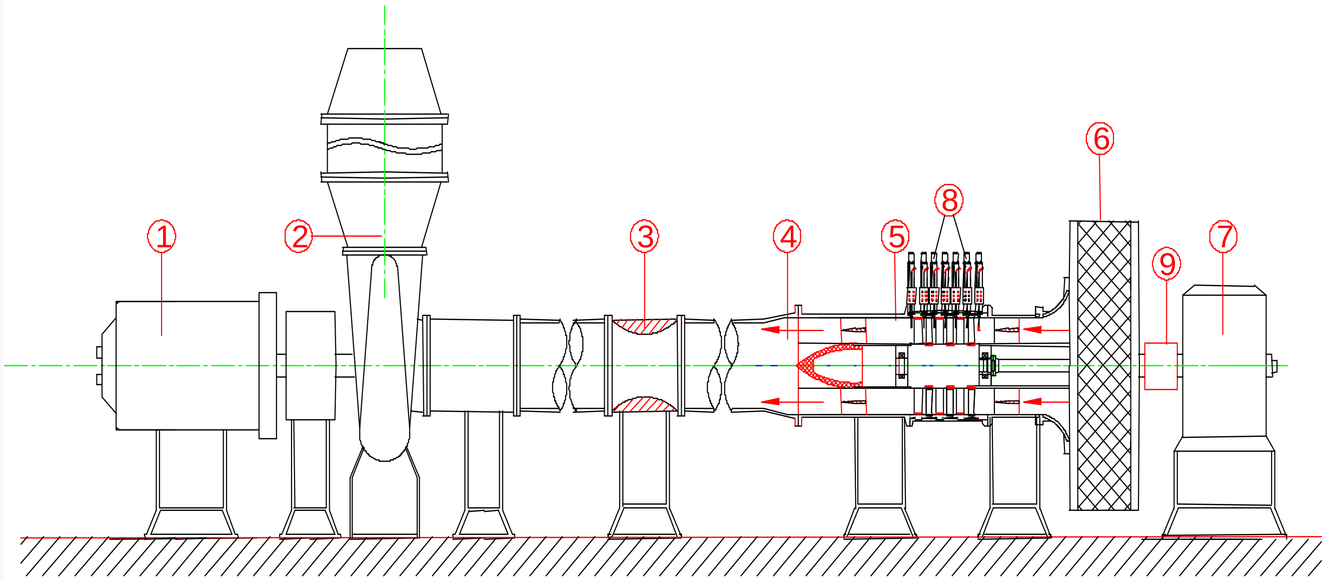
- **Preparation of the research turbine facility for reference case measurements**
  - **Inter-stage flow measurements**
  - **Design and off-design efficiency and performance measurements. These are essential to compare the contoured rotor with the reference non-contoured case**

Because of a marginal efficiency improvement it is imperative to perform precision calibration of all instruments attached the turbine facility, these are among others to <u>keep the uncertainty of the final results as small as possible</u>

- **Dynamometer calibration**
- **Torque meter calibration**
- **All probes including five- hole probes, pressure scanner calibrations**
- **All thermocouples**

Experimental Facility, Turbine Rig

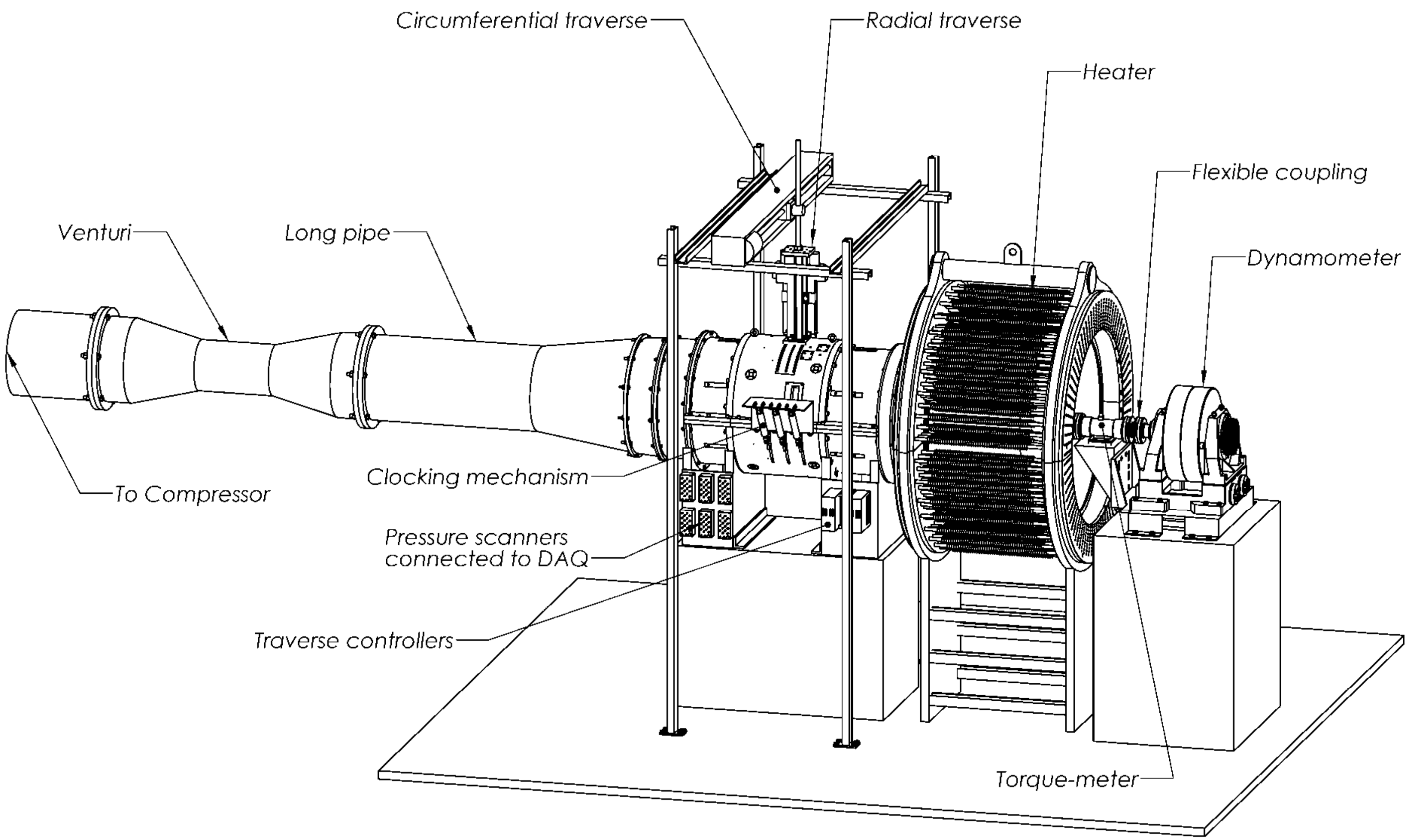
- **Schematic of the Three- stage turbine facility at the Turbomachinery Performance and Flow Laboratory, Texas A&M Univ.**
- **Developed and designed 1997 to address turbine aerodynamics, performance and heat transfer issues**



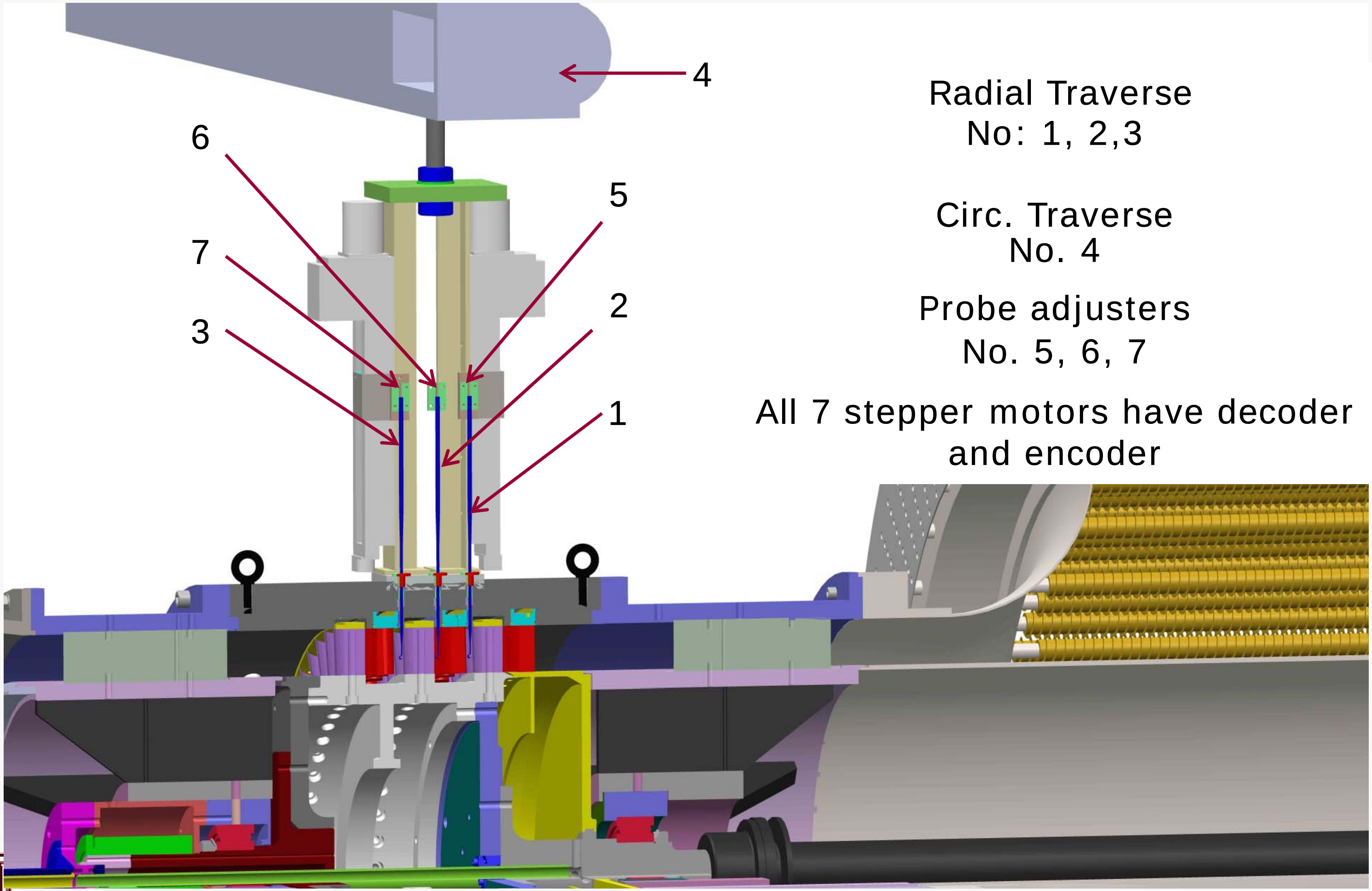
① Electric drive ③ Calibrated Venturi ⑤ Research Turbine ⑦ Dynamometer ⑨ Torquemeter

② Silence chamber ④ Exit diffuser ⑥ Turbine inlet with heater ⑧ Traversing systems

