Heat Transfer from Rotating Blade Platforms with and without Film Cooling

Texas A&M University

J.C. Han and M.T. Schobeiri

SCIES Project 03-01-SR113

DOE COOPERATIVE AGREEMENT DE-FC26-02NT41431

Tom J. George, Program Manager, DOE/NETL
Richard Wenglarz, Manager of Research, SCIES

Project Awarded 07/01/2003 (36 Month Duration)

$461,024 Total Contract Value ($361,024 DOE)

Gas Turbine Needs

- **Improved Turbine Power Efficiency by Increasing Turbine Blade Cooling Performance**
  - Increase Turbine Inlet Temperature while Minimizing Coolant Flow
- Need Detailed Heat Transfer Data on Rotating Blade Platforms
  - Improve Current Rotor Blade Cooling Schemes
  - Provide Options for New Rotor Blade Cooling Designs
- Need Accurate and Efficient CFD Codes to Improve Flow and Heat Transfer Predictions and Guide Rotor Blade Cooling Designs

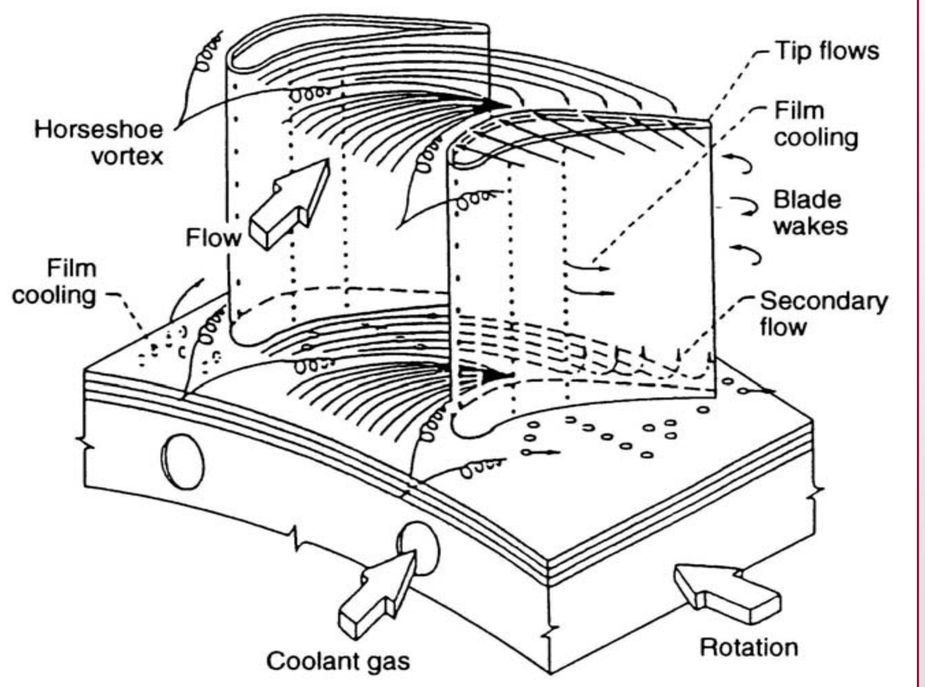
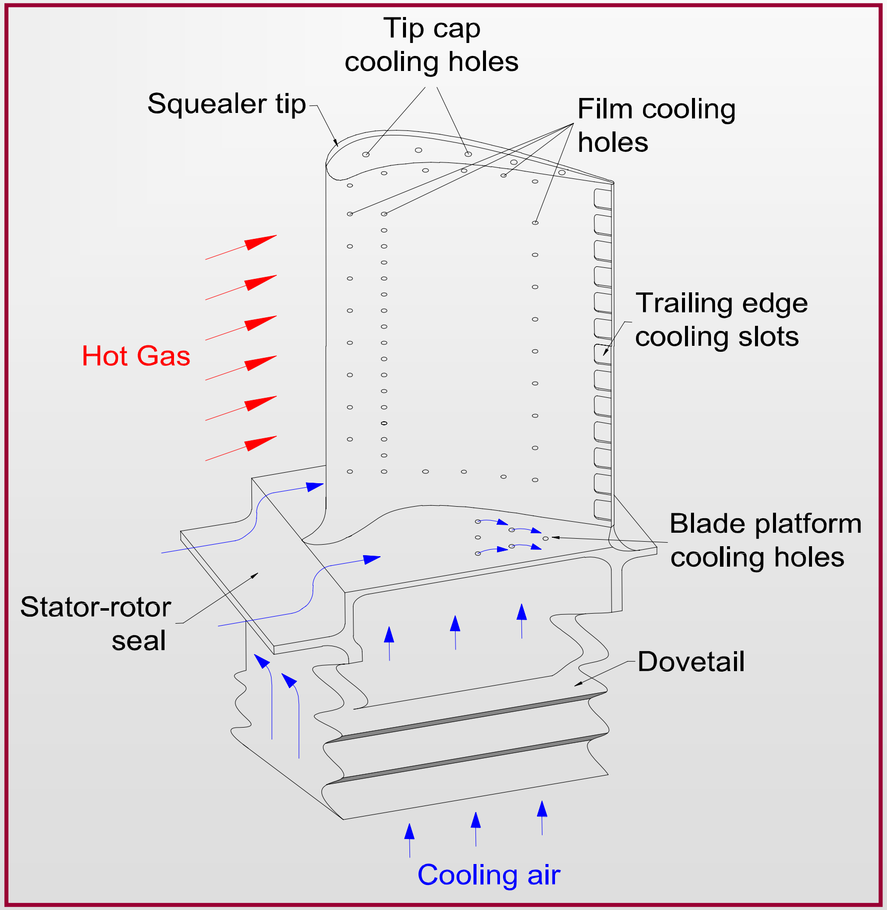


Figure 3.1: A typical cooled airfoil (Hyams et al., 1996).

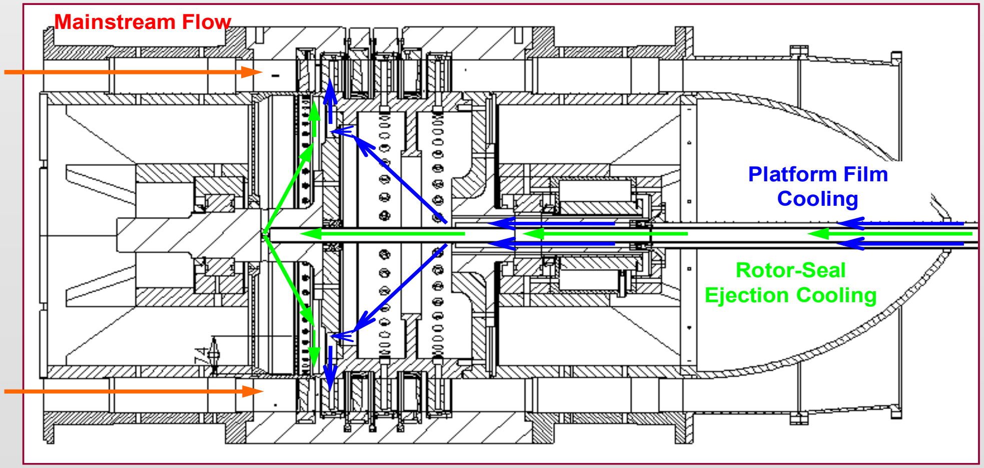
Project Objectives

- **Provide Designers with New Rotating Blade Platform Heat Transfer and Film Cooling Data and Numerical Predictions**
  - Improve Cooling Performance and Thermal Efficiency of Gas Turbine Engines
- **Part I: Experimental Rotating Heat Transfer**
  - Pressure, Heat Transfer Coefficient, and Film Cooling Effectiveness Distributions on Rotating Blade Platforms with Stator-Rotor Seal Ejection and Film Cooling
- **Part II: Flow Measurements and Numerical Predictions**
  - Detailed Flow Measurements and Surface Heat Transfer Predictions on Rotating Blade Platforms under Rotating Conditions



Project Approach

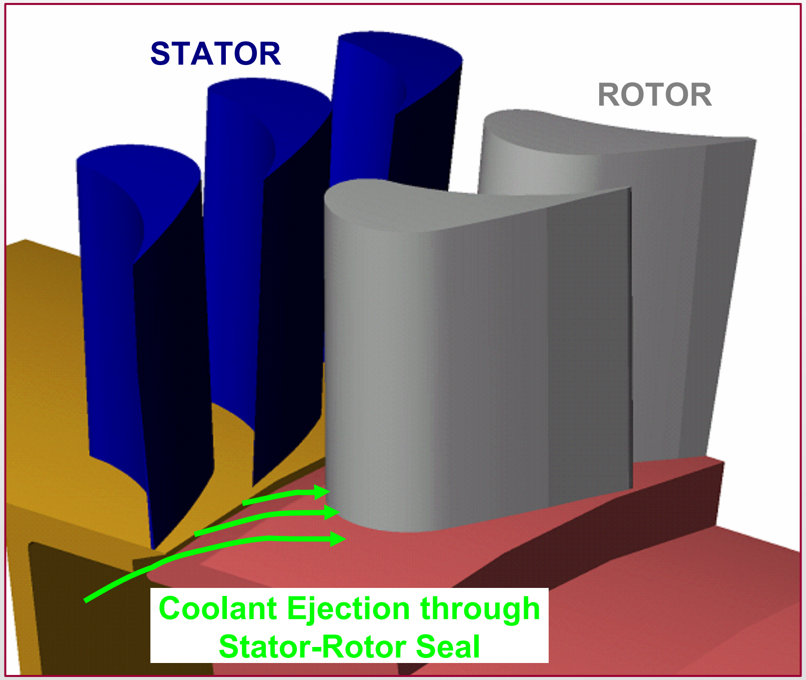
- **This Project Contains Three Tasks for Rotating Blade Platforms Using Experimental and Computational Methods**
- **Task 1: Rotor Platform Modification and Measurement Technique Development**
  - Design, Fabrication, Installation, and Instrumentation of Modified Rotor with Coolant Ejection from Stator-Rotor Seal and Film Cooling for Platform
  - Design and Calibration of Several Miniature Five-Hole Probes and Preliminary Flow Measurements
  - Development of Pressure Sensitive Paint (PSP) and Temperature Sensitive Paint (TSP) Techniques
  - Preliminary Flow and Heat Transfer Predictions using FLUENT Code (secondary effort)



Project Approach

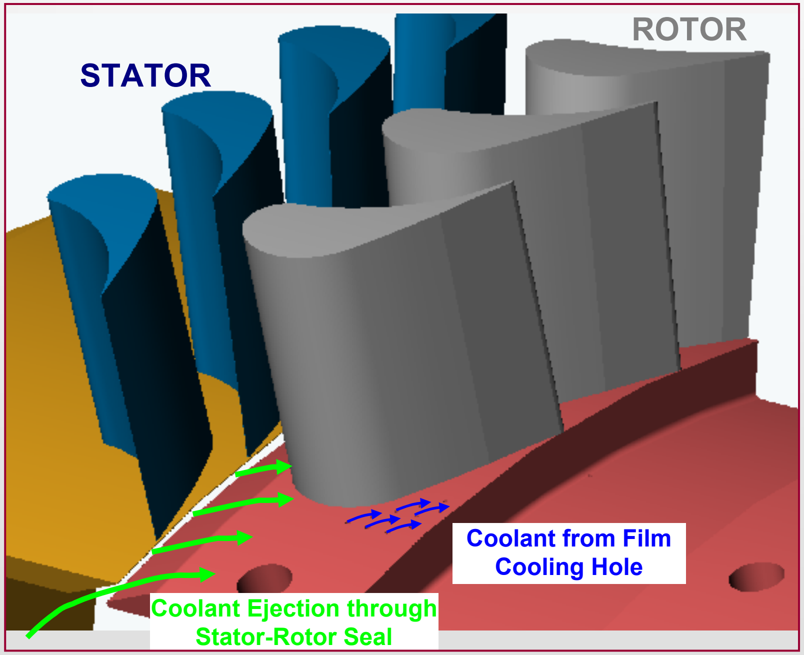
- **This Project Contains Three Tasks for Rotating Blade Platforms Using Experimental and Computational Methods**

- **Task 2: Rotor Blade Platforms with Stator-Rotor Seal Ejection**
  - Detailed Flow Measurements Using Miniature Five-Hole Probes
  - Detailed Pressure and Film Effectiveness Distributions using Pressure Sensitive Paint (PSP)
  - Detailed Heat Transfer Coefficient Distributions using Temperature Sensitive Paint (TSP)
  - Predicted Flow and Heat Transfer Distributions using FLUENT code (a secondary effort)



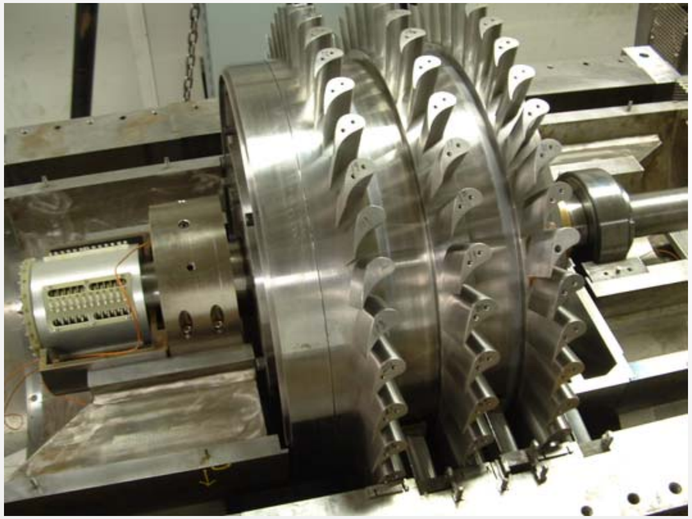
Project Approach

- **This Project Contains Three Tasks for Rotating Blade Platforms Using Experimental and Computational Methods**
- **Task 3: Rotor Blade Platforms with Stator-Rotor Seal Ejection and Film Cooling Holes**
  - Detailed Flow Measurements Using Miniature Five-Hole Probes
  - Detailed Pressure and Film Effectiveness Distributions using PSP
  - Detailed Heat Transfer Coefficient Distributions using TSP
  - Predicted Flow and Heat Transfer Distributions using FLUENT code (a secondary effort)

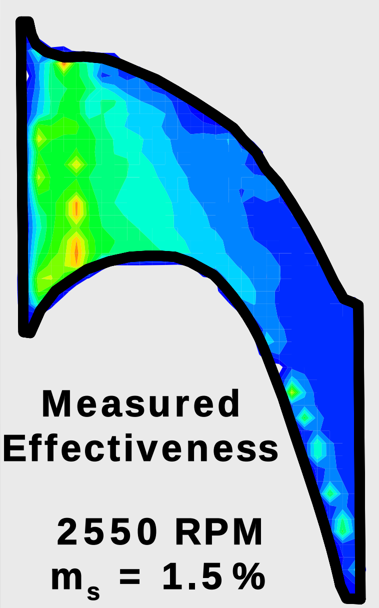


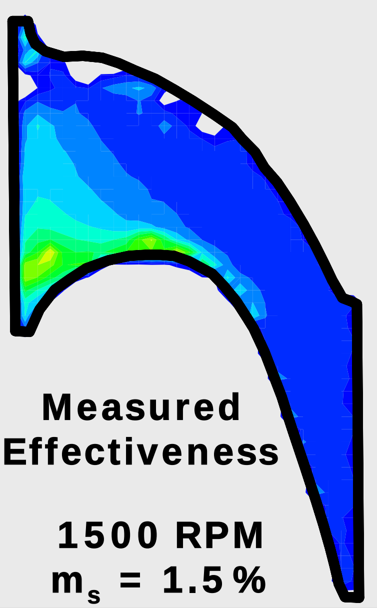
Project Accomplishments

- **Task 1 (Year 1) – Rotor Platform Modification**
  - Rotor Fabrication, Installation, & Instrumentation is Complete
  - PSP and TSP Measurement Techniques have been Successfully Developed



