Aerodynamic Losses and Heat Transfer in a Blade Cascade with 3-D Endwall Contouring

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DOE COOPERATIVE AGREEMENT DE-FC26-02NT41431

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Project Awarded (5/1/2002, 36 Month Duration)

$302,373 Total Contract Value ($302,373: DOE)

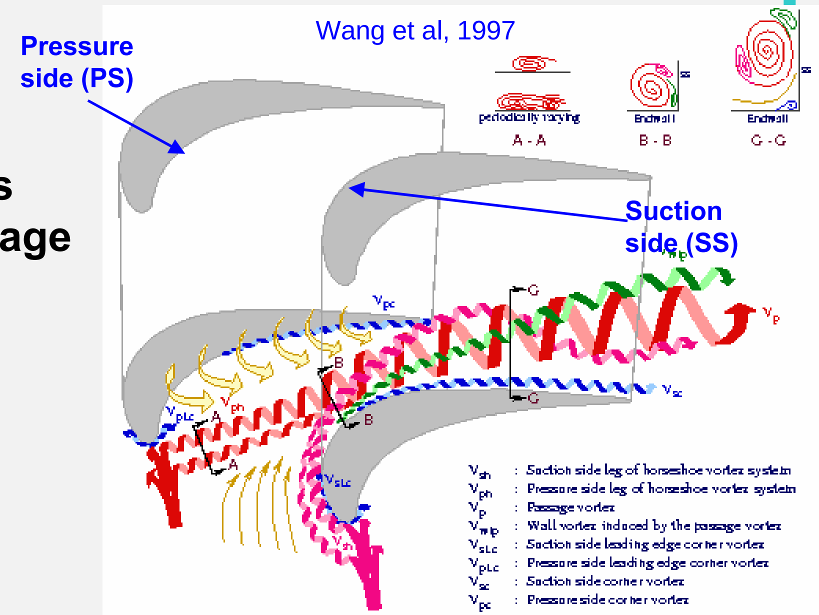
Gas Turbine Need

- Effect of passage vortex structure in vane/blade passages:
  - **enhanced thermal loading on passage walls**
  - **enhanced aerodynamic losses across passage**
  - **reduced film cooling effectiveness**

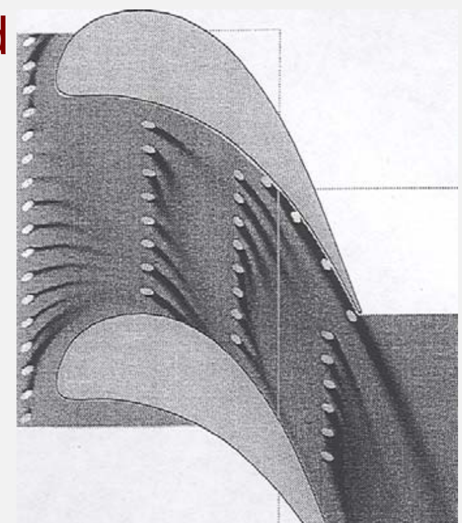
- Weakening of secondary vortex flows will reduce:
  - **thermal loading on passage walls**
  - **aerodynamic losses**
  - **usage of coolant flows**

  leading to lower component maintenance and higher turbine efficiency.

- Uniform pressure distributions at blade passage exit will reduce:
  - **hub-coolant leakage flow**
  - **non-uniformity in exit-flow angle**



Wang et al, 1997

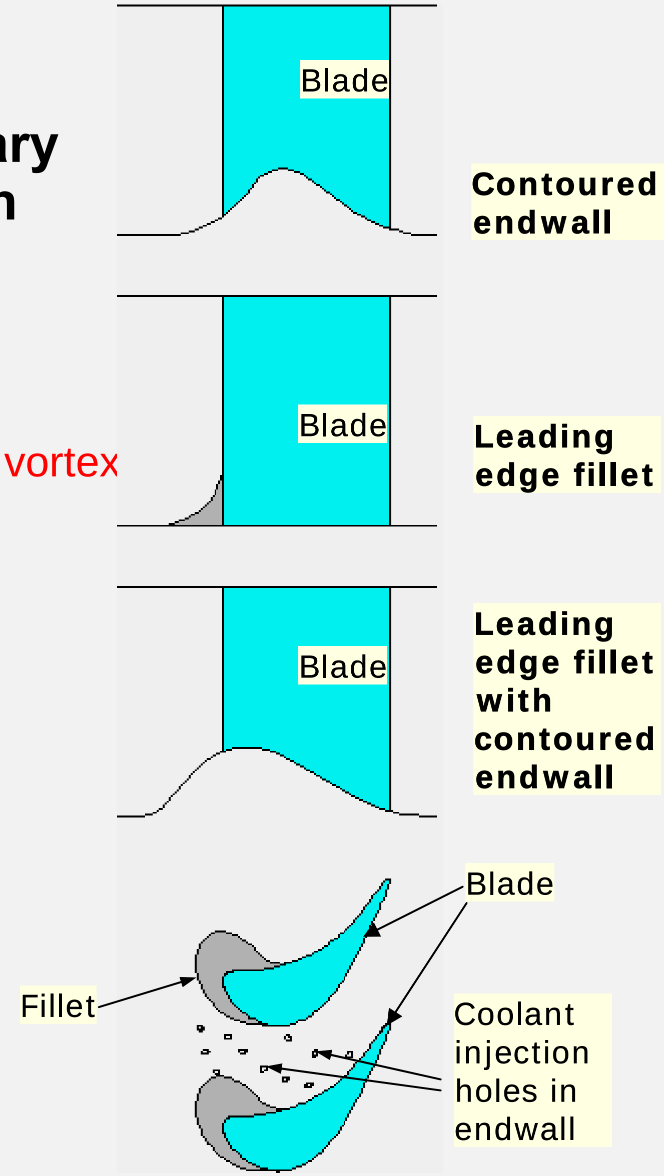

Friedrichs et al, 1996

Project Objectives

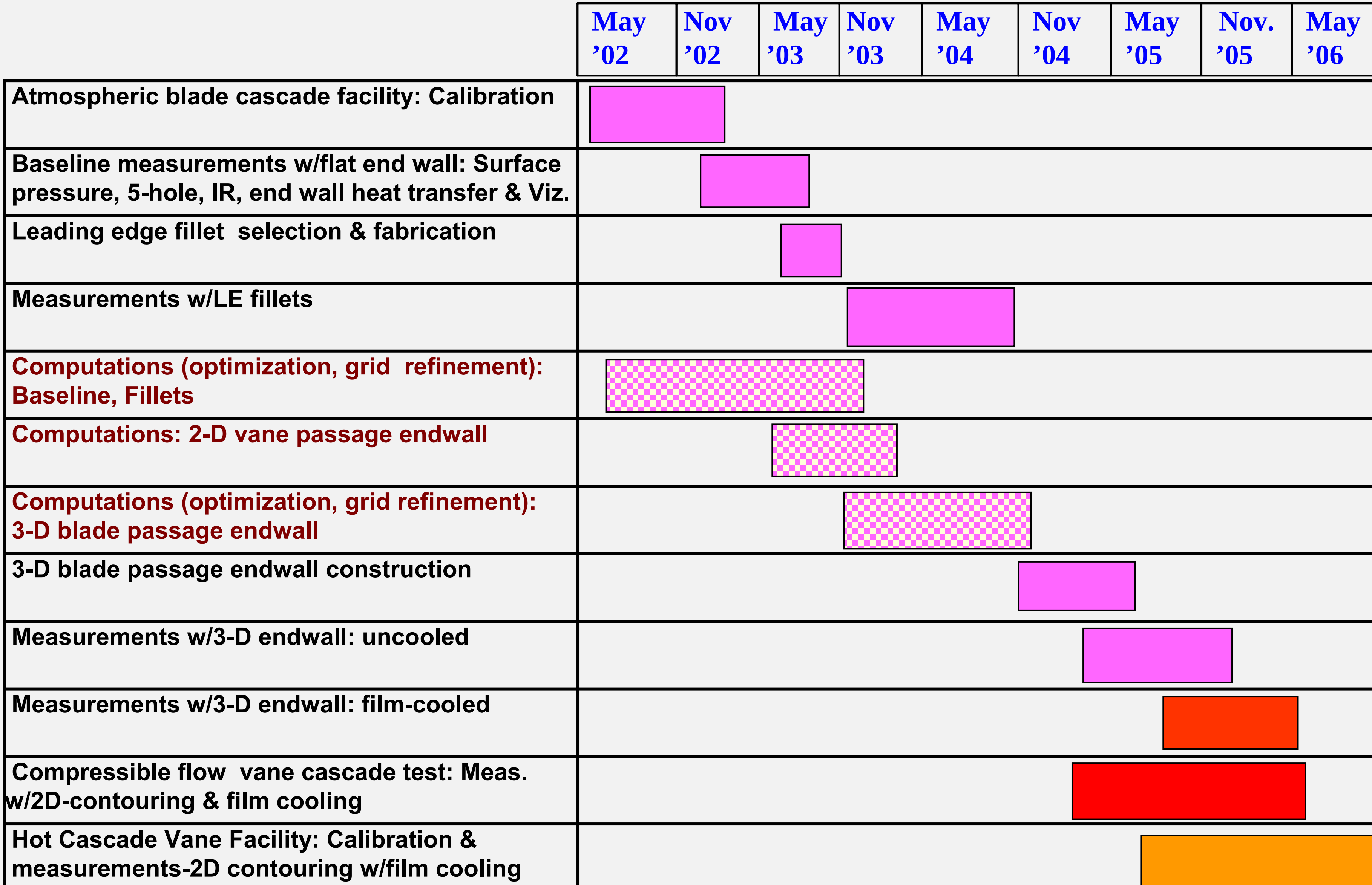
- **Explore strategies for reducing secondary flows in the blade/vane passage through**
  - leading edge fillets
    - Reduces leading edge vortex formation
  - contoured passage endwall
    - 2D:flow acceleration, lower δ and secondary vortex
    - 3D:reduced near-wall pressure gradients

  without and with coolant injection from strategic locations on the endwall

- **Performance metrics to be improved (reduced) include**
  - Heat transfer on passage wall
  - Aerodynamic losses



Project Approach



Accomplishments in 2005

Measurements (cascade)

- Flow field, pressure and end-wall heat transfer for
  - baseline flat endwall blade passage
  - with & without LE fillets
  - **with 3-D contoured endwall without and with endwall film cooling****
  - With 2-D contoured endwall w/film cooling (vane)

- Film cooling effectiveness & flow field with 3-D contoured endwall.

Numerical simulations (RANS)

- Linear **vane** passage with and without endwall axi-symmetric contouring (compressible and incompressible flows).

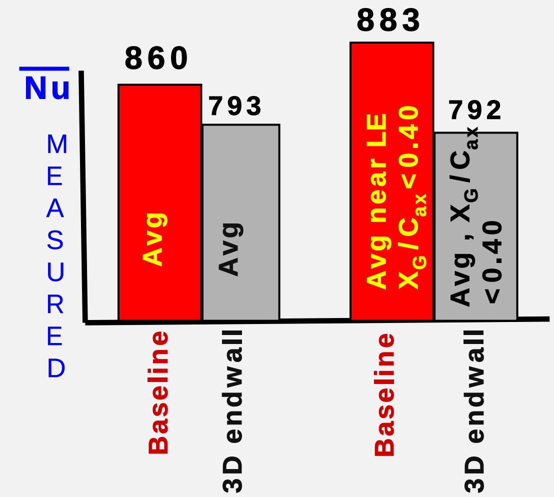
- Linear **blade** passage with and without leading edge fillets (incompressible flow).

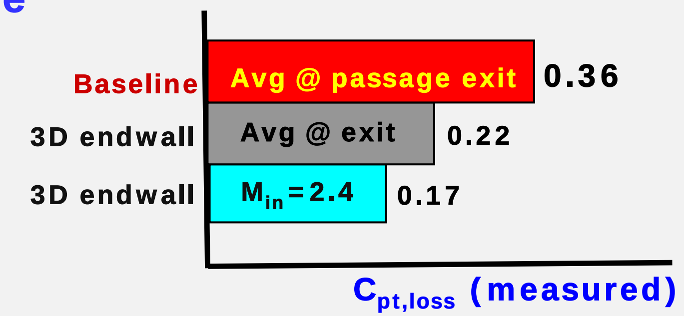
- Linear blade passage with 2-D axi-symmetric and **3-D endwall contouring**** (incompressible flow).