TPFL Three-Stage Research Turbine Facility



7-Axes Traversing System



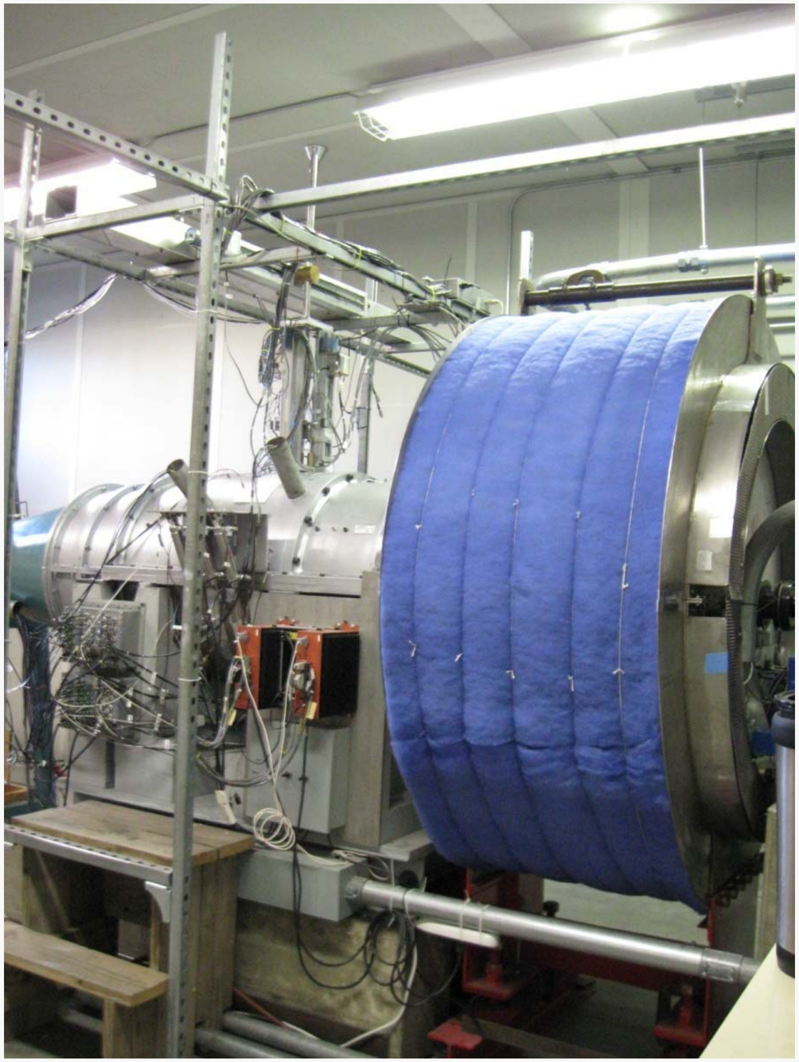
Radial Traverse
No: 1, 2,3

Circ. Traverse
No. 4

Probe adjusters
No. 5, 6, 7

All 7 stepper motors have decoder and encoder

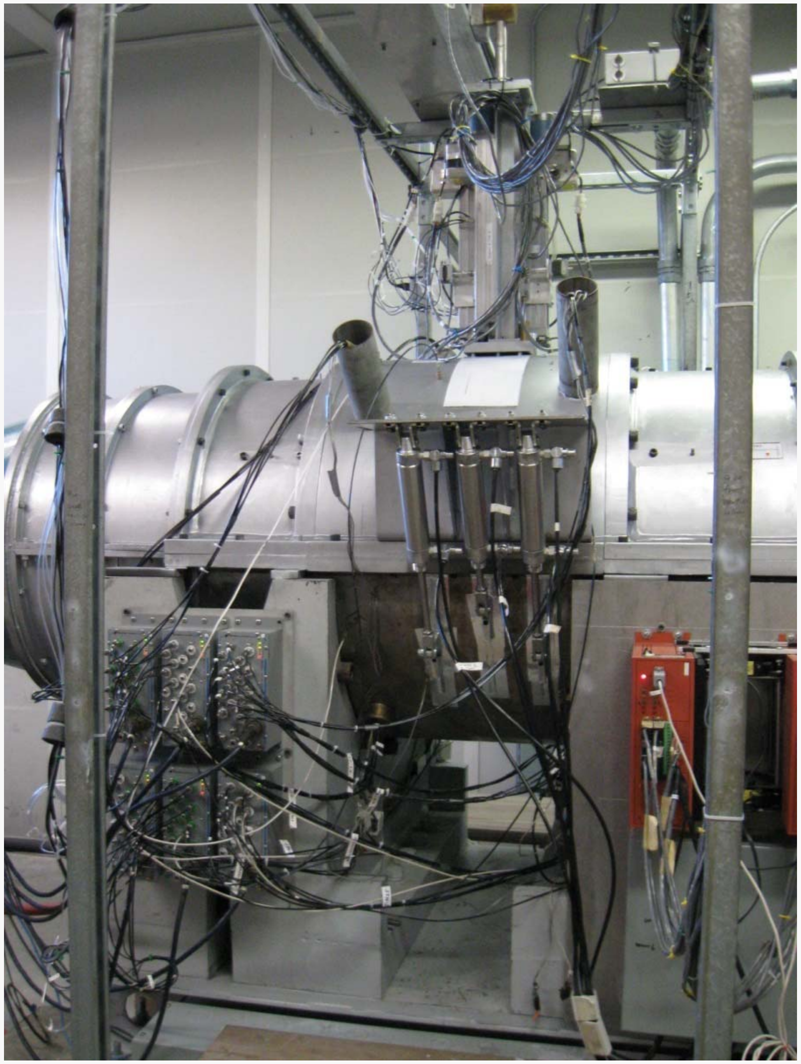
TPFL Three-Stage Research Turbine Facility



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

Project DE-FOA-0000031
October 2009

TPFL Three-Stage Research Turbine Facility

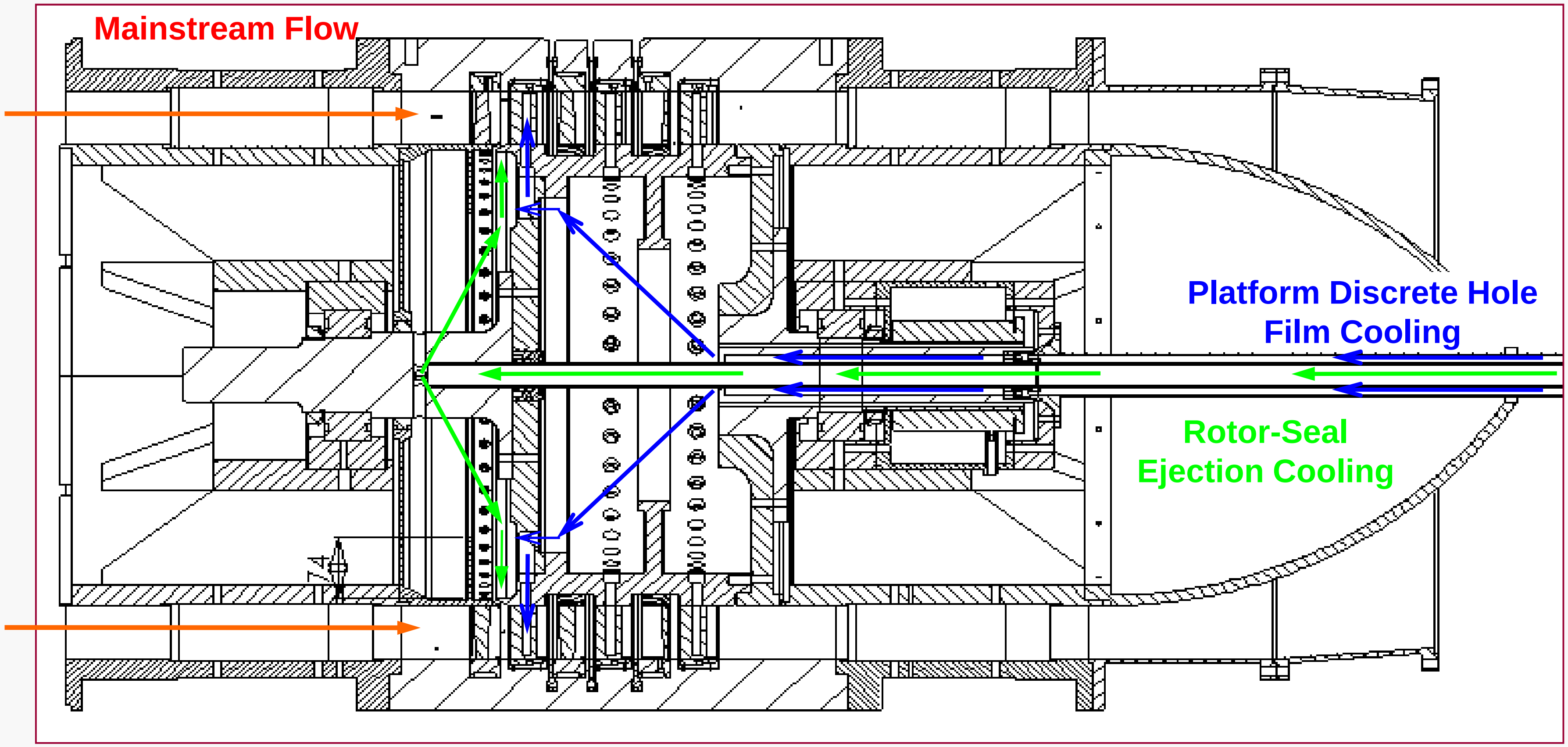


***TPFL*: The Turbomachinery Performance and Flow Research Laboratory**
Texas A&M University
M. T. Schobeiri

Project DE-FOA-0000031
October 2009

New Turbine Rotor

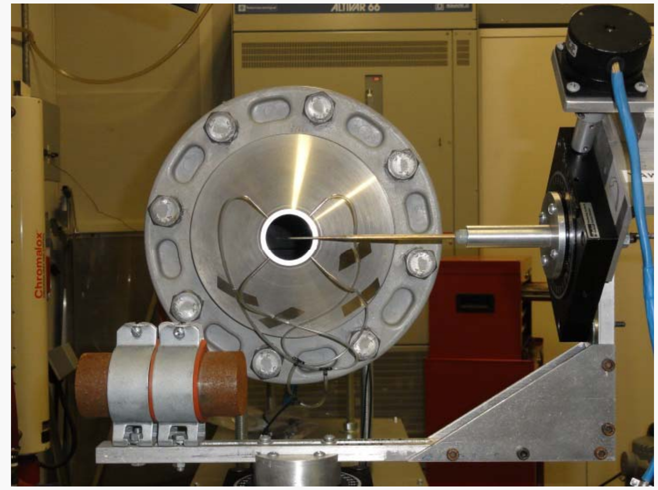
New Turbine Rotor with two Independent Coolant Flow Loops, DOE-Project 2006



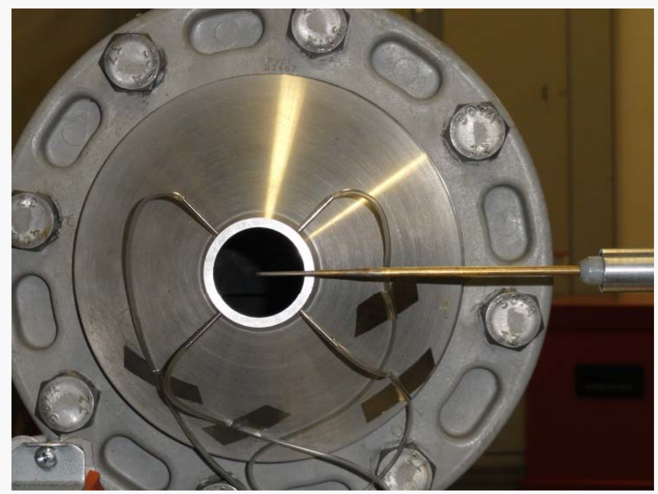
Tow Independent Coolant Loops for Coolant Injection from Stator-Rotor Seal and Downstream Film Cooling Holes