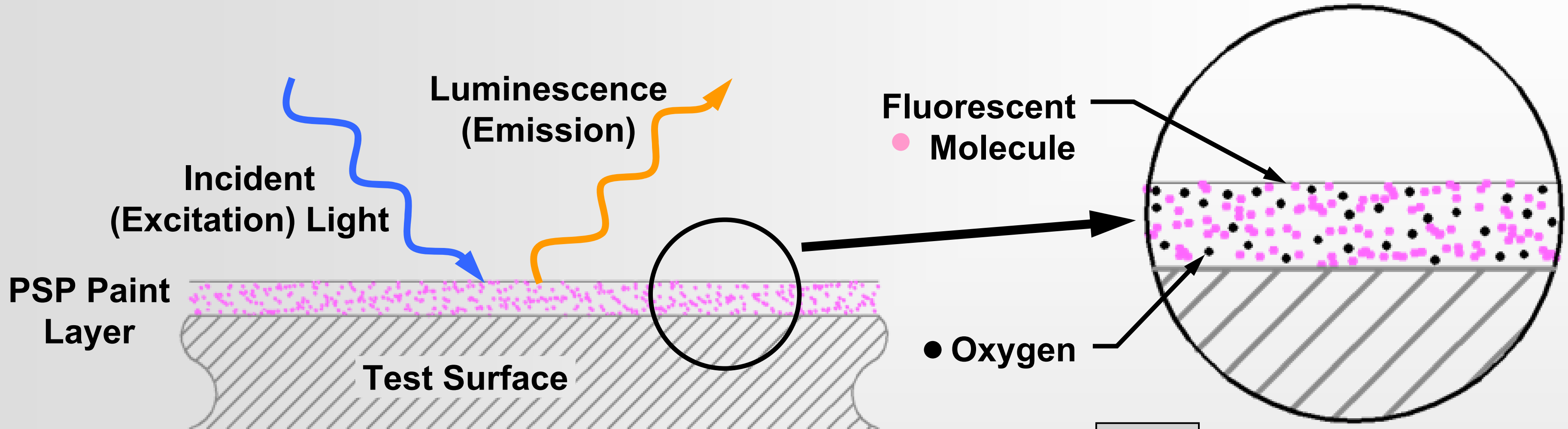
- **Task 2 (Year 2) – Film Cooling Effectiveness and Heat Transfer Measurement on the Rotating Platform with Seal Leakage**
  - Film Cooling Effectiveness has been Measured on the Rotating Platform with Seal Ejection
  - Numerical Predictions for both the Film Effectiveness and Heat Transfer Coefficients have been Obtained



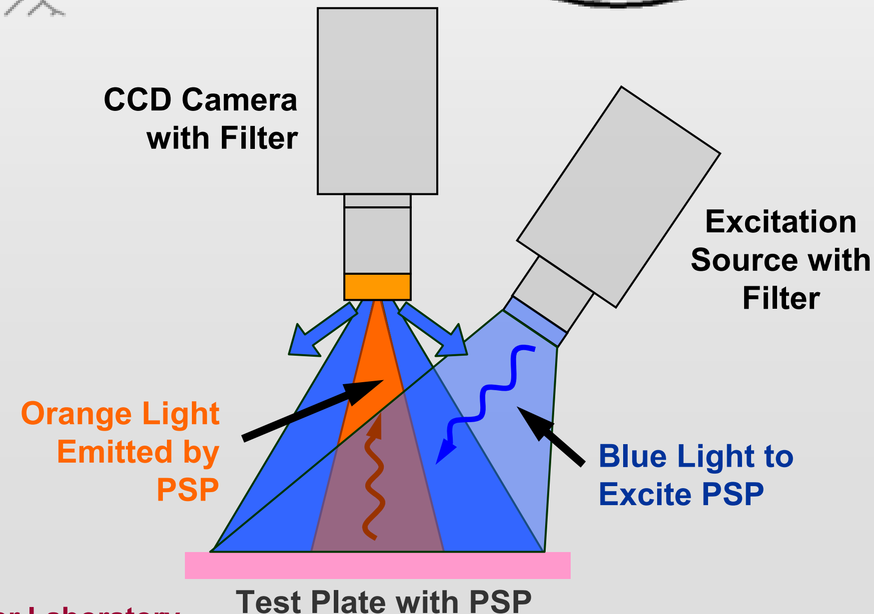


Project Technical Results

Part I – Measurement Techniques – Pressure Sensitive Paint (PSP) Technique Used to Measure the Pressure Distribution and Film Cooling Effectiveness

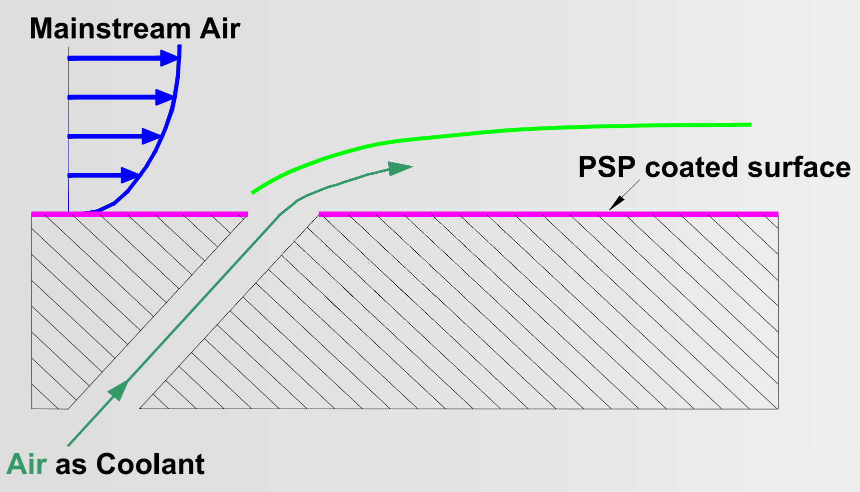


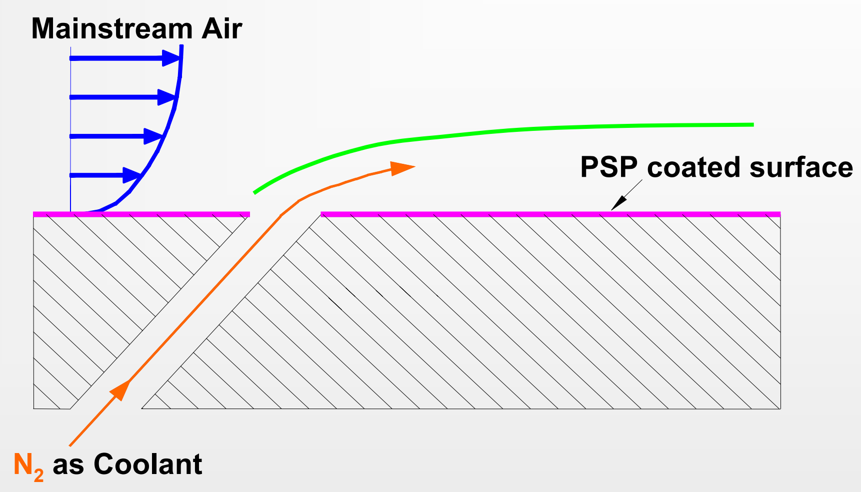
- Luminescence Material
  - Luminescent Molecules
  - Permeable, Polymer Binder
- Luminescent Intensity Decreases with the Increasing Partial Pressure of Oxygen *(Oxygen Quenching)*



Project Technical Results

Part I – Measurement Techniques – Pressure Sensitive Paint (PSP) Technique Used to Measure the Film Cooling Effectiveness

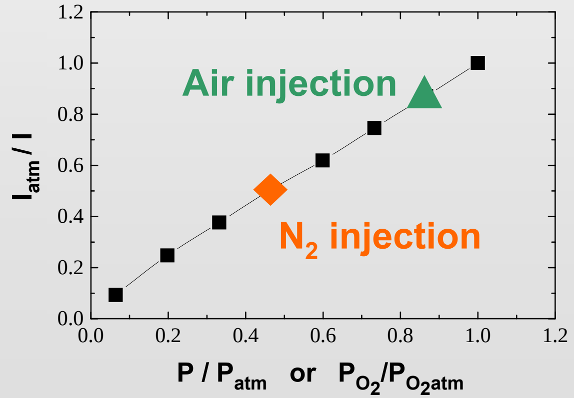




Film Cooling Effectiveness

$$\eta = \frac{C_\infty - C_{mix}}{C_\infty} = \frac{(P_{O2})_{air\ injection} - (P_{O2})_{N2\ injection}}{(P_{O2})_{air\ injection}}$$

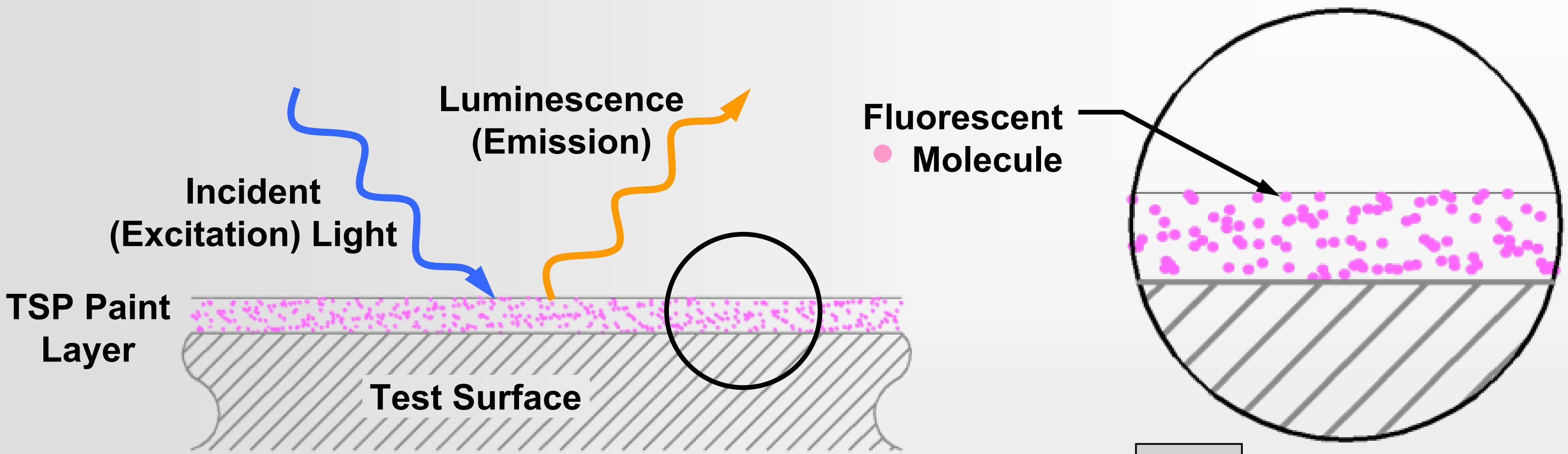
$$\eta \approx 1 - \frac{(I)_{air\ injection}}{(I)_{N2\ injection}}$$



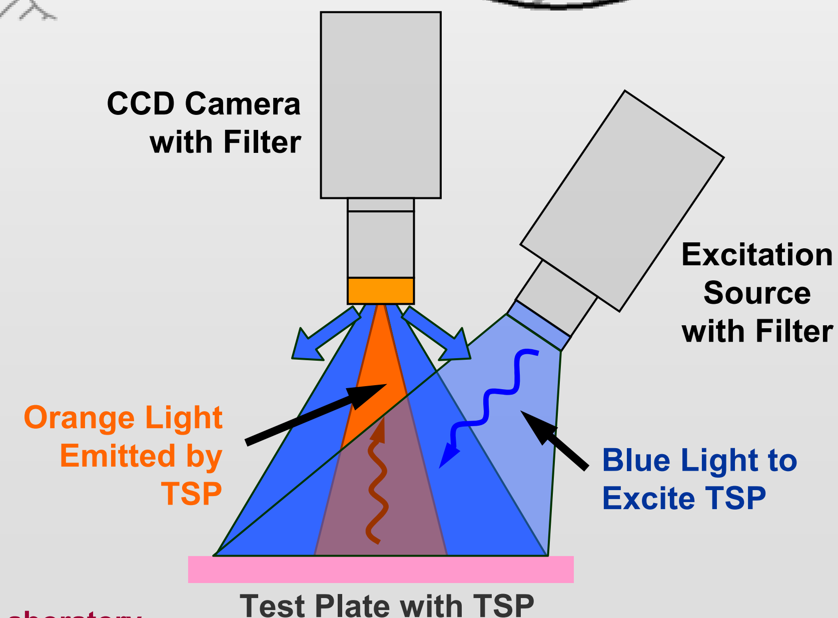
Calibration curve

Project Technical Results

Part I – Measurement Techniques – Temperature Sensitive Paint (TSP) Technique Used to Measure the Heat Transfer Coefficient Distribution

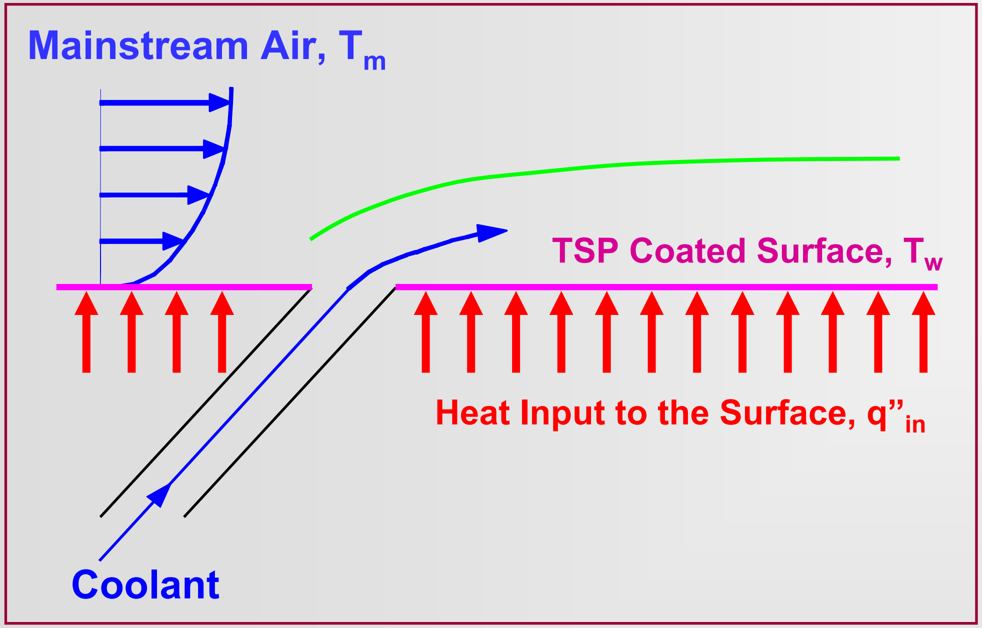


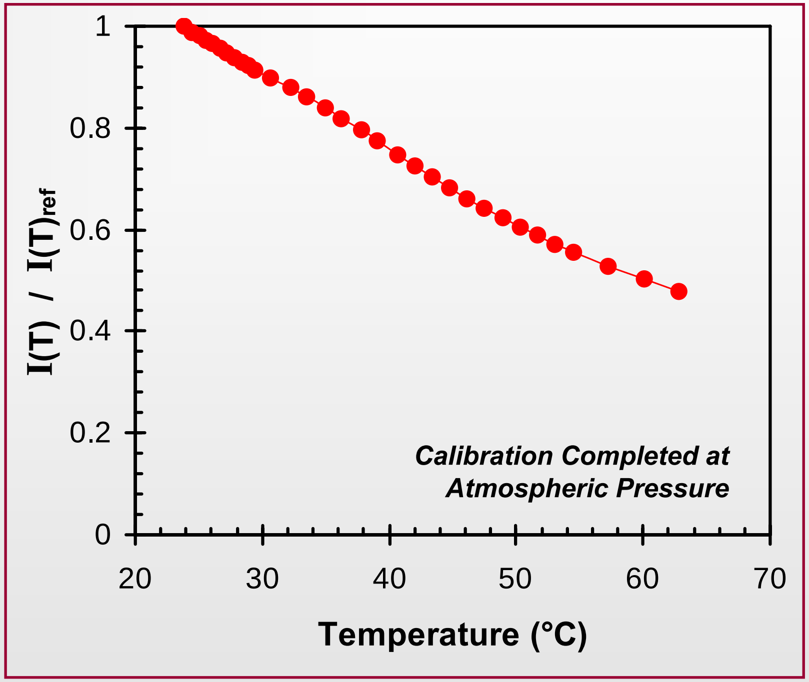
- Luminescence Material
  - Luminescent Molecules
  - Impermeable, Polymer Binder
- Luminescent Intensity Decreases with the Increasing Molecule Temperature *(Temperature Quenching)*



