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

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Graduate Students: Lu, K, Rezasoltani, M.
PIs: M.T. Schobeiri, J.C Han
Department of Mechanical Engineering
Texas A&M University

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Content

Introduction

I: Endwall Contouring Recap: Impact on Efficiency

- **Brief recap of *Continuous Diffusion Method* introduced by Texas A&M for endwall contouring of any arbitrary airfoil geometry**
- **Experimental validation**

II: Impact of Endwall Contouring and Purge Injection on Film Cooling

- **Applying the endwall contouring method into the first rotor hub to investigate the behavior of film effectiveness under the impact of purge flow**
- **Numerical, experimental results**

III: Blade Tip Ejection

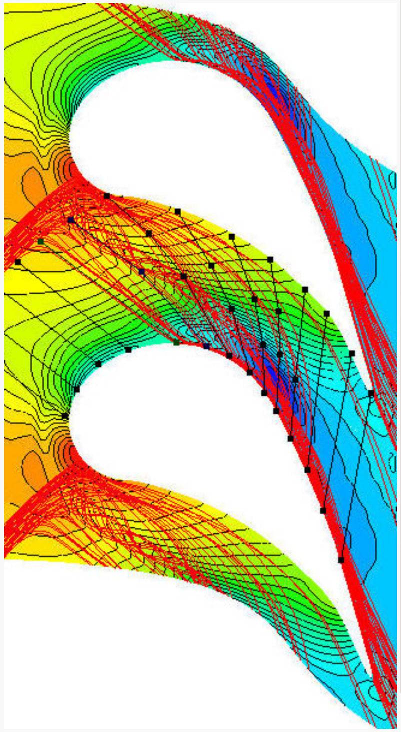
- **Numerical Results, Experimental**

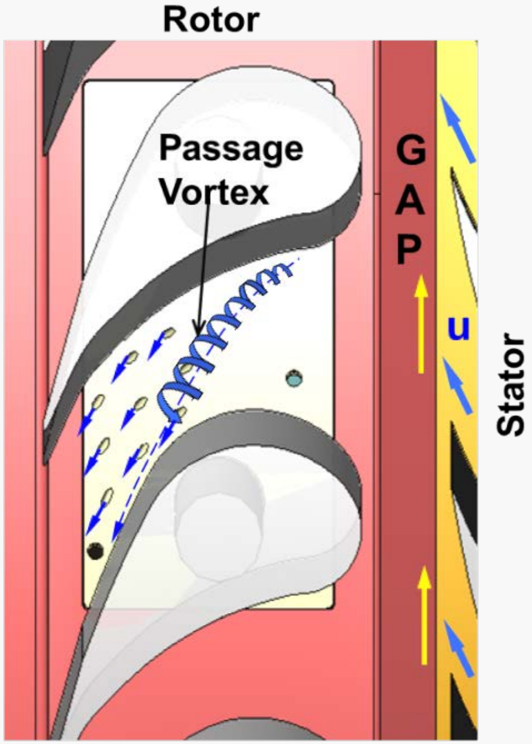
Conclusions, Ongoing work

I 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





I 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 toincidence change when turbines operate at off-design conditions with incidence change from - 30º to + 30º (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**

I Endwall Contouring Design

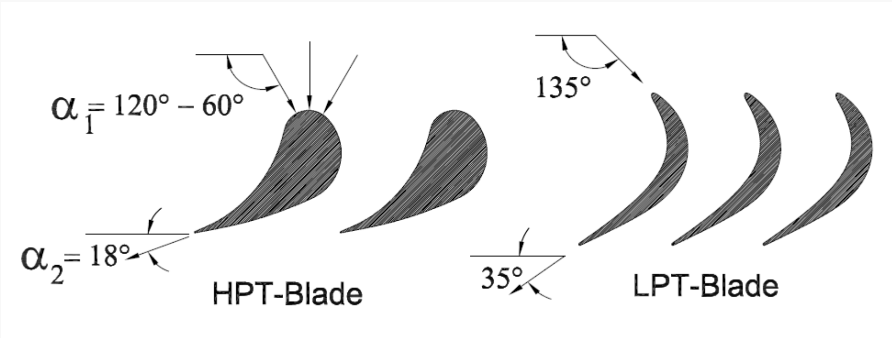
Zweifel coefficient guides designer, how to contour the endwall

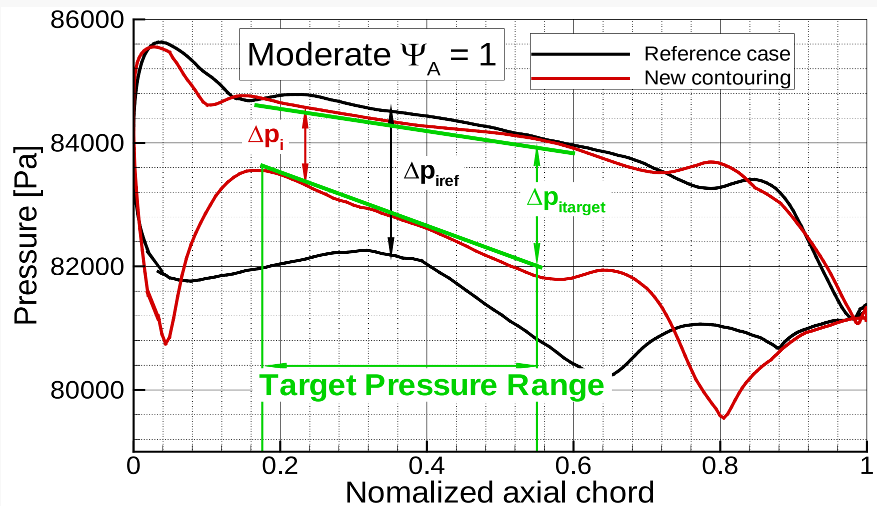
- **Determine the Zweifel Coefficient Ψ_A**
- **Is $\Psi_A < 1$: A single continues diffusion process sufficient**
- **Is $\Psi_A > 1$: Requires a compound diffusion process**

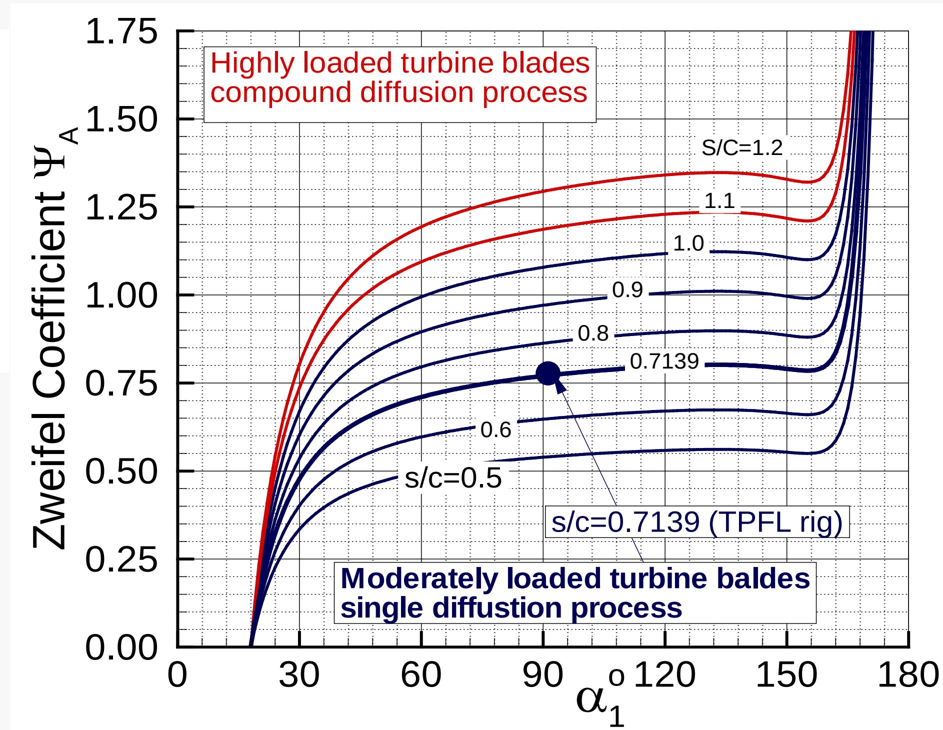
The magnitude of ψ_A decides how the contouring should be designed. Based on the particular blade design, a system of diffusion process similar to the above can be designed such that the pressure difference between the suction and pressure side is reduced by a compound contouring. This requires designing a positive contouring (hills) followed by a negative contouring (valleys) for each target pressure. The design process is the same as detailed above.

I Endwall Contouring Design

Zweifel coefficient how to contour the endwall

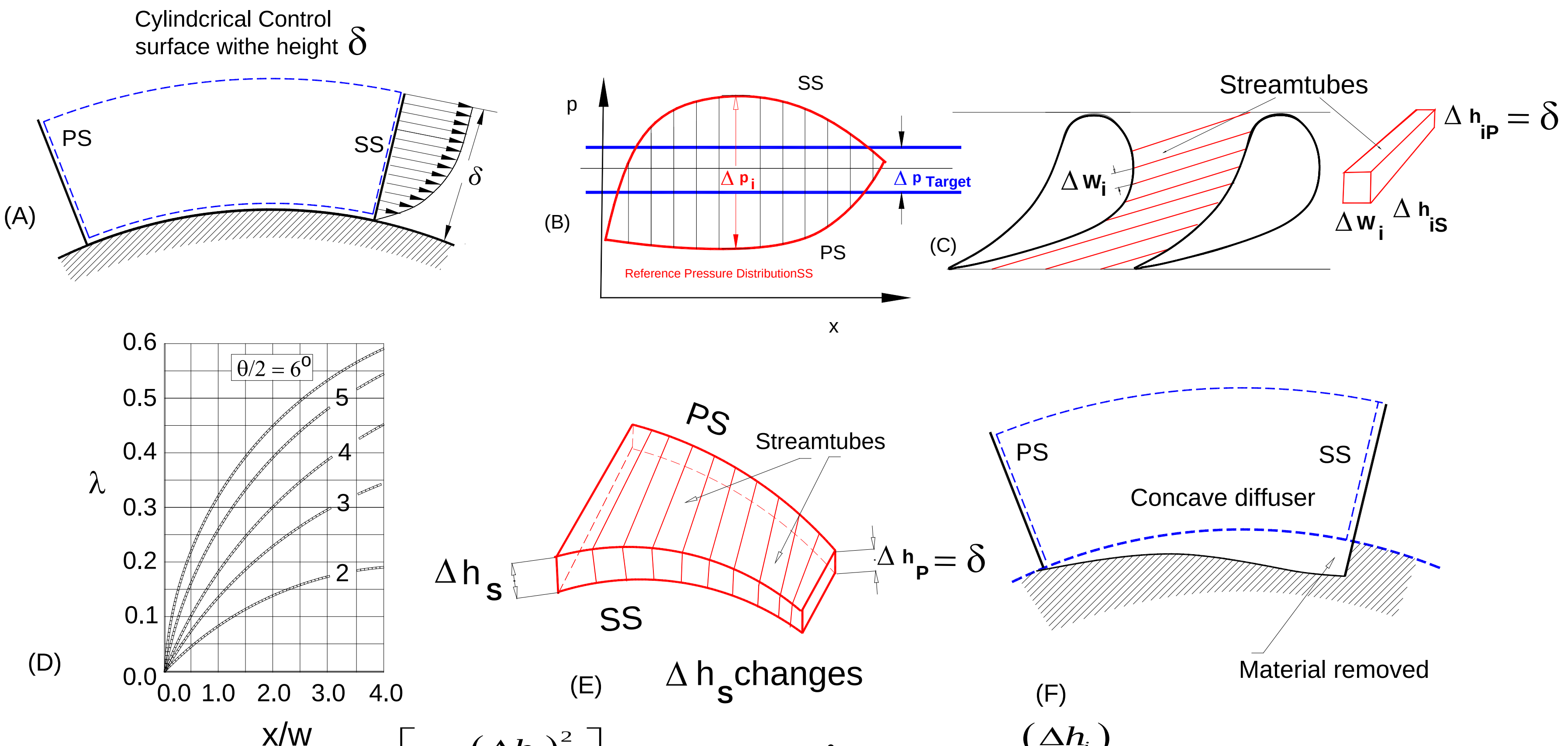






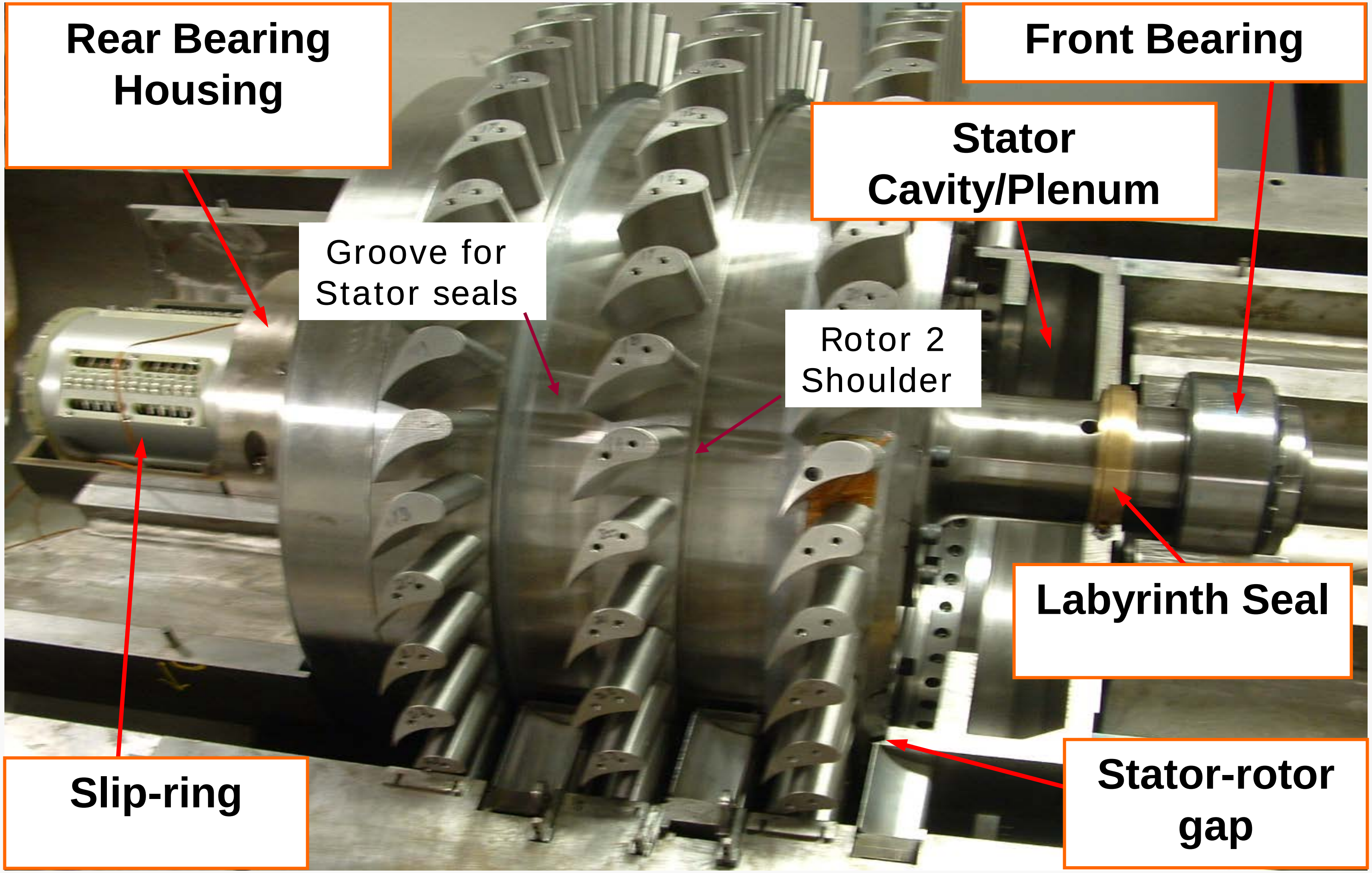
From: M.T. Schobeiri: Turbomachinery Flow Physics and Dynamic Performance, 2nd Edition, Springer Verlag