TPFL Calibration Facility

TPFL 5 Hole Probe Calibration Facility

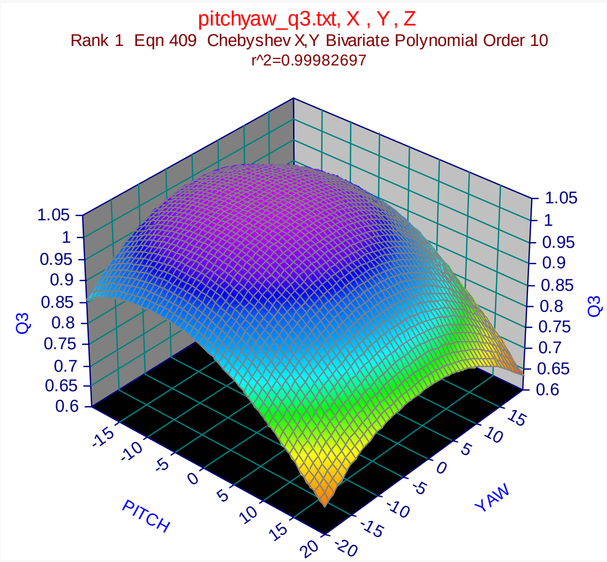


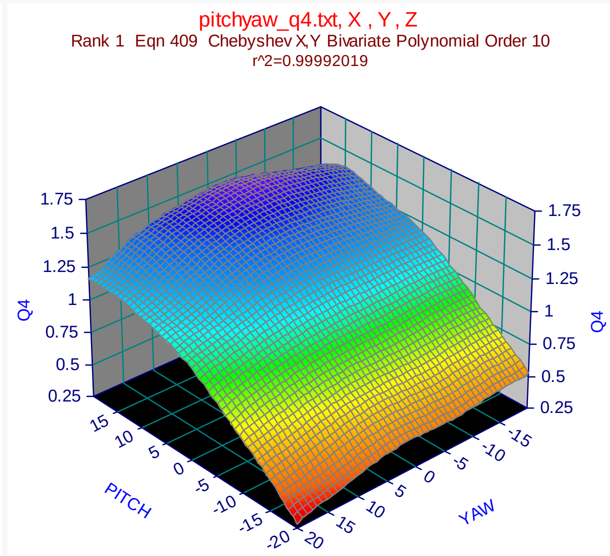
Turn Table for Probe Alignment

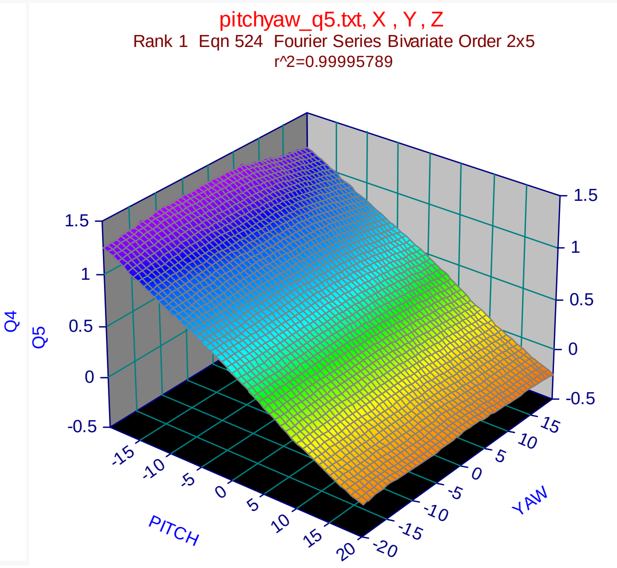


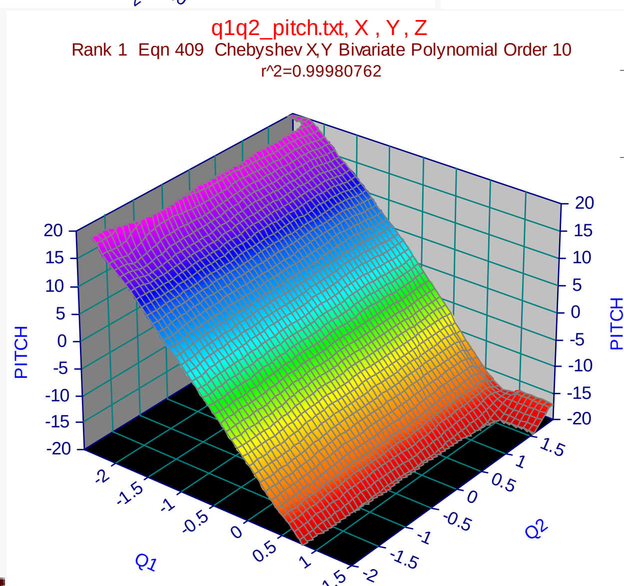
Probe Tip and Flow Alignment

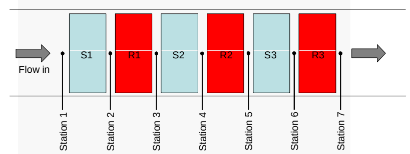
Calibration Precision Examples: Results, Station 4