Project Technical Results

Part I – Measurement Techniques – Temperature Sensitive Paint (TSP) Technique Used to Measure the Heat Transfer Coefficient Distribution

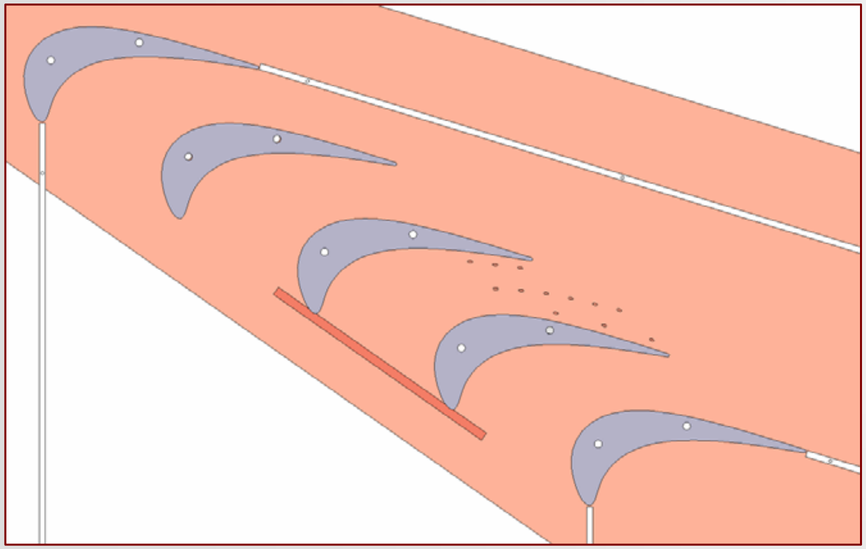


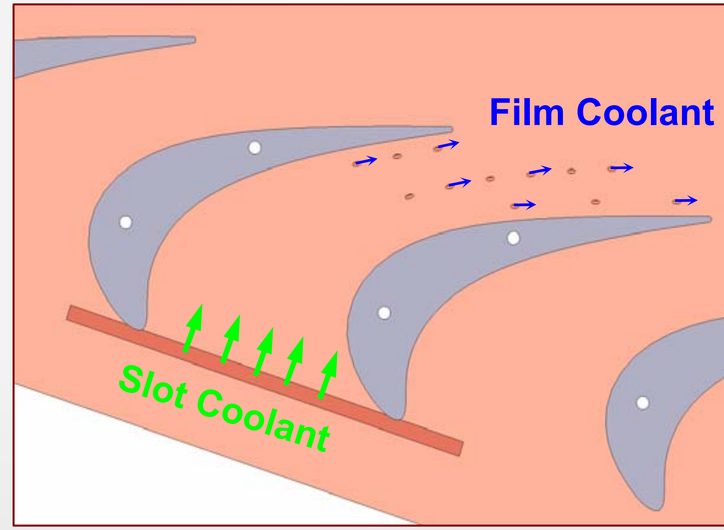


$$h = \frac{q''_{in} - q''_{loss}}{T_w - T_m}$$

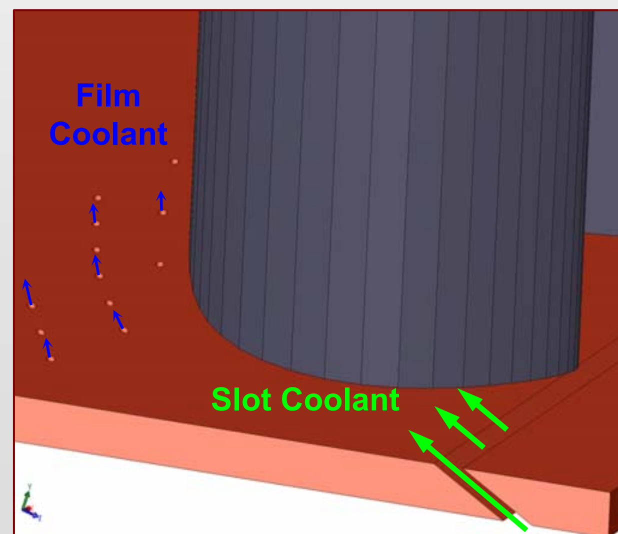
Project Technical Results

Part I – Supplement for Rotating Heat Transfer – *5-Blade, Linear Cascade Used to Demonstrate Measurement Techniques & Investigate Multiple Seal and Discrete Film Hole Configurations*



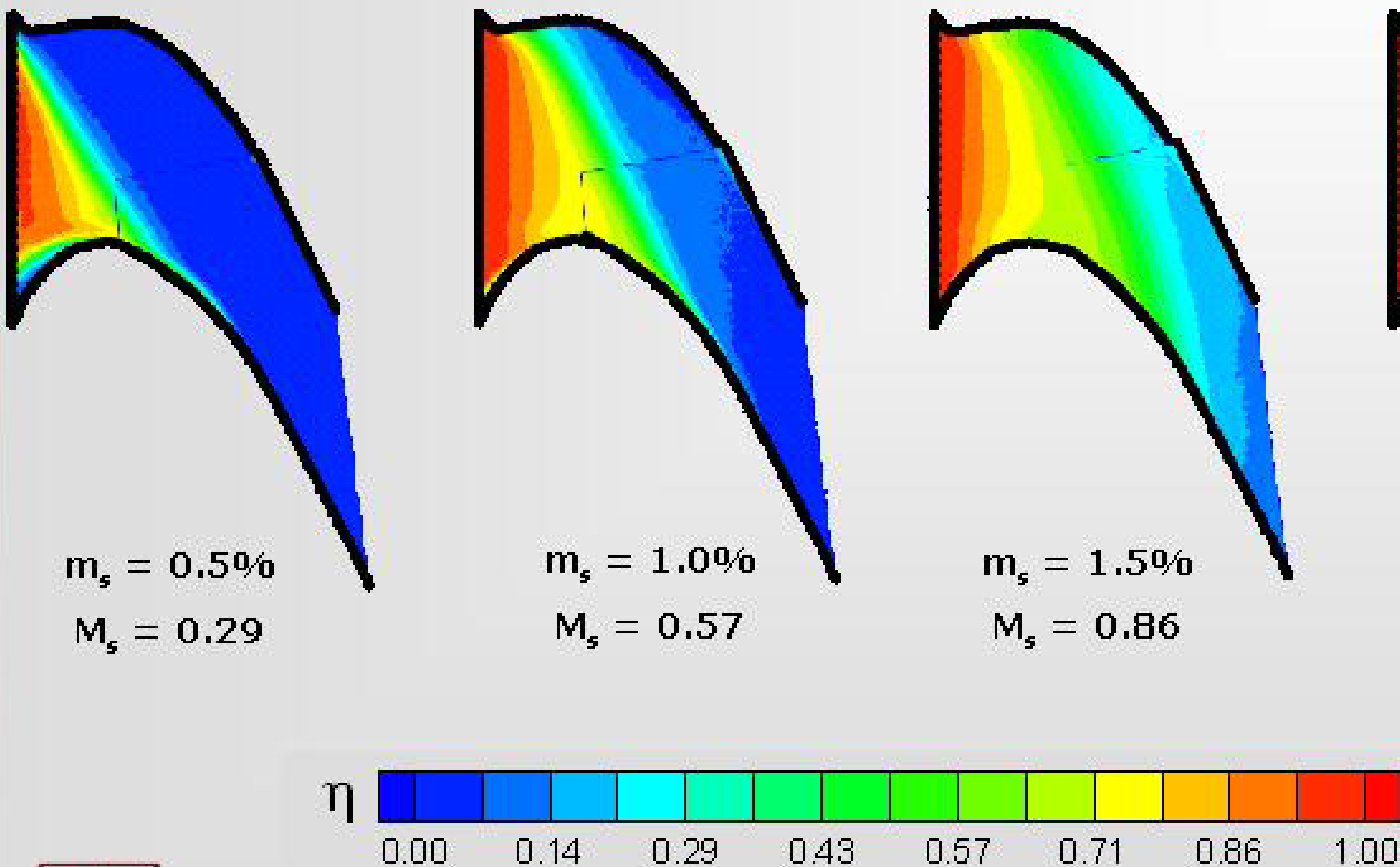


- **Re = $5.6*10^5$ (axial chord length & exit velocity)**
- **Inlet Velocity = 20 m/s,   Exit Velocity = 50 m/s**
- **Stator-Rotor Ejection: Cooling Flow = 0.5% ~ 2% of Mainstream**
- **Platform Film Cooling: Blowing Ratio ($M=\rho_c V_c/\rho_{2\infty} V_{2\infty}$) = 0.5 ~ 2**
- **Density Ratio (DR=ρ_c/ρ_∞) = 1 (N_2 Injection)**



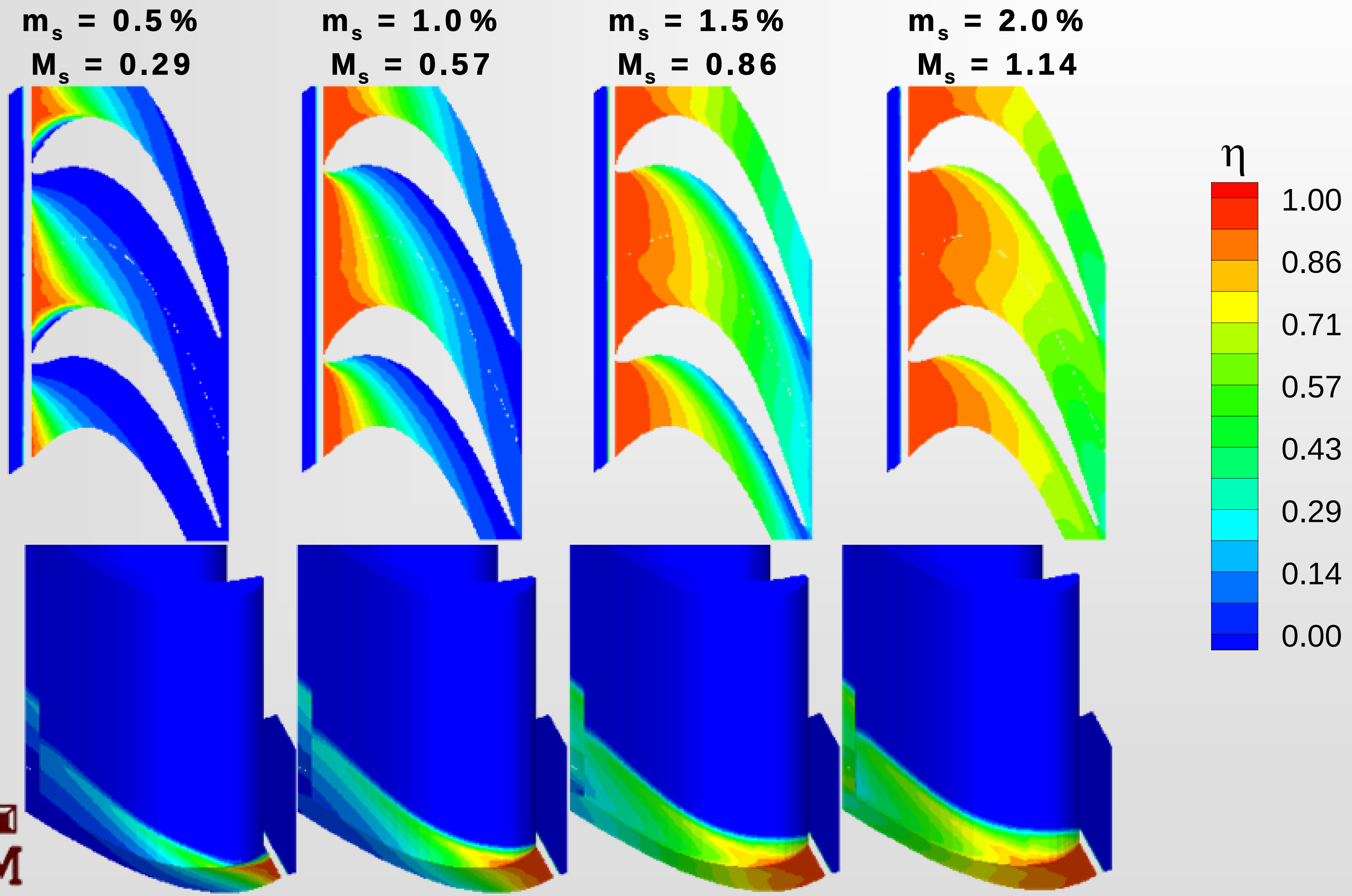
Project Technical Results

Part I – Supplement for Rotating Heat Transfer – *Measured Film Cooling Effectiveness on the Endwall of a 5-Blade, Linear Cascade by PSP*