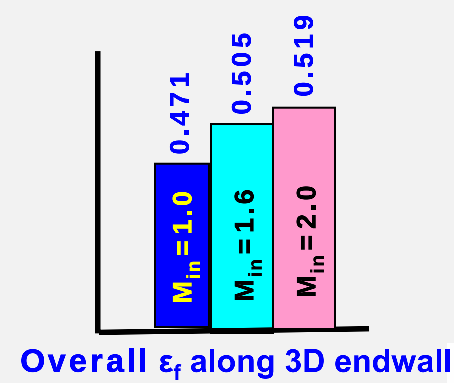
** Focus of today's presentation

Key Results

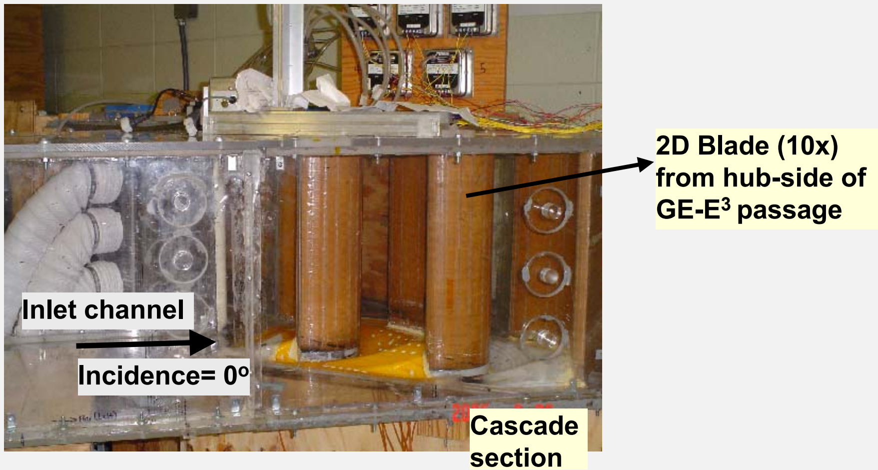
- Optimum 3-D contour endwall profile obtained from numerical simulations. Average Nusselt number measured w/3-D endwall profile reduces endwall heat transfer by ~10%.
- 3-D endwall reduces heat transfer coefficient associated with the PS vortex by ~15% pitch-averaged, and ~24% locally.
- 3-D endwall profile reduces strength and size of passage vortex significantly (factor of 1.5 at TE).
- 3-D endwall profile reduces overall total pressure loss by 39%
- Insignificant effects of 3-D endwall on blade surface pressure distributions in free-stream region.
- Film cooling flow at 3-D endwall at high blowing ratios (>1.6) reduces total exit pressure coefficient (higher exit total pressure) relative to the uncooled case. At M_{in}=2.4 reduction is ~25%
- Adiabatic film cooling effectiveness at 3-D endwall increases by ~10% as blowing ratio doubles from M_{in}=1.0.





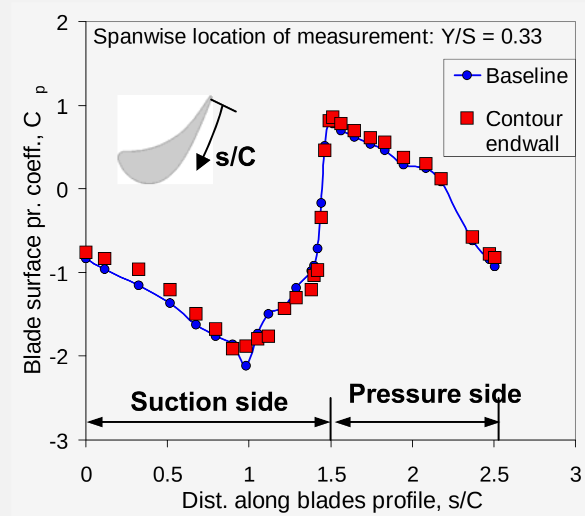


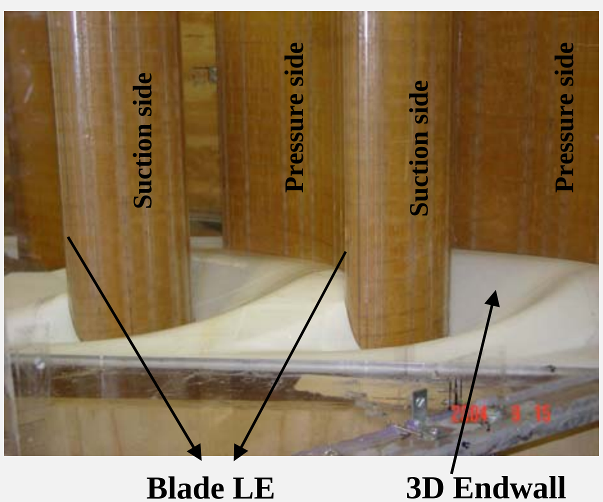
Test Facility & Optimum Contour Profile

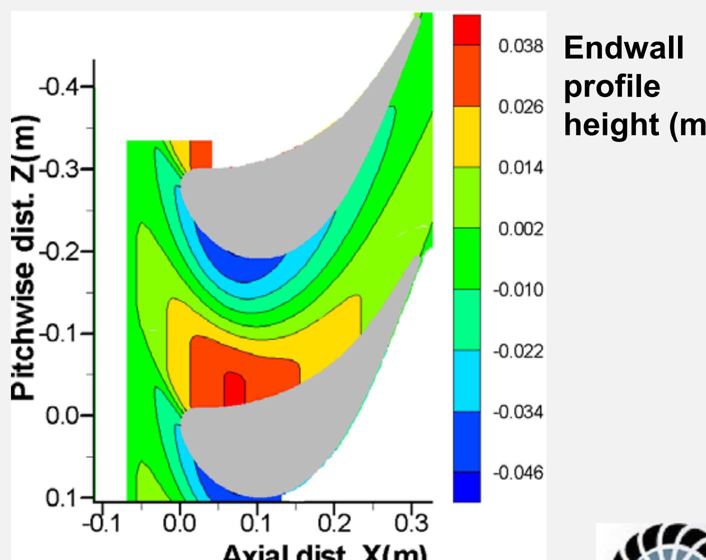


Test facility

Reynolds No.= 230,000

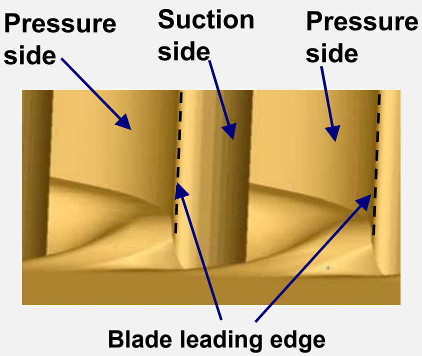


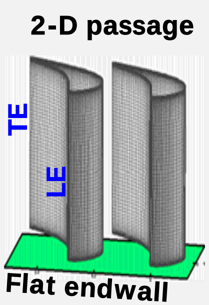


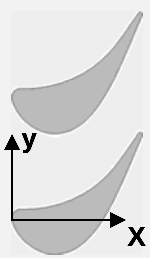


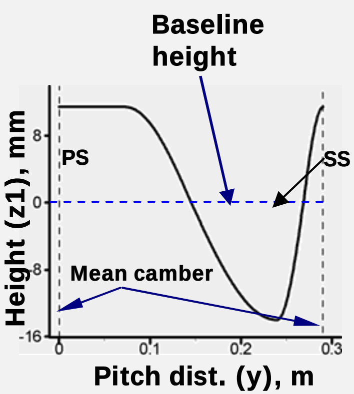
Computational Optimization: Non-Axisymmetric Contour Endwall Profile (Rotor Passage)

S=457mm, C=304 mm





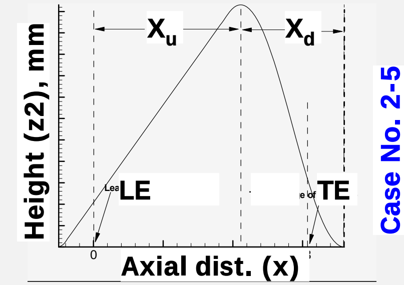


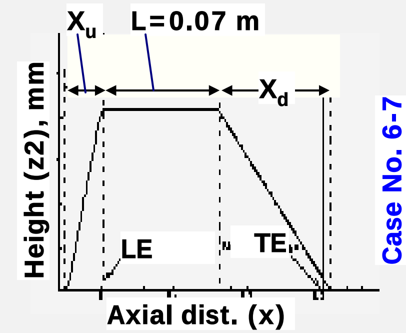


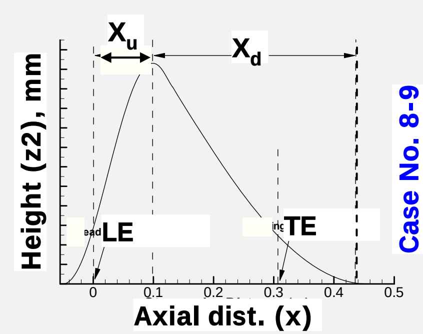
Case No.	Axial dist. (X_u, X_d) meter	Profile ht. (Z_{max}, Z_{min}) meter	Average Nu & $C_{pt,loss}$ (exit)
1	Flat endwall (baseline)	(0.0, 0.0)	736 0.2592
2	X_u= 0.21 X_d= 0.15	Z_{max}= 0.039 Z_{min}= -0.047	710 0.2674
3	X_u= 0.18 X_d= 0.18	Z_{max}= 0.039 Z_{min}= -0.046	709 0.2641
4	X_u= 0.16 X_d= 0.20	Z_{max}= 0.039 Z_{min}= -0.045	704 0.2599
5	X_u= 0.13 X_d= 0.23	Z_{max}= 0.039 Z_{min}= -0.045	697 0.2603
6	X_u= 0.16 X_d= 0.16	Z_{max}= 0.019 Z_{min}= -0.023	691 0.2585
7	X_u= 0.16 X_d= 0.16	Z_{max}= 0.029 Z_{min}= -0.035	678 0.2589
8	X_u= 0.15 X_d= 0.21	Z_{max}= 0.039 Z_{min}= -0.046	689 0.2596
9	X_u= 0.10 X_d= 0.34	Z_{max}= 0.039 Z_{min}= -0.046	678 0.2548

Optimum profile

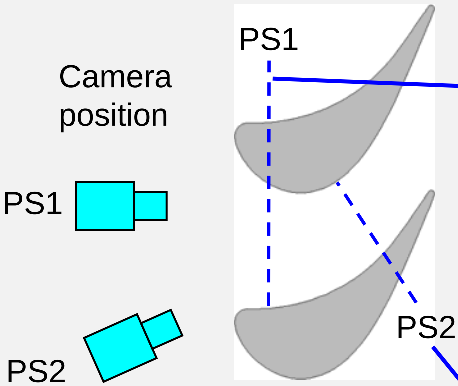
Profile ht. (Z) at (x,y) = z1 * z2





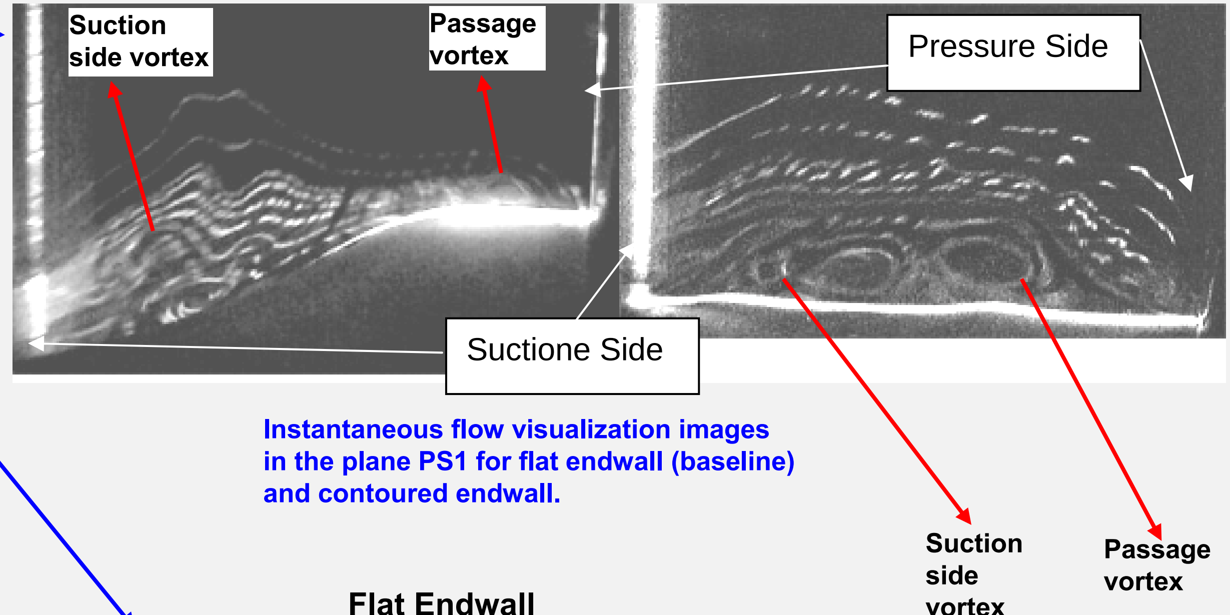


Flow Visualization with Smoke (U_o=1.0 m/s)



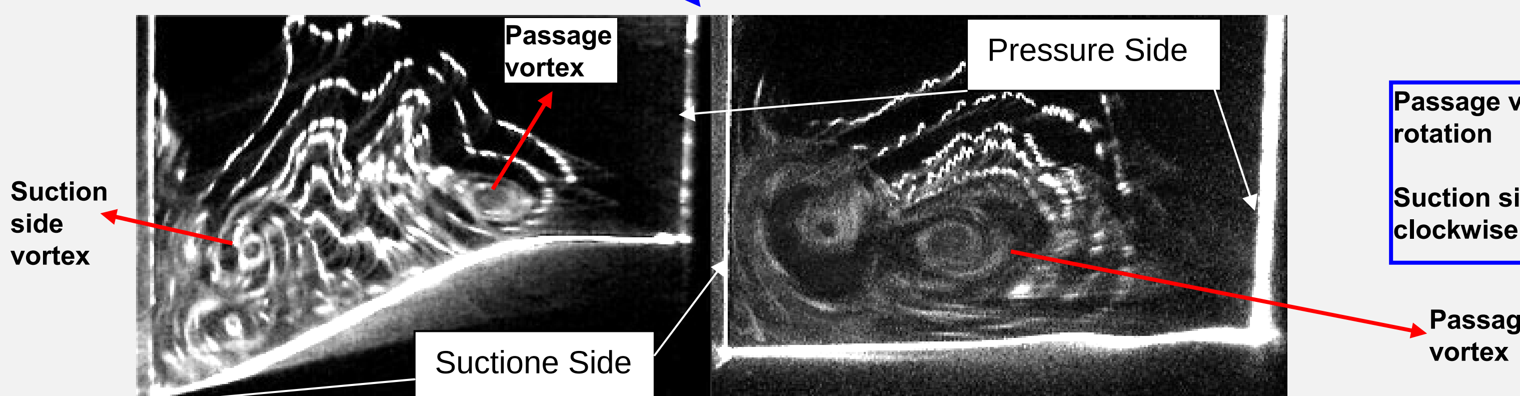
Visualization planes and camera positions relative to the visualization planes.