Continuous Diffusion: Summary of the Working Principle

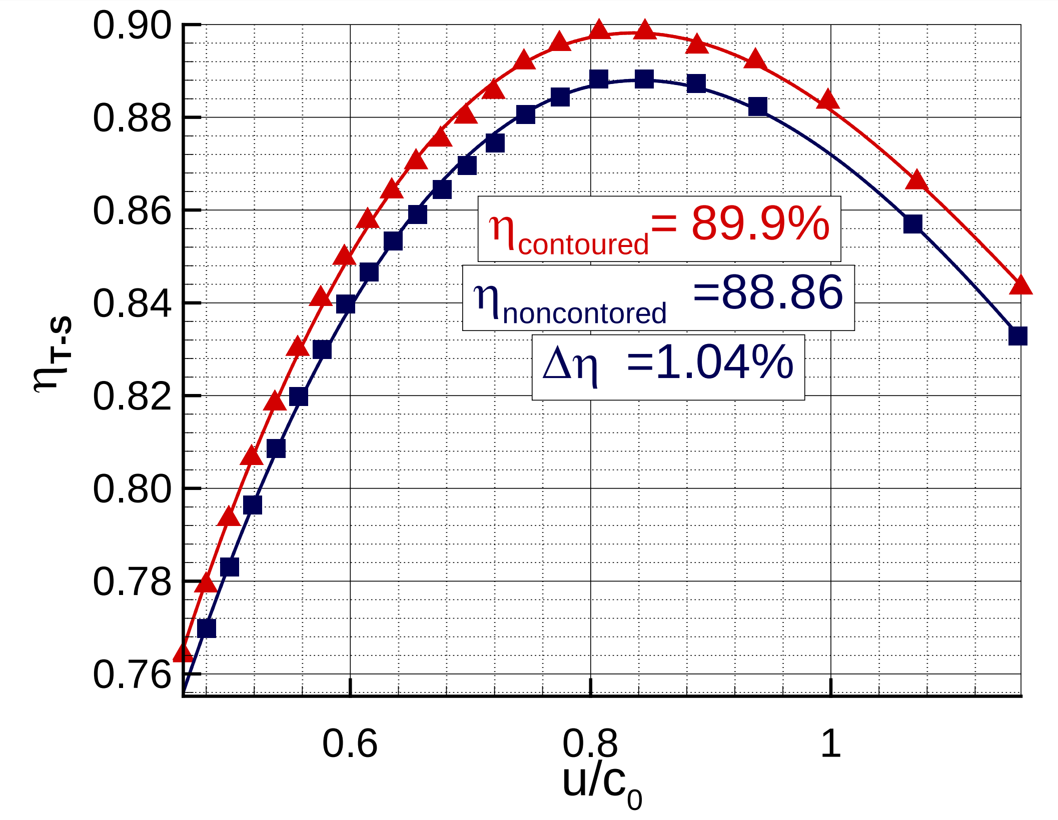


$$\left[1-\frac{(\Delta h_i)_P^2}{(\Delta h_i)_S^2}\right]=\lambda \quad \text{Results in:} \quad (\Delta h_i)_s=\frac{(\Delta h_i)_P}{\sqrt{1-\lambda}}$$

Endwall Contouring Applied to First and Second Rotor Hub

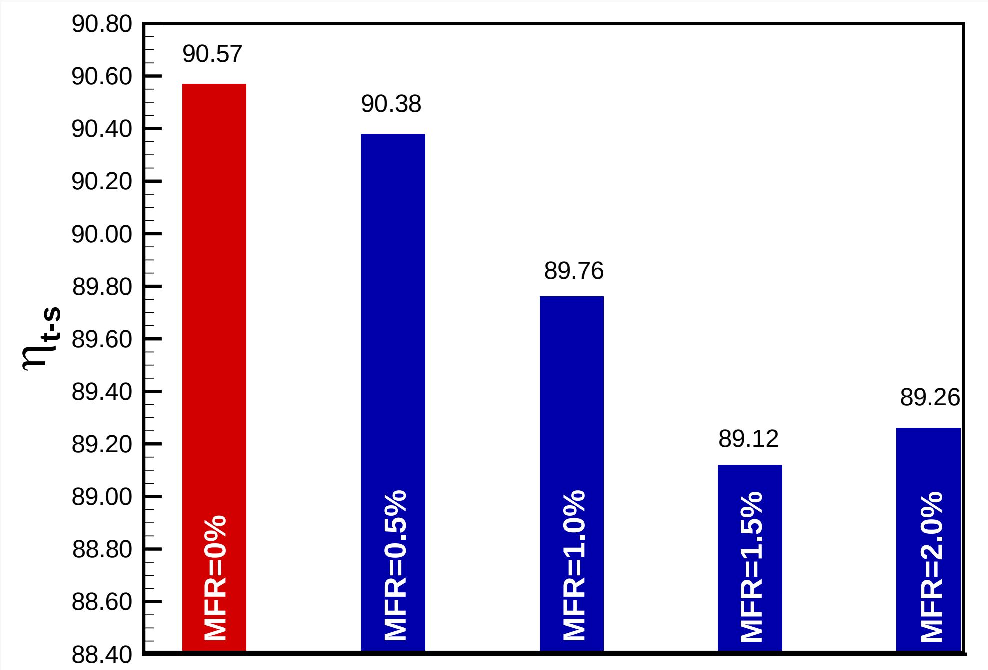


I Concept Validation: Second Rotor Endwall Contoured

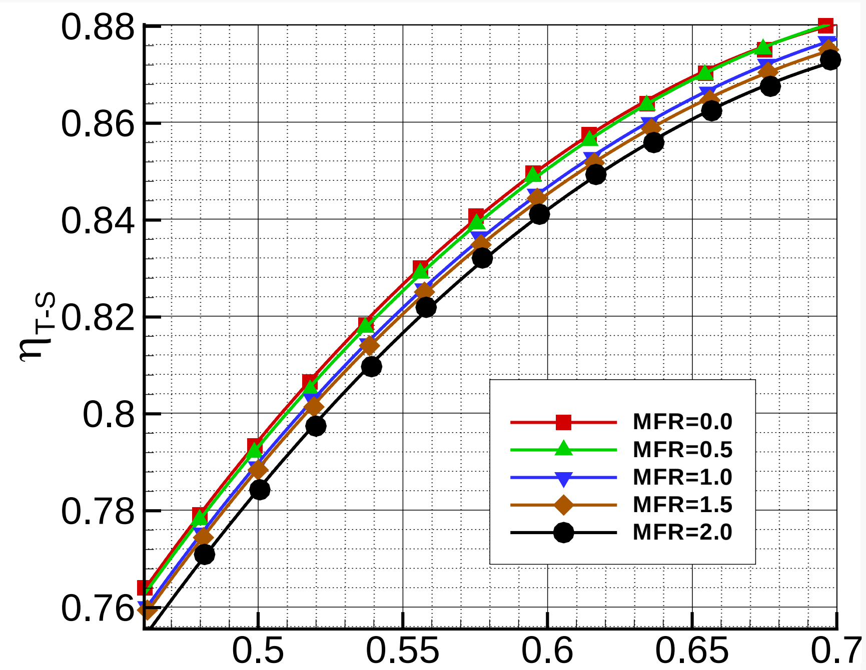


Rotor:	**Three-stage**
Contoured:	**Second rotor hub**
Predicted	**η_{T-S} = 89.33%**

I Effect of MFR on Rotor Efficiency



RANS Calculation

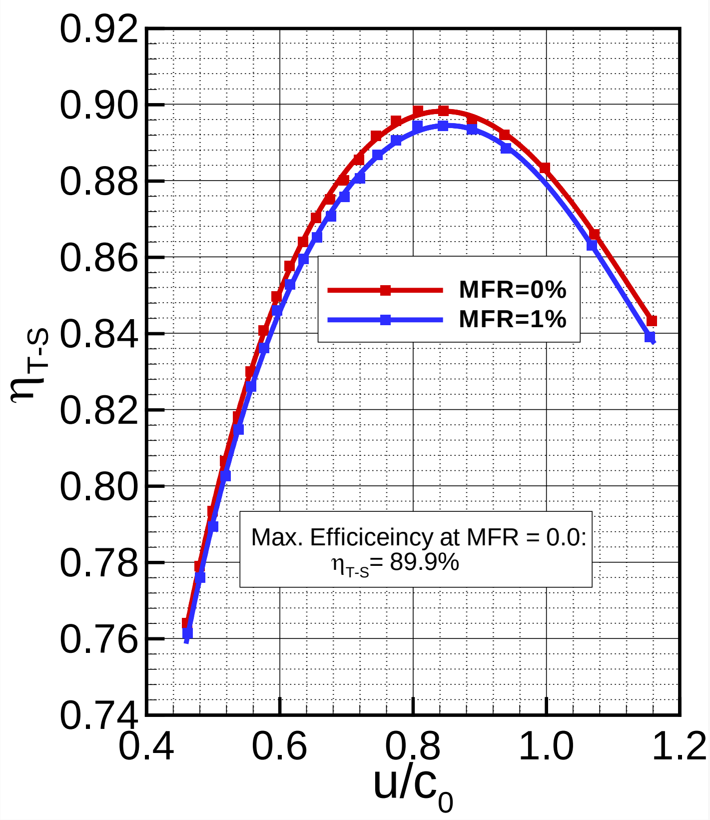


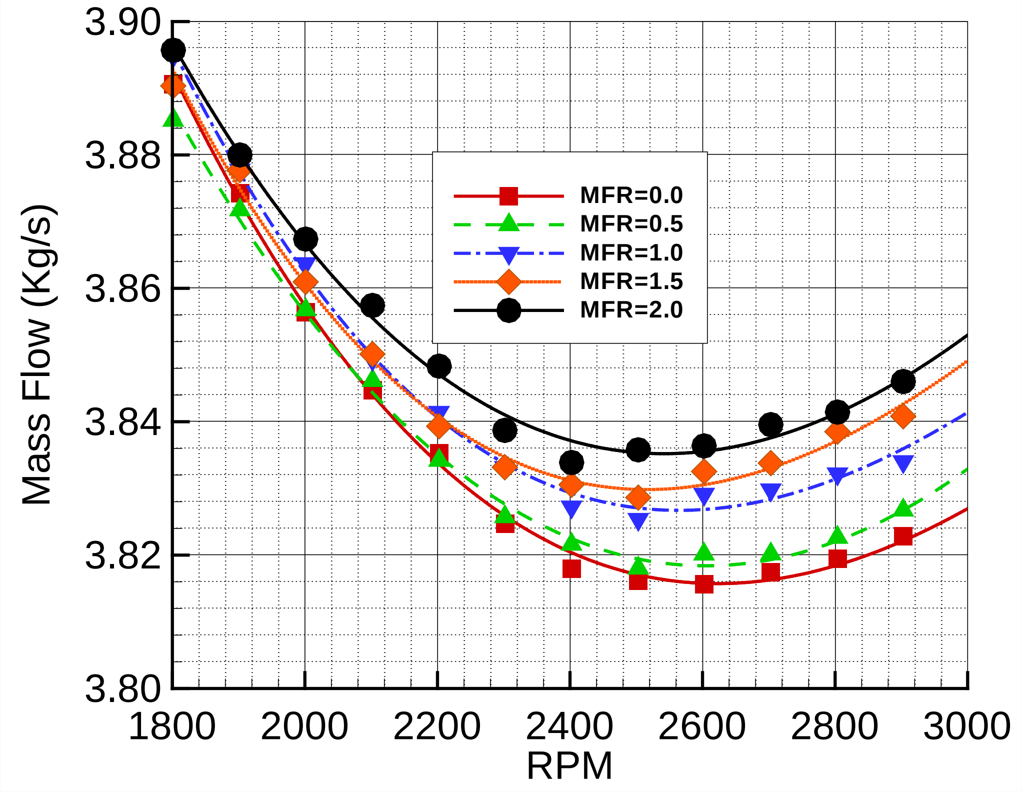
Turbine Experiment

Cause of the above over prediction:

1) **Lack of appropriate transition model**
2) **Deficient dissipation model**

I Efficiency and Performance Deterioration with Purge





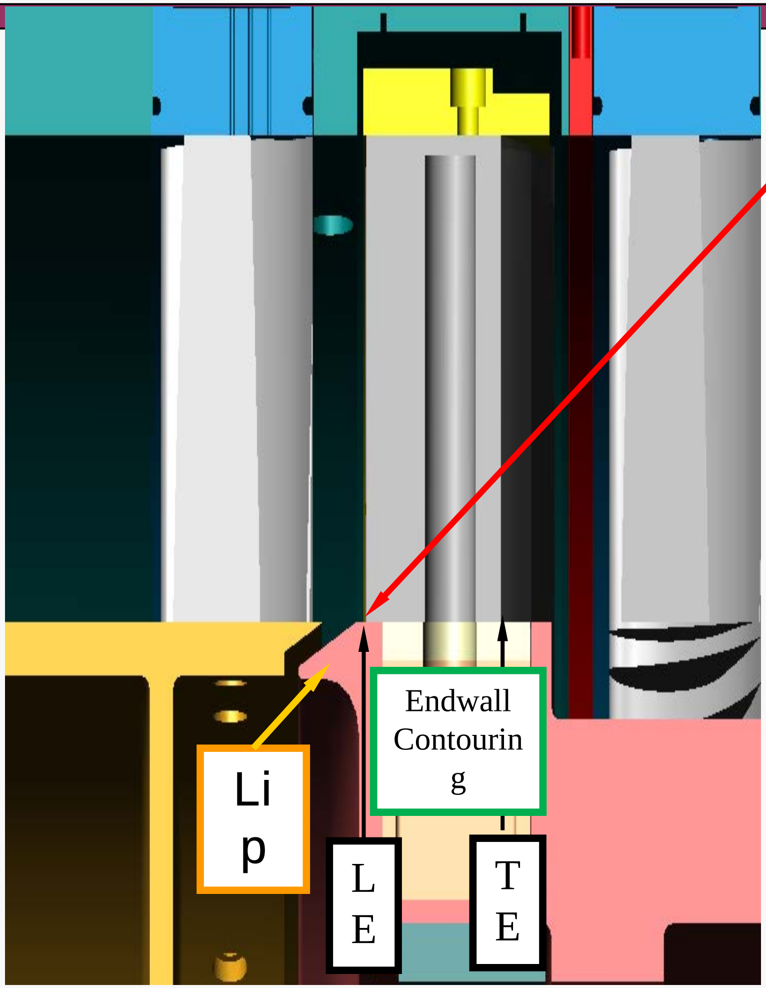
Efficiency as a function of u/c_0 (left) and rpm (right) with MFR as a parameter