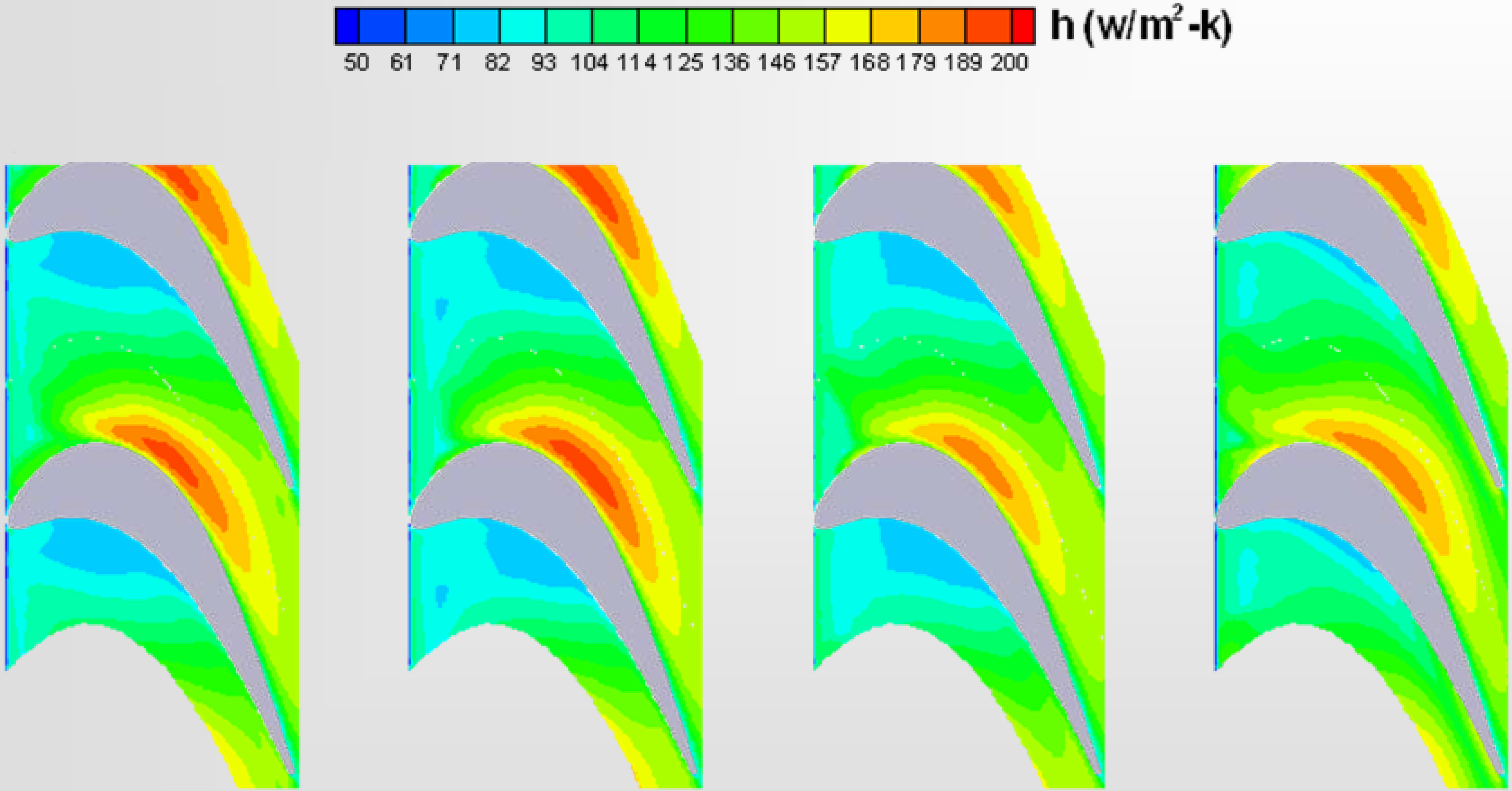
Project Technical Results

Part II – Supplement for Rotating Heat Transfer – *Predicted Film Cooling Effectiveness on the Endwall of a 5-Blade, Linear Cascade*



Project Technical Results

Part II – Supplement for Rotating Heat Transfer – *Predicted Heat Transfer Coefficients on the Endwall of a 5-Blade, Linear Cascade*



m_s = 0.5 % M_s = 0.29

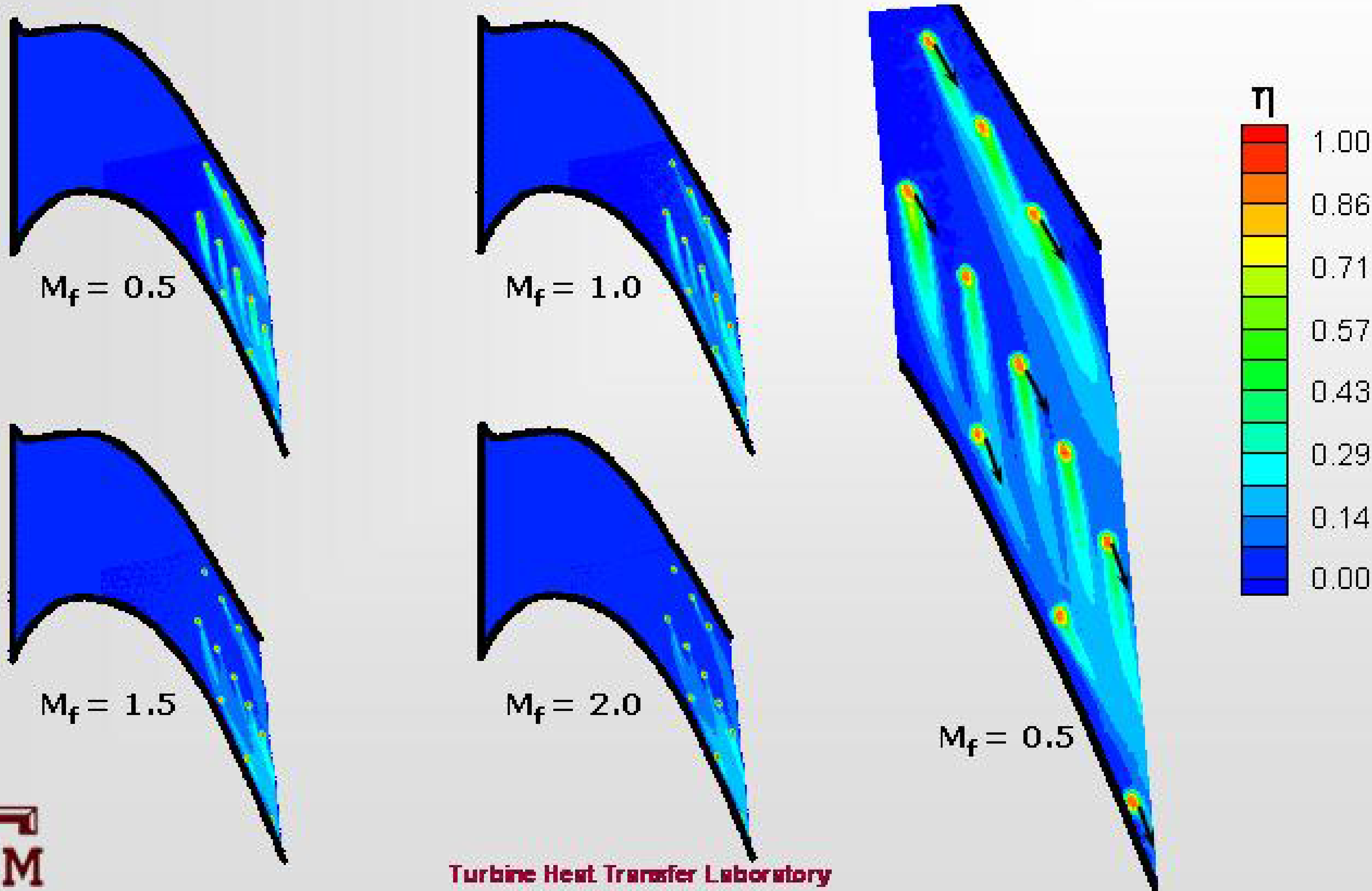
m_s = 1.0 % M_s = 0.57

m_s = 1.5 % M_s = 0.86

m_s = 2.0 % M_s = 1.14

Project Technical Results

Part I – Supplement for Rotating Heat Transfer – *Measured Film Cooling Effectiveness on the Endwall of a 5-Blade, Linear Cascade by PSP*



Project Technical Results

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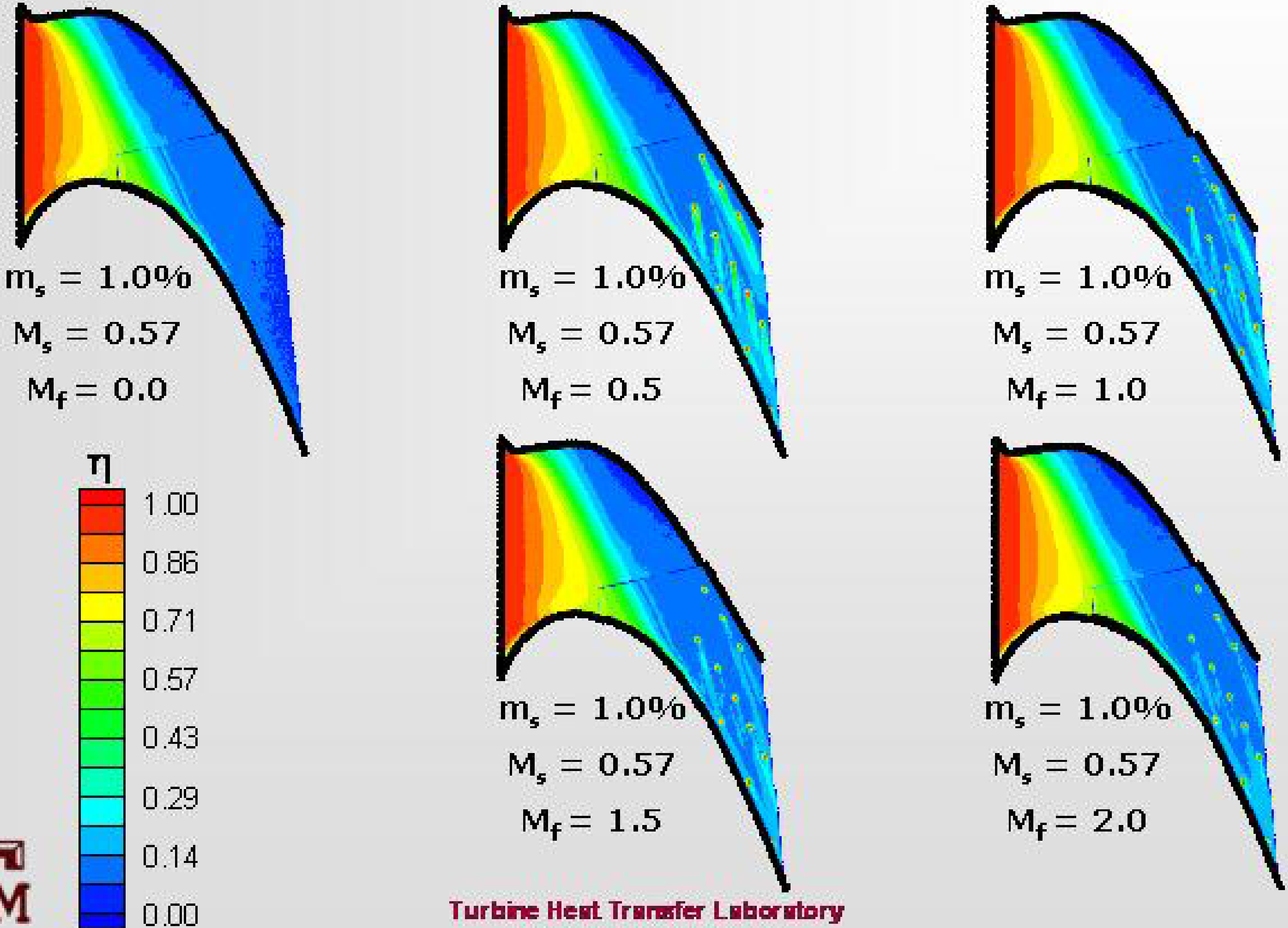

Project Technical Results

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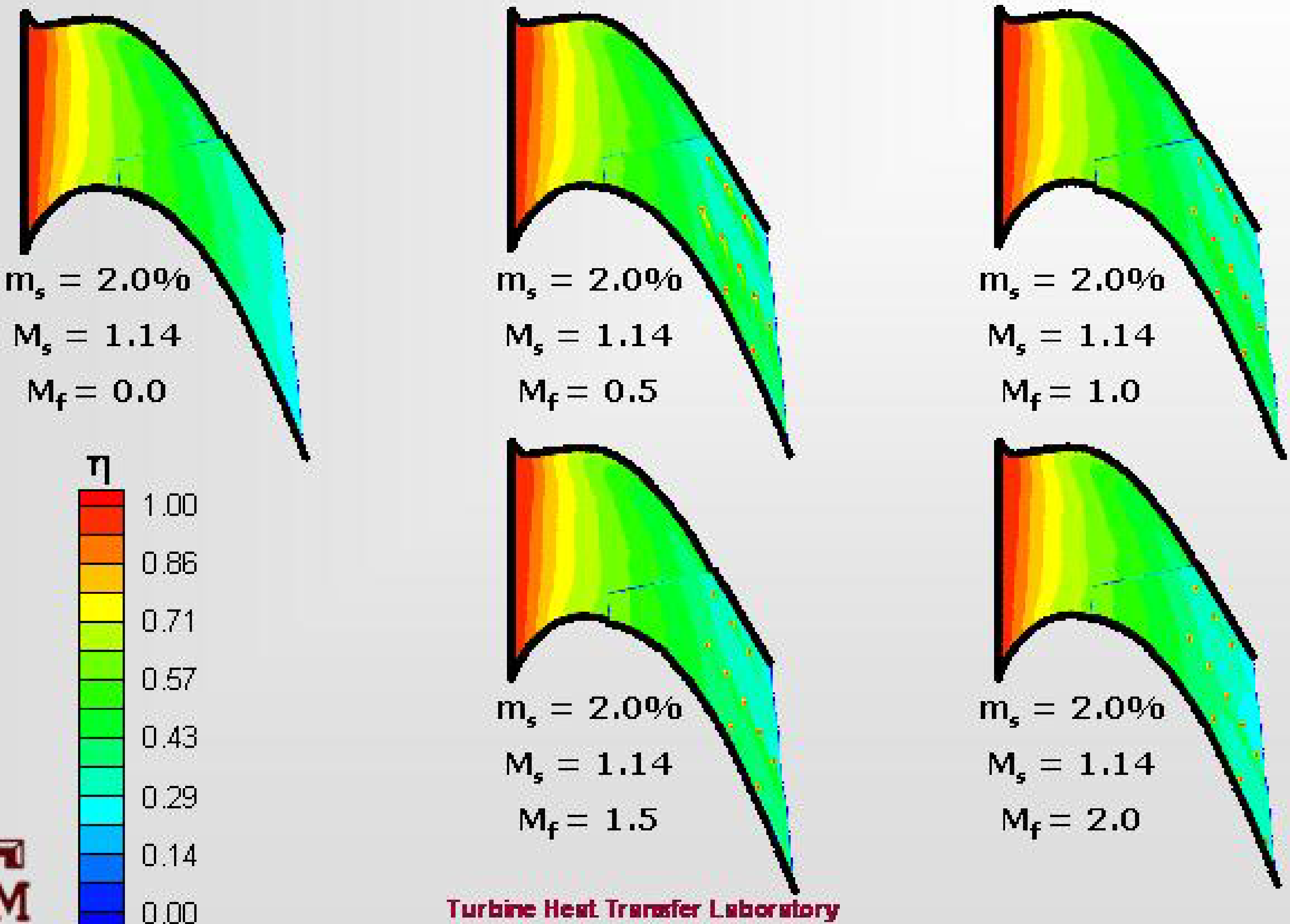
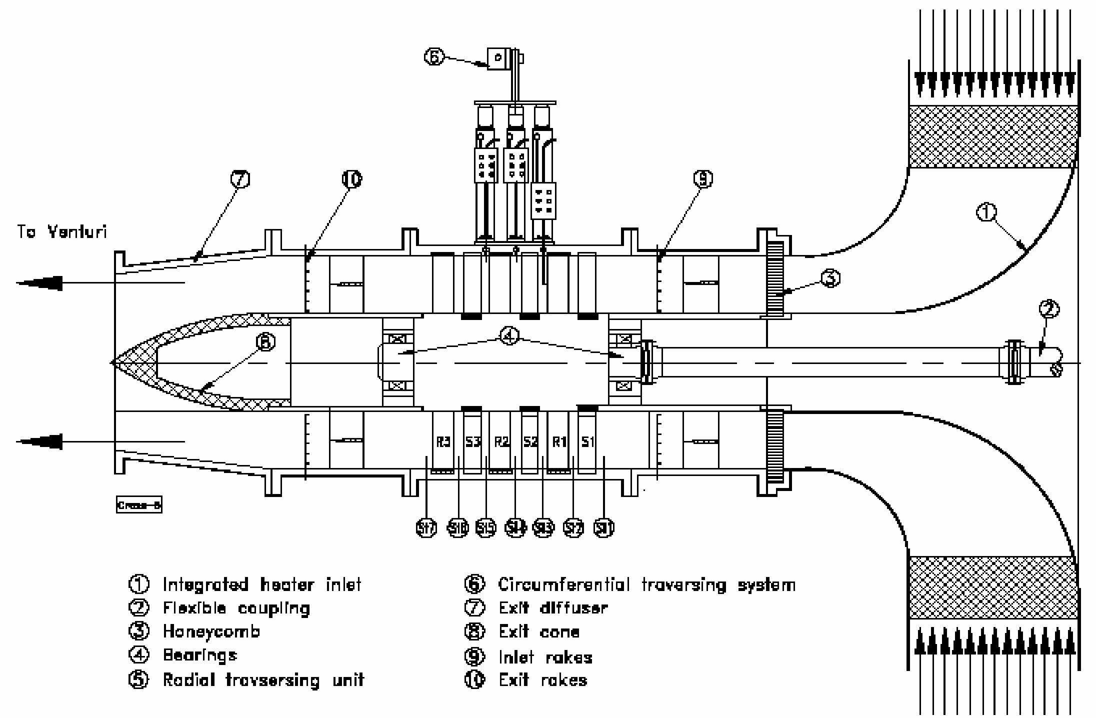