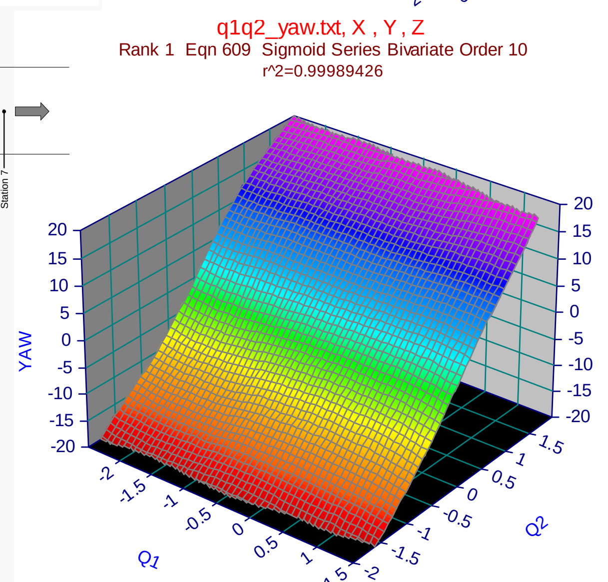




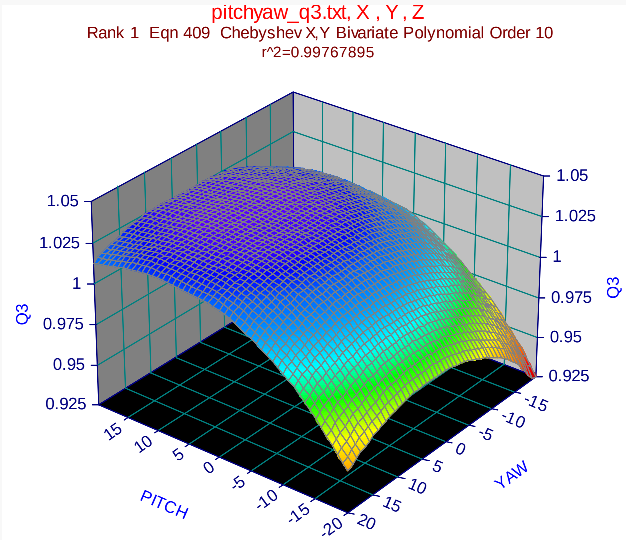


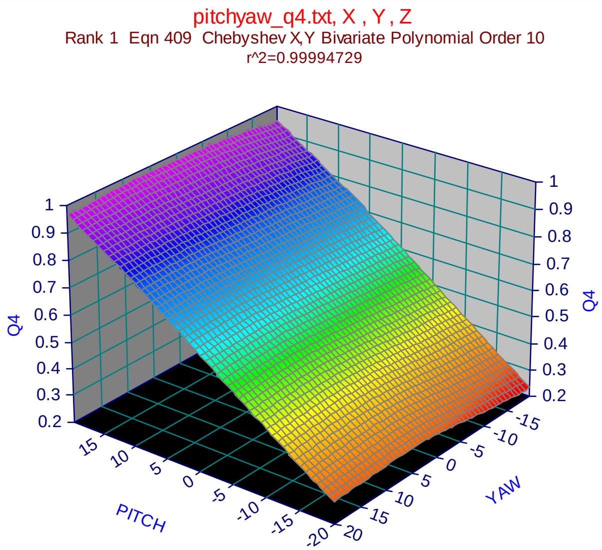


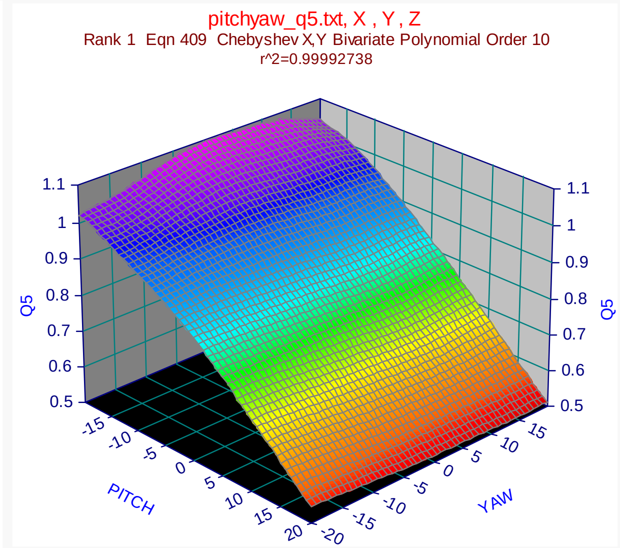


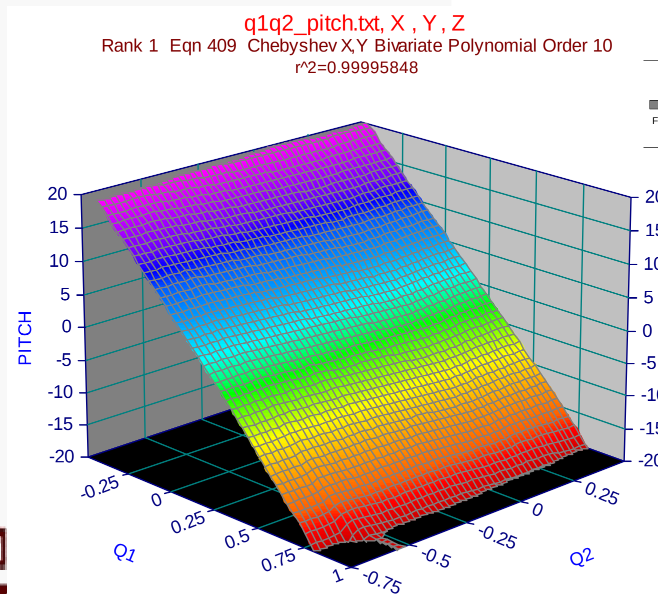


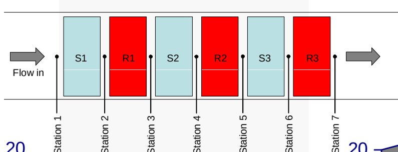
Calibration Results, Station 5

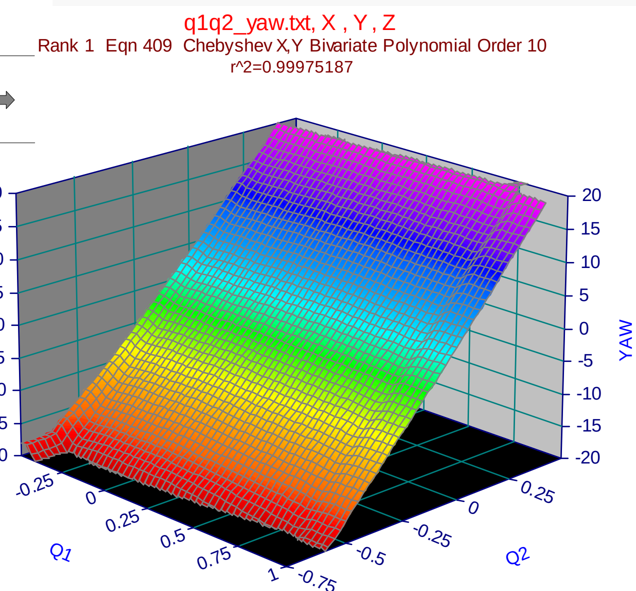




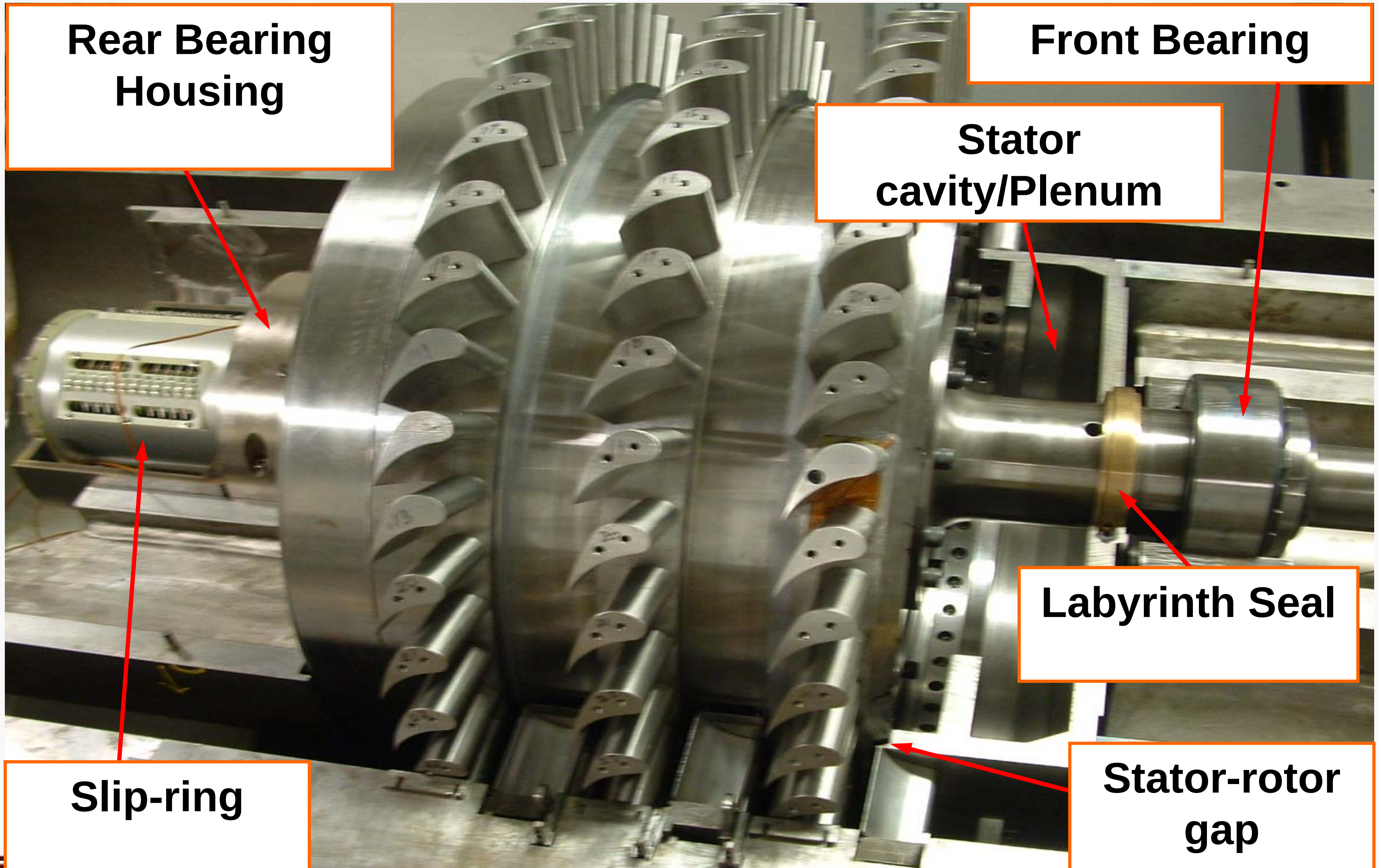






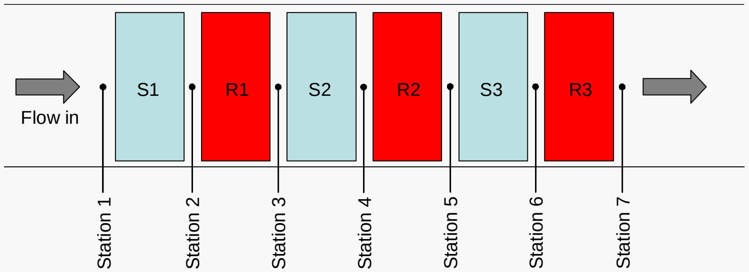


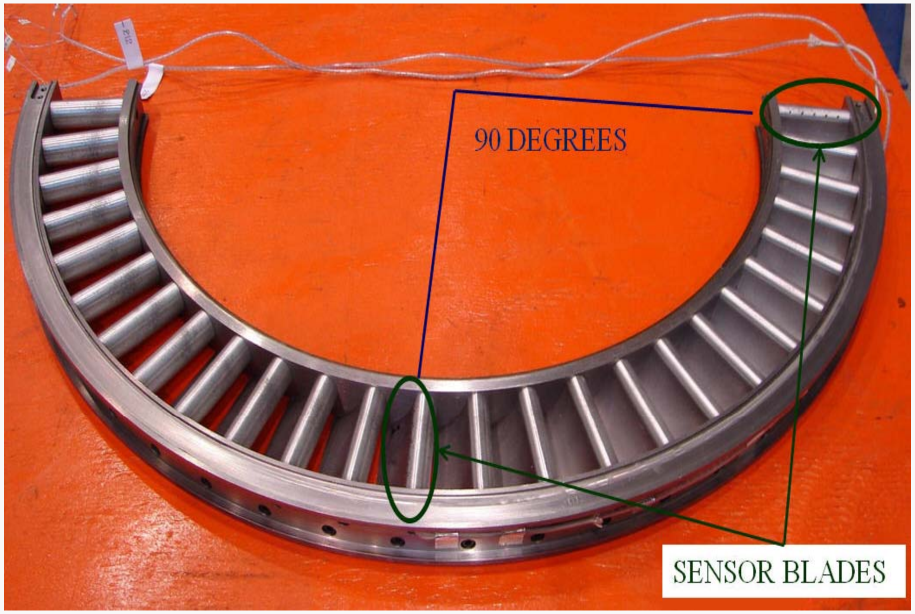
Experimental Facility: New Turbine Rotor Features

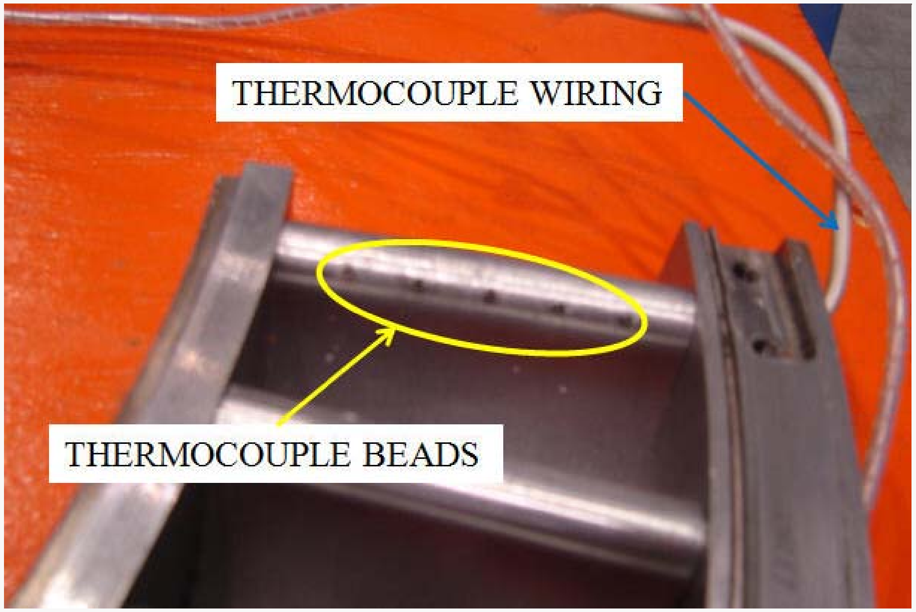


Experimental Facility, Inter-stage Temperature Measurement

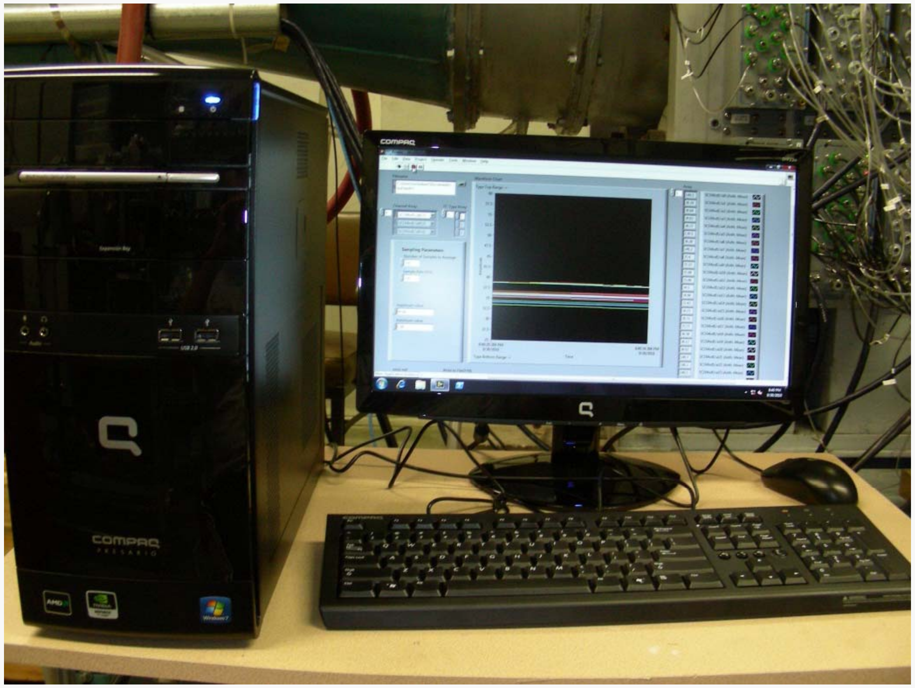
Each stator row from three stages were instrumented with five precision thermocouples in radial direction.