II: Impact of Endwall Contouring, Purge Injection on Film Cooling

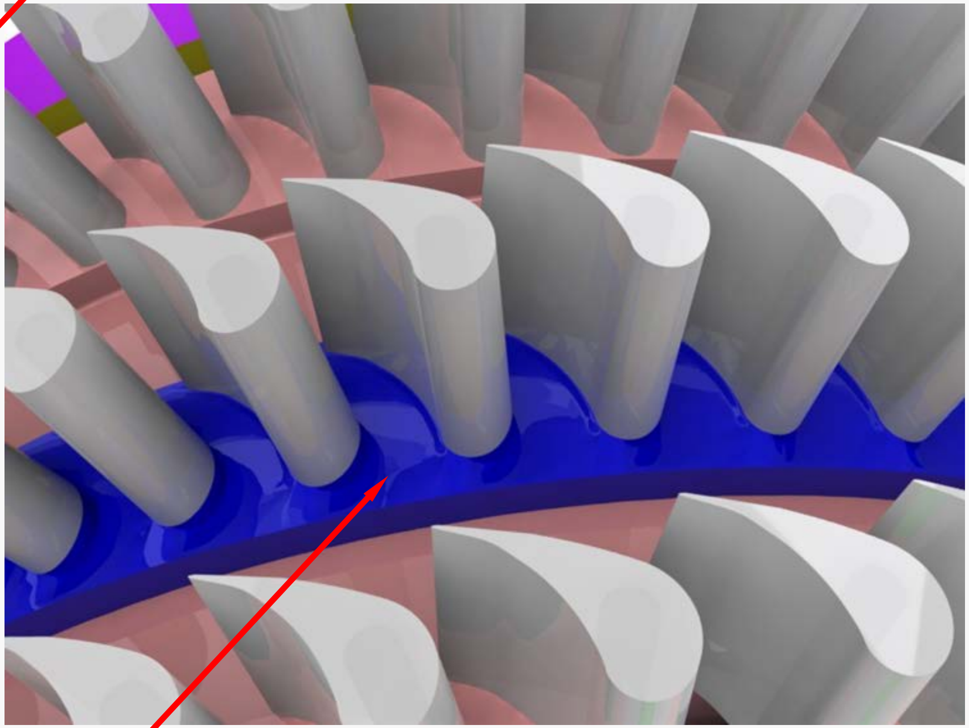
Design constraints dictated by the existing turbine hardware:

- **Film cooling measurements with pressure sensitive paint had to be performed on the endwall of the first rotor row because of optical access for CCD-Camera**
- **First rotor row is directly exposed to purge flow injection**
- **No possibility to extend the contouring upstream of the blade leading edge**
- **Contouring had to start immediately at the leading edge**
- **This constraint required particular attention to the endwall contouring design**

II: Endwall Contouring Design for First Rotor



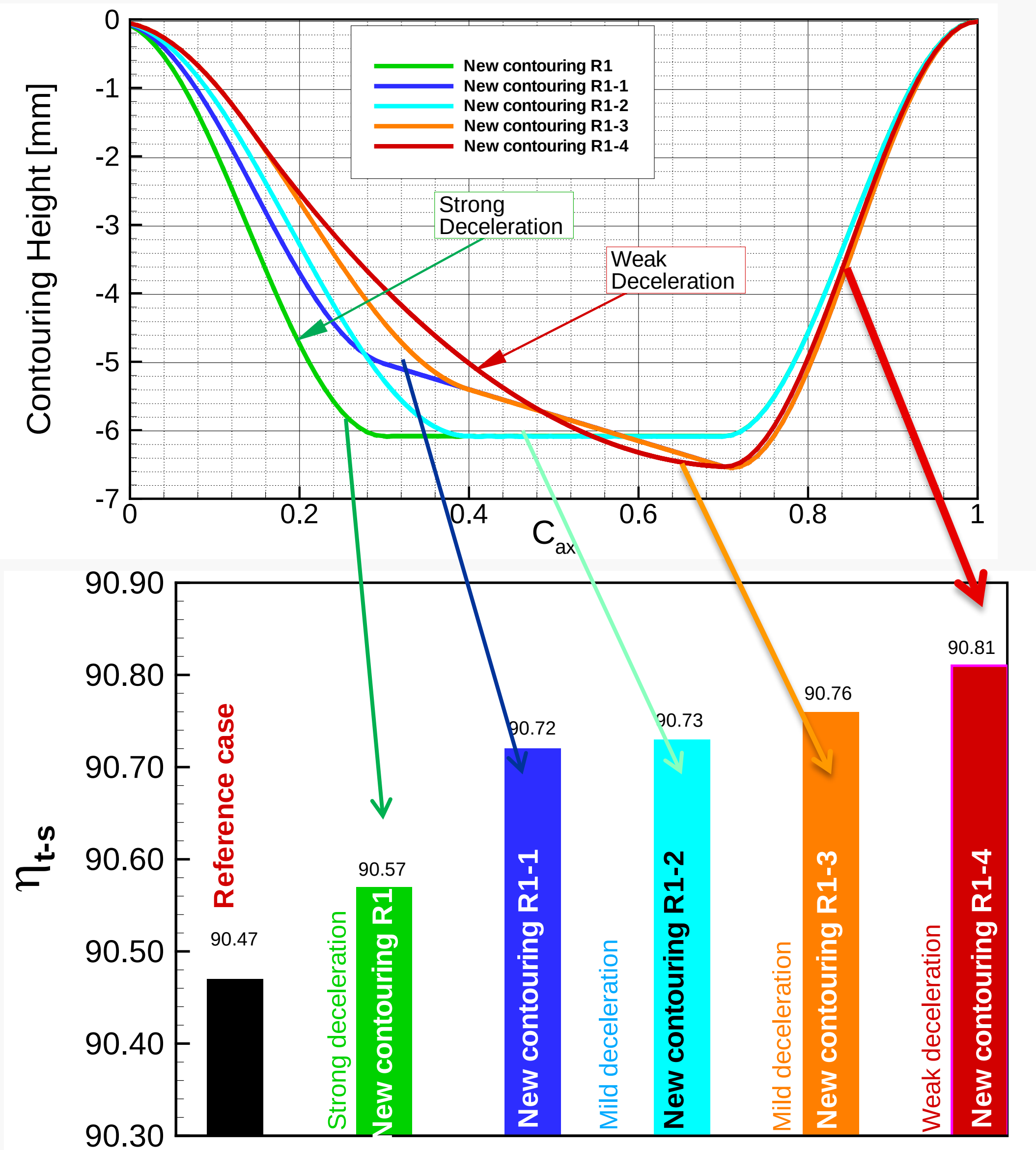
No space for upstream extension of first rotor

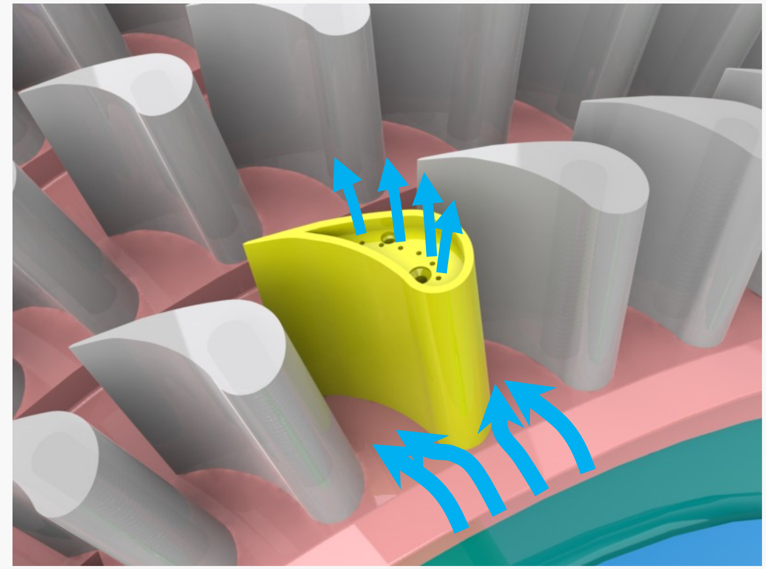


2nd rotor ring extended upstream to ensure efficeincy improvement.

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

II: Endwall Contouring Design of First Rotor Row

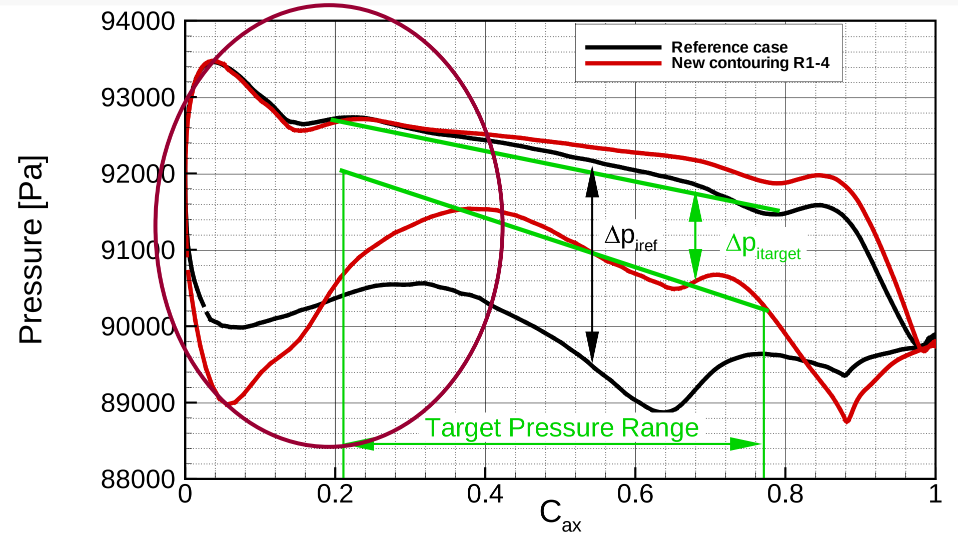


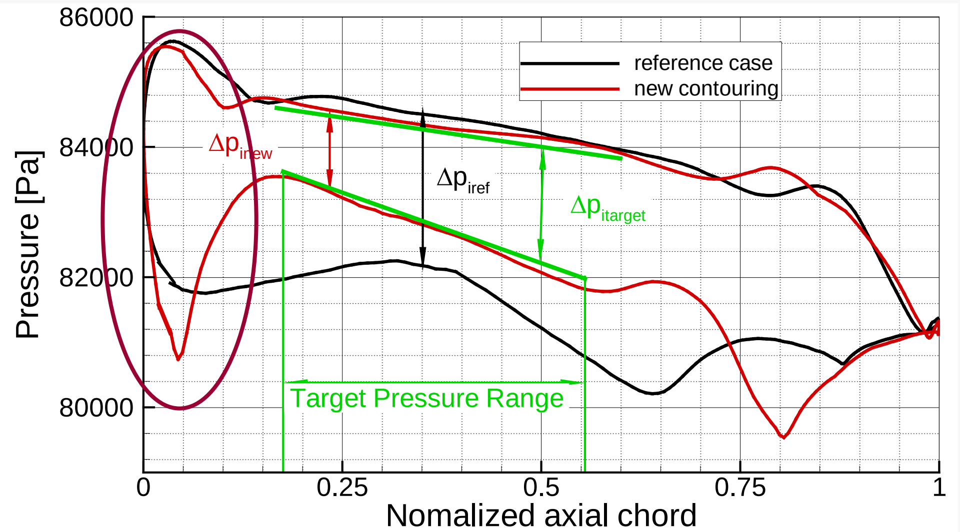


Secondary flow deceleration process from pressure to suction surface

II: Endwall Contouring Using Target Pressure Difference

First rotor blade row exposed to purge flow injection. Contouring starts Immediately at the leading edge. Second rotor contouring extends upstream





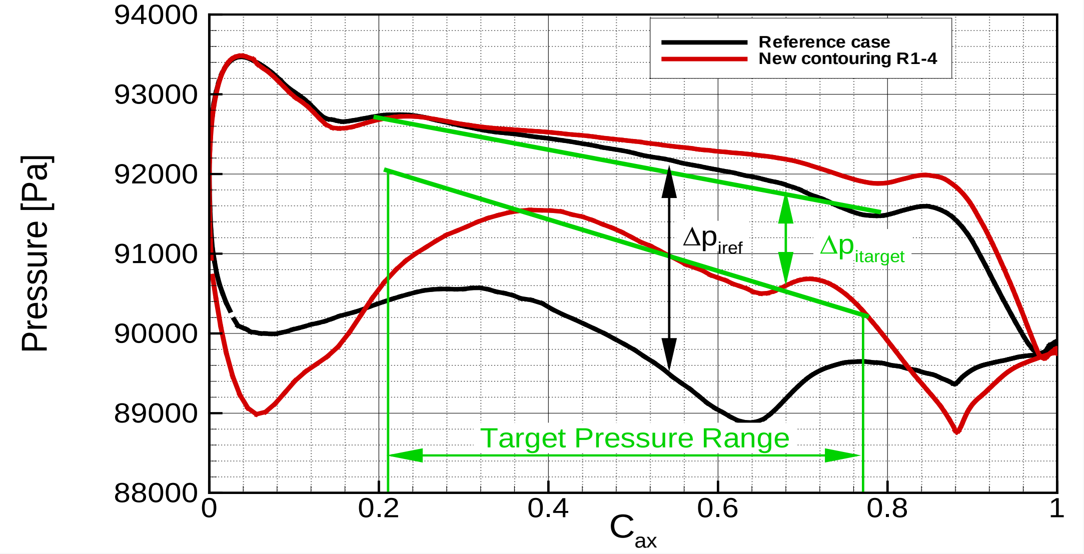
First Rotor row Pressure distribution Second Rotor row Pressure distribution

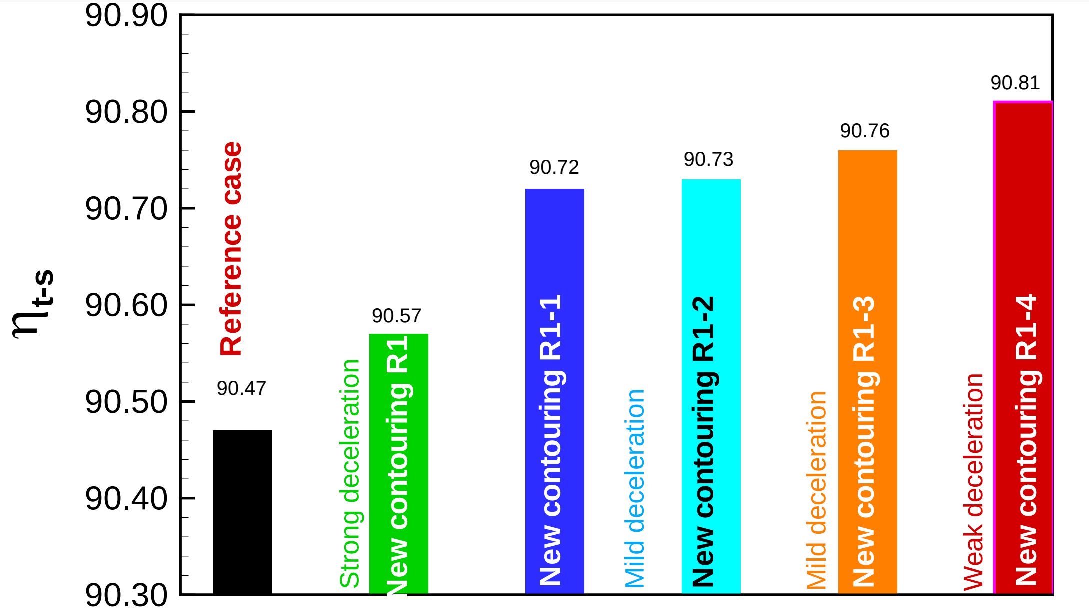
Pressure distribution directly on endwall