Project Technical Results

Part II – Flow Measurements – Existing Research Turbine Facility

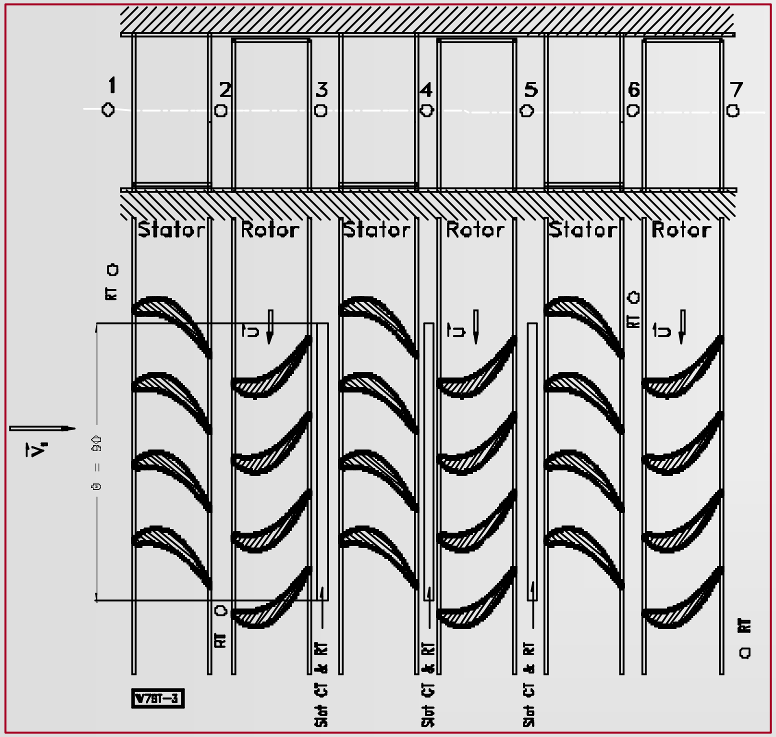
The Research Turbine Component
TPFL, Turbomachinery Performance and Flow Research Laboratory
Prof. Dr.-Ing. M.T.Schobeiri

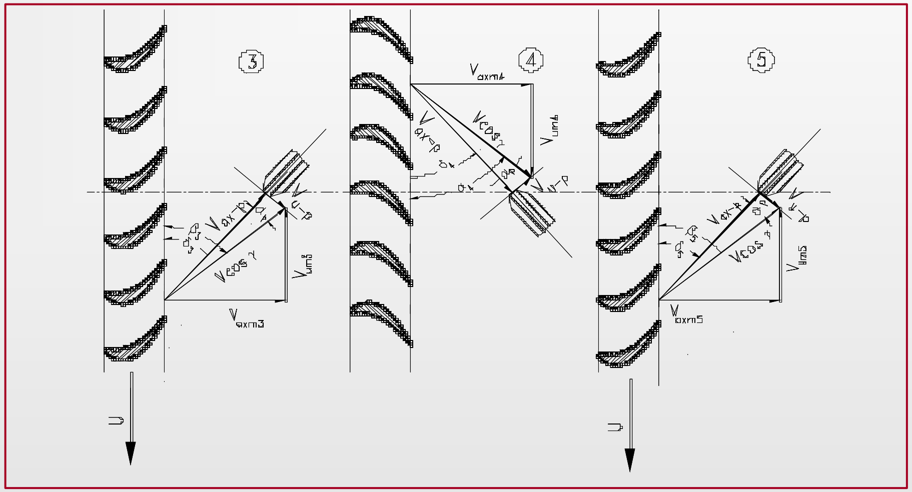


A Schematic Cross Section of the TPFL-Research Turbine with its Major Components

Project Technical Results

Part II – Flow Measurements – Existing Research Turbine Facility

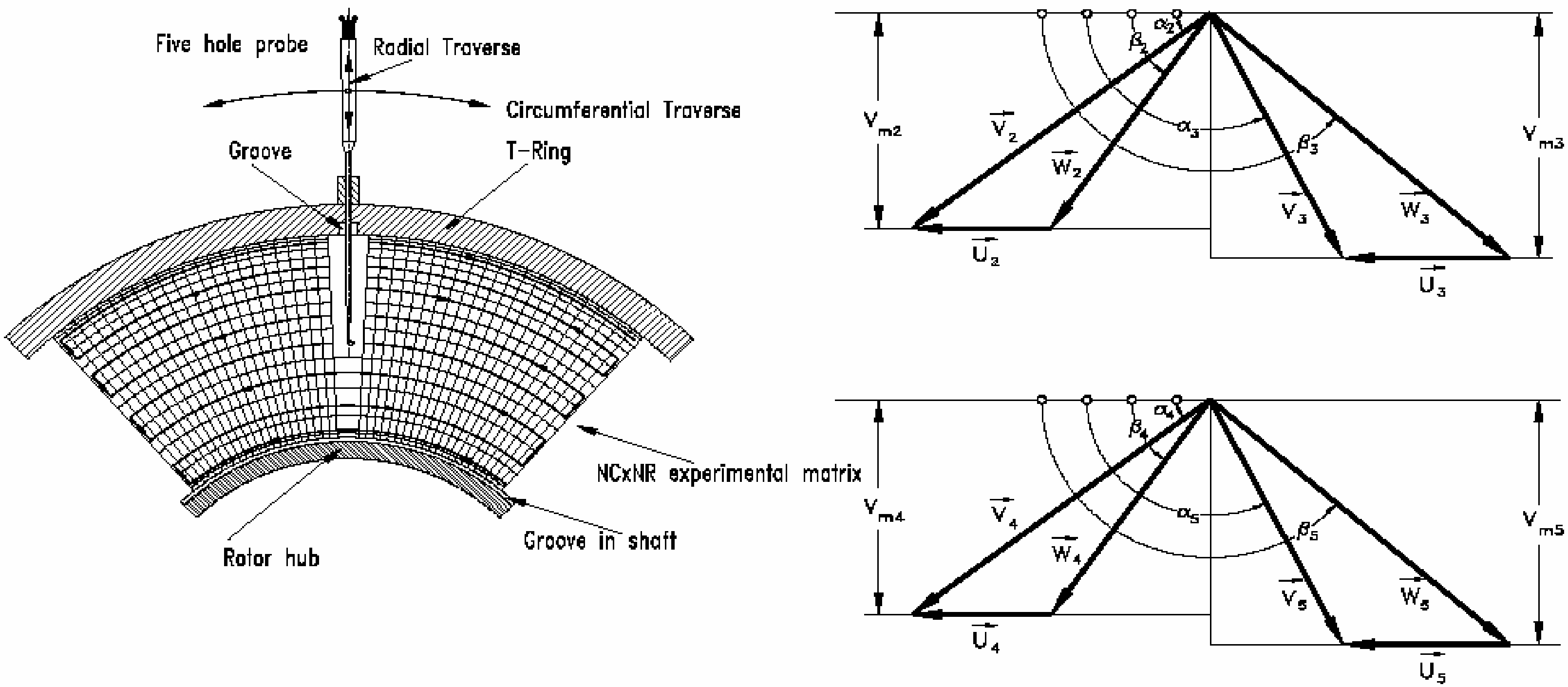




Fully Sealed Traversing Slots and Angular Positions of the Five-Hole Probes at Stations 3, 4, and 5

Project Technical Results

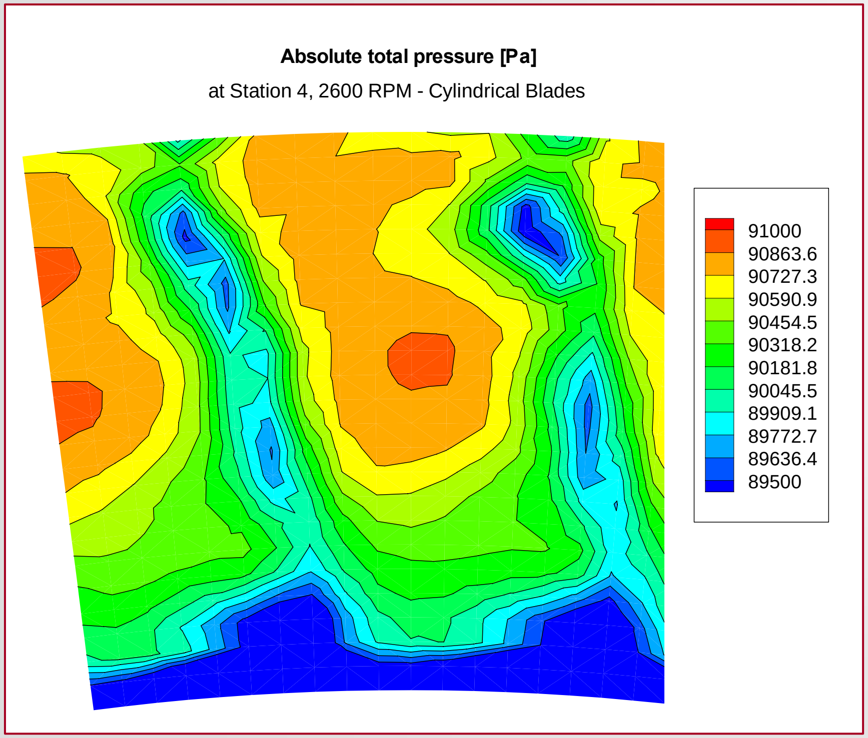
Part II – Flow Measurements – Existing Research Turbine Facility



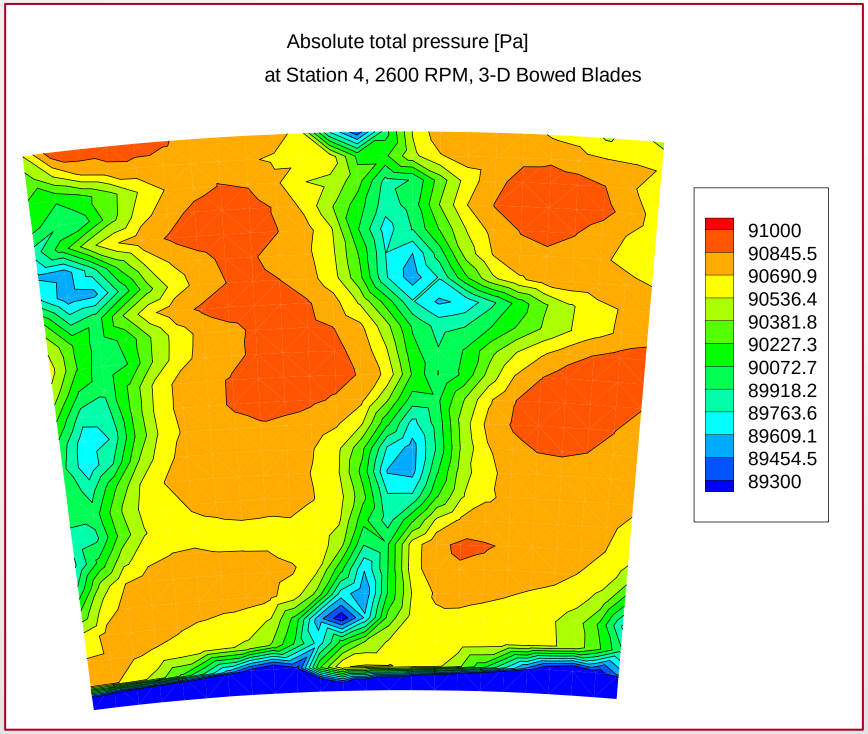
Interstage Traversing Schedule and Angle Definitions at Stations 3, 4, and 5

Project Technical Results

Part II – Flow Measurements – Existing Research Turbine Facility



Cylindrical Blades



3-D Bowed Blades

Absolute Total Pressure Contour Plots at Station 4 for Cylindrical and 3-D Bowed Blades

Project Technical Results

Part I – Rotating Heat Transfer – Turbine Stage Operating Conditions

- **1^{st} Rotor**
  - Inlet Velocity = 35.8 m/s
  - Inlet Mach Number = 0.1
  - Inlet Temperature = 46°C
  - Exit Velocity = 107 m/s
  - Exit Mach Number = 0.3
  - Exit Temperature = 43°C
- **Re = $2.0*10^5$ (axial chord length and exit velocity)**
- **Inlet Total – to – Exit Pressure Ratio = 1.4**
- **Angular Velocity = 2550 rpm, 2000 rpm (off-design)**
- **Stator-Rotor Ejection: Cooling Flow ~ 0.5% ~ 2% of Mainstream**
- **Platform Film Cooling: Blowing Ratio ($M=\rho_c V_c/\rho_\infty V_\infty$) ~ 0.5 ~ 2**
- **Density Ratio ($DR=\rho_c/\rho_\infty$) = 1 (N_2 Injection)**