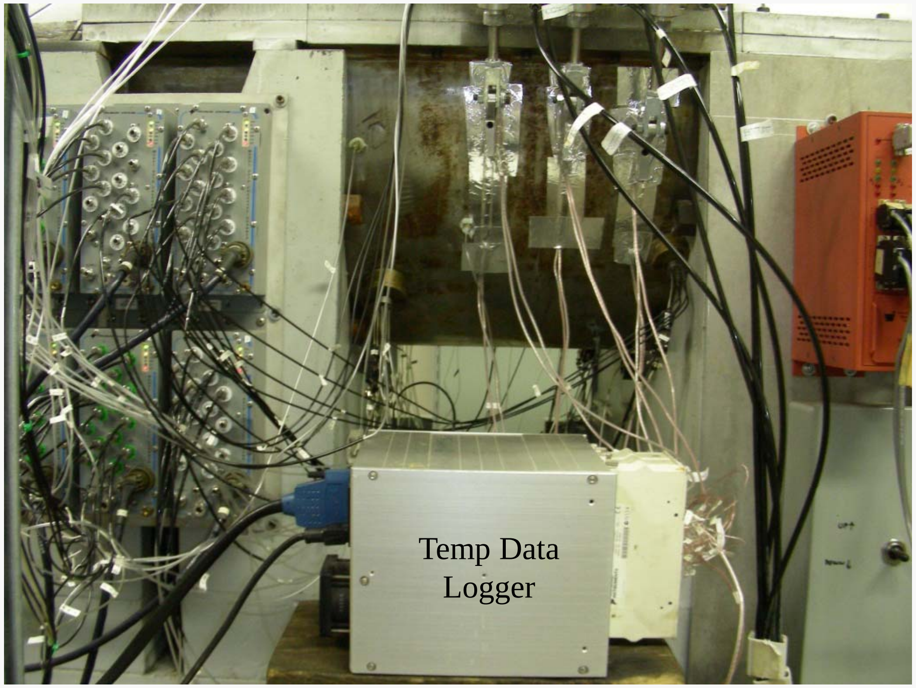




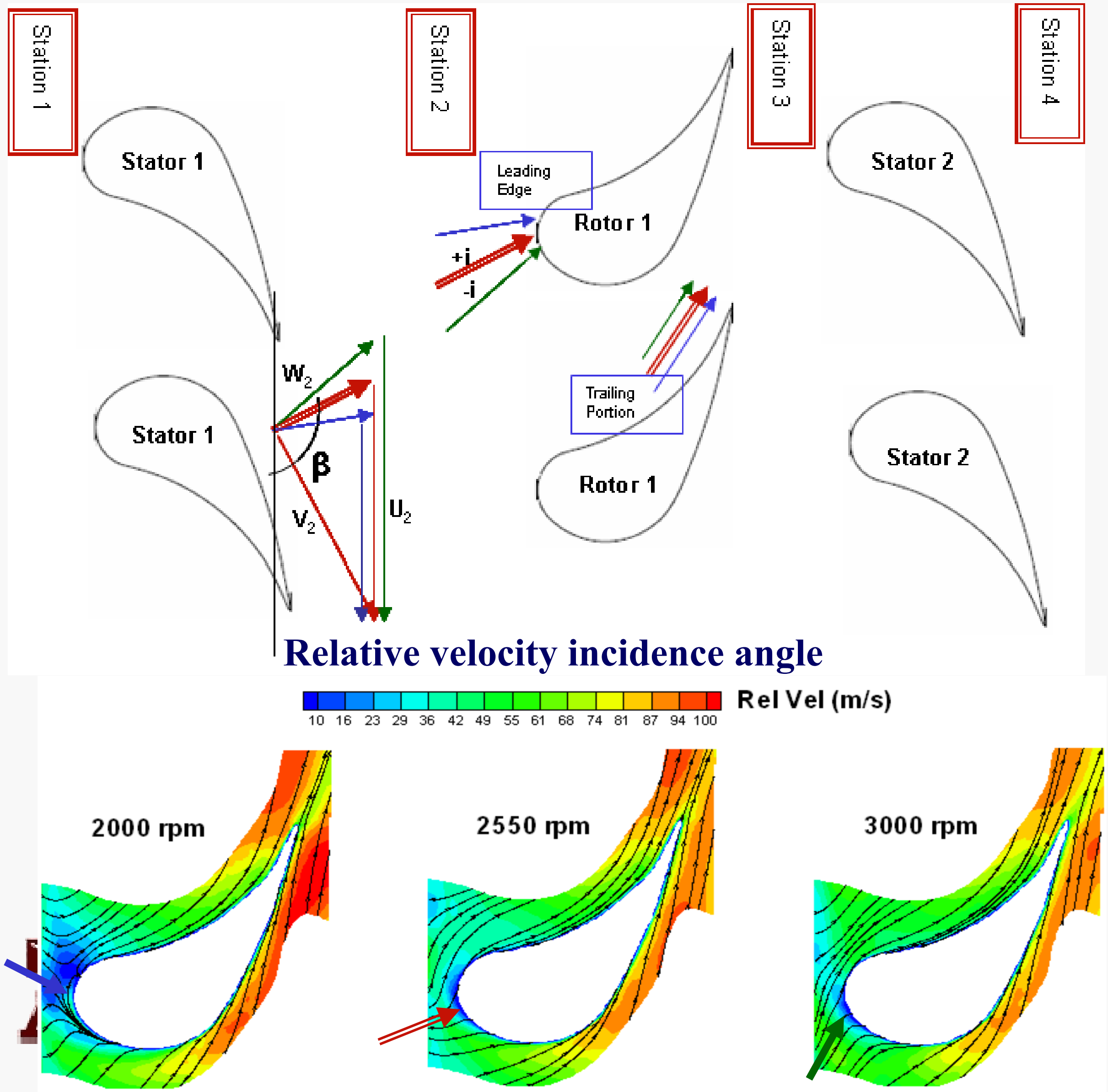


Experimental Facility, Inter-stage Temperature Measurement



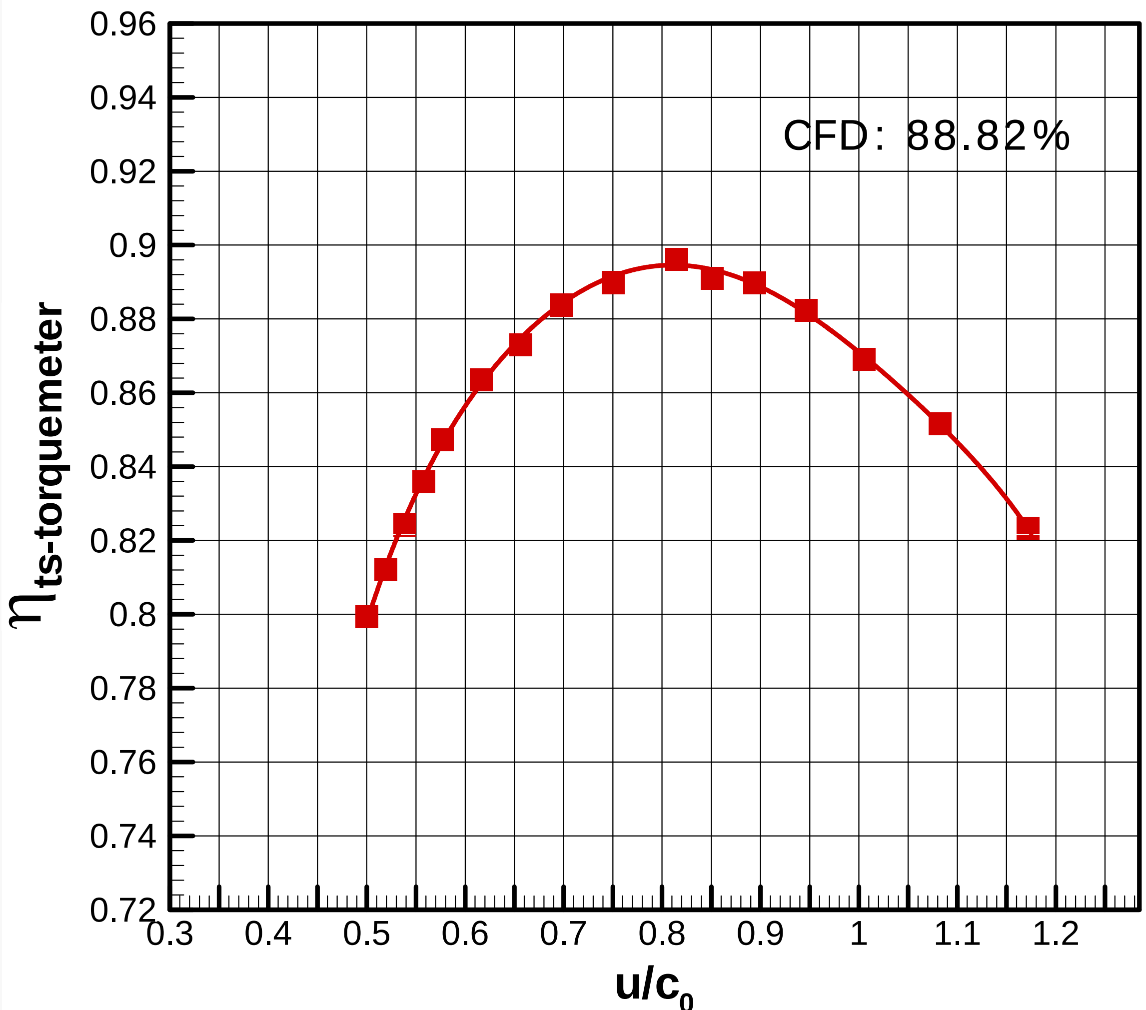


Velocity Diagrams Incidence, Off-Design Incidence



- W_2 changes with rotating speed U_2, so does the flow angle β.
- Increasing rotating speed, the flow angle β increases; the flow stagnation point moves from pressure side to suction side.

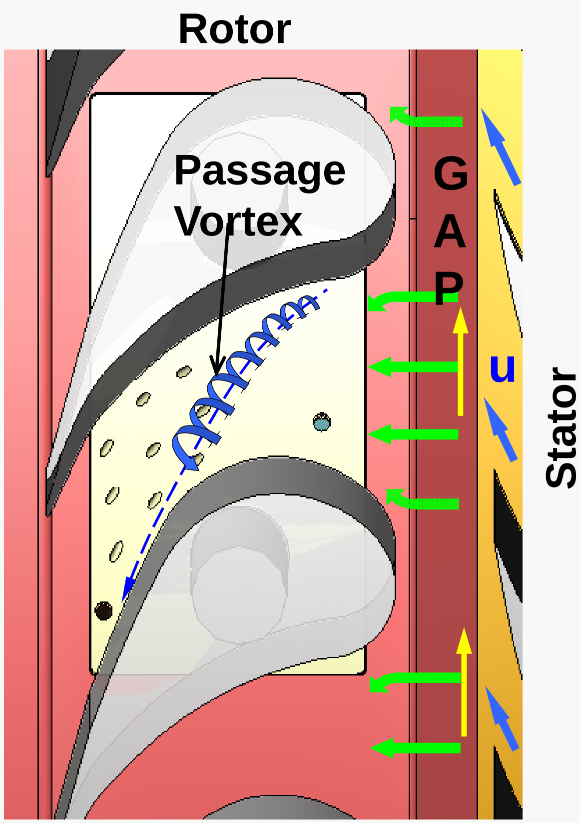
Efficiency and Performance Results:

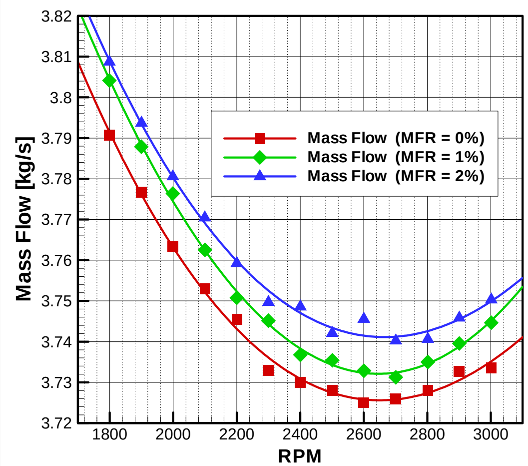


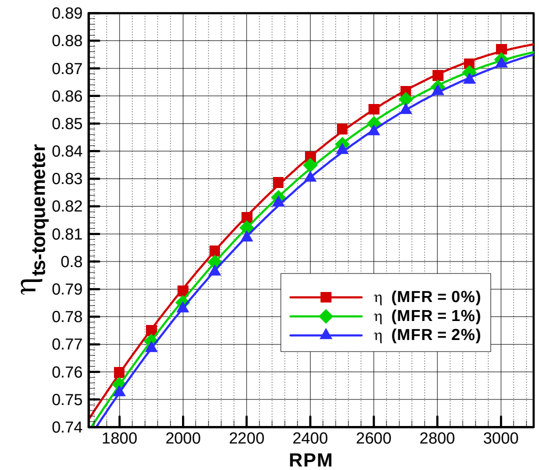
Efficiency and Performance: Gap Ejection

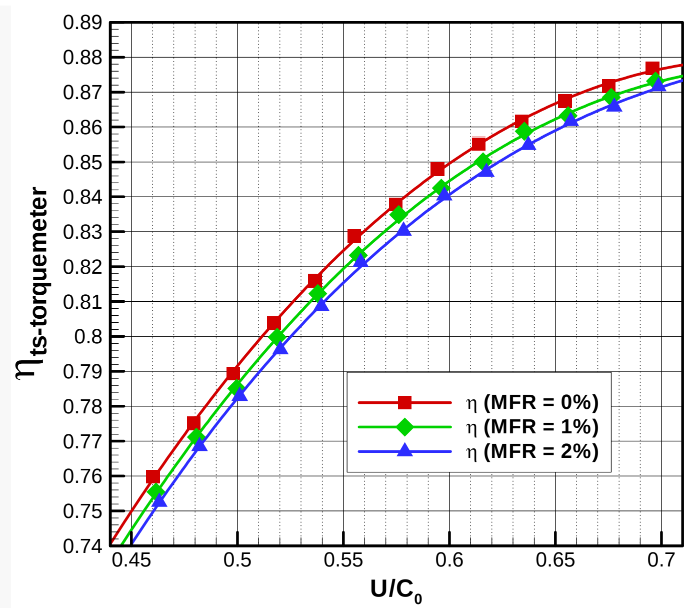
Pitchwise Averaged Film Cooling Efficiency– Stator-Rotor Gap Seal Ejection