Contoured Endwall **Flat Endwall**



Instantaneous flow visualization images in the plane PS1 for flat endwall (baseline) and contoured endwall.

Contoured Endwall **Flat Endwall**

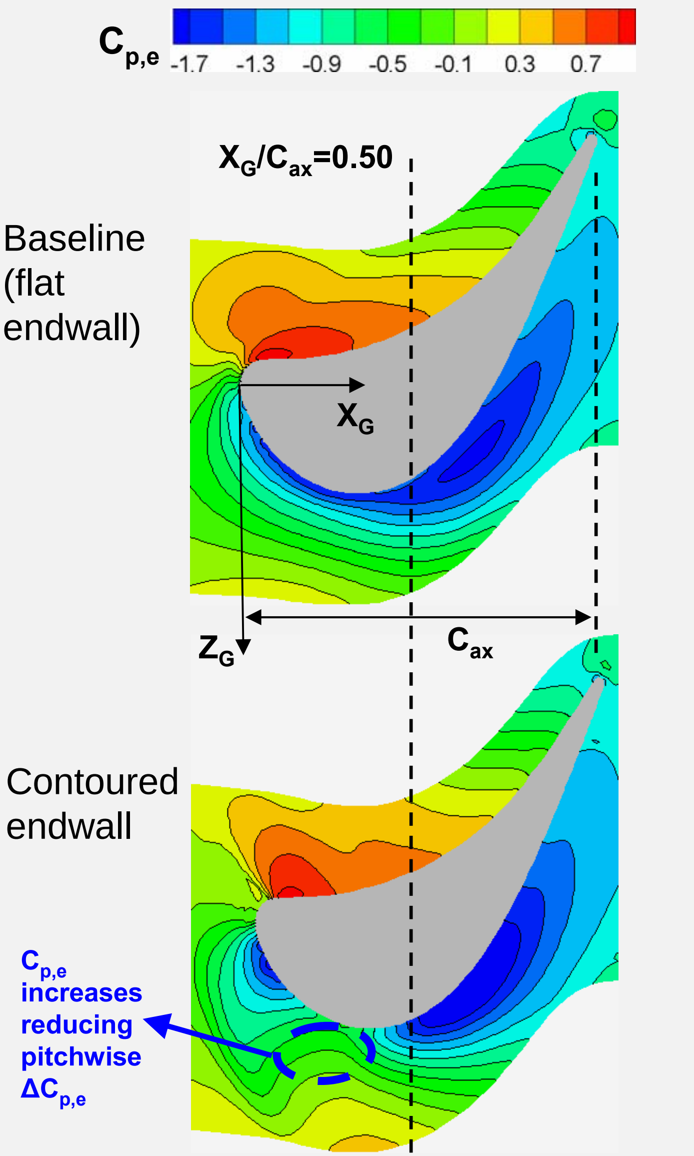


Passage vortex: clockwise rotation

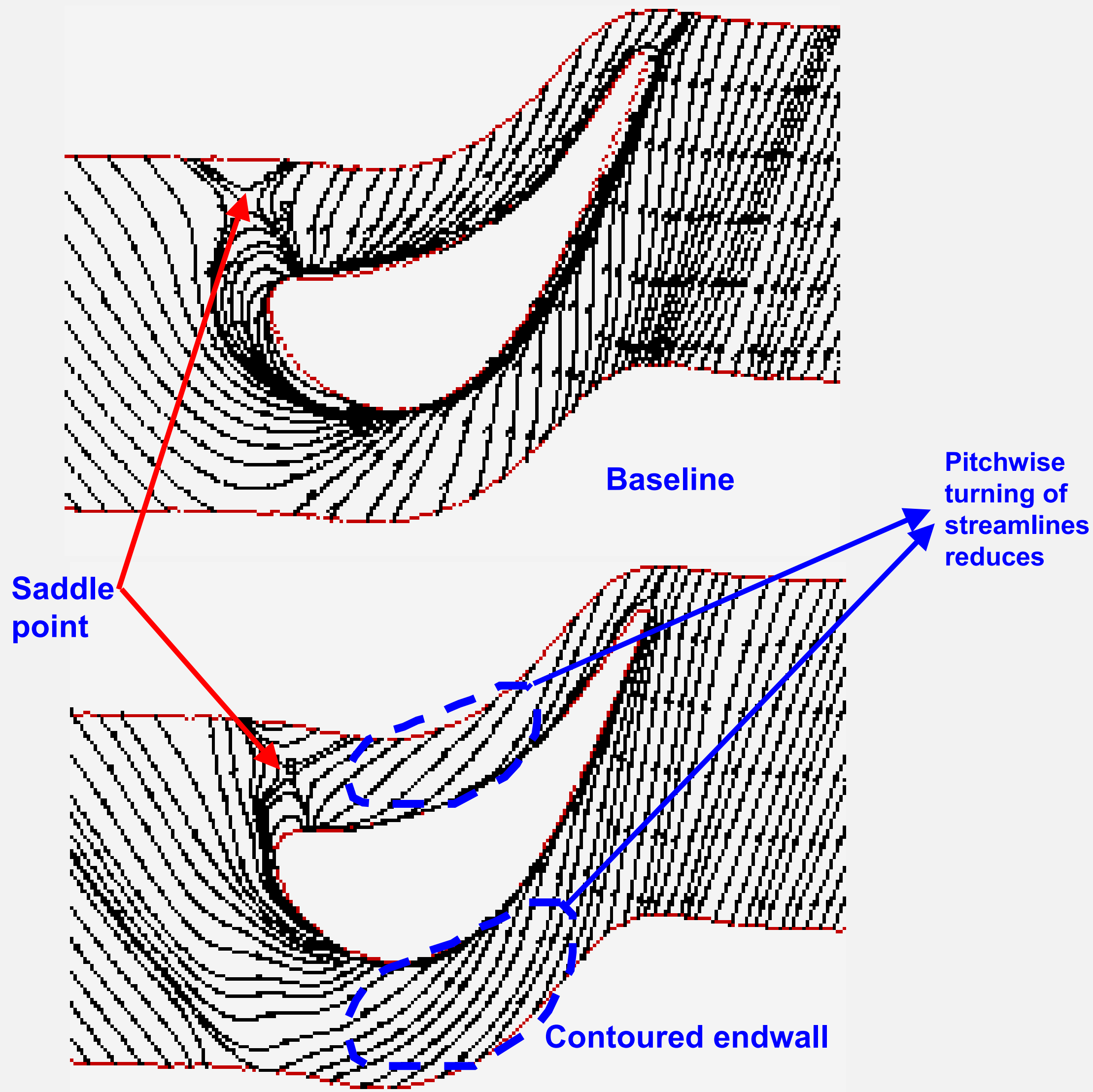
Suction side vortex: counter-clockwise rotation

Instantaneous flow visualization images in the plane PS2 for flat endwall (baseline) and contoured endwall.

Endwall Region Pressure and Streamlines (Computations)