Defined Target Pressure on endwall

Contoured pressure distribution

Results: First Stage Rotor Endwall Contouring





Pressure distribution directly on endwall

Defined Target Pressure on endwall

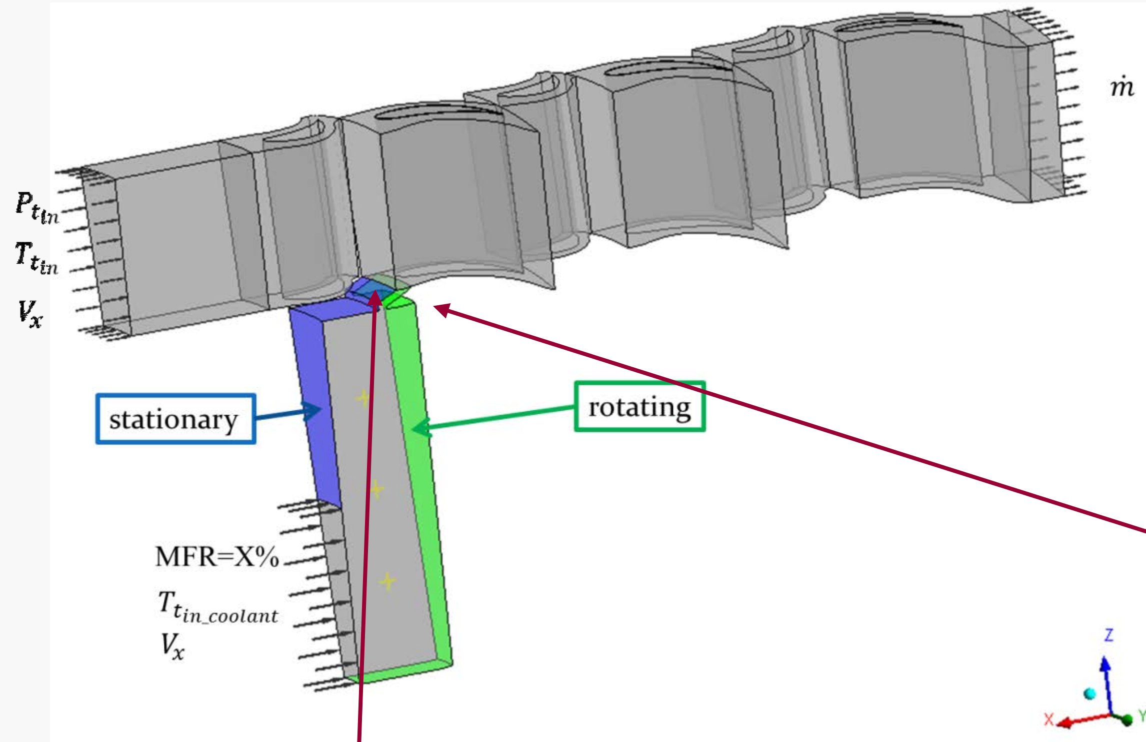
Contoured pressure distribution

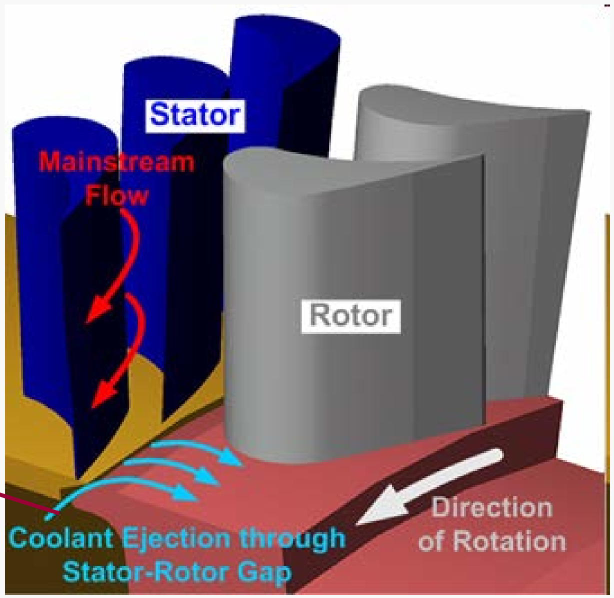
II: Purge Flow Injection, Endwall Contouring, Film Cooling

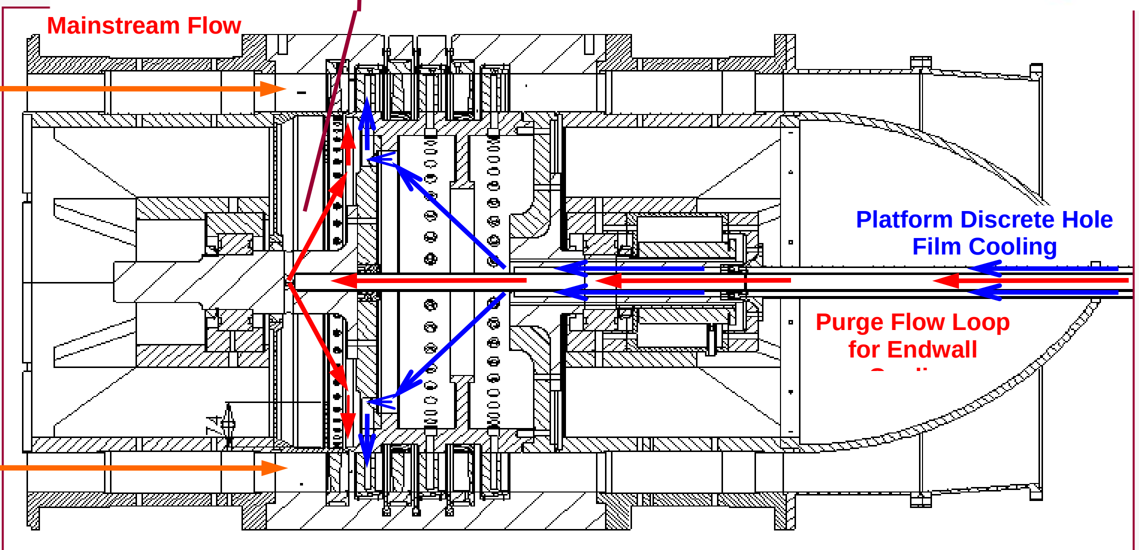
Effect of purge flow Injection on aerodynamic performance and film cooling effectiveness on a rotating turbine with and without endwall contouring is numerically investigated. Following steps were performed:

- **A grid was generated, its density optimized to ensure grid independence results. It starts from:**
- **Rotor cavity**
- **Turbine inlet,**
- **Followed by the first rotor row (contoured)**

II: Purge Flow Injection, Endwall Contouring, Film Cooling



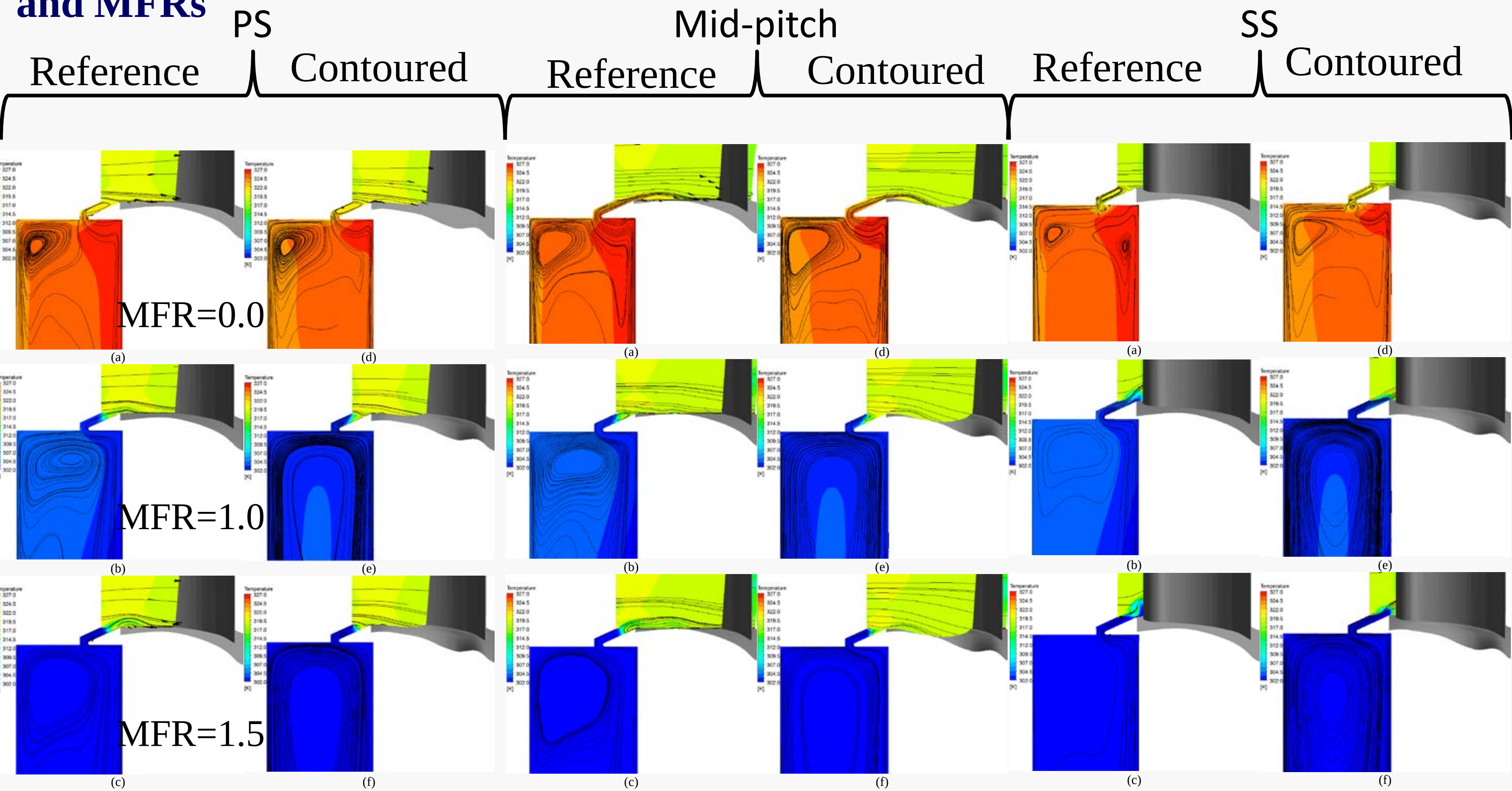




Number elements: 2M
Total elements: 9M
Number of nodes: 22 at the wall
Numerical simulation: RANS (CFX)
Turbulence model: SST

II: Interaction of Endwall Contouring with the Cavity

Temperature distributions within the cavity at three circumferential positions and MFRs



II: Results: First Rotor Endwall Exposed to Flow Injection

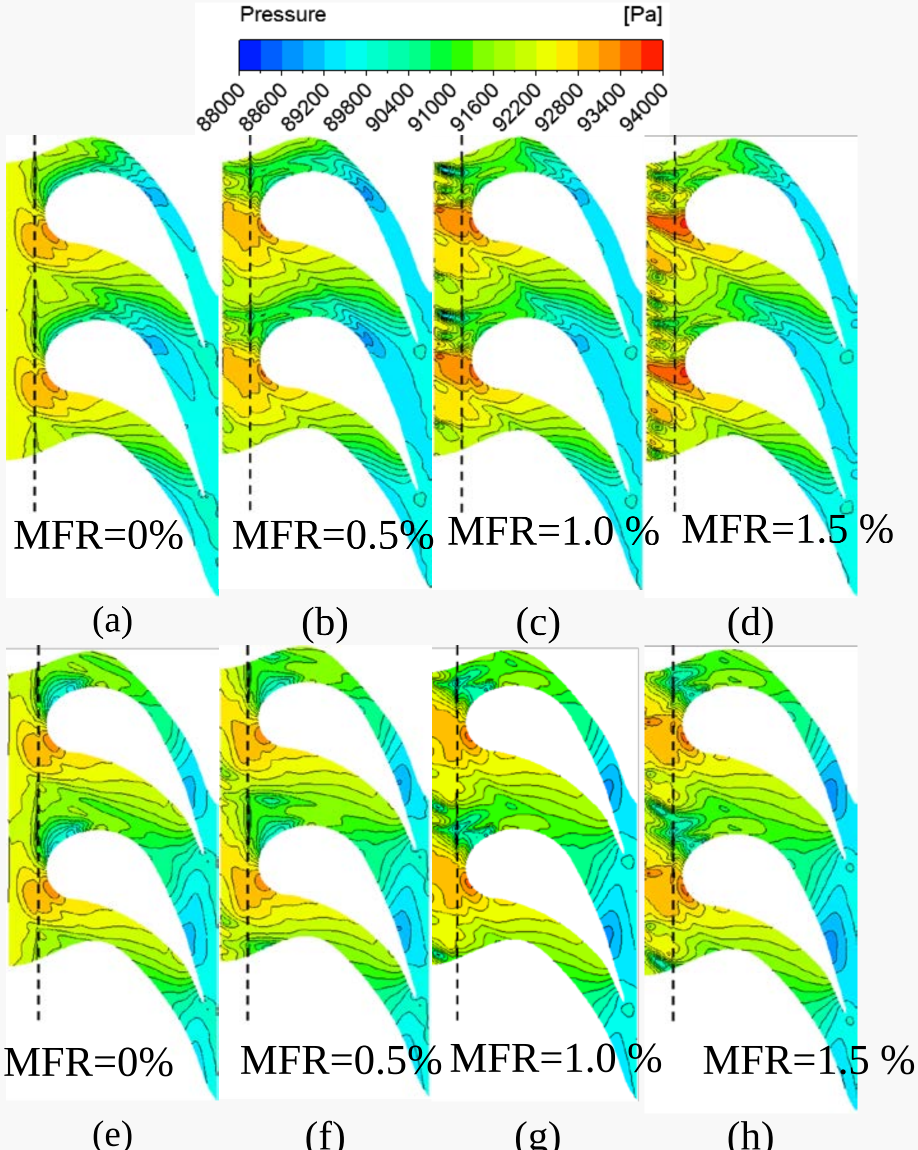
Pressure distribution at 0% span:

◆**Reference case with different mass flow ratios**

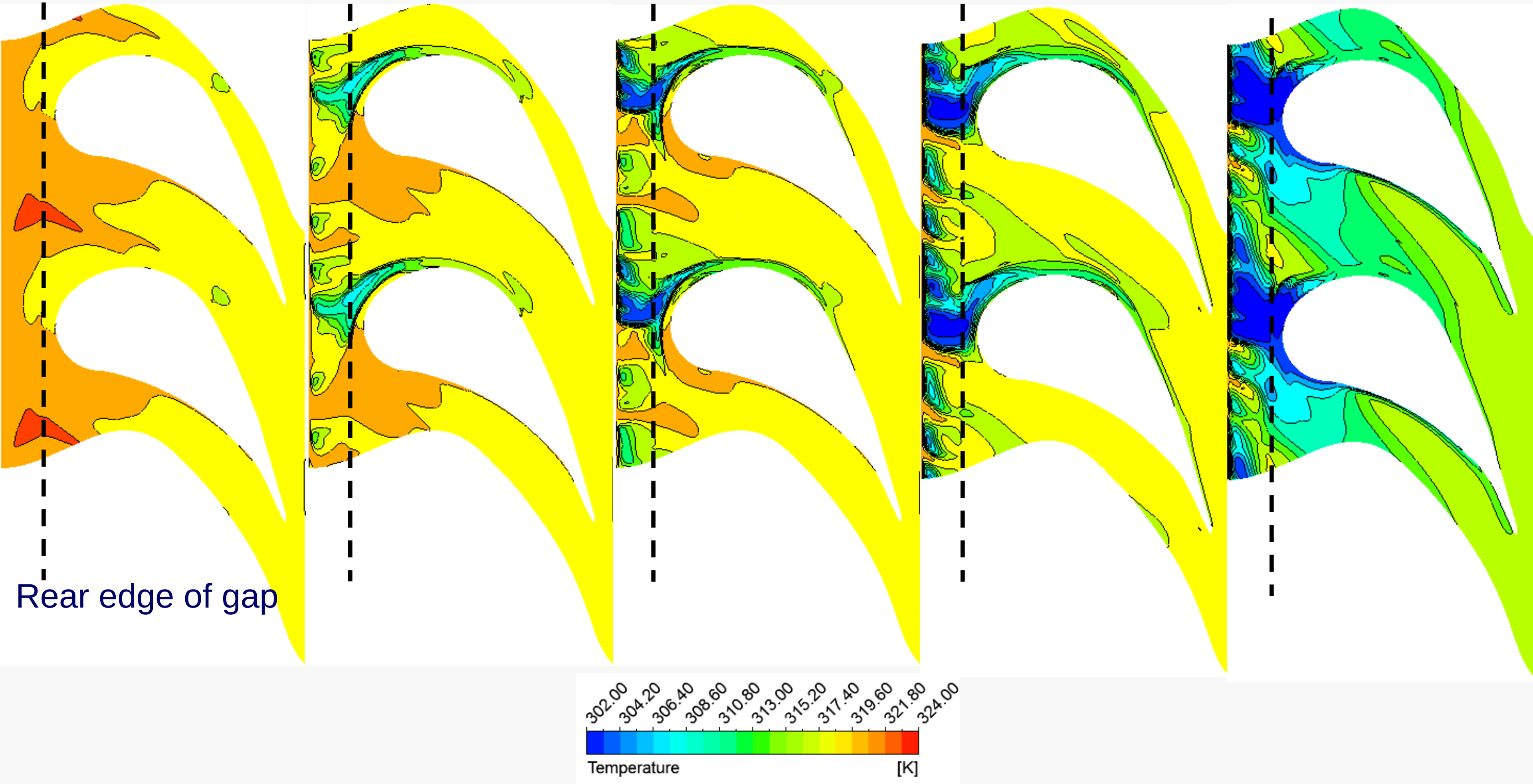
(a) Reference case with MFR=0%
(b) Reference case with MFR=0.5%
(c) Reference case with MFR=1.0%
(d) Reference case with MFR=1.5%

◆**New contouring with different mass flow ratios**

(e) New contouring with MFR=0%
(f) New contouring with MFR=0.5%
(g) New contouring with MFR=1.0%
(h) New contouring with MFR=1.5%.



II: Temperature Distribution Contour at 0% Span



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

II : Purge Flow Injection, Film Cooling Effectiveness

Pressure distribution at 0% span:

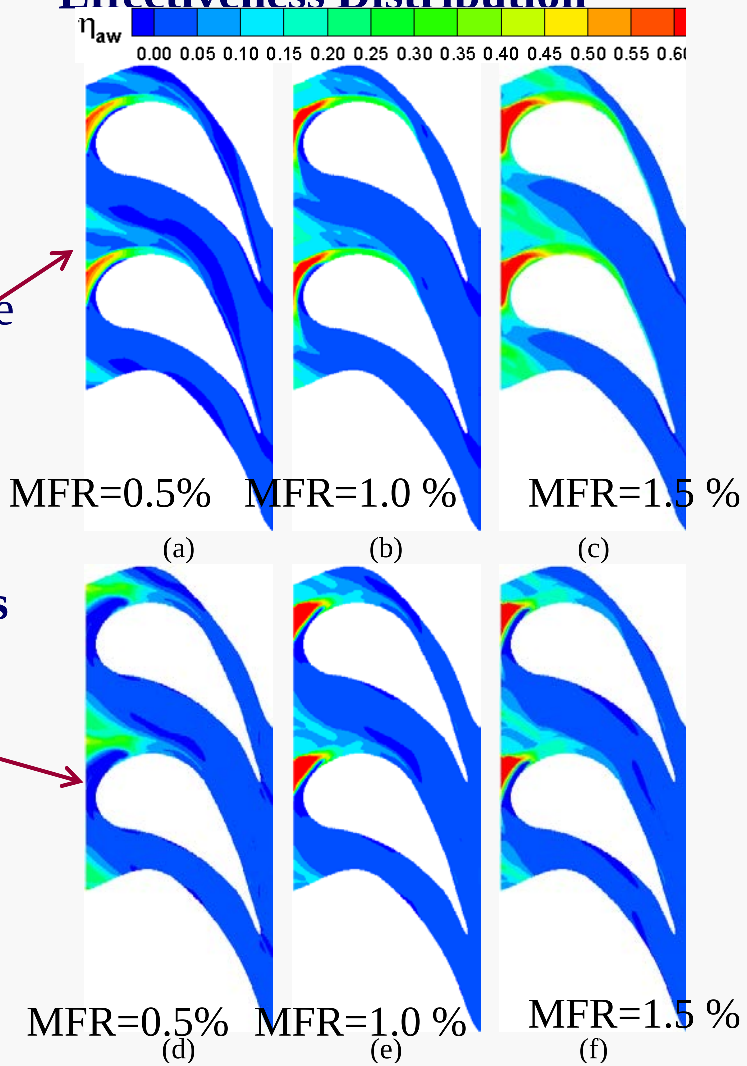
Reference case with different mass flow ratios

(a) Reference case with MFR=0%
(b) Reference case with MFR=0.5%
(c) Reference case with MFR=1.0% (d) Reference case with MFR=1.5%

New contouring with different mass flow ratios

(e) New contouring with MFR=0%
(f) New contouring with MFR=0.5%
(g) New contouring with MFR=1.0%
(h) New contouring with MFR=1.5%.

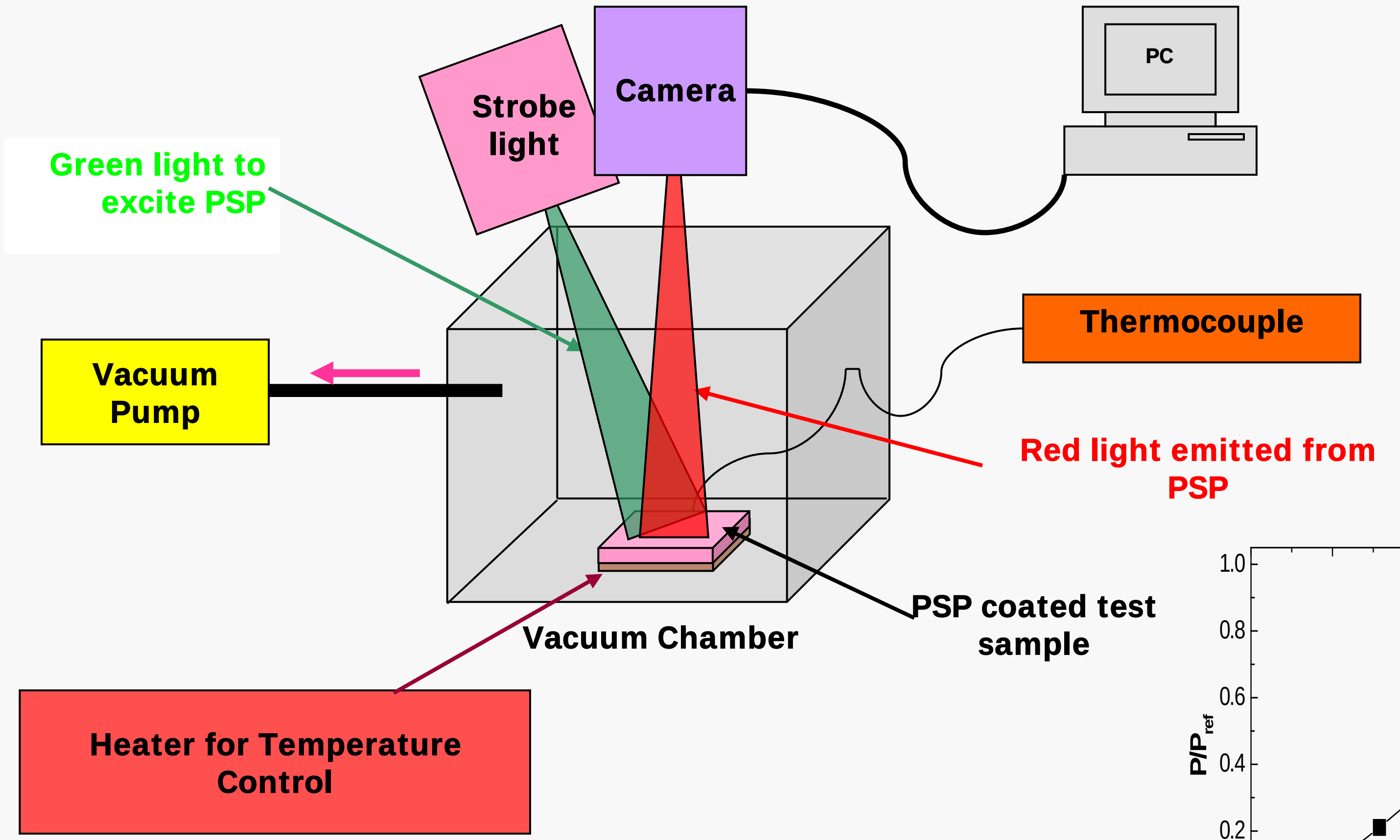
Effectiveness Distribution



II Experimental Results: Film Cooling Under Purge Flow

- **Pressure sensitive paint (PSP) is used to measure the film cooling effectiveness on the 1st rotor row endwall.**
- **The paint is first calibrated under different pressure and temperature conditions.**
- **Endwall test cases (completed, ongoing)**
  - **Reference Case: 2400 rpm, 2550 rpm and 3000 rpm (Completed)**
  - **Contoured case: 3000 rpm, MFR=1 (Competed)**
    - **MFR=0.5, 1.5 (Ongoing)**
    - **The process will be repeated for 2400 rpm and 2550 rpm**

PSP - Calibration



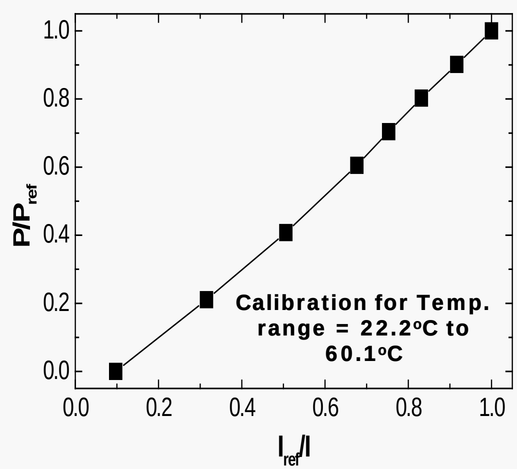
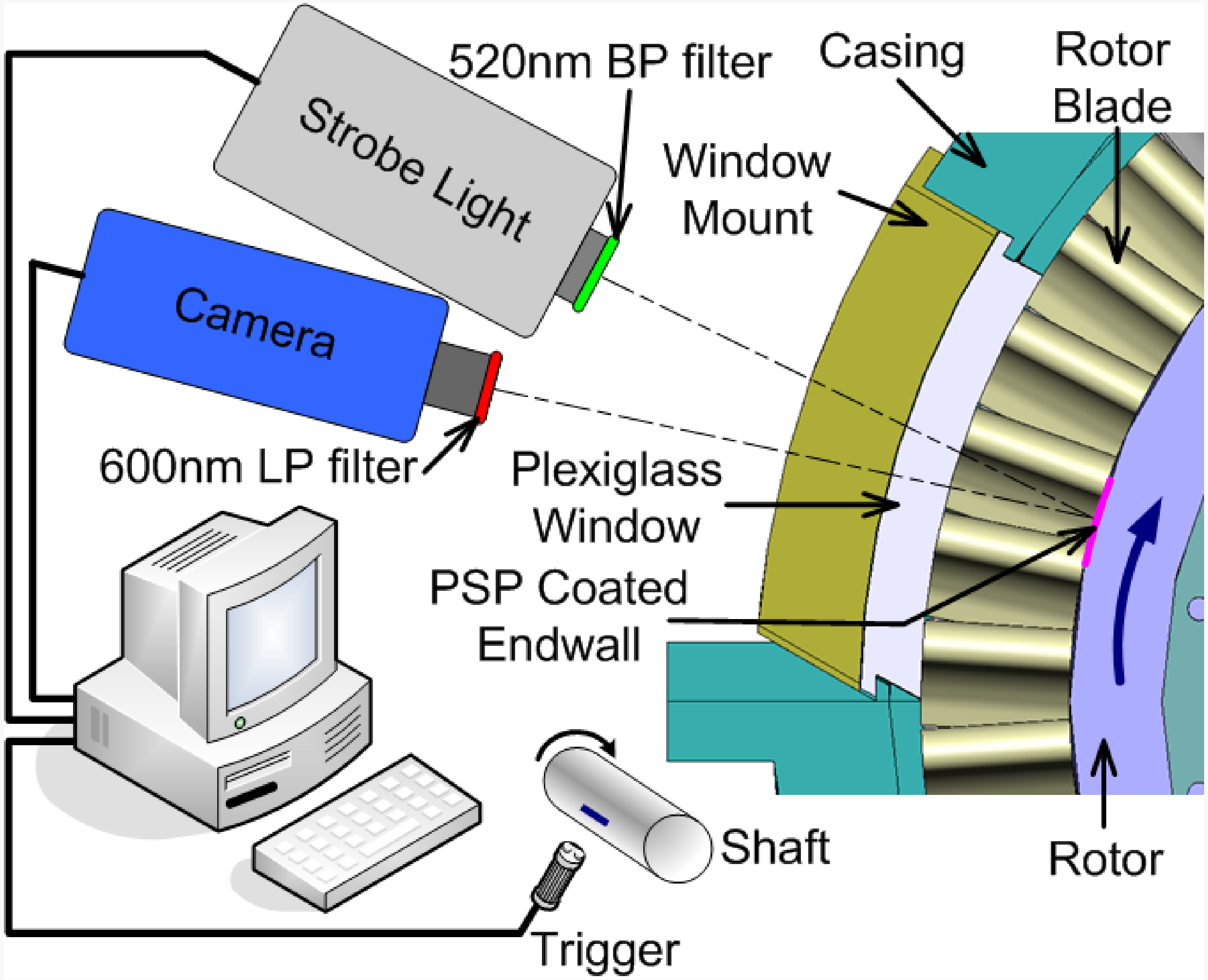