Project Technical Results

Part I – Rotating Heat Transfer

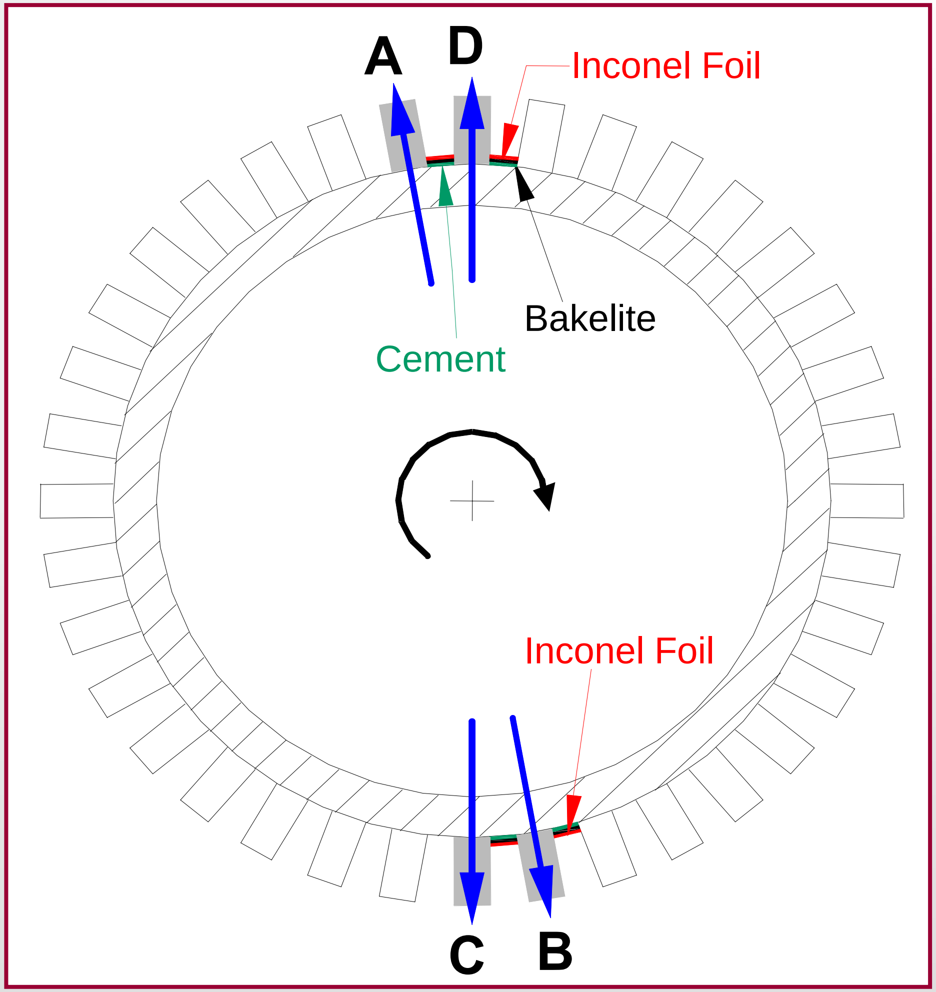
Blade Arrangement for Platform Film Cooling Measurements

A – Stator-Rotor Seal Ejection for PSP Measurement

B – Stator-Rotor Seal Ejection for TSP Measurement

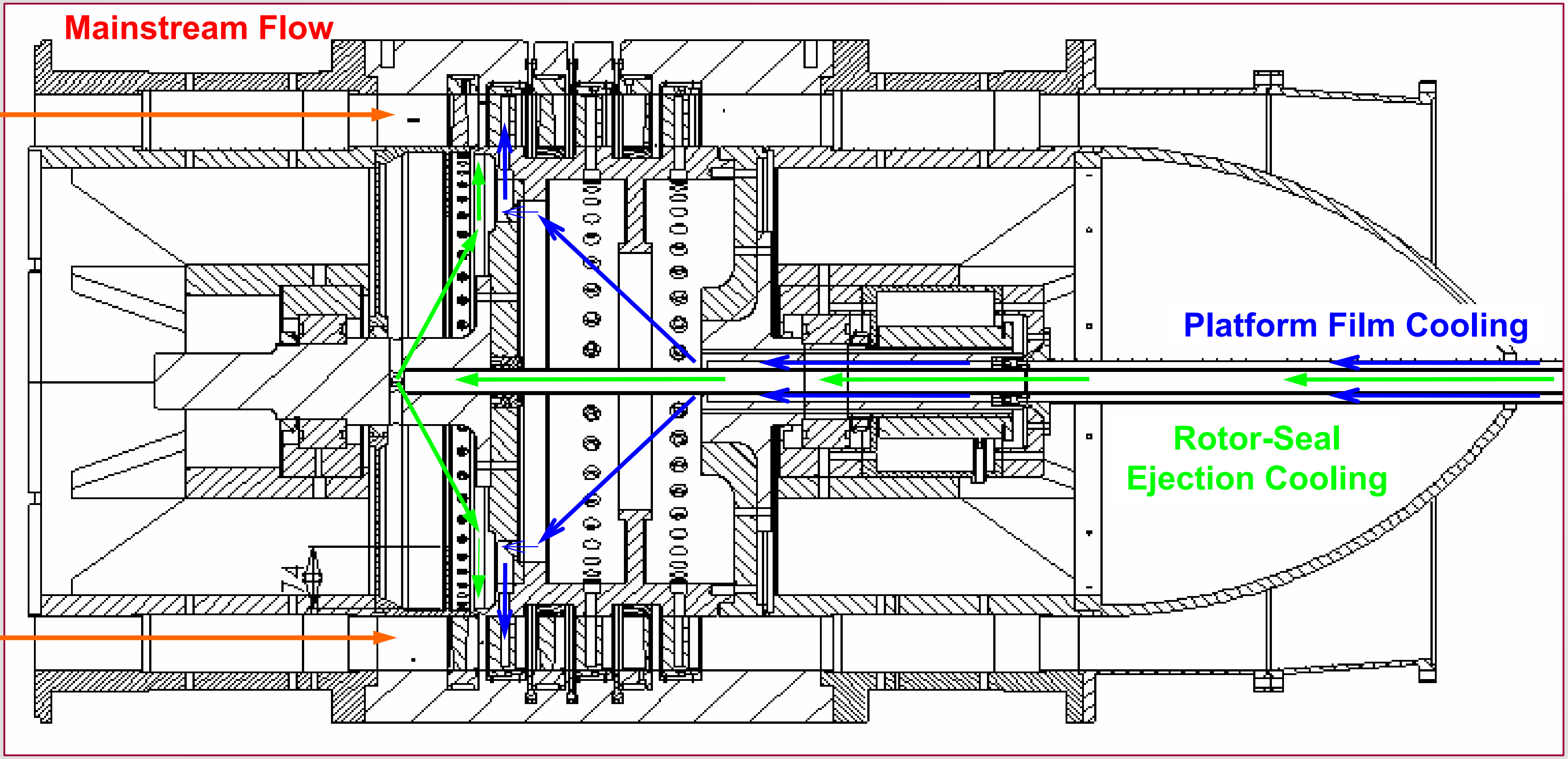
C – Stator-Rotor Seal Ejection and Film Cooling for PSP Measurement

D – Stator-Rotor Seal Ejection and Film Cooling for TSP Measurement



Project Technical Results

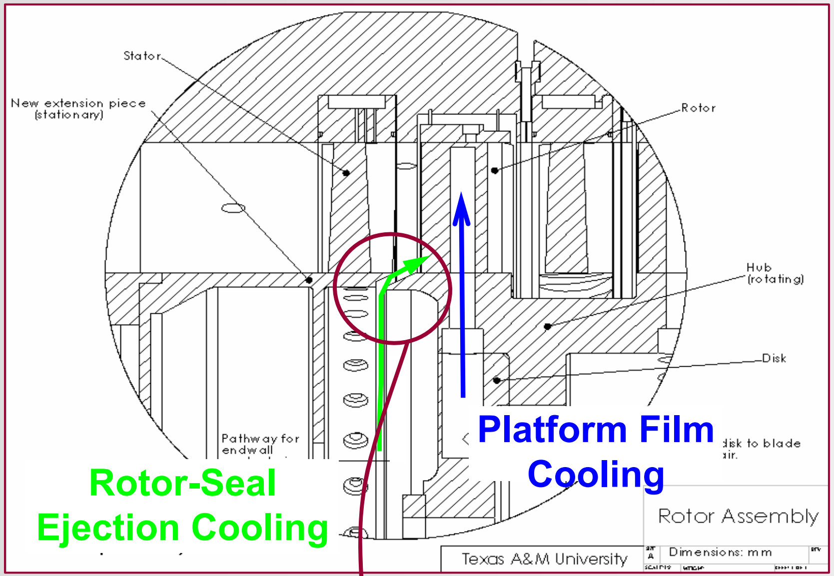
Part I – Rotating Heat Transfer – Rotor Platform Modifications for Two Coolant Flow Loops

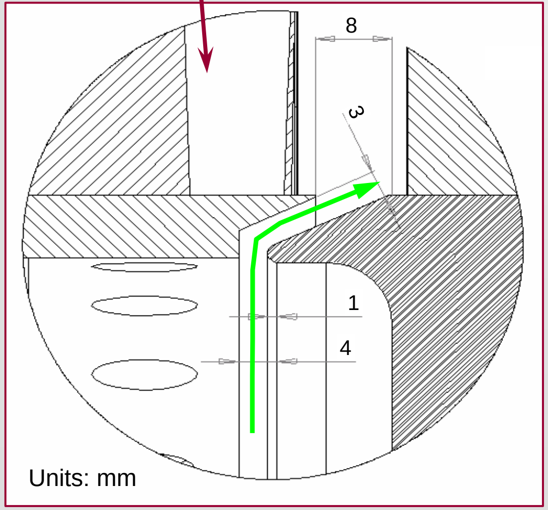


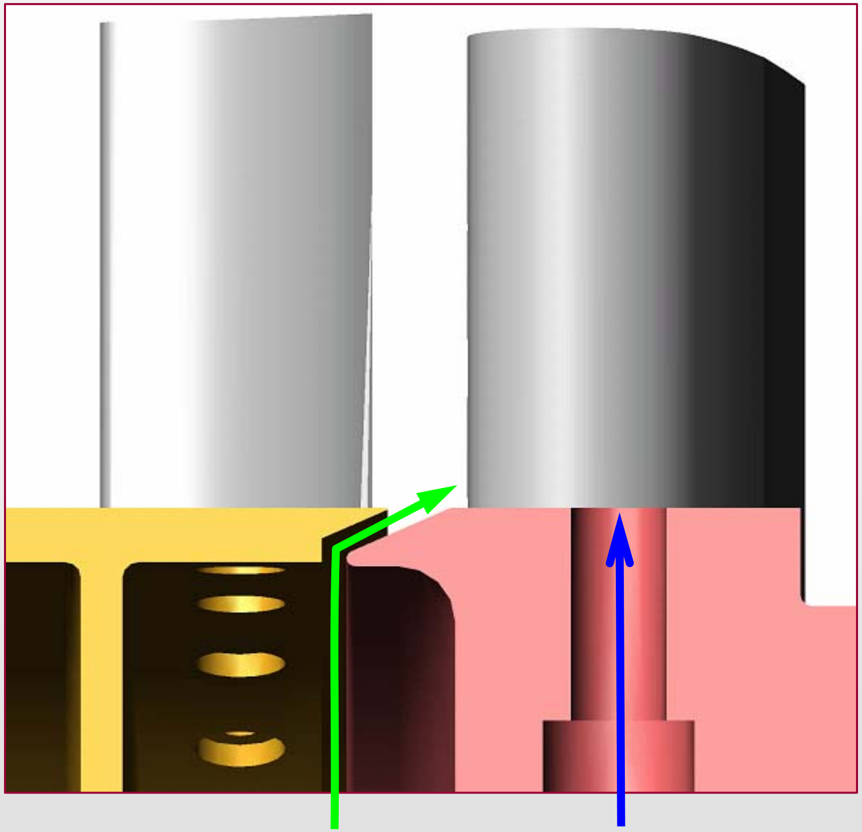
Independent Coolant Loops for Coolant Ejection from Stator-Rotor Seal and Film Cooling from Platform

Project Technical Results

Part I – Rotating Heat Transfer – Rotor Platform Modifications for a Typical Stator-Rotor Seal Geometry



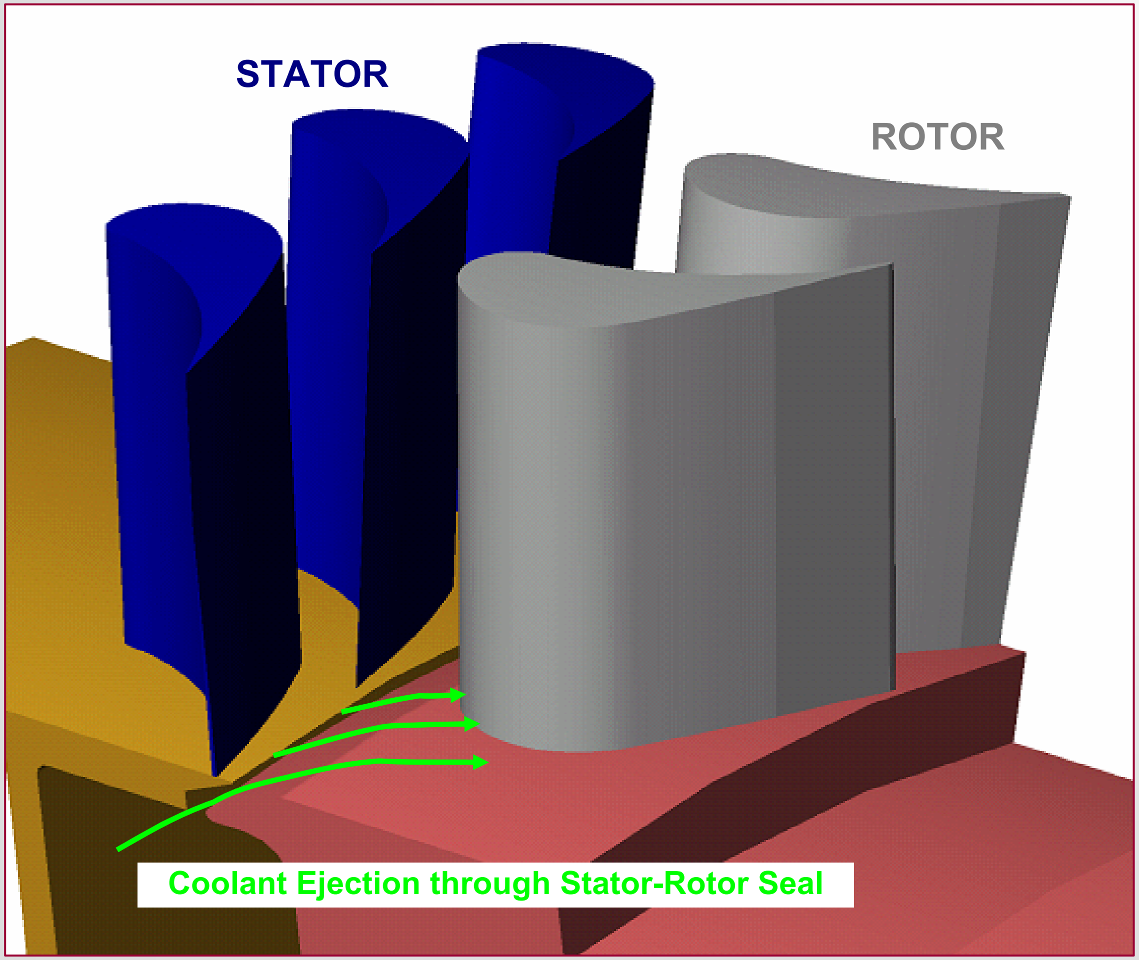


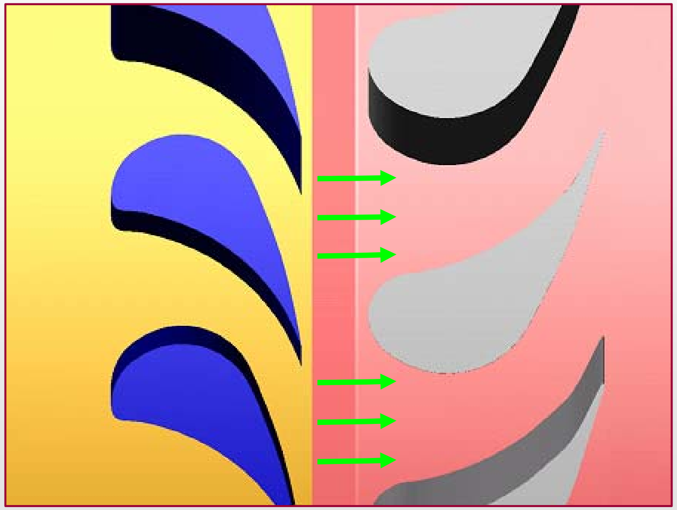


Coolant Ejection and Film Cooling Paths

Project Technical Results

Part I – Rotating Heat Transfer – Rotor Platform Modifications for Typical Stator-Rotor Seal Geometry