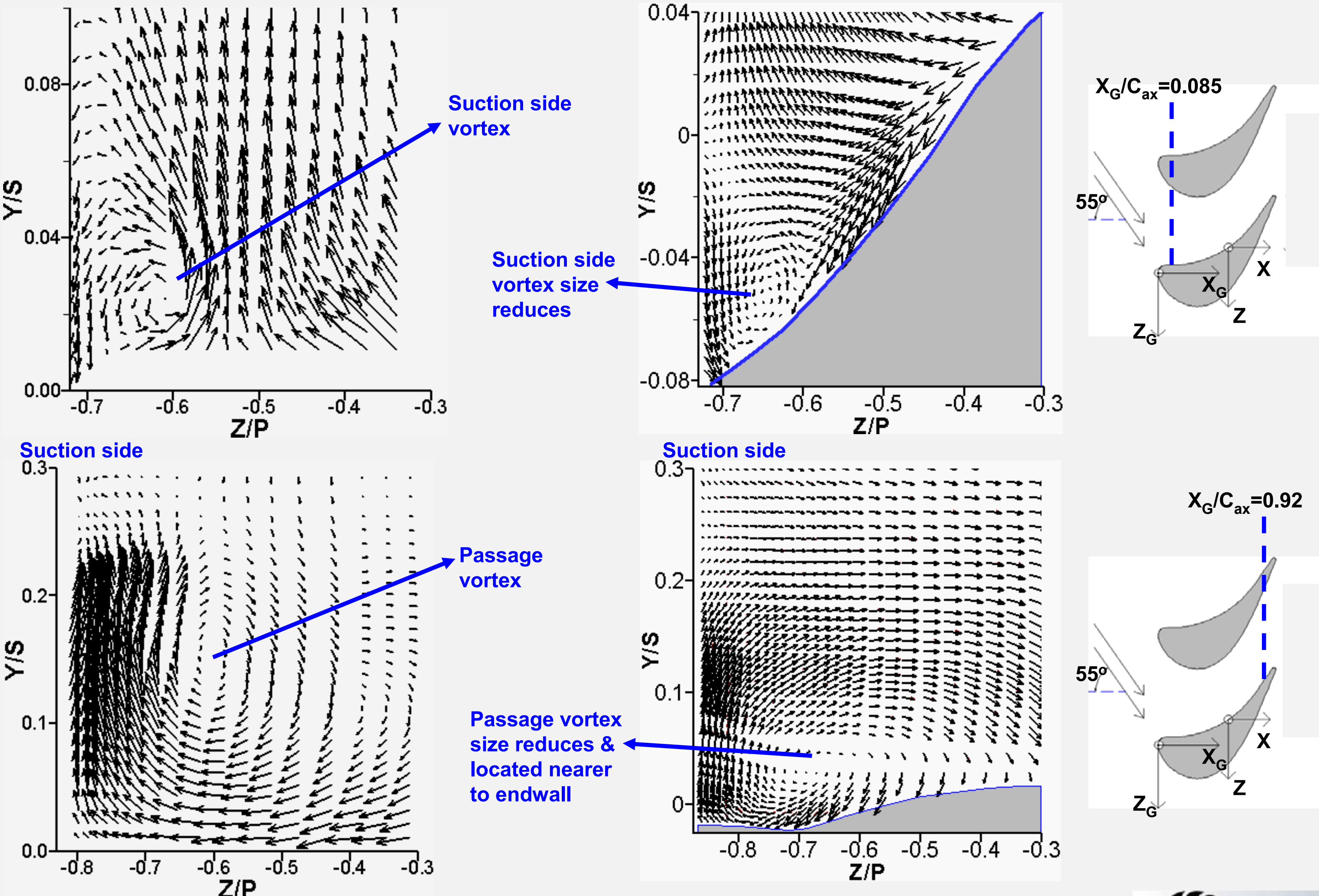


Endwall static pressure coefficient



Surface streamlines from friction velocities

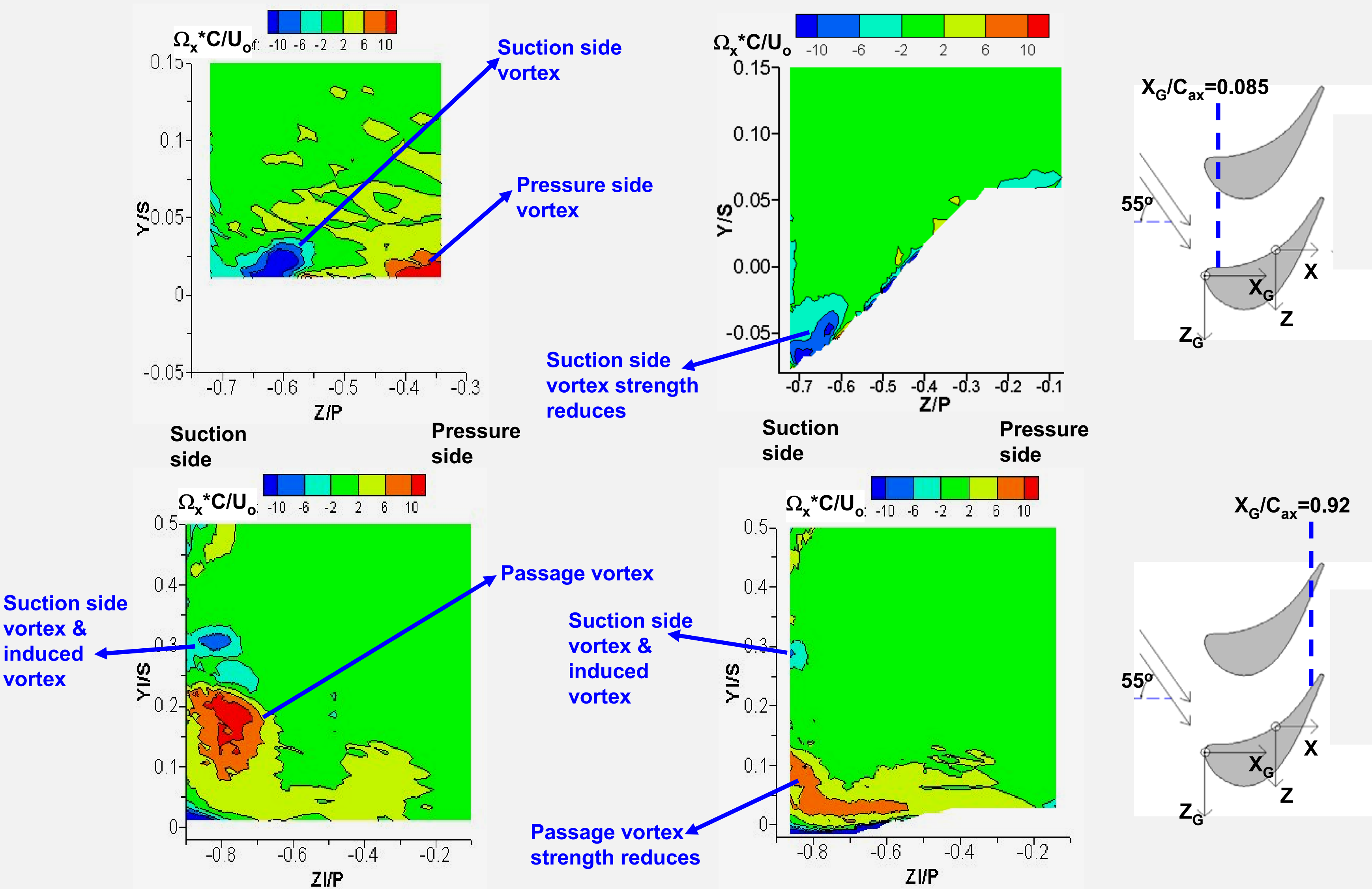
Velocity Vectors in Pitchwise Planes (Measurements)



Baseline

Contoured endwall

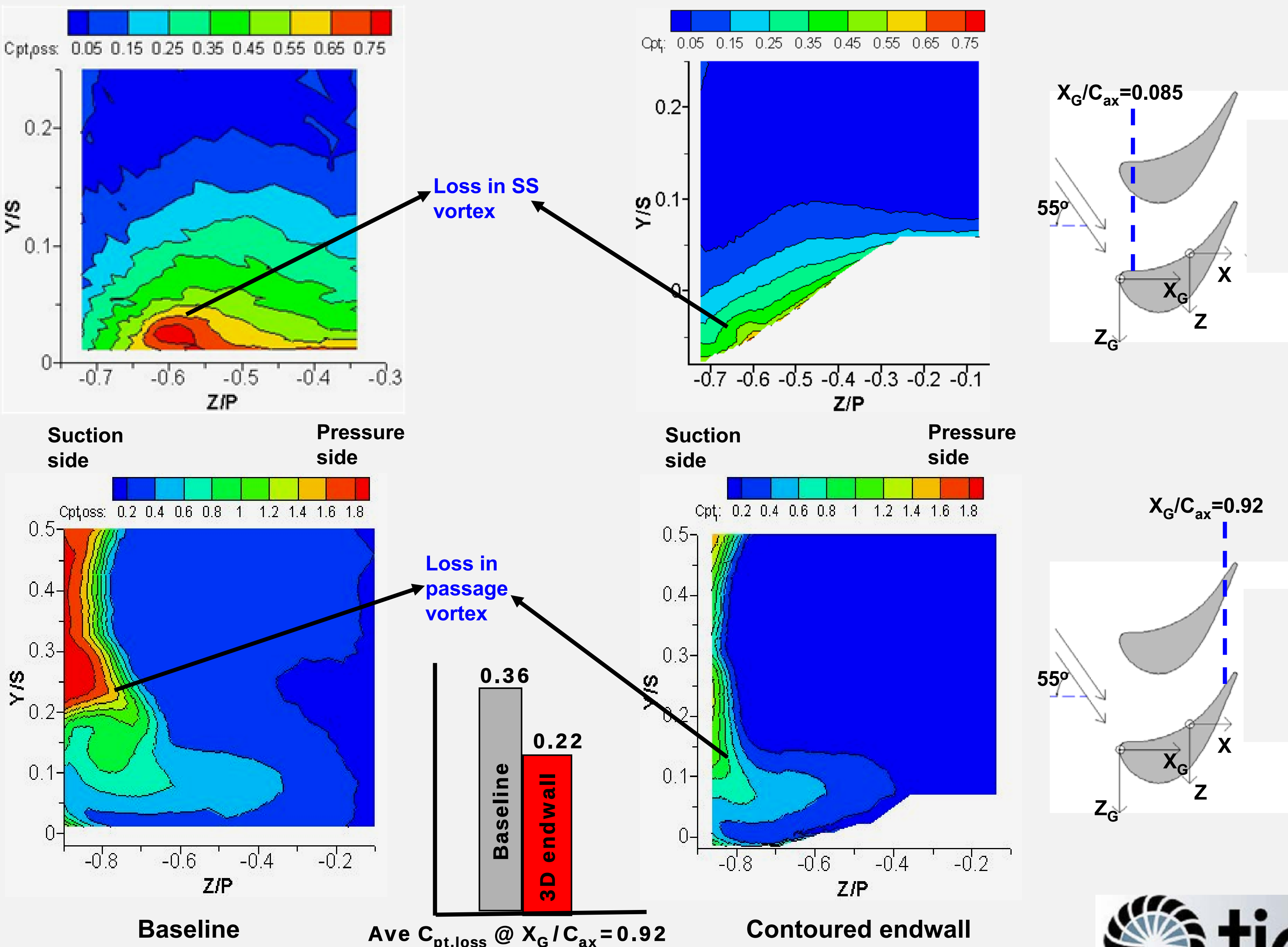
Axial Vorticity in Pitchwise Planes (Measurements)



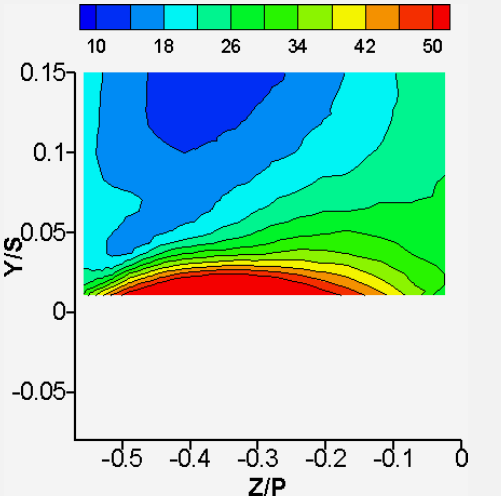
Baseline Peak~12

Contoured endwall Peak~8.5

Total Pressure Loss Coeff., $C_{pt,loss}$ in Pitchwise Planes (Measurements)

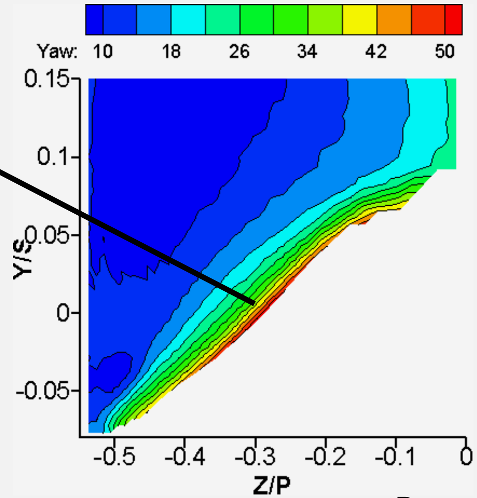


Yaw Angle (Pitchwise Flow Deviation) in Pitchwise Planes (Measurements)



Suction side

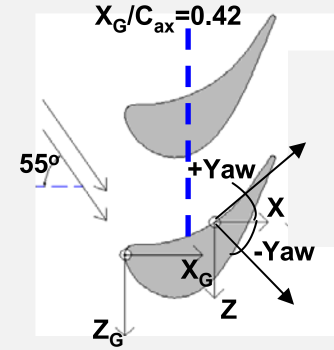
Pressure side

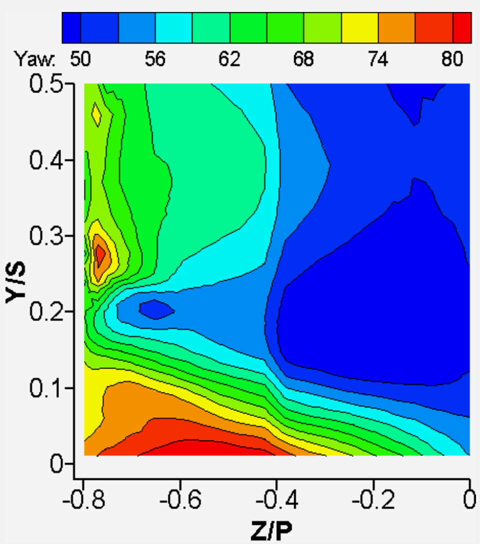


Suction side

Pressure side

Yaw angle reduces (flow turns less toward SS)

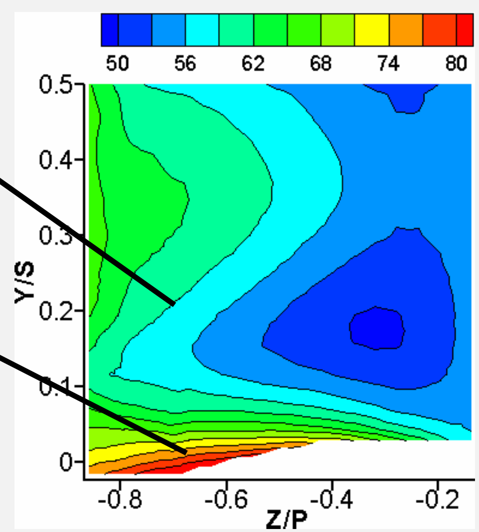




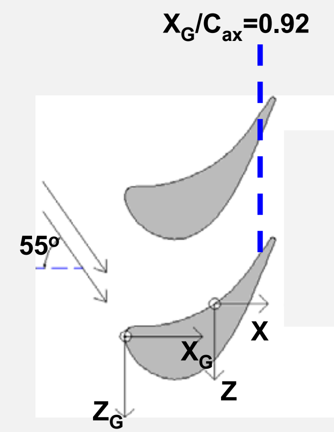
Baseline

Yaw angle increases due to weaker passage vortex

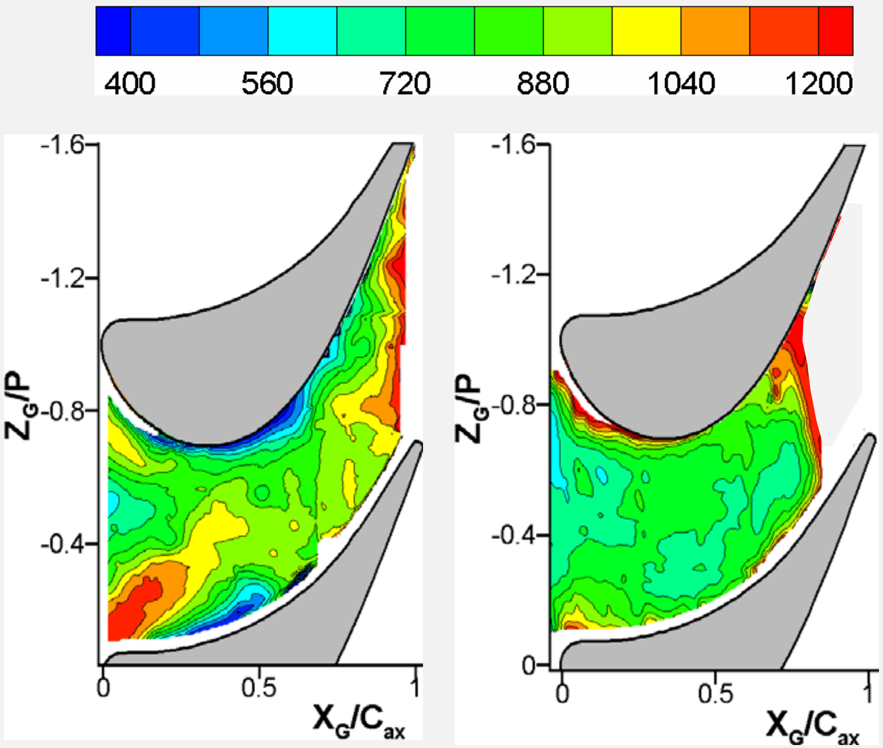
Yaw angle reduces (flow turns less toward SS)