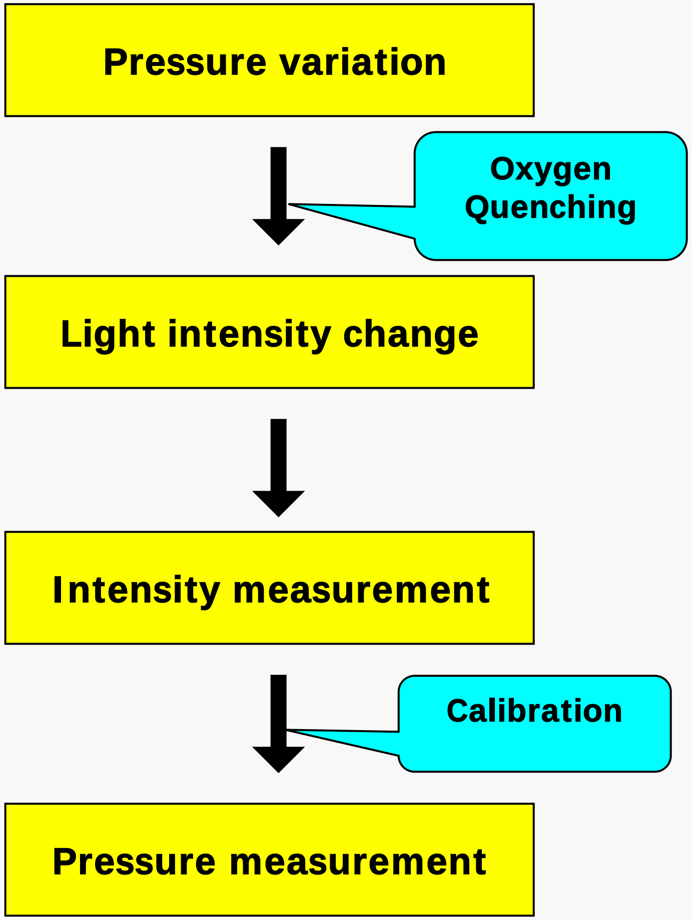
Fig. 6 Calibration Curve for PSP

II: Experimental Facility

- **Block diagram of the experimental facility**



- **PSP measurement methodology**

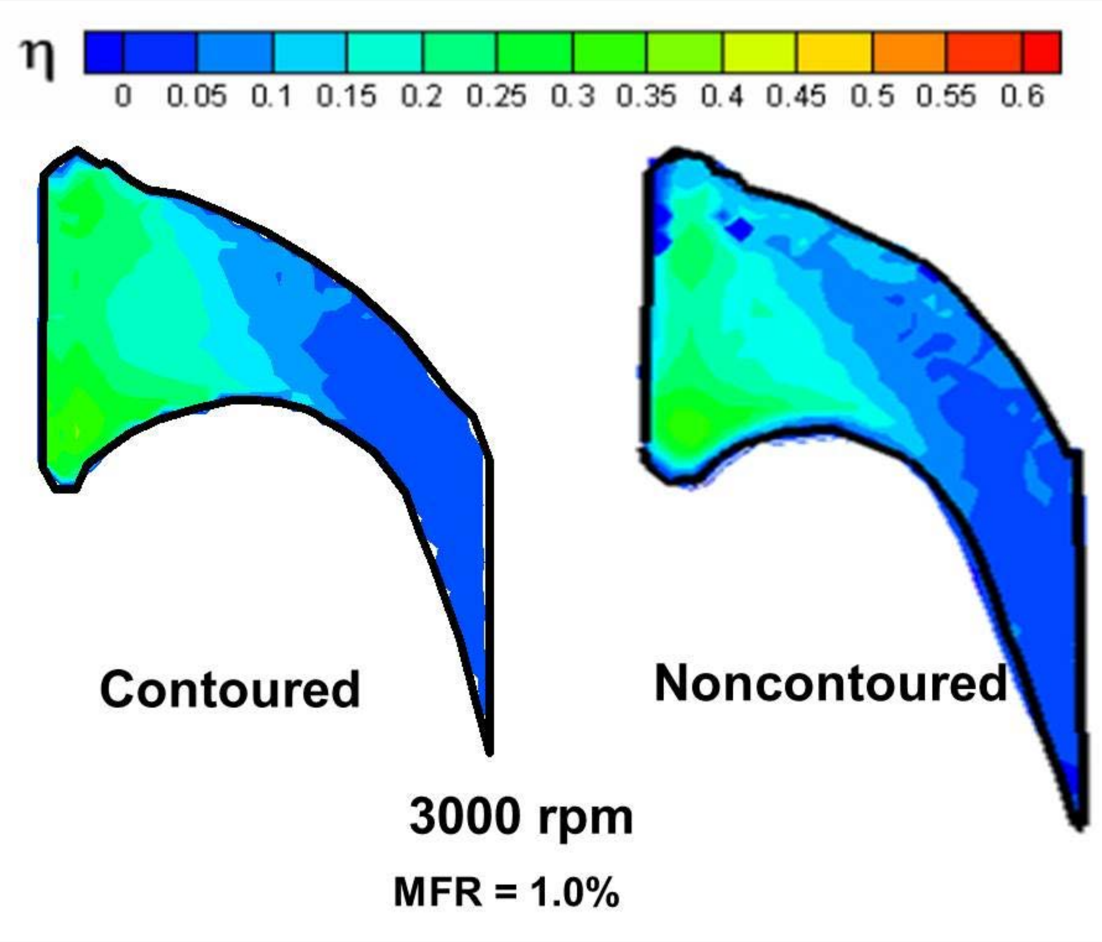


II: Results, Contoured vs. Non-contoured

Completed:
MFR = 1.0 at 3000 rpm

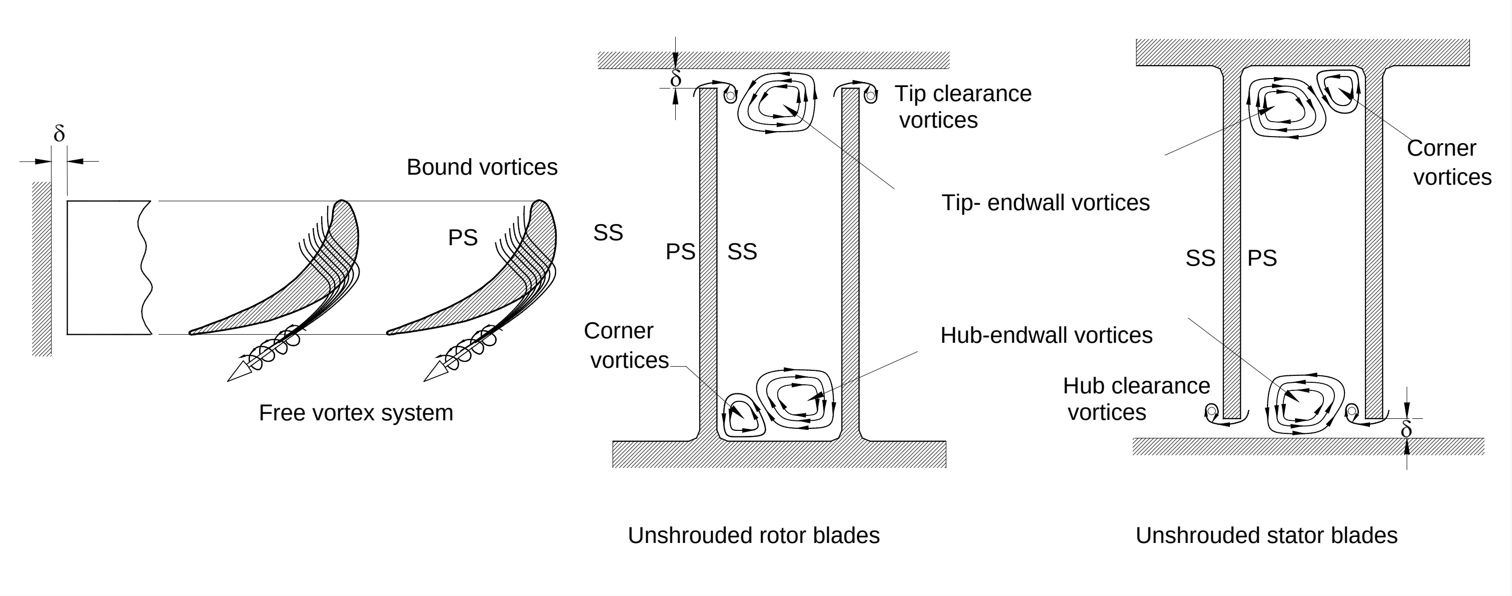
In progress:
MFR = 0.5, 1.5, 2.0

October 2012-
Experiments at 2400, 2550 rpm and the above MFR



III: Blade Tip Film Cooling

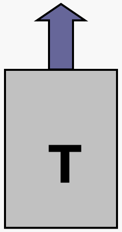
Major body of publicly available literature relative to tip clearance aerodynamics and heat transfer deal with stationary cascade flow.

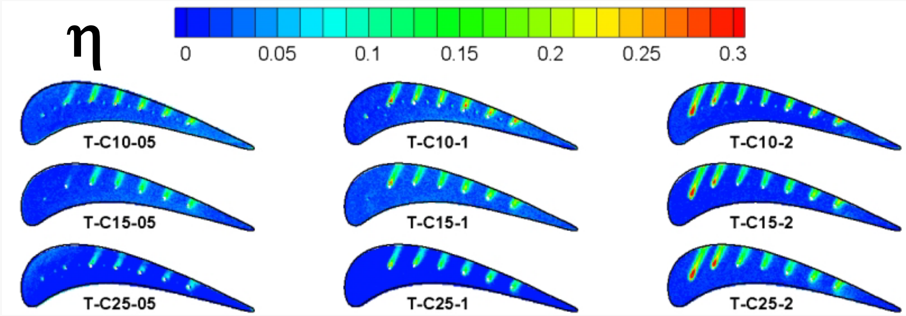


Non-rotating cascade:
Fluid particles move from pressure to suction surface and build a system of bound vortices.

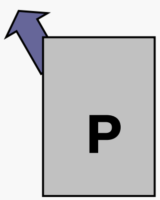
From: M.T. Schobeiri: Turbomachinery Flow Physics and Dynamic Performance, 2nd Edition, Springer Verlag, 2010

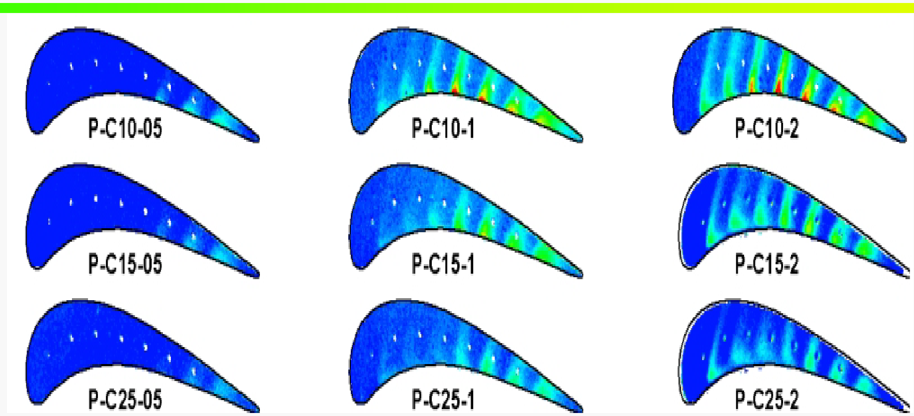
Results – Film Effectiveness on Plane Tip, Combinations



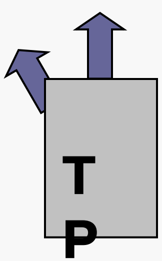


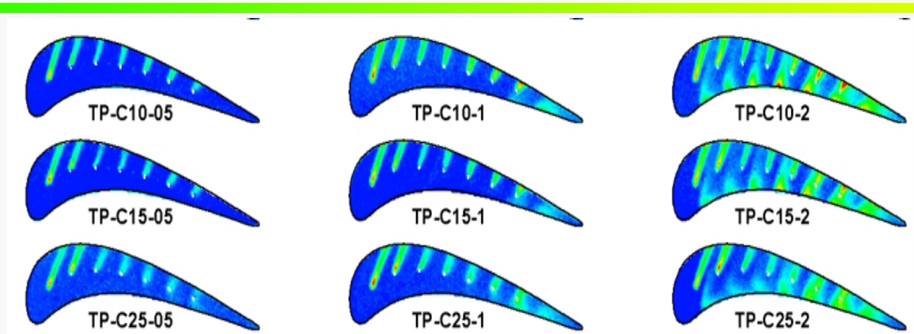
Conventions
T-C10-05 Means
T = Top ejection
C10 = 1.0% Clearnce
05 = Blowing ratio of 0.5