$M=\rho_c V_c / \rho_\infty V_\infty$; $MFR=(ms_c / ms)$





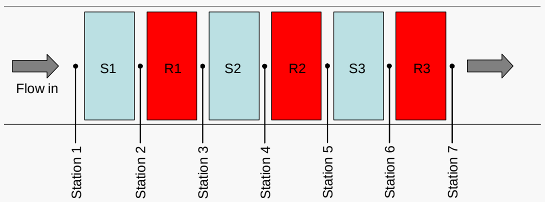


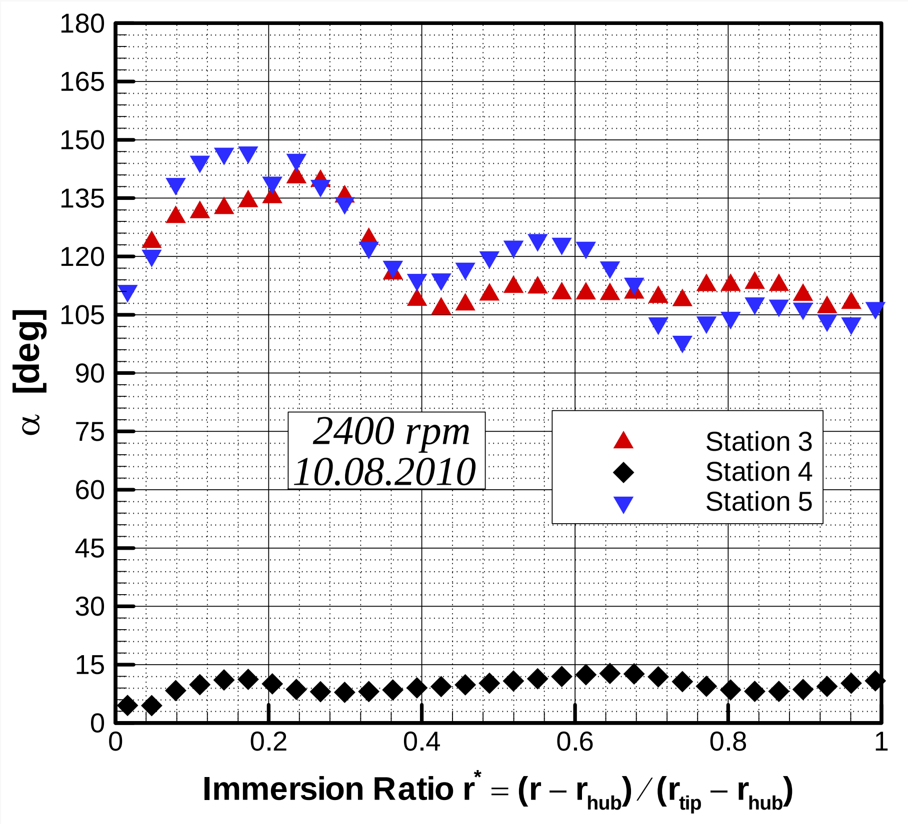


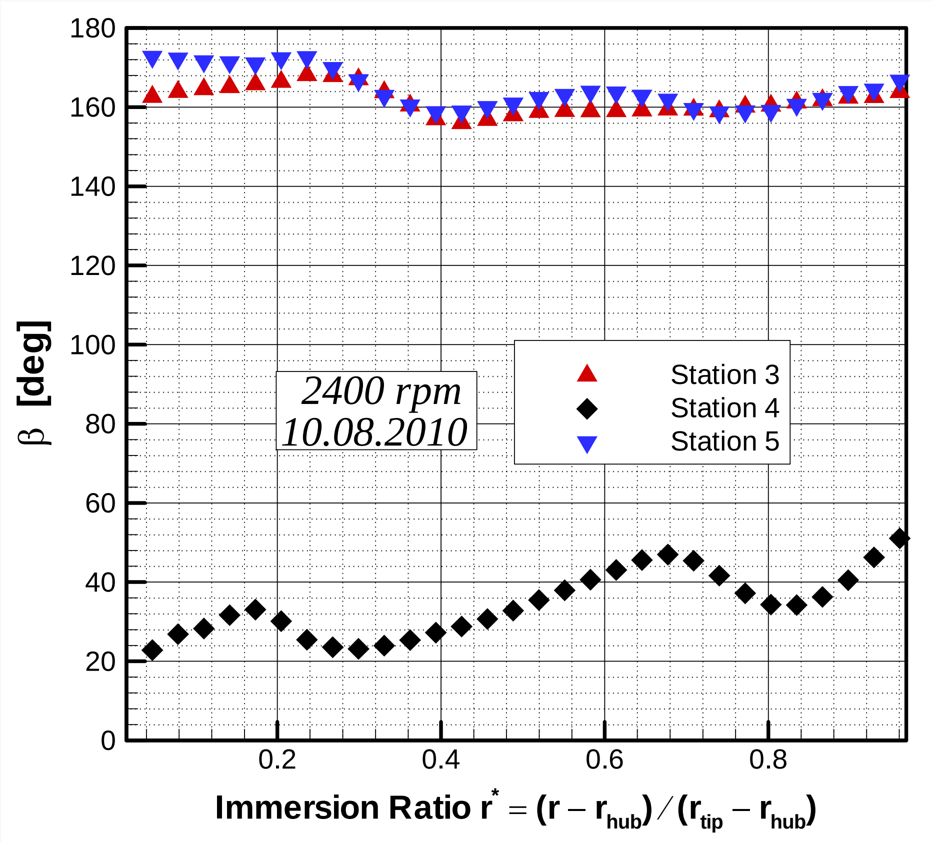
***TPFL*: The Turbomachinery Performance and Flow Research Laboratory**
Texas A&M University
M. T. Schobeiri

Project DE-FOA-0000031
October 2009

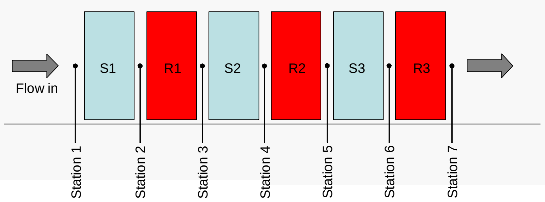
Interstage: Absolute (α) and Relative (β) Flow Angles