Contoured endwall

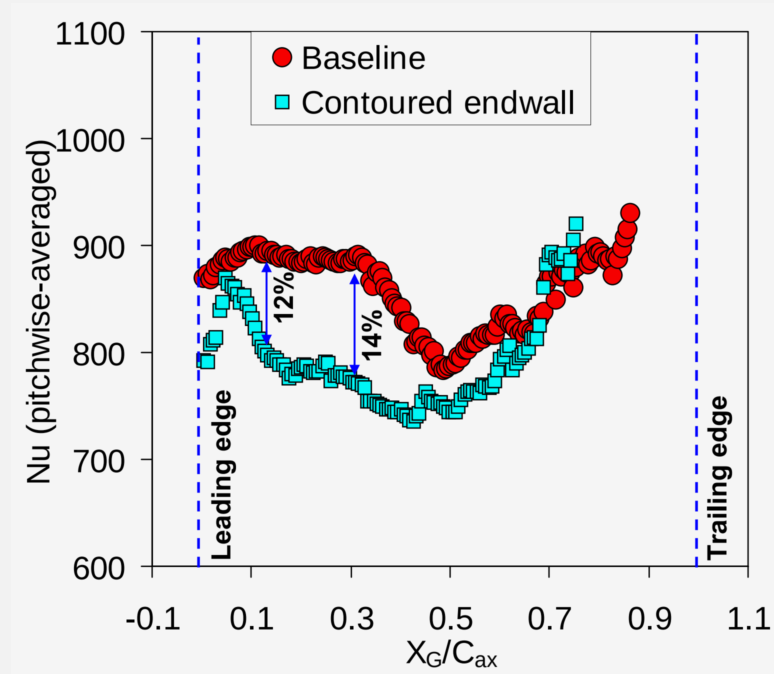


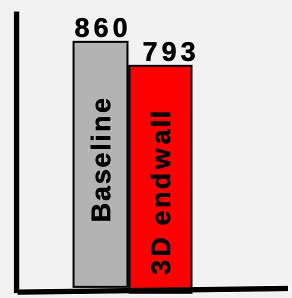
Endwall Nusselt Number (Measurements)



Baseline

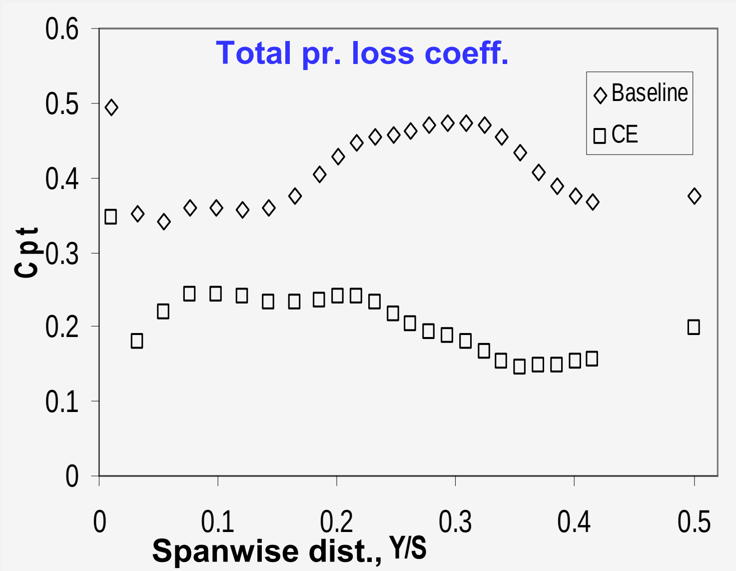
Contoured endwall

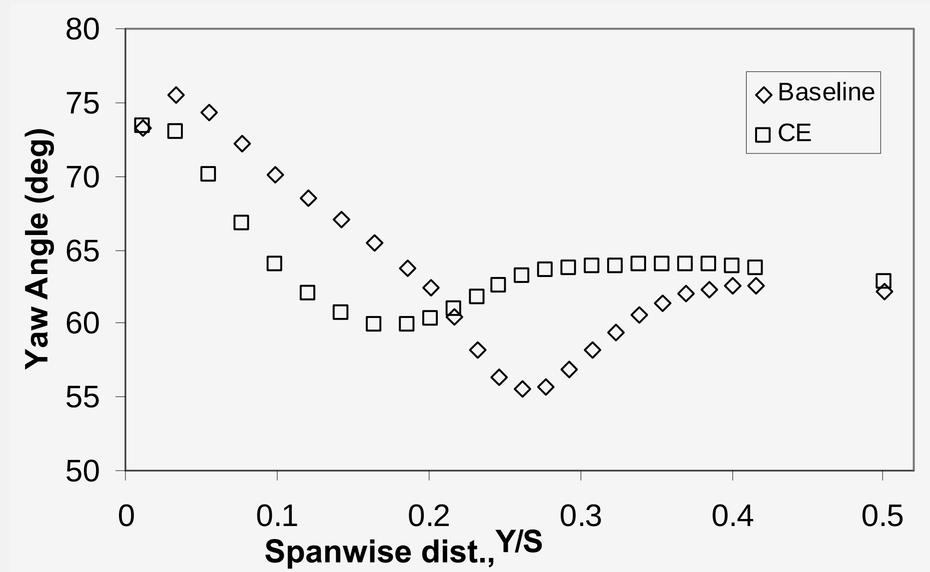


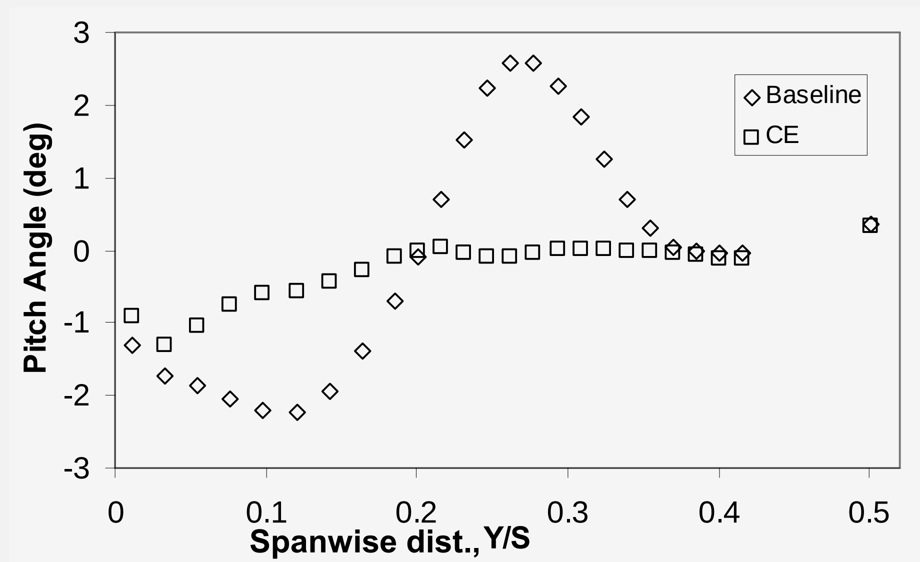


Ave Nusselt number for $X_G/C_{ax} < 0.90$

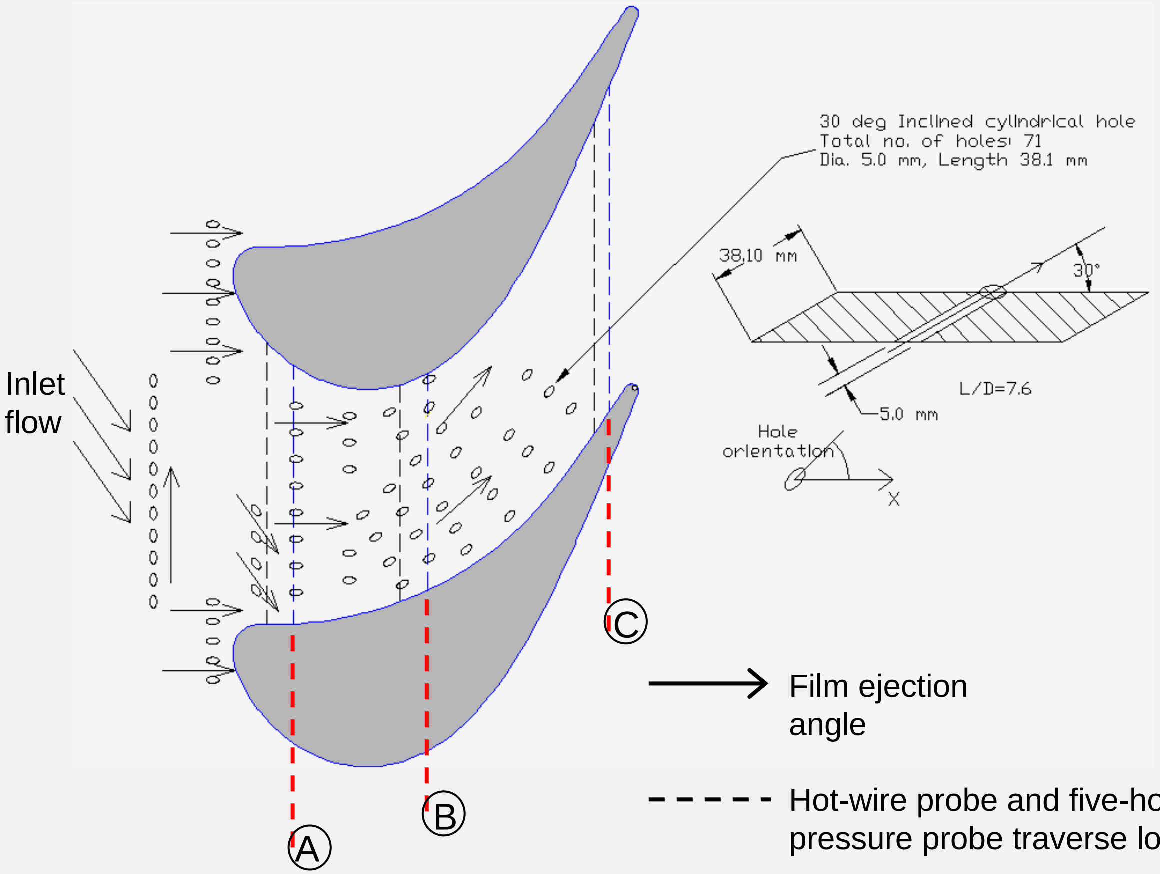
Pitchwise Mass-Averaged Pressure Loss & Flow Angles Near Passage Exit