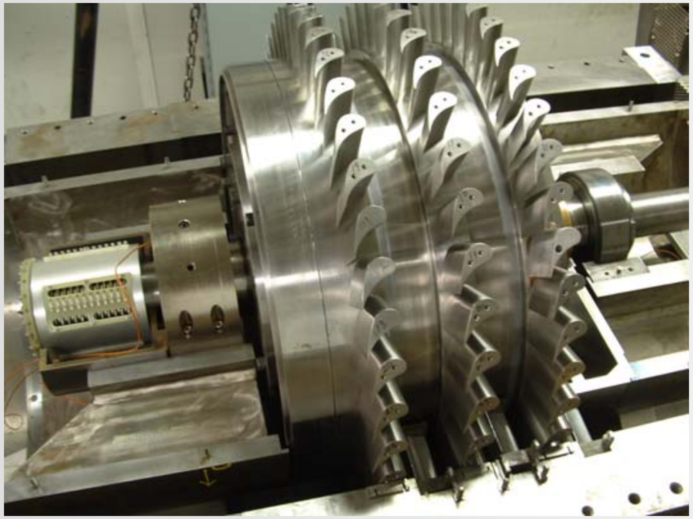


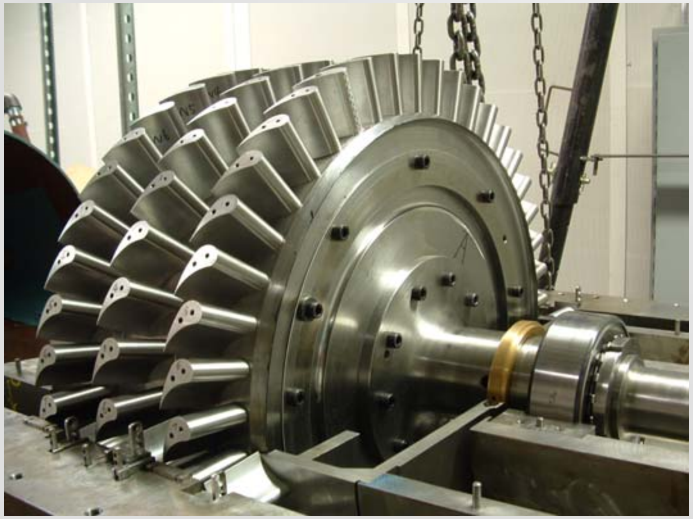


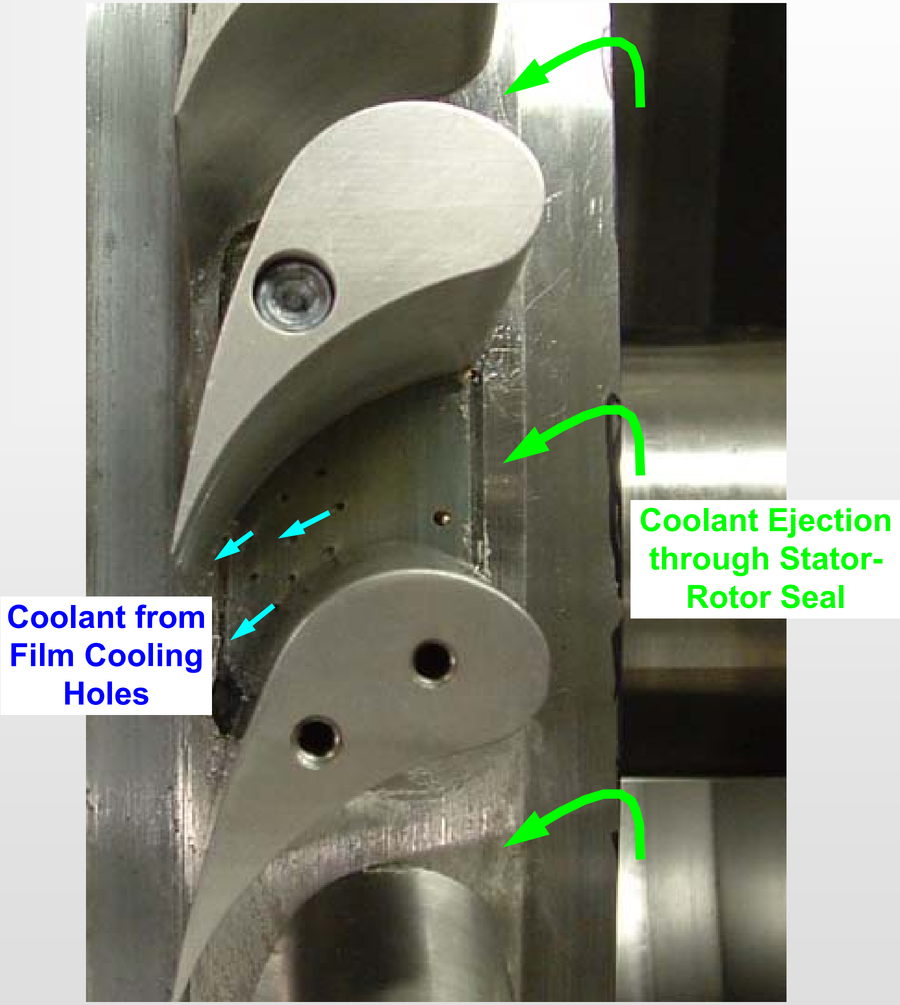
Coolant Ejection on the Rotor Blade Platform

Project Technical Results

Part I – Rotating Heat Transfer – New Rotor Installed in Existing Research Facility

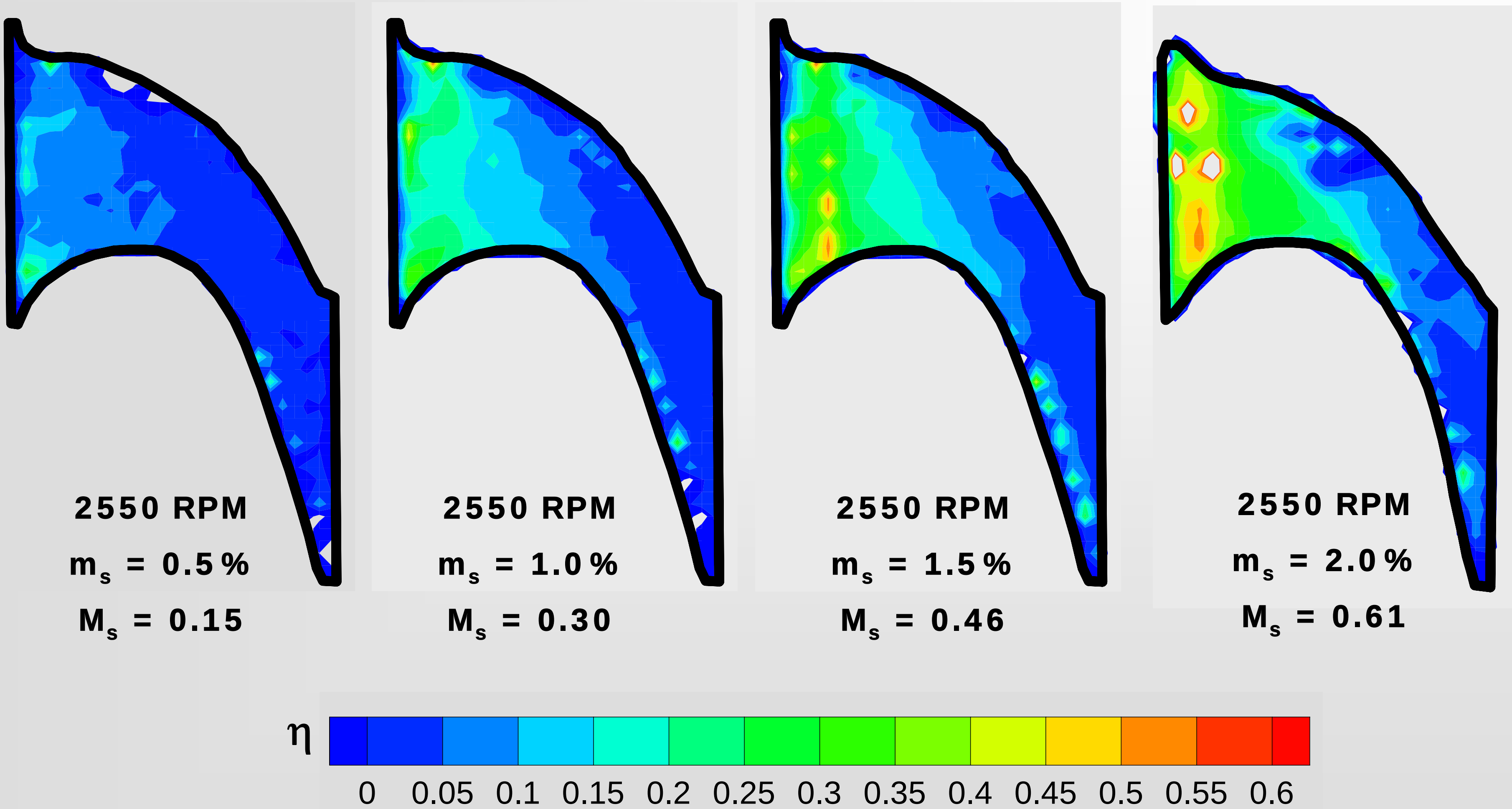






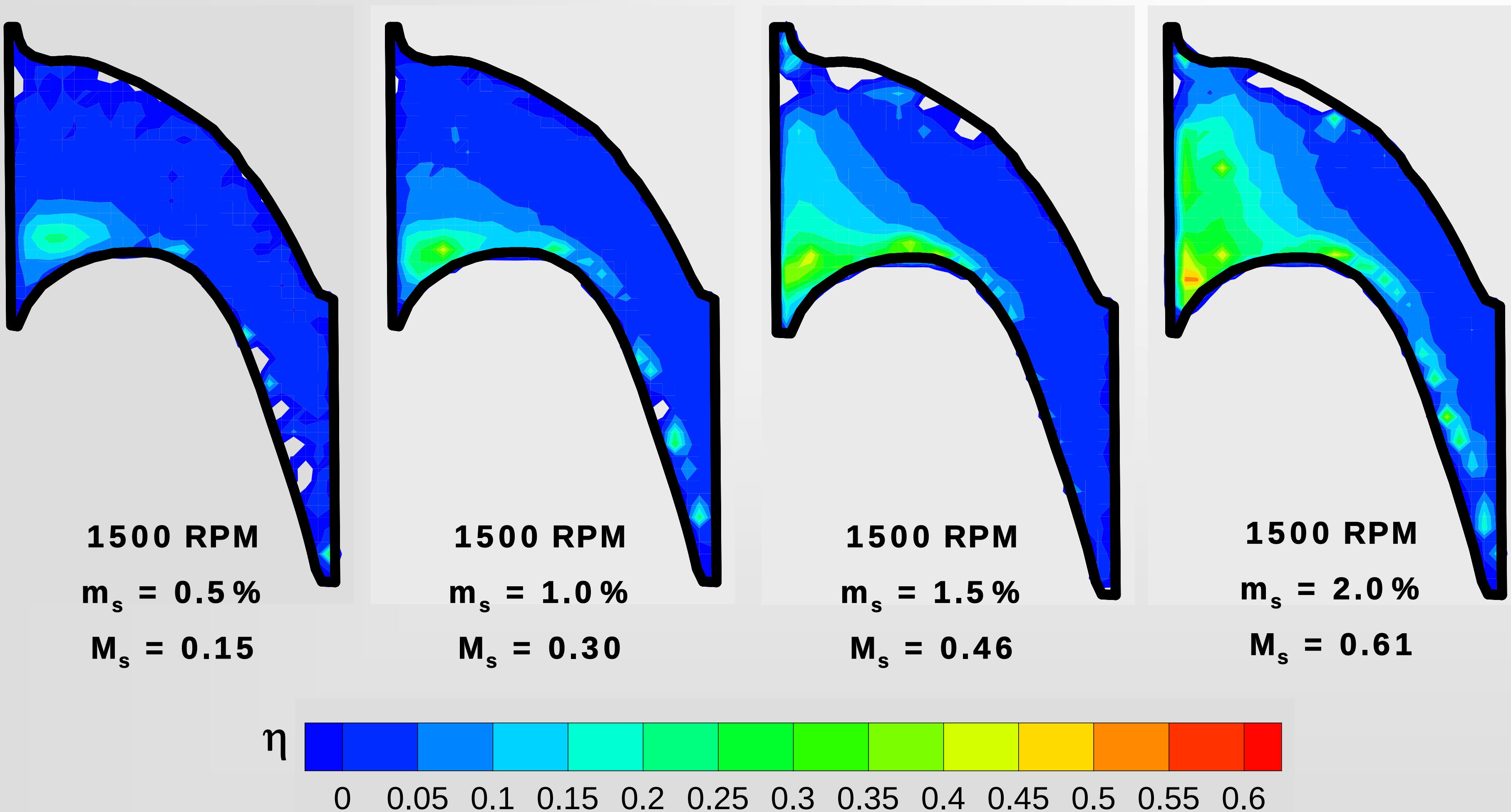
Project Technical Results

***Part I – Rotating Heat Transfer –** Measured Film Cooling Effectiveness on the Rotating (Design Point) Platform by PSP*



Project Technical Results

Part I – Rotating Heat Transfer – *Measured Film Cooling Effectiveness on the Rotating (Off-Design) Platform by PSP*