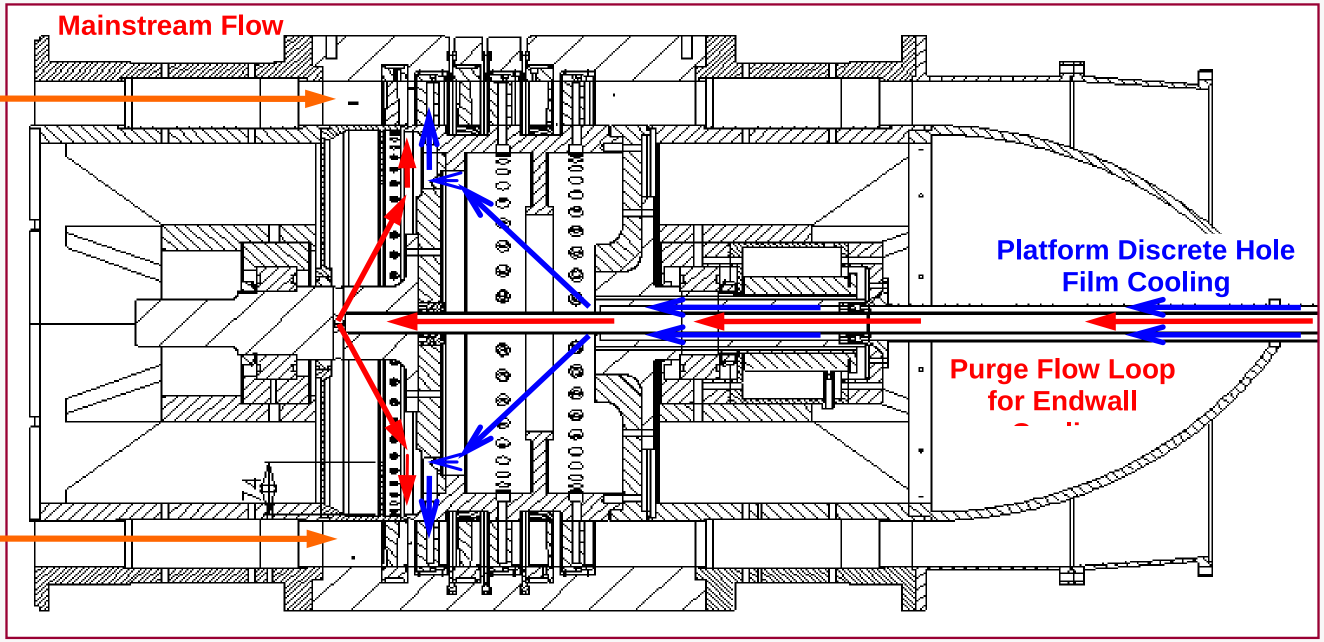


From:
Han et al.
GT-2004-53249



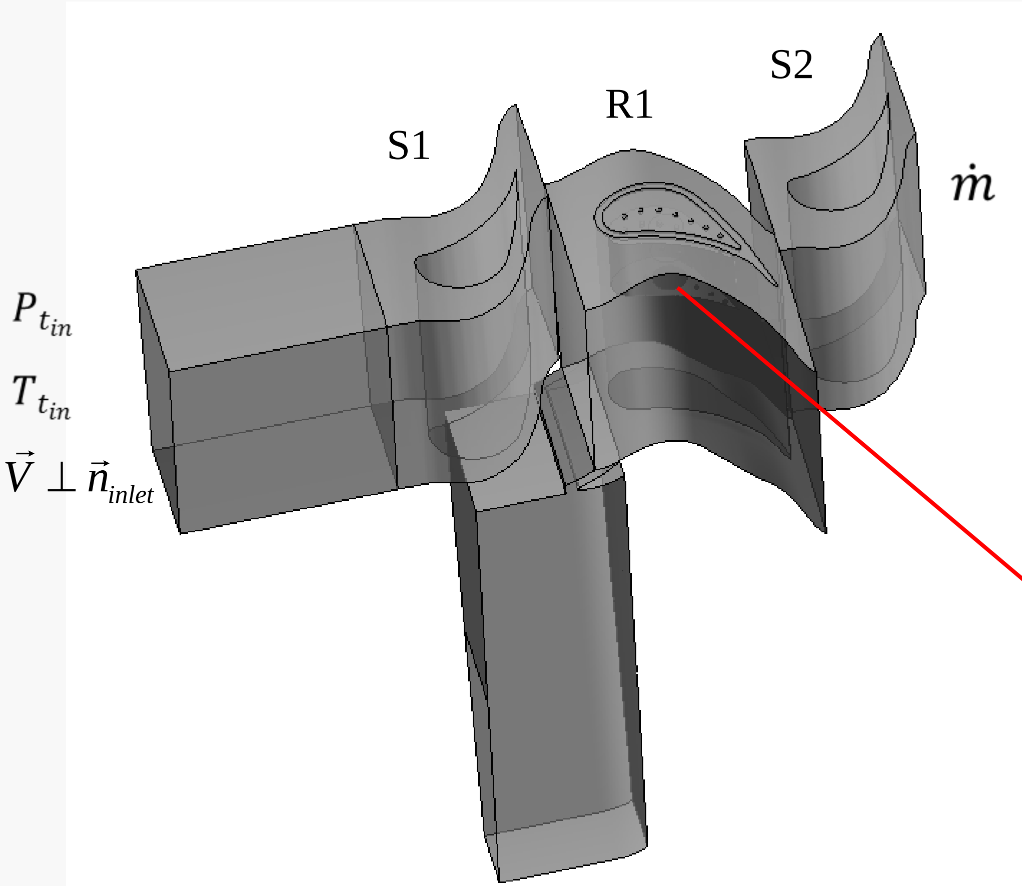


II: Purge Flow Injection, Endwall Contouring, Film Cooling

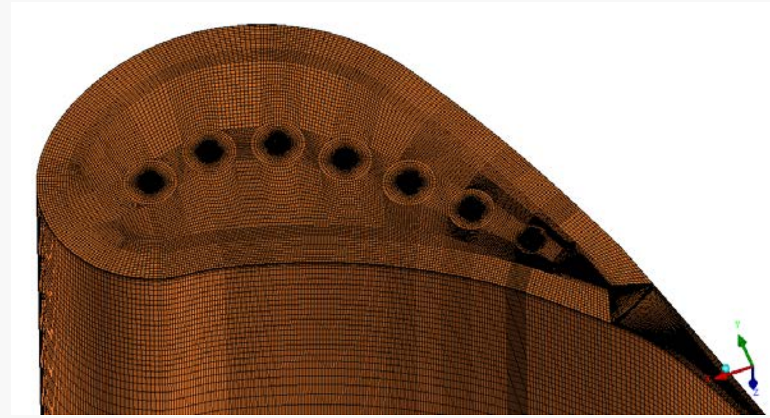


External cooling loop provides cooling fluid (air, N2) to blades with tip ejection holes

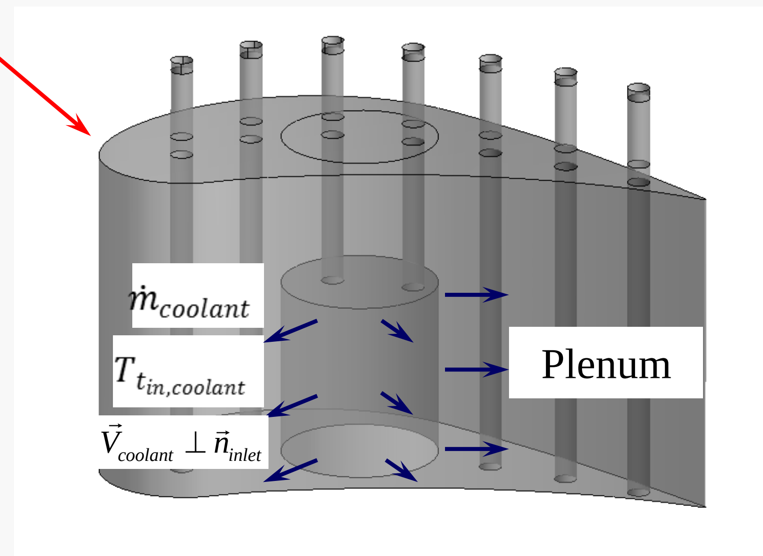
Prediction of Plane Tip with Tip Hole Cooling



Computational domain includes the first stator (S1), first rotor (R1) and second stator (S2).

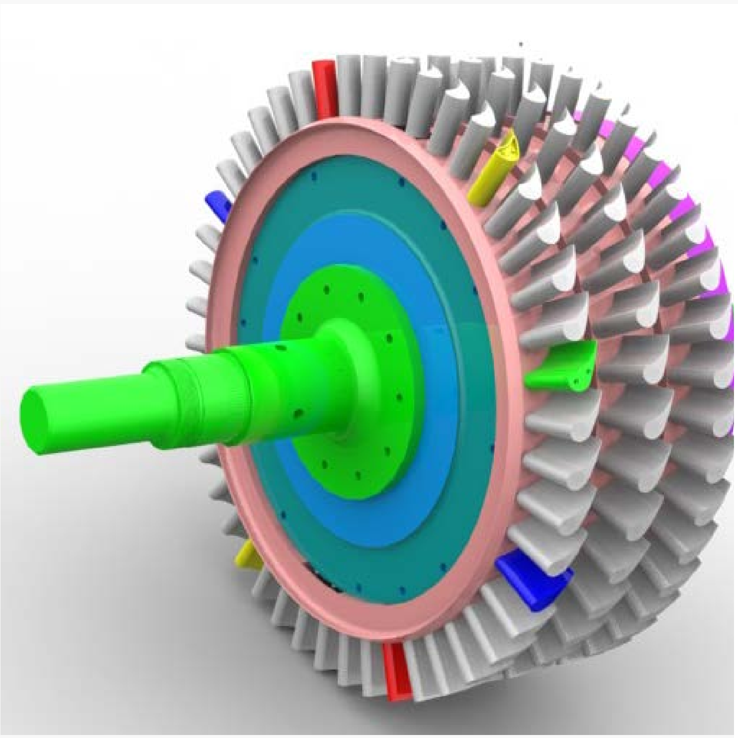


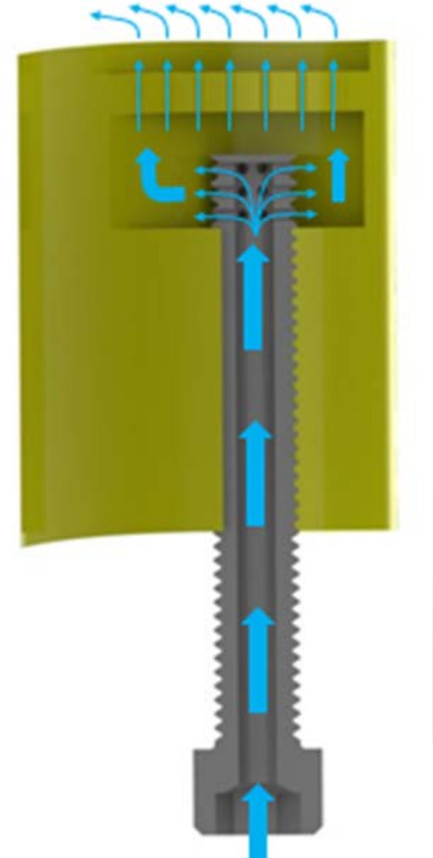
Mesh at blade tip with seven perpendicular cooling holes along the mean camber Line.



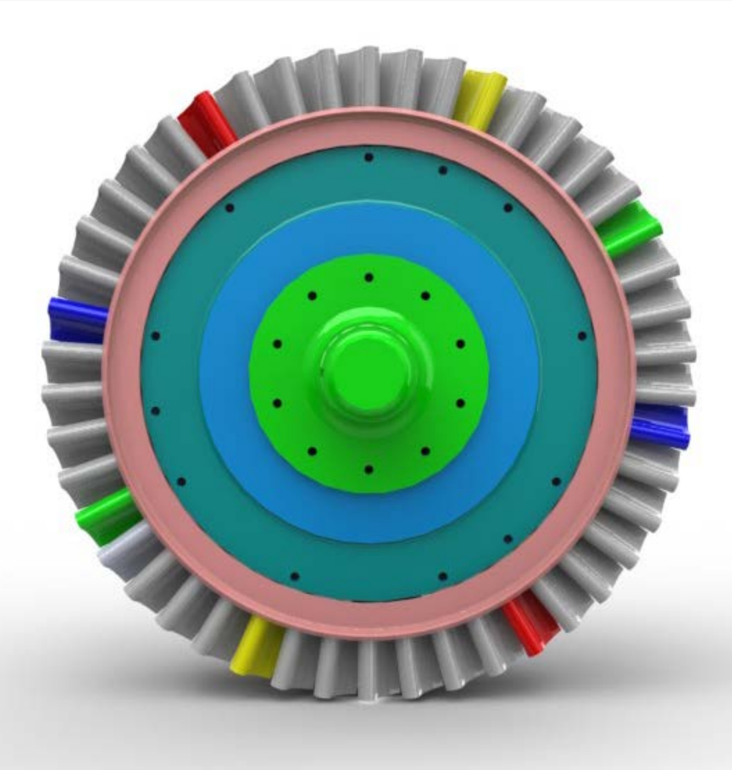
Ongoing Research Work: Blade Tip Film Cooling

- Four pairs of blades with different ejection hole geometries are attached to the hub
- Blades with identical geometry are arranged diametrically

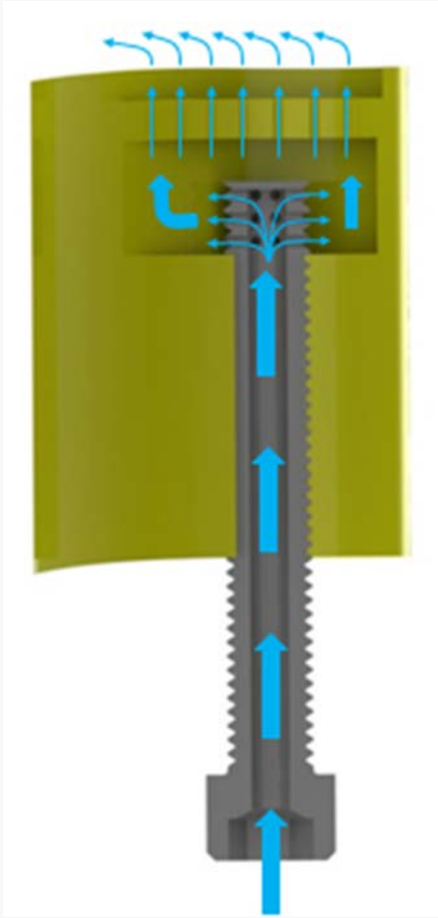


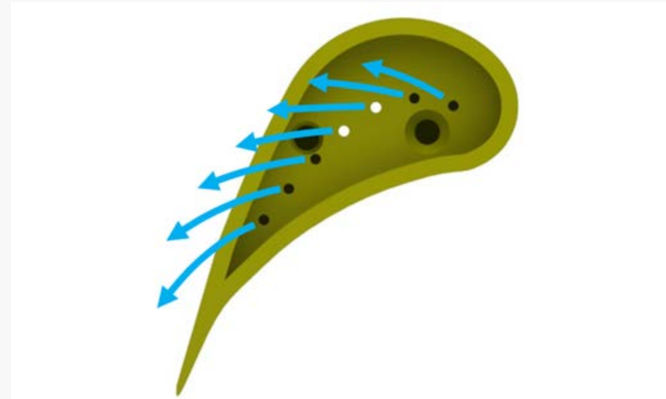


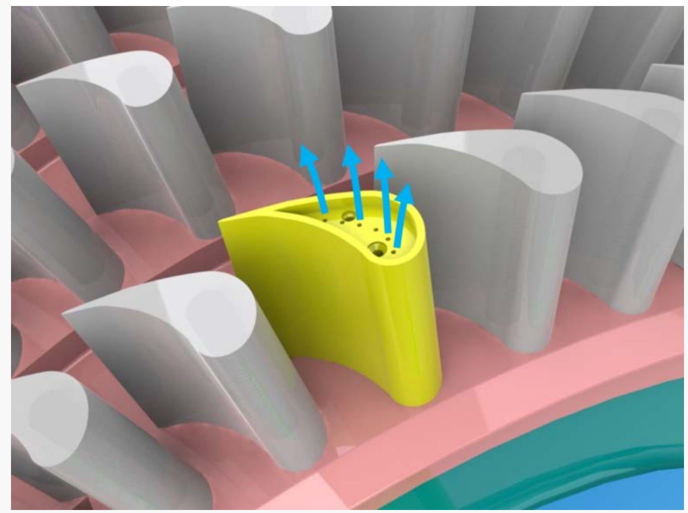
Coolant injected from external loop



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.

III: Prediction of Plane Tip with Tip Hole Cooling

Adiabatic Film Cooling Effectiveness

$$\eta_{aw} = \frac{T_{aw,f_0} - T_{aw,f}}{T_{aw,f_0} - T_c}$$

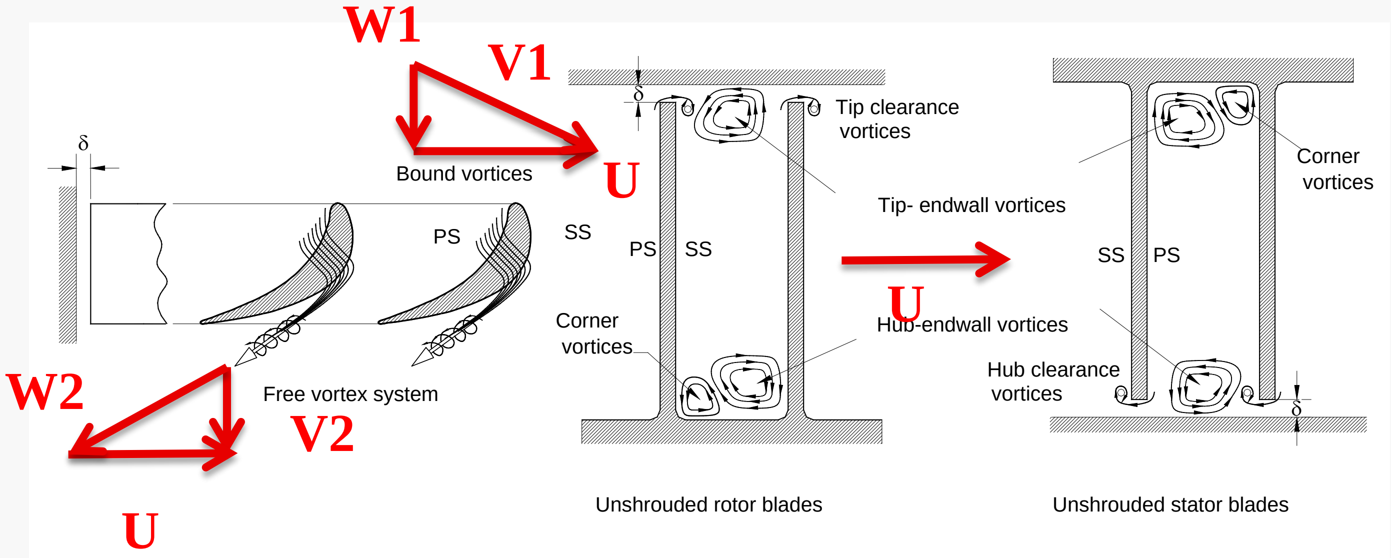
T_{aw,f_0}: adiabatic wall temperature obtained with the coolant that is as hot as mainstream.