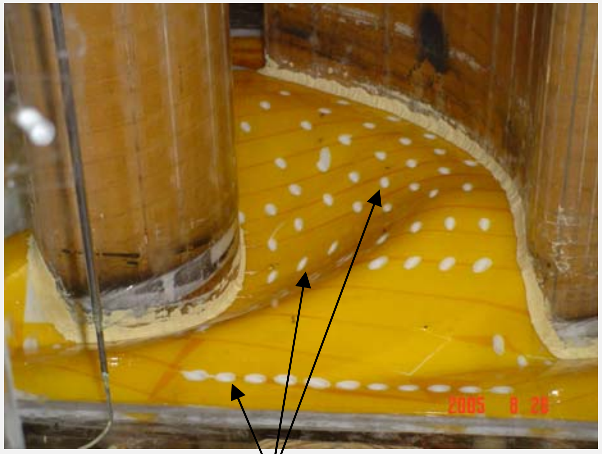






3D Non-Axisymmetric Contour Endwall with Film Cooling Holes





Film cooling hole locations in 3D endwall

→ Film ejection angle

- - - - Hot-wire probe and five-hole pressure probe traverse location

- - - - Temperature probe traverse location

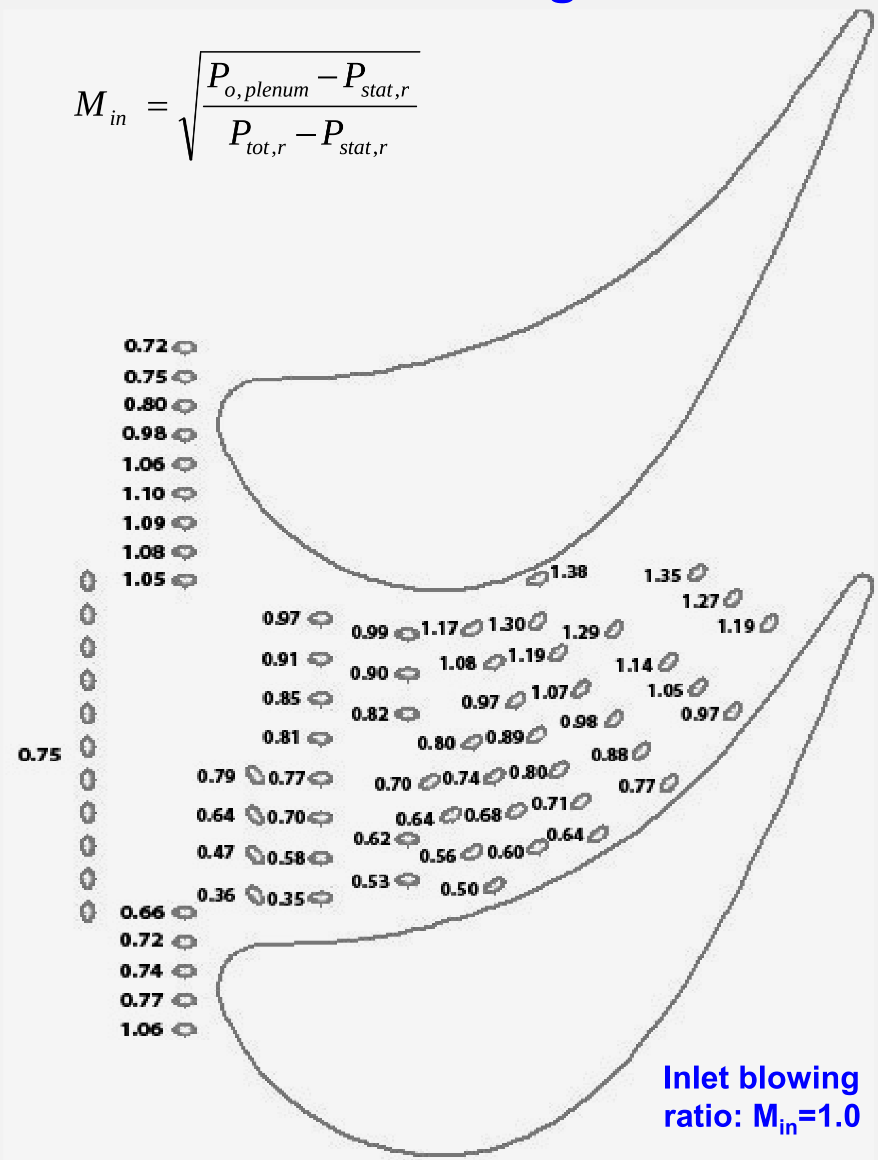
Temperature meas. plane	Location, X_G/C_{ax}
A	0.152
B	0.493
C	0.954

Local Blowing Ratio from Coolant Holes in 3D Endwall

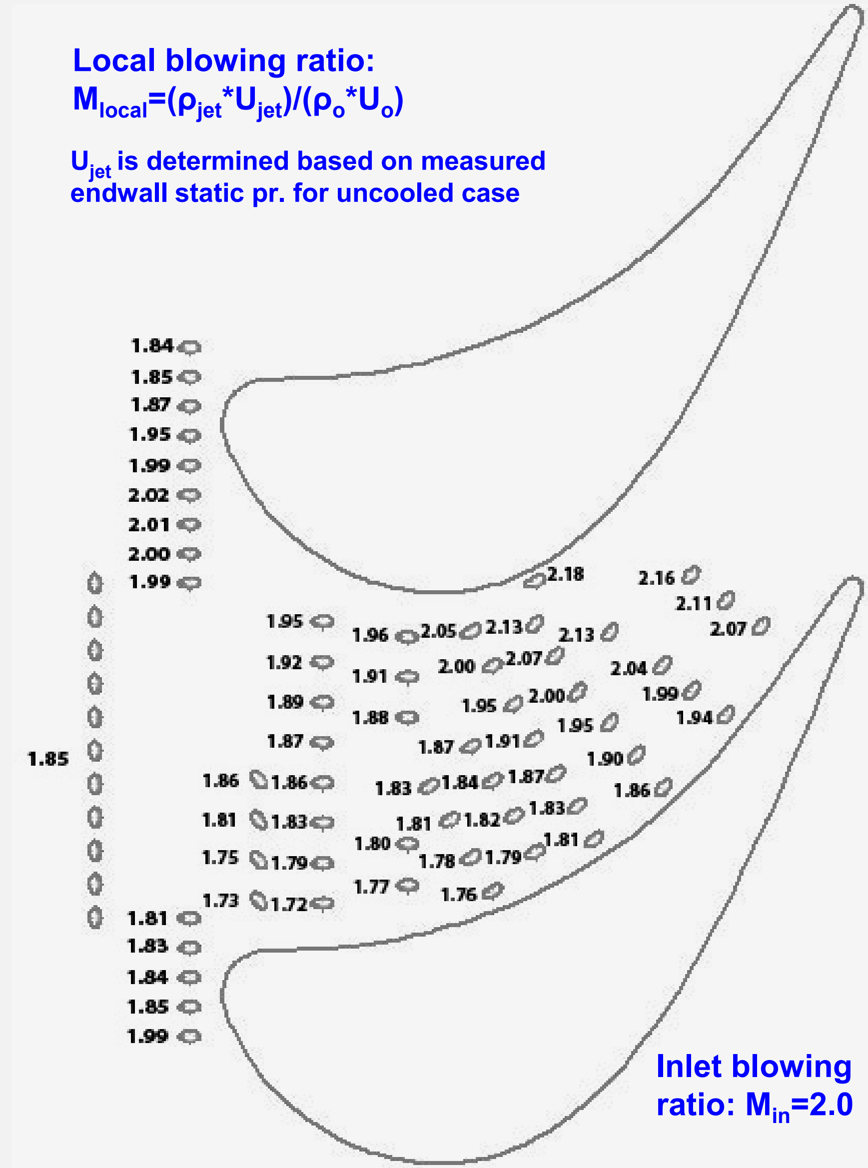
$$M_{in} = \sqrt{\frac{P_{o,plenum} - P_{stat,r}}{P_{tot,r} - P_{stat,r}}}$$