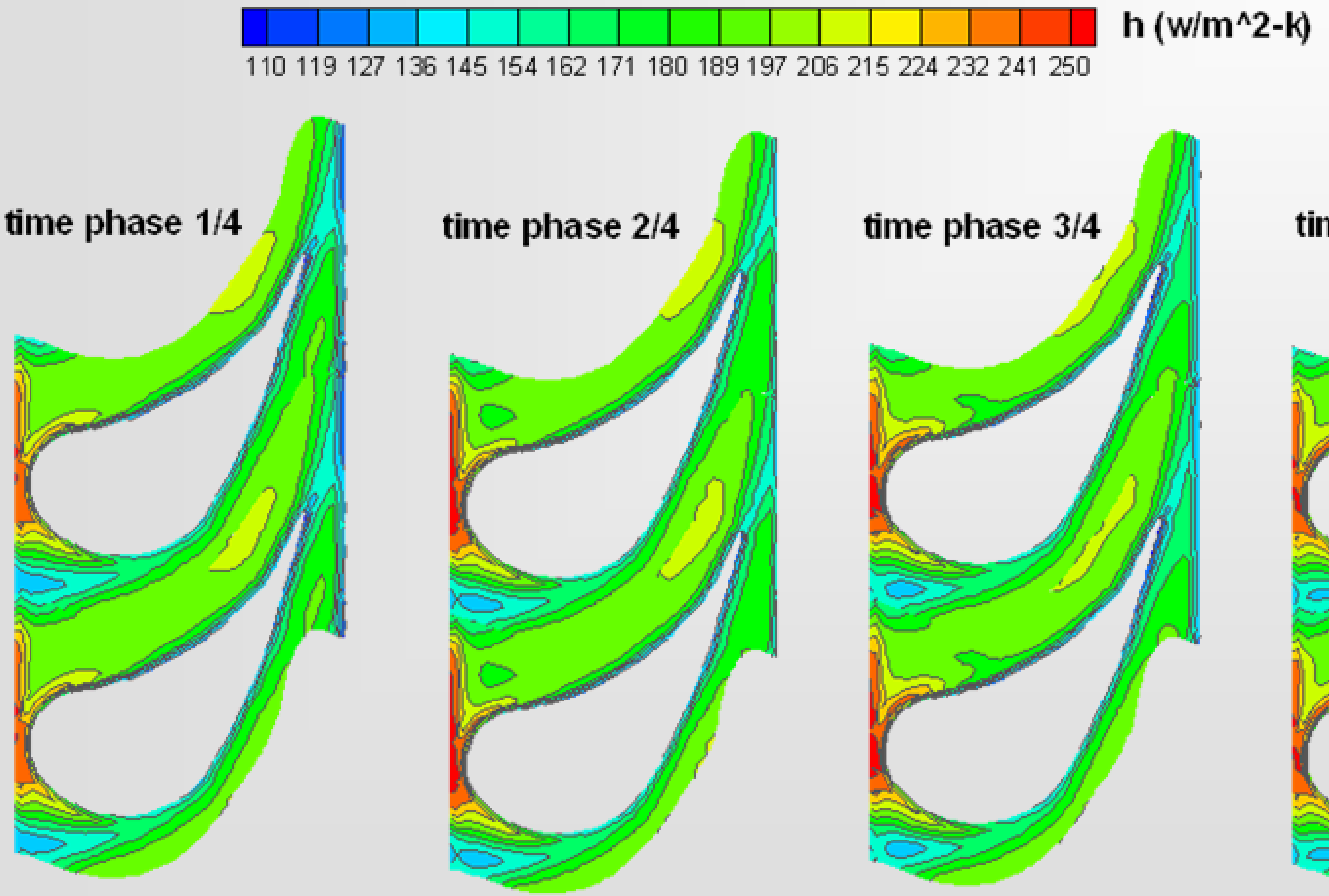
Project Technical Results

Part II – Rotating Heat Transfer – *Predicted Heat Transfer Coefficients on the Rotating (2550 RPM, Design Point) Platform*

2550 RPM

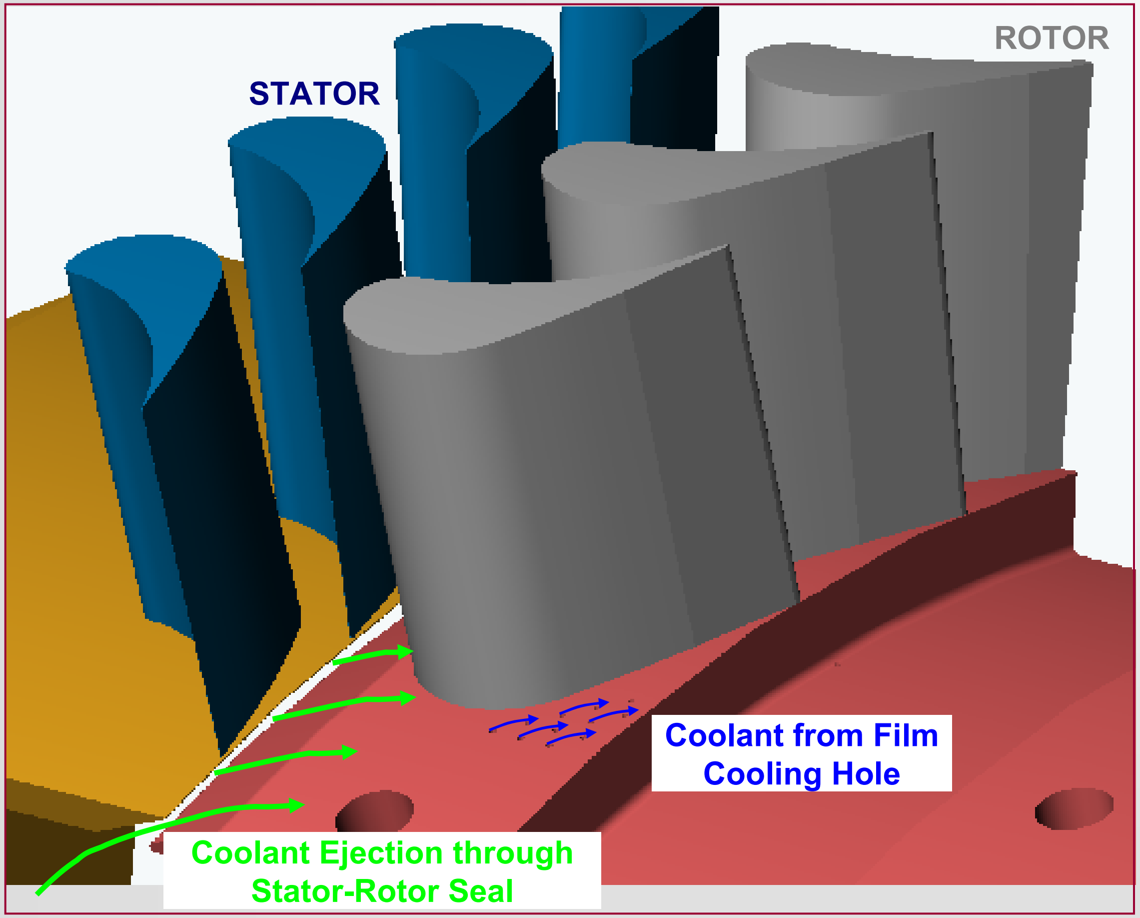
m_s = 0.5%

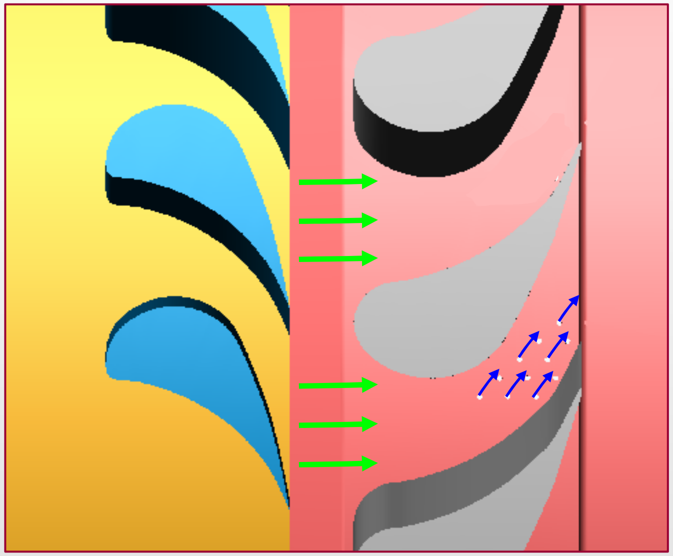
M_s = 0.15



Future Work

Part I – Rotating Heat Transfer – Film Cooling Effectiveness and Heat Transfer Coefficients with Stator – Rotor Seal Leakage and Downstream Film Cooling

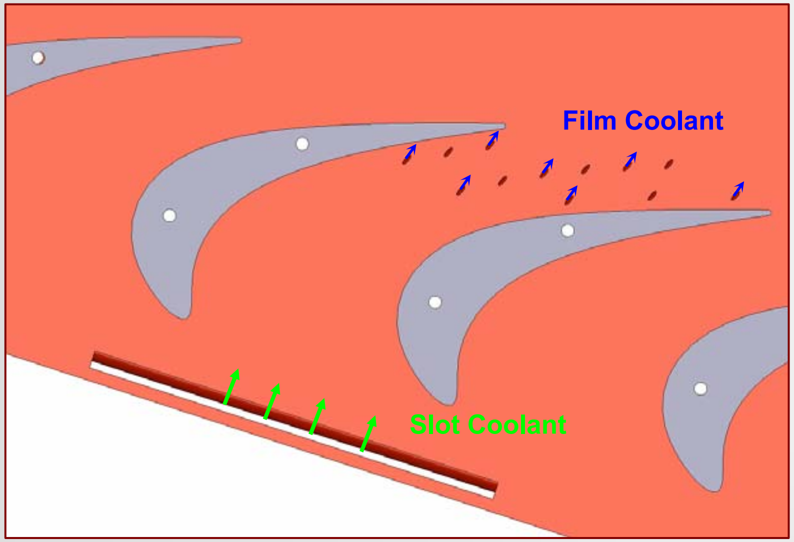


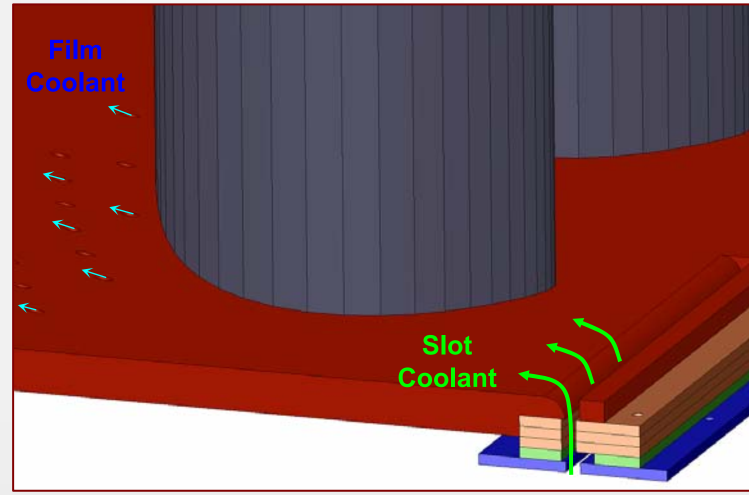


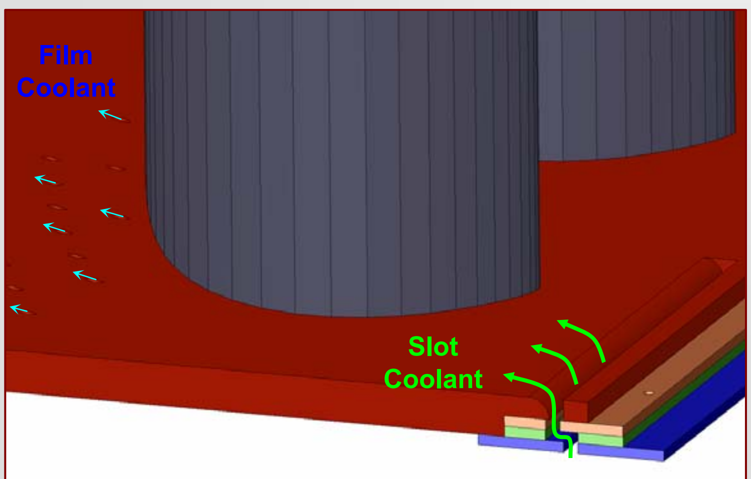
Coolant Ejection and Film Cooling on the Rotor Blade Platform

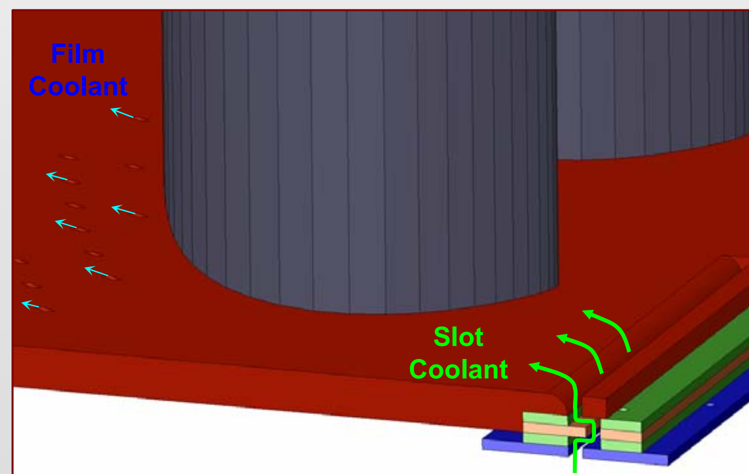
Future Work

Part I – Supplement for Rotating Heat Transfer – Advanced Stator-Rotor Seal Configurations with Varied Downstream Film Holes







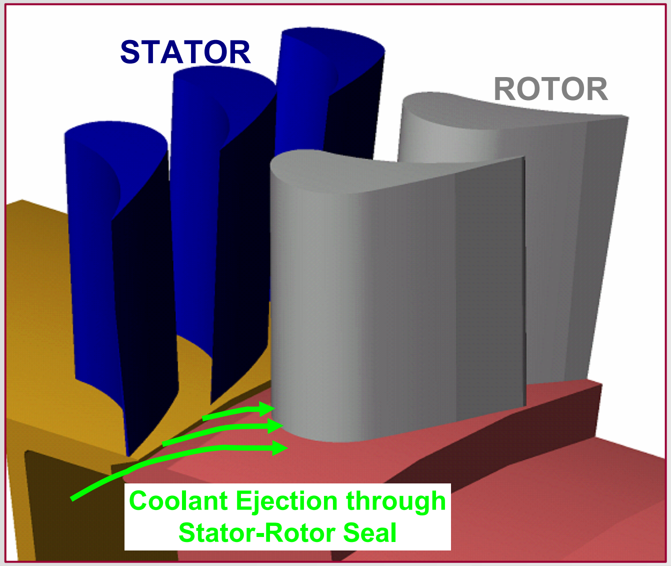


Project Summary

- **Experimental Rotating Platform Heat Transfer**
  - Design, Fabrication, Installation, and Instrumentation of New Rotating Platform is Complete
  - Film Cooling Effectiveness has been Measured on the Rotating Platform with Stator-Rotor Seal Ejection by PSP
  - Film Cooling Effectiveness has been Measured on the Cascade Endwall with Seal Ejection and Discrete Film Holes by PSP

- **Flow Measurements and Numerical Simulations**
  - Several Miniature Five-Hole Probes have been Calibrated and Used for Flow Measurements in the Rotating Research Facility
  - Numerical Predictions have been Completed for the Film Cooling Effectiveness and Heat Transfer Coefficients on the Rotating Platform with Stator-Rotor Seal Ejection
  - Numerical Predictions have also been Completed for the Cascade Endwall with Seal Ejection

Questions



Solar Turbines: ***Hee-Koo Moon*** *– Provided Rotor-Stator Geometry*

Texas A&M:

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Jaeyong Ahn*, Ph.D. – PSP Measurement*
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