$T_{aw,f}$: adiabatic wall temperature obtained with the coolant that is cooler than mainstream.

T_c: coolant temperature that is lower than mainstream.

III: Difference between Stationary and Rotating Cascade

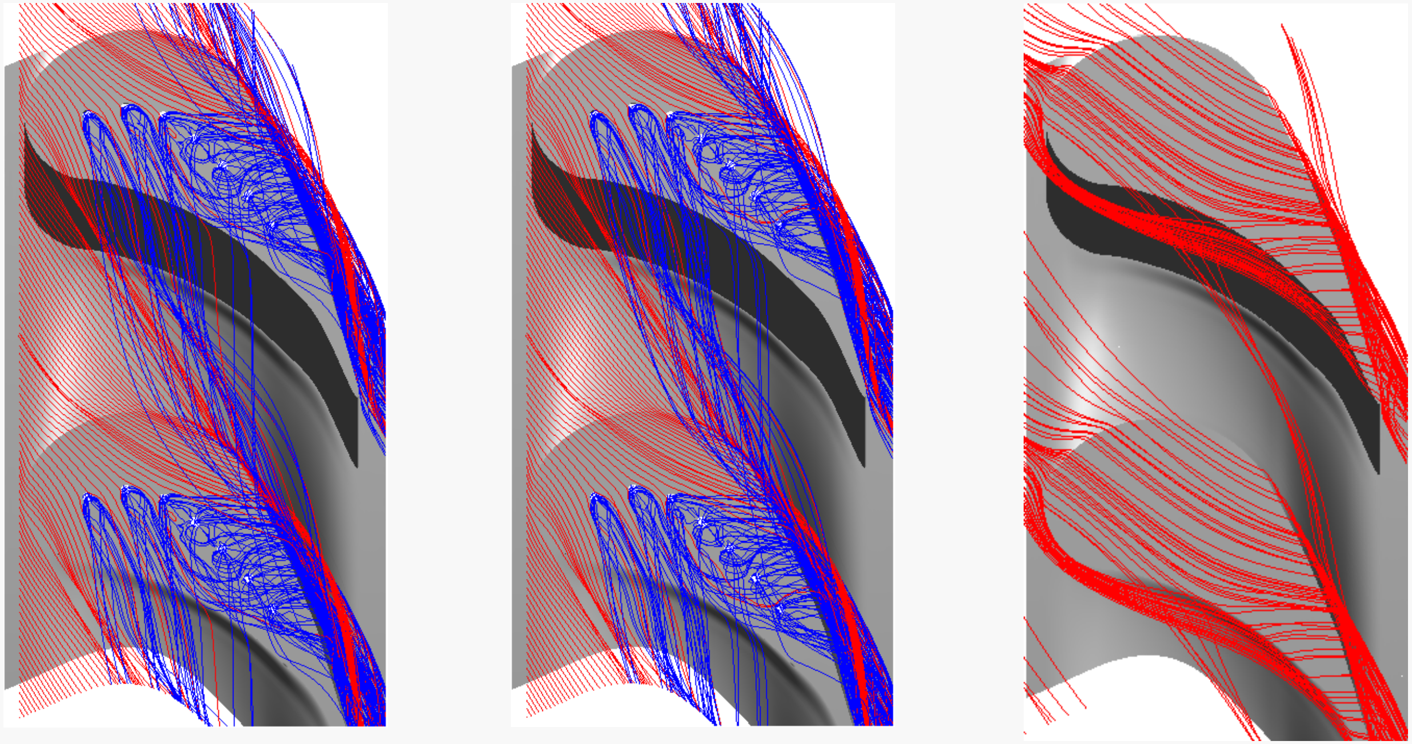
This simple sketch shows what will change when the stationary blade start rotating



Rotating cascade:
Fluid particles move from the suction to pressure surface and push the cooling jet away from the blade tip.

Prediction of Plane Tip with Tip Hole Cooling

Streamlines in rotating frame at blade tip region



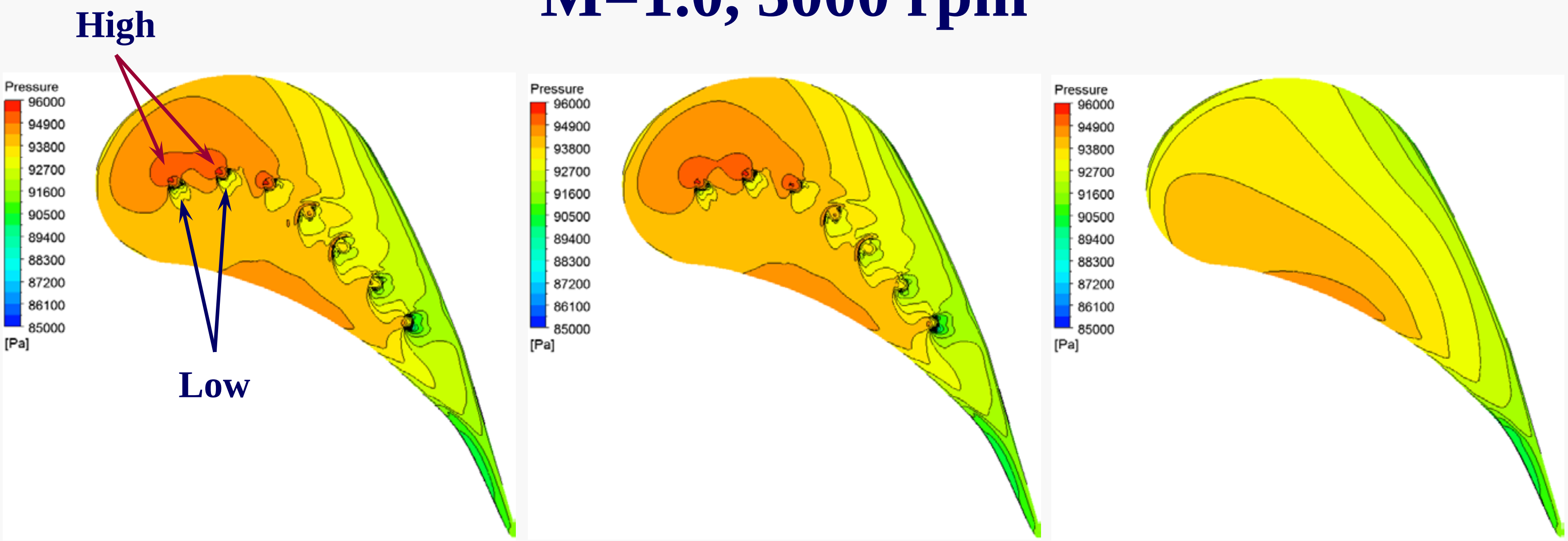
(a) $T_{t,\ coolant}$=318K (b) $T_{t,\ coolant}$=300K (c) Without film cooling

Note: The red streamlines mark the hot mainstream flow, while the blue ones mark the film cooling.

Prediction of Plane Tip with Tip Hole Cooling

Pressure distribution at blade tip

M=1.0, 3000 rpm

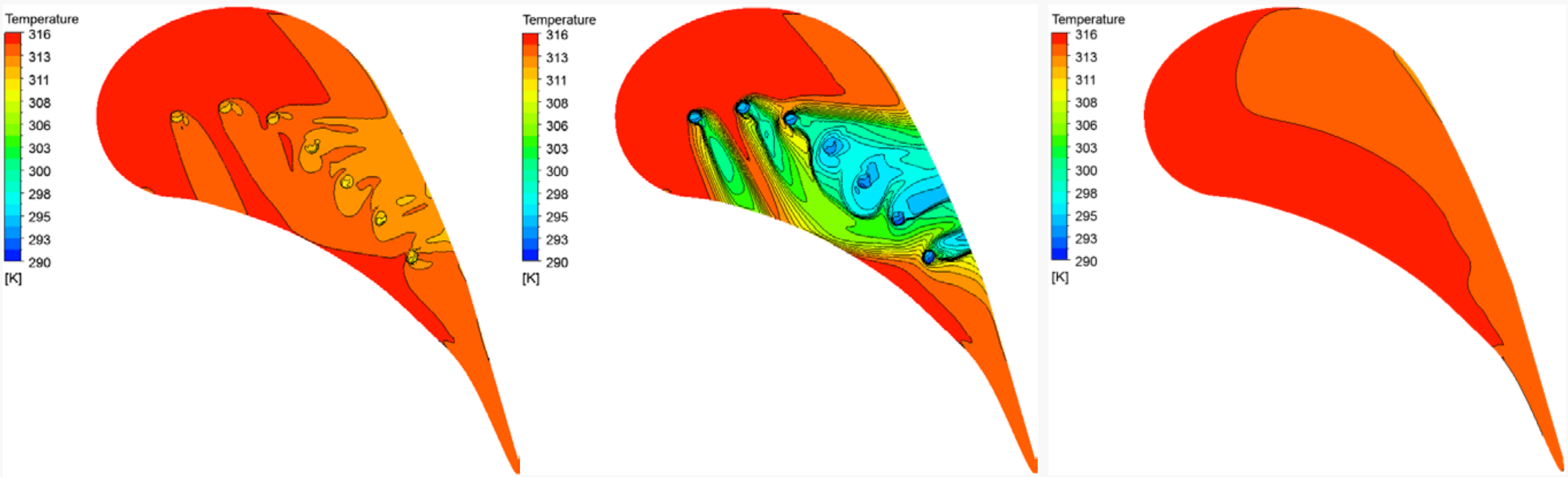


(a) $T_{t,\ coolant}$=318K **(b) $T_{t,\ coolant}$=300K** **(c) Without film cooling**

Prediction of Plane Tip with Tip Hole Cooling

Adiabatic wall temperature distribution at blade tip

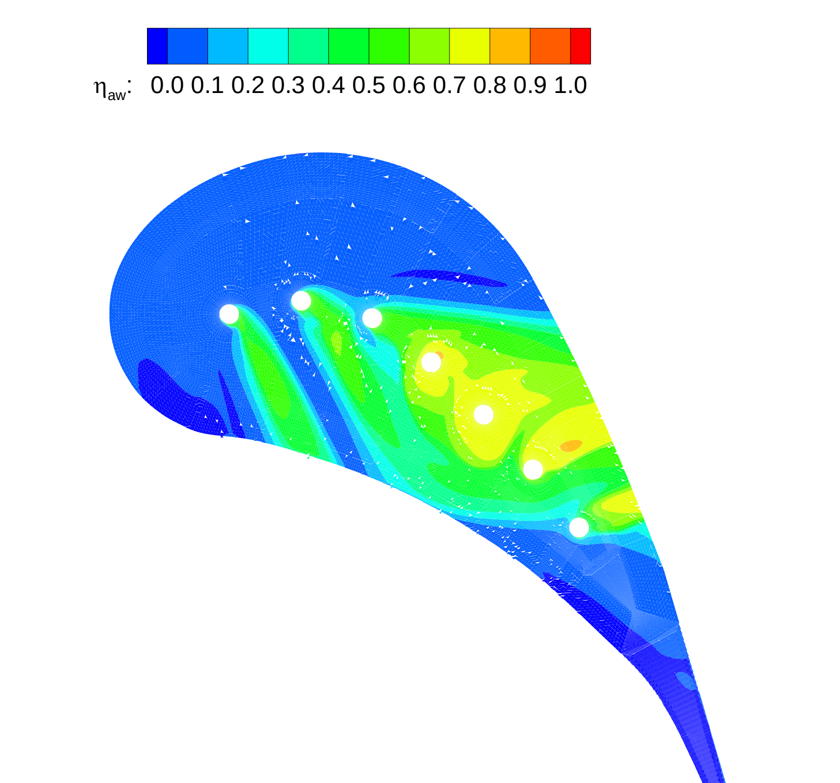
M=1.0, 3000 rpm



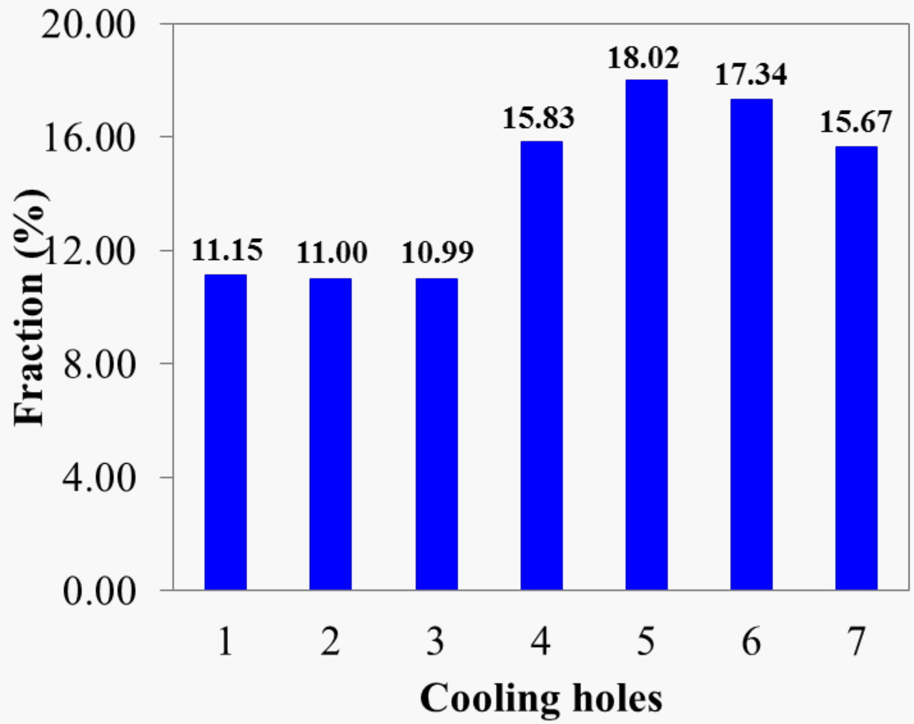
(a) $T_{t,\ coolant}$=318K **(b) $T_{t,\ coolant}$=300K** **(c) Without film cooling**

Prediction of Plane Tip with Tip Hole Cooling

Distribution of adiabatic film cooling effectiveness at blade tip



M=1.0, 3000 rpm



MFR fraction of each cooling hole

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

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Conclusions

I Endwall contouring

- Applying the new, physics based endwall contouring method to the second rotor row of an existing three-stage turbine with six rows, an increase of $\Delta\eta = 1.04\%$ has been achieved, which is above the predicted $\Delta\eta = 0.68\%$.
- The method is equally applicable to gas and steam turbine. In context of IGCC, the application of the endwall contouring to a 16-stage 200 MW HP-bottoming unit will improve the efficiency up to 4%.

II: Purge Flow Injection

- Due to the existence of the circumferential ejection slot for purge flow, the contouring for the 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.

Prediction of Plane Tip with Tip Hole Cooling

II First rotor row under exposed to purge

No substantial changes in efficiency and film coverage compared to non-contoured reference case.

III Blade Tip Ejection

The film cooling under rotating condition is distinctively different from the one without rotation. Thus, the arrangement of the holes their location and ejection angle must be based on the rotational condition.

Thanks for Your Time and Attention.