Local blowing ratio:
$M_{local}=(\rho_{jet}*U_{jet})/(\rho_o*U_o)$

U_{jet} is determined based on measured endwall static pr. for uncooled case

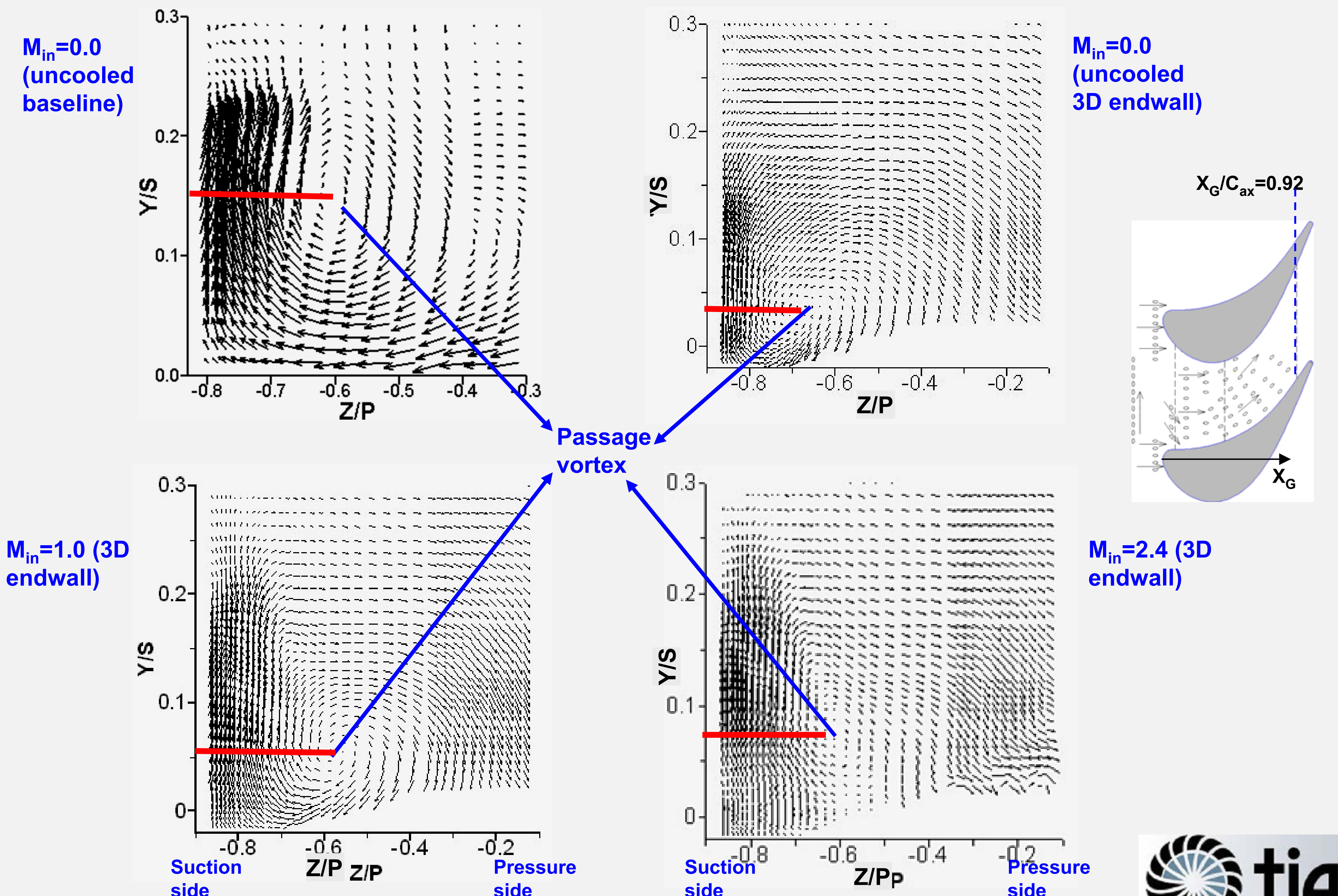


%coolant flow rate-1.2

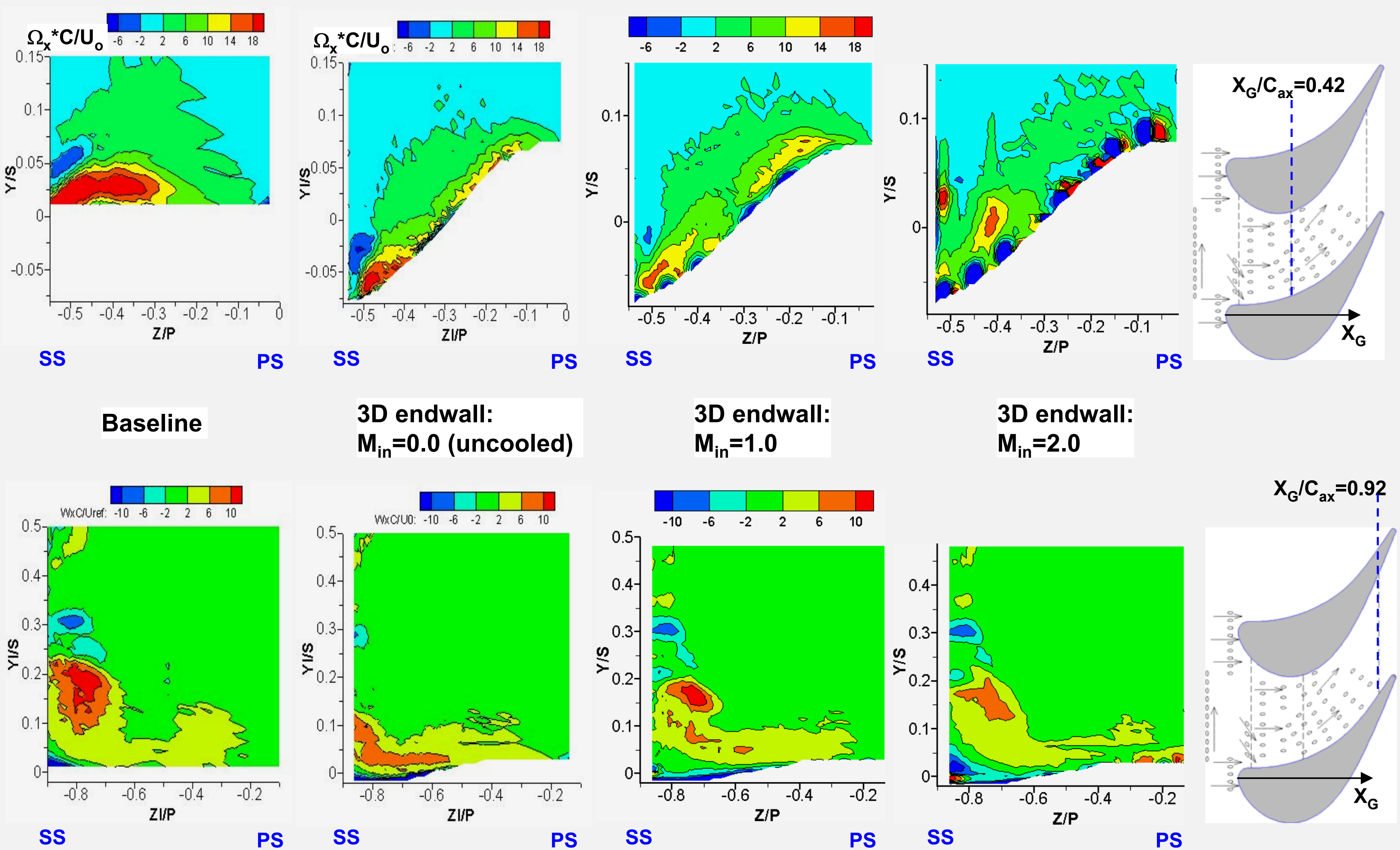


%coolant flow rate-2.7

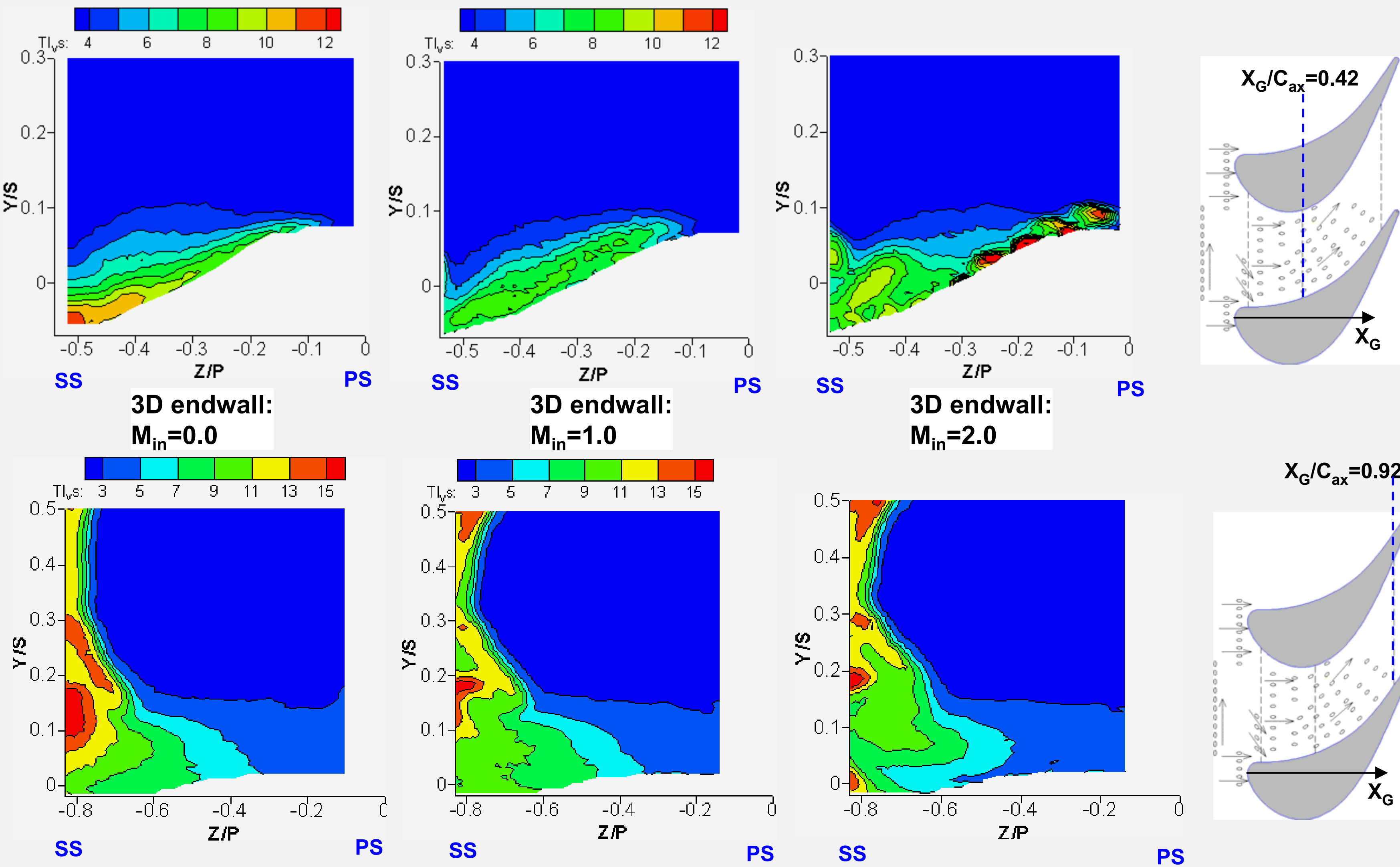
Velocity Vector with and without Film Cooling Flow Near Exit



Axial Vorticity, $\Omega_x C/U_o$ with and without Film Cooling Flow



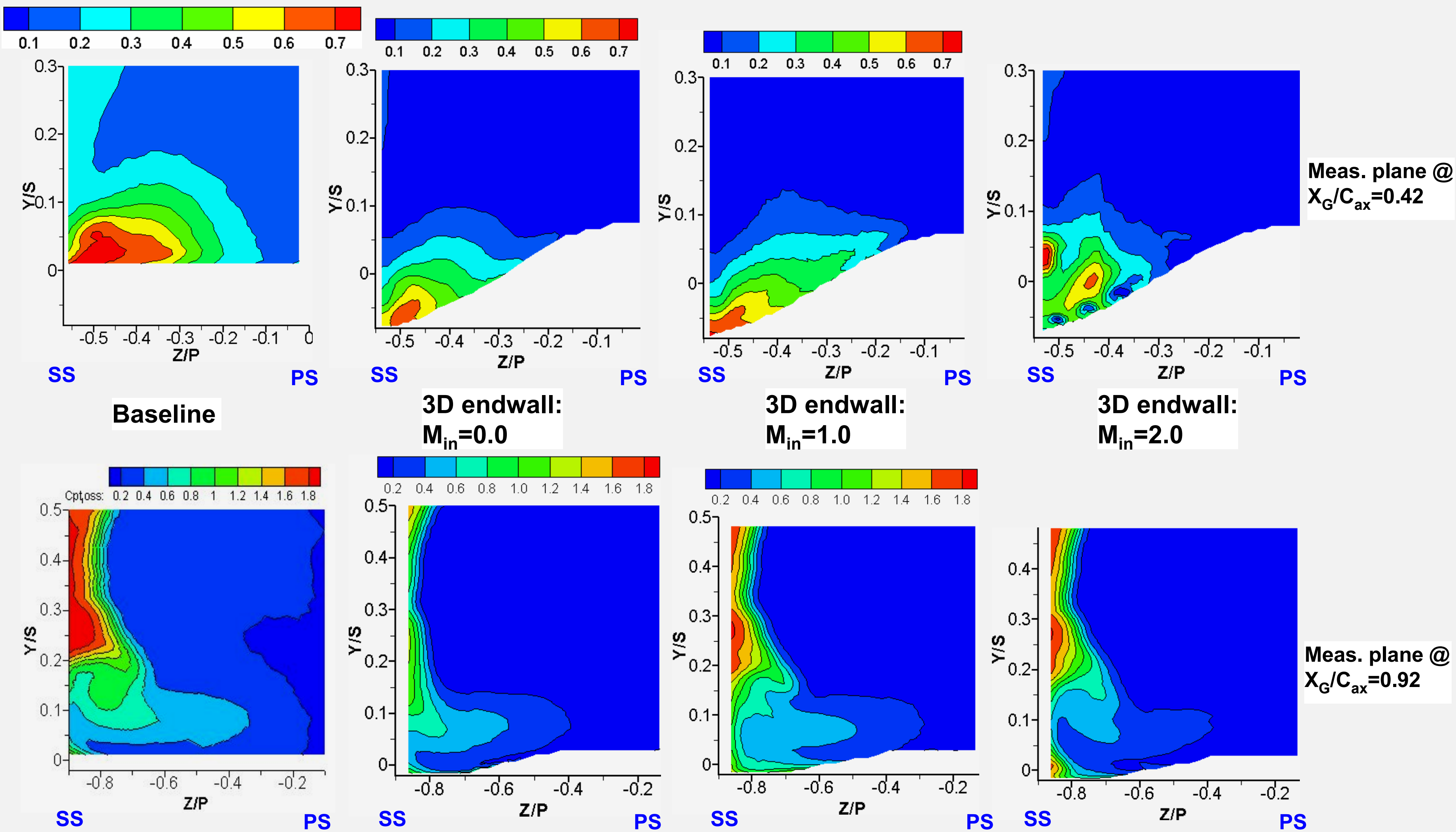
Streamwise Turbulence Intensity(%) with and without Film Cooling Flow



Mass-averaged @ X_G/C_{ax}=0.92

M_{in}	0.0	1.0	1.3	1.6	1.8	2.0	2.4
TI%	4.63	4.61	5.09	4.70	4.66	4.46	4.66

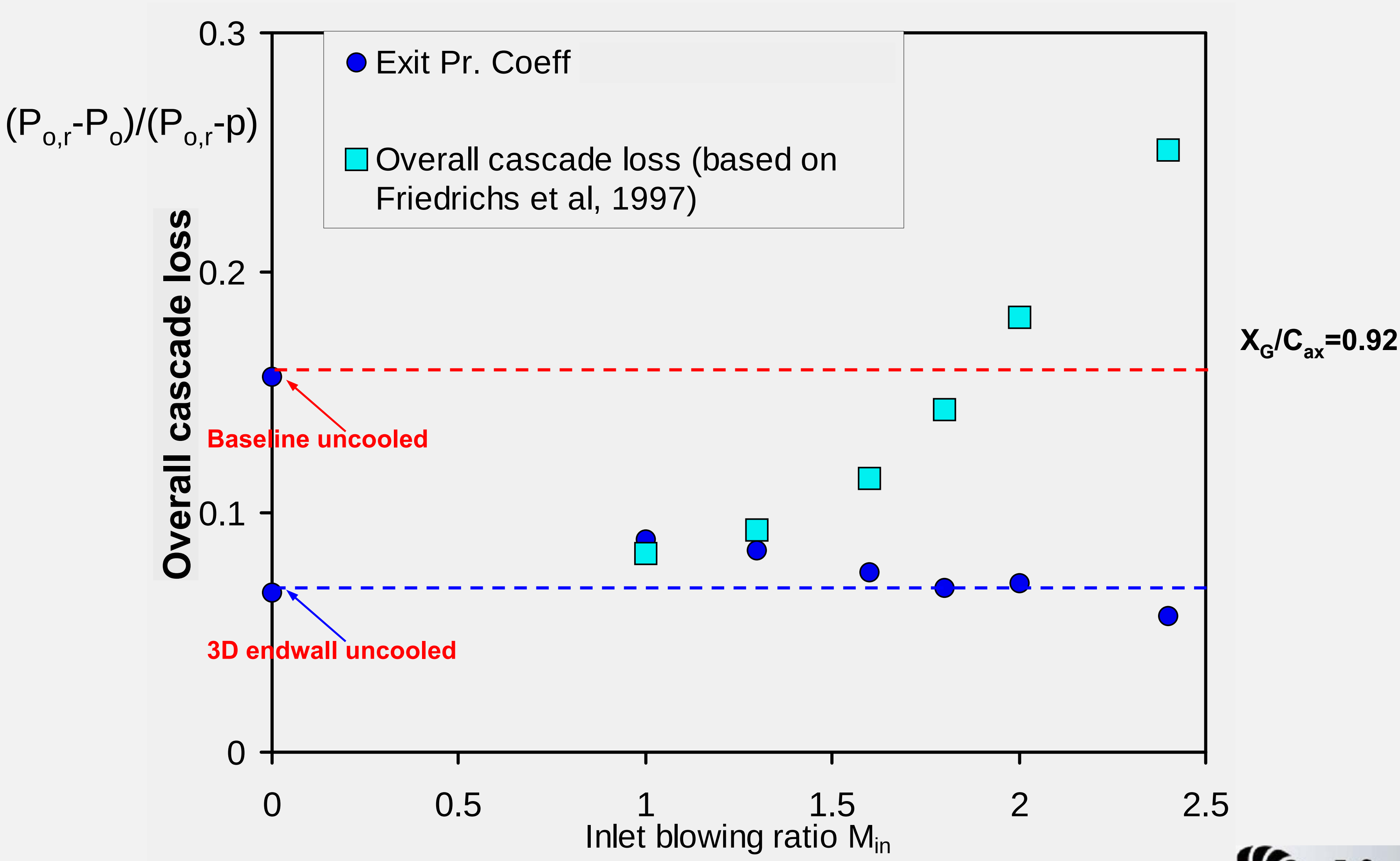
Total Pressure Loss (Diff) Coeff., $C_{pt,loss}$ with & without Film Cooling