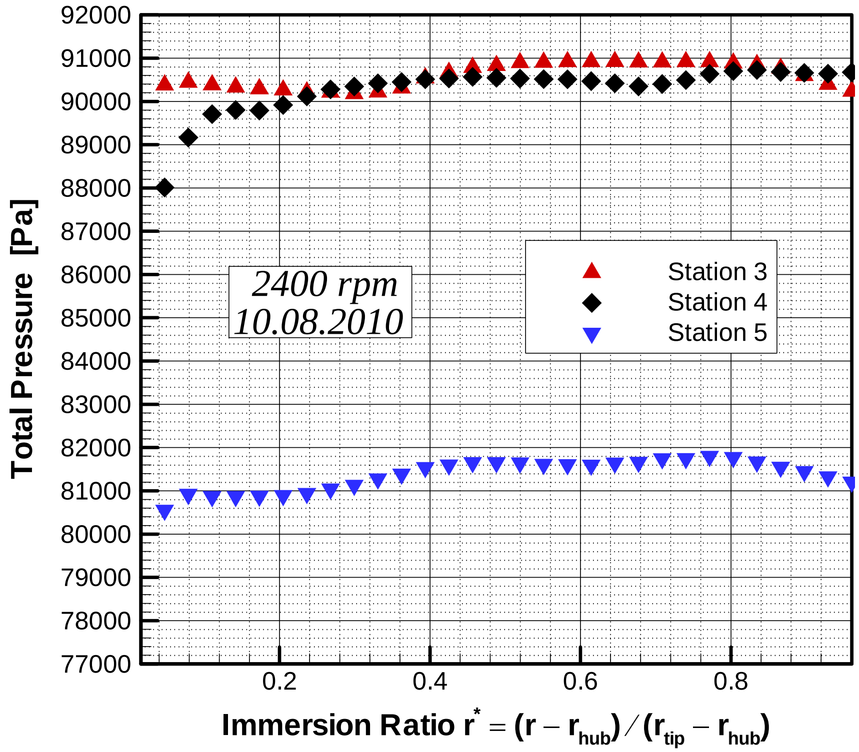


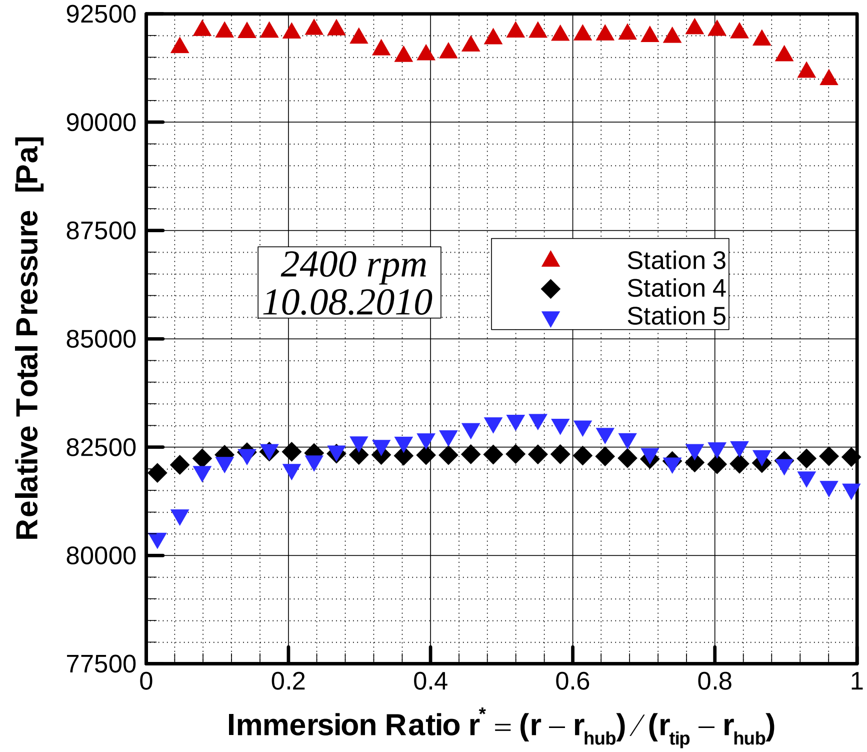




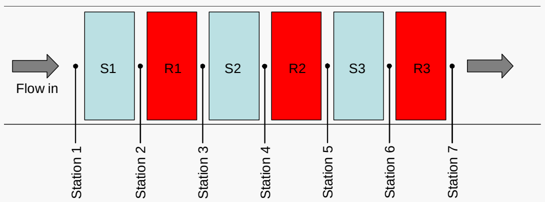
Absolute and Relative Total Pressure

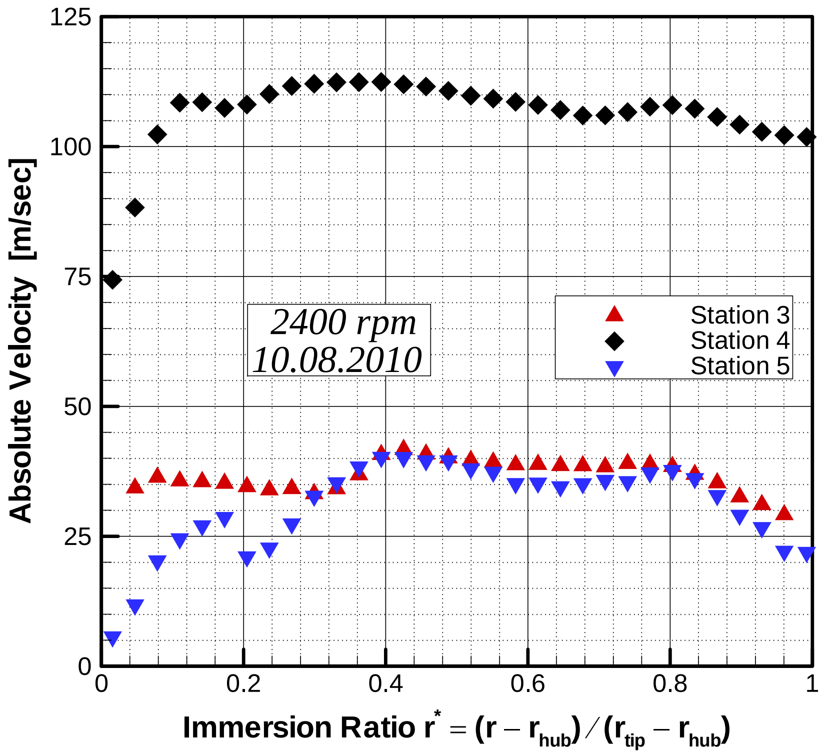


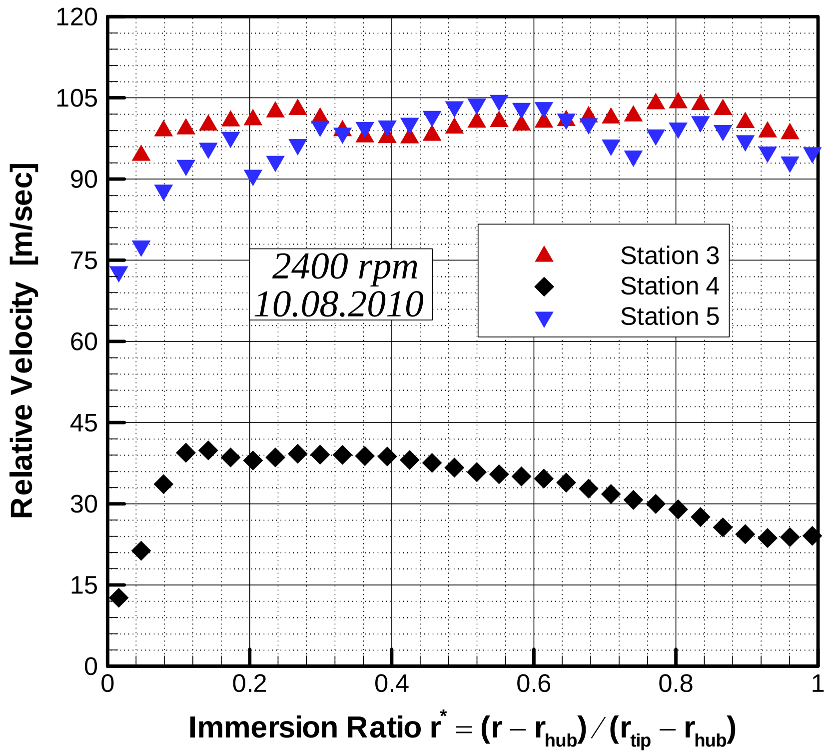




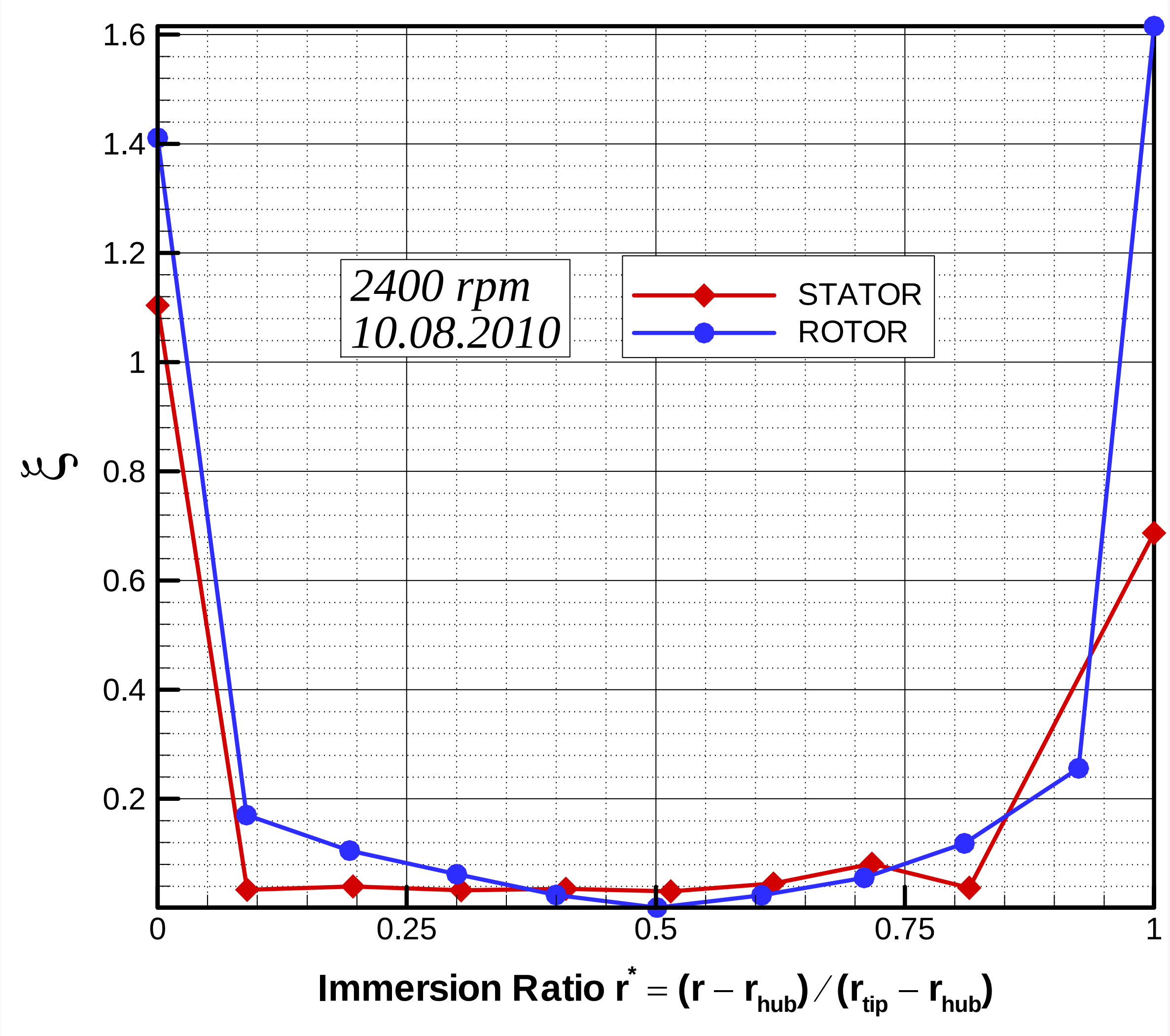
Absolute and Relative Flow Velocities



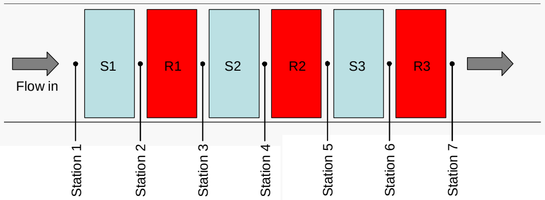




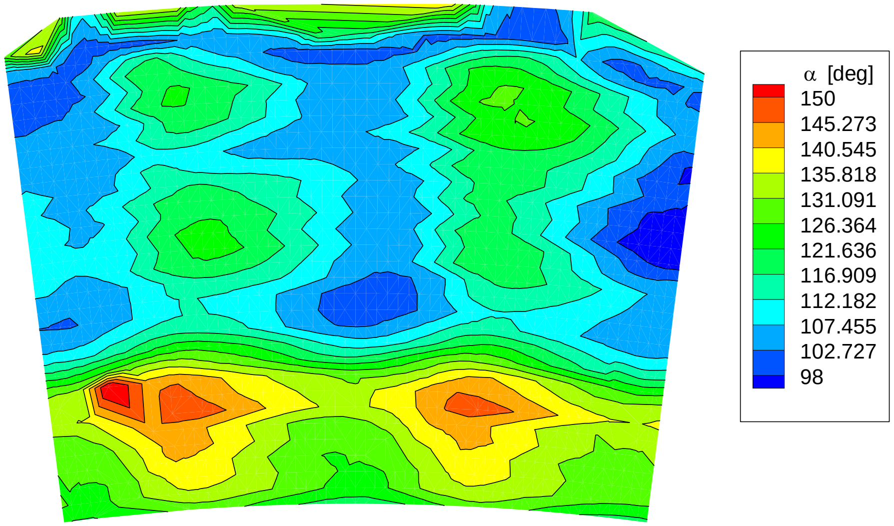
Total Pressure Loss Coefficient



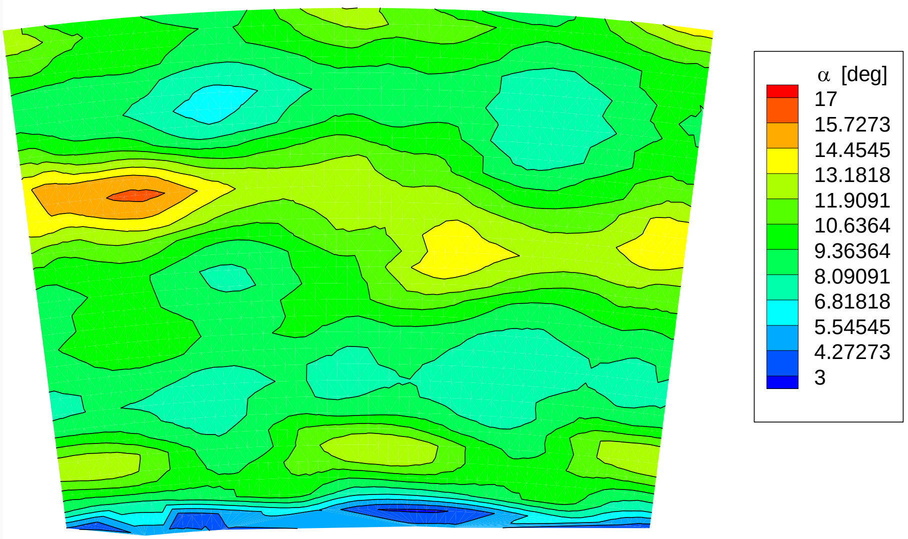
Absolute Flow Angle – Contour Plot



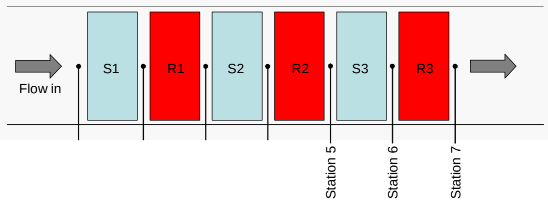
Station - 3
2400 rpm
10.08.2010



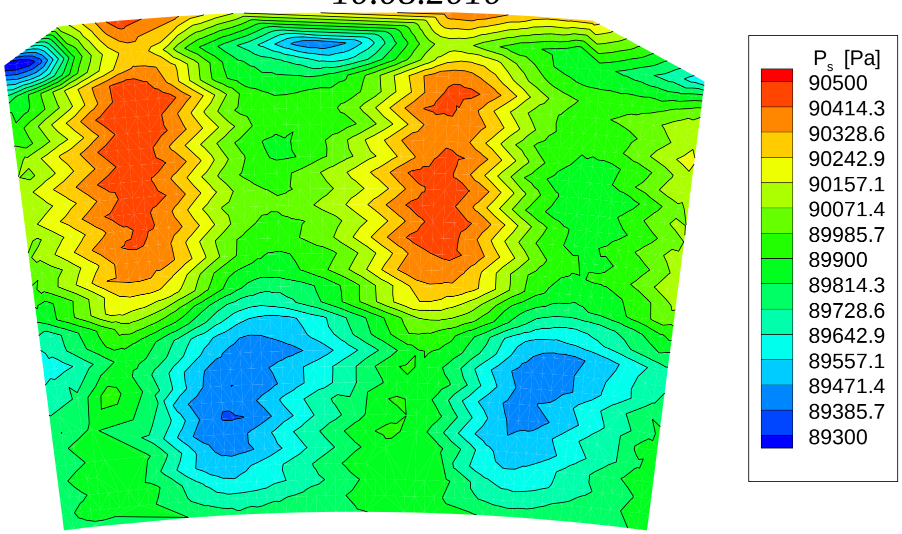
Station - 4
2400 rpm
10.08.2010



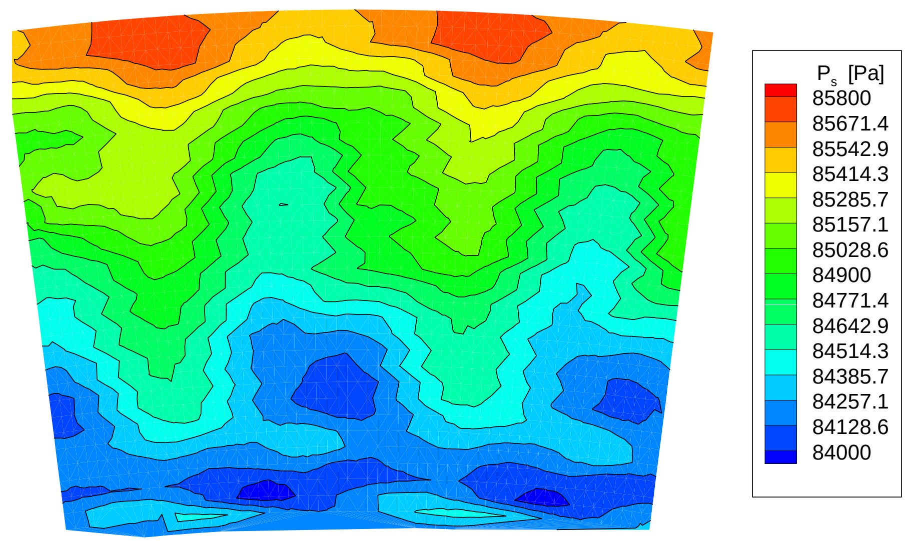
Static Pressure – Contour Plot



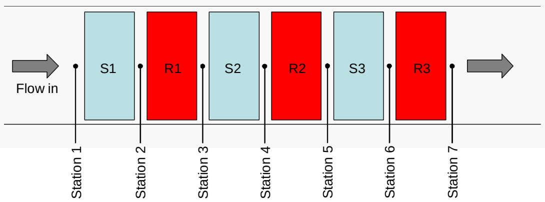
Station - 3
2400 rpm
10.08.2010

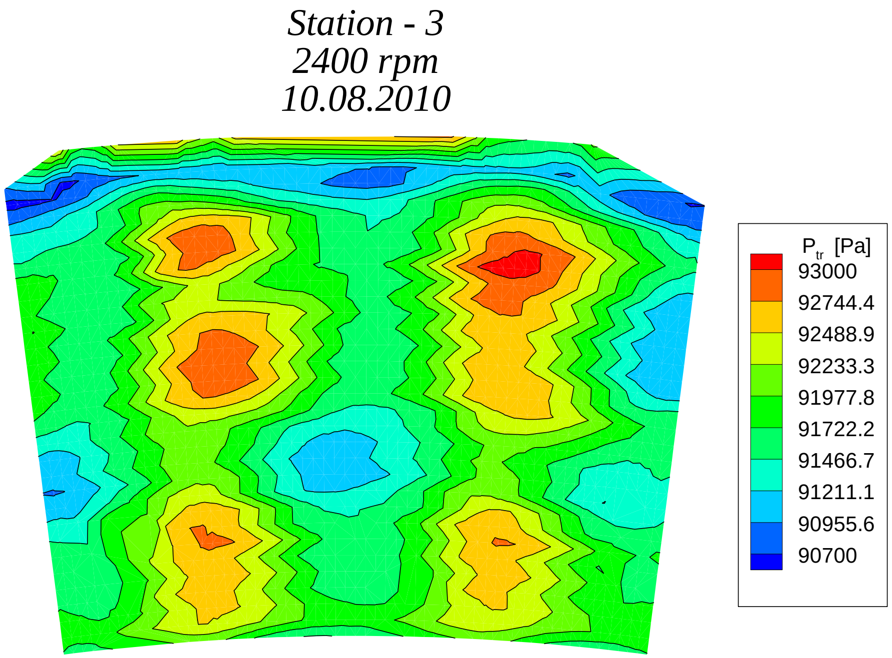


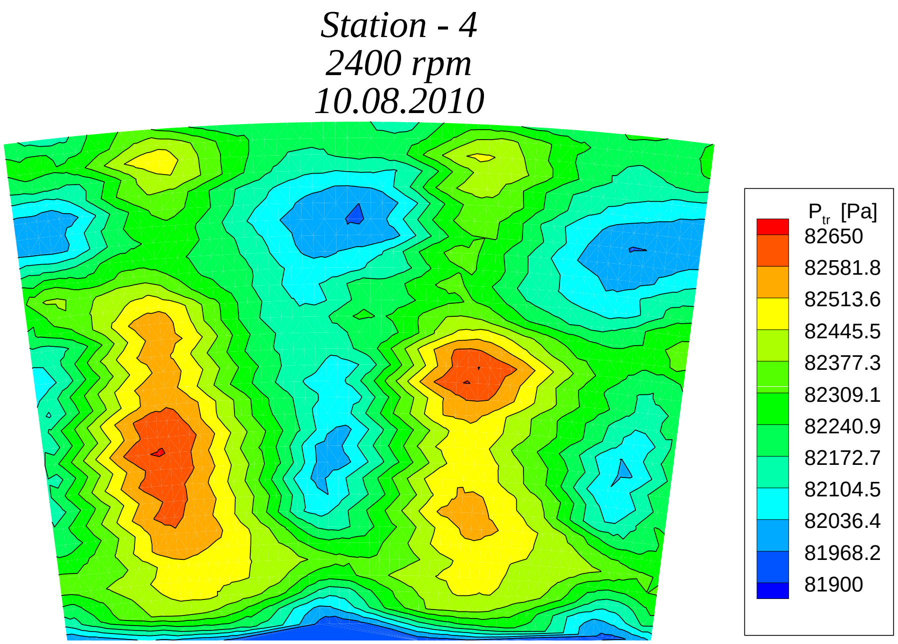
Statio - 4
2400 rpm
10.08.2010



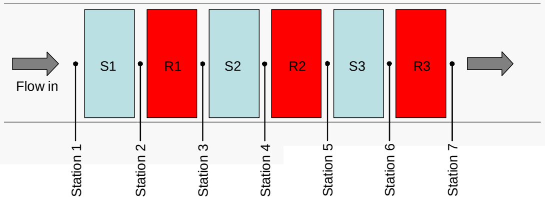
Relative Total Pressure – Contour Plot



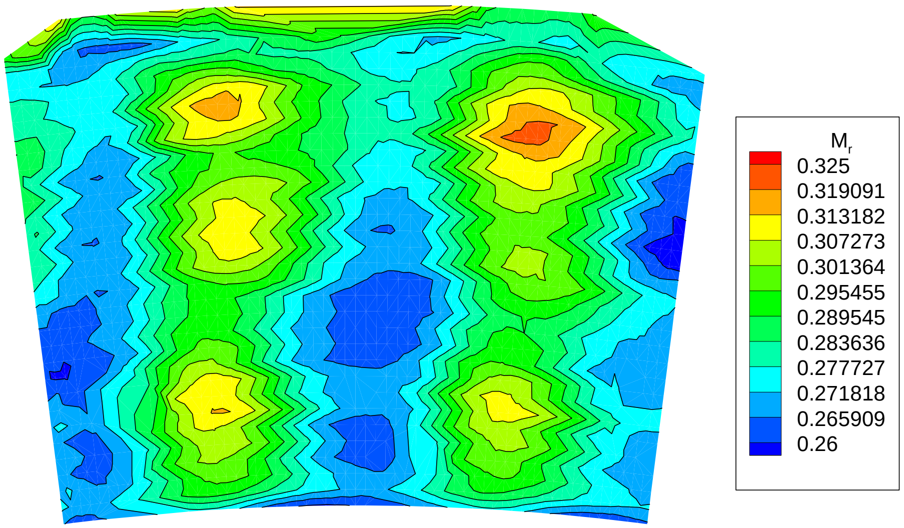




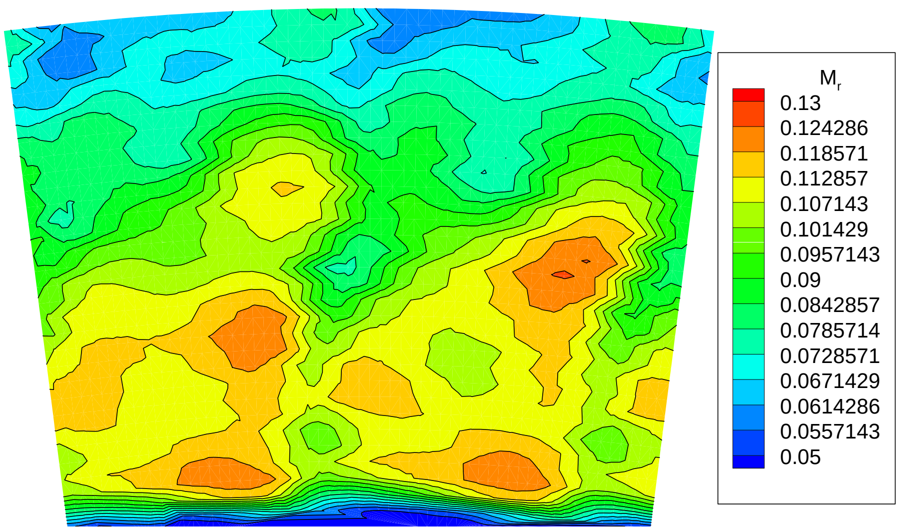
Relative Mach Number – Contour Plot



Station - 3
2400 rpm
10.08.2010



Station - 4
2400 rpm
10.08.2010



Conclusions

- CFD calculations show that an increase of 0.51% in rotor efficiency has been achieved after applying the Continuous Diffusion Technology to contouring design.
- The new technology is able to significantly reduce the pressure difference between the pressure surface and suction surface near hub, which is the primary driving force of endwall secondary flow.
- The new technology also reduces the yaw angle of flow close to hub, which implies that the turning of flow is decreased. Also, the relative total pressure loss near the hub reduces too.
- 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.
- It is quite promising to combine leading-edge filleting with the new endwall contouring technology which may greatly decrease the loss due to secondary flow close to hub and therefore considerably enhance the performance of turbines.

Conclusions Turbine Rig Reference Experiments, Year 2 Work

- Turbine rig prepared for the planned comprehensive interstage aerodynamics , efficiency and performance experiments proposed for endwall contouring measurements.
- The reference turbine has undergone critical efficiency, performance and interstage tests.
- The test results are essential for comparisons with endwall contoured cases.
- Year 2: After completion of contouring design optimization, we will start manufacturing the rotor hub contouring.
- The rotor will be sent for balancing,
- It will be inserted into the casing, aligned and will be ready for final test proposed for the year 2.

Thanks for Your Time and Attention.