Mass-averaged @ X_G/C_{ax}=0.92

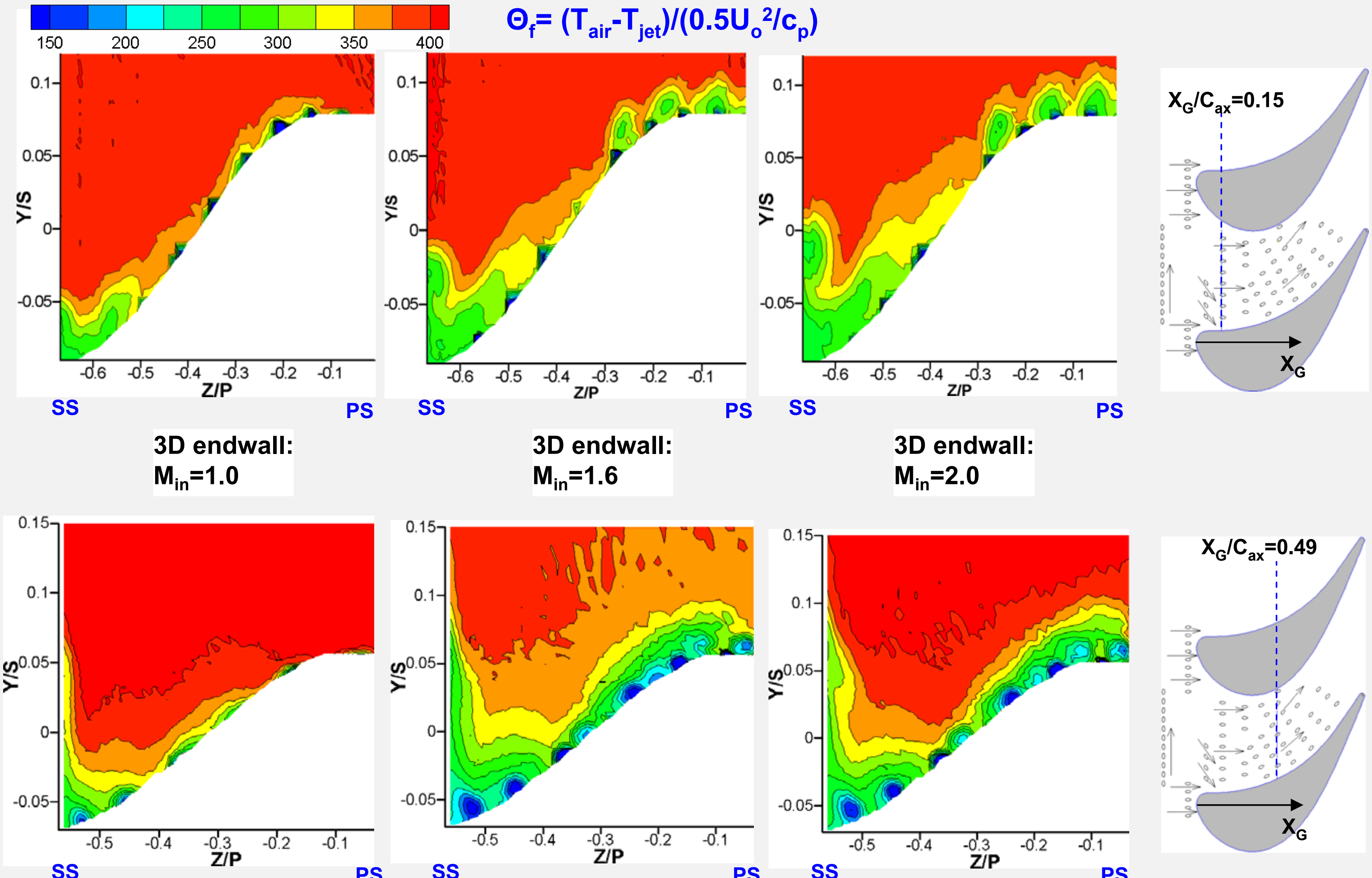
M_{in}	Flat	0.0	1.0	1.3	1.6	1.8	2.0	2.4
$C_{pt,loss}$	0.36	0.22	0.24	0.23	0.21	0.187	0.192	0.17

Overall Cascade Losses with and without Film cooling Flow (Based on Friedrichs et al., 1997)

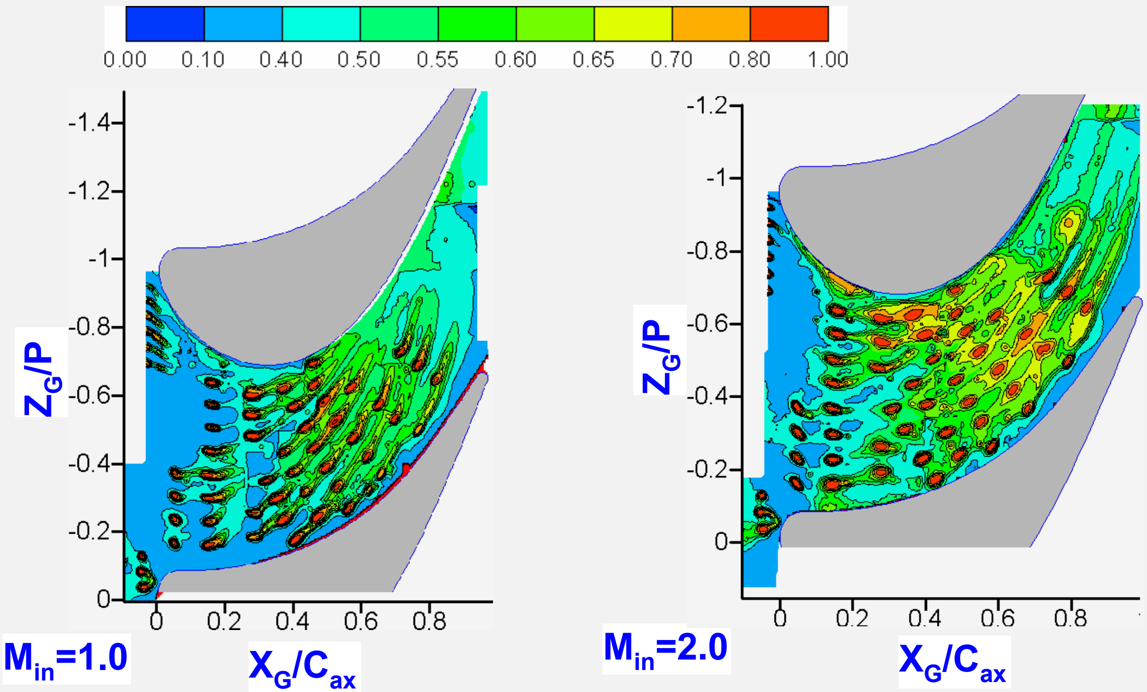


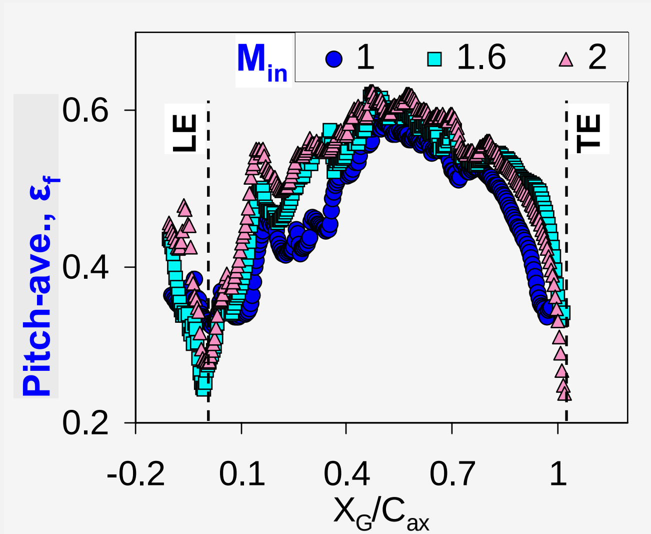
Non-dimensional Flow Temperature, θ_f with Film cooling Flow

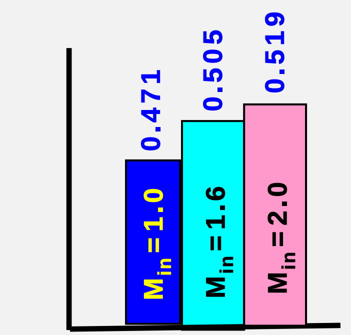
$$\Theta_f = (T_{air} - T_{jet})/(0.5U_o^2/c_p)$$



Adiabatic Film Cooling Effectiveness, ε_f with 3D Endwall (Measurements)







$\varepsilon_f = (T_o - T_{aw})/(T_o - T_{jet})$

T_o=Main stream temp.

Project Summary

- **Goal of the project- explore strategies for reducing secondary flows and heat transfer in blade/vane passages through the *use of endwall contouring, and leading edge fillets with and without coolant injection*.**

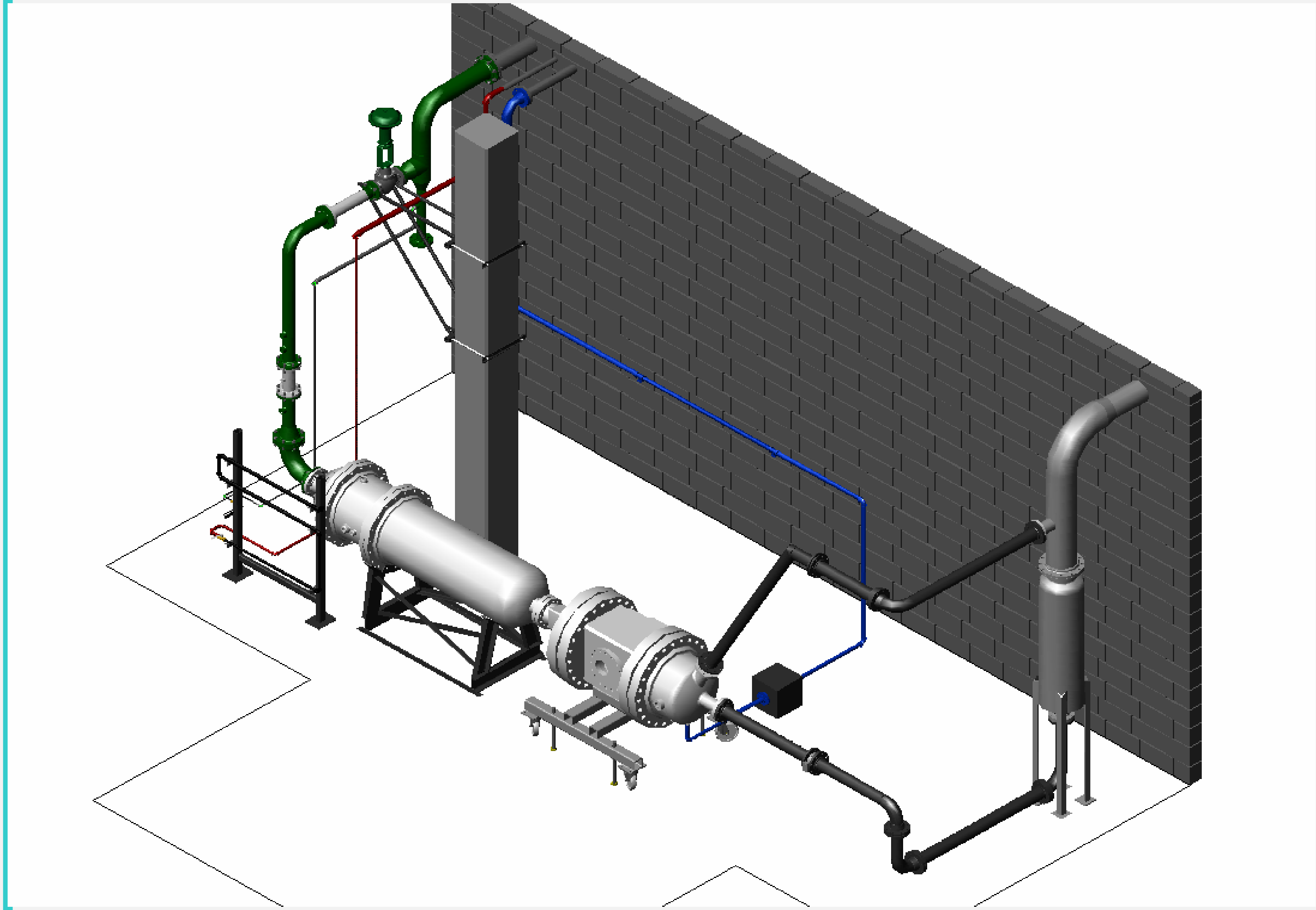
- **Performance metrics of interests are endwall heat transfer and aerodynamic losses.**

- **CFD codes used to predict several profiles of 3-D endwall and to make recommendations for experimental measurements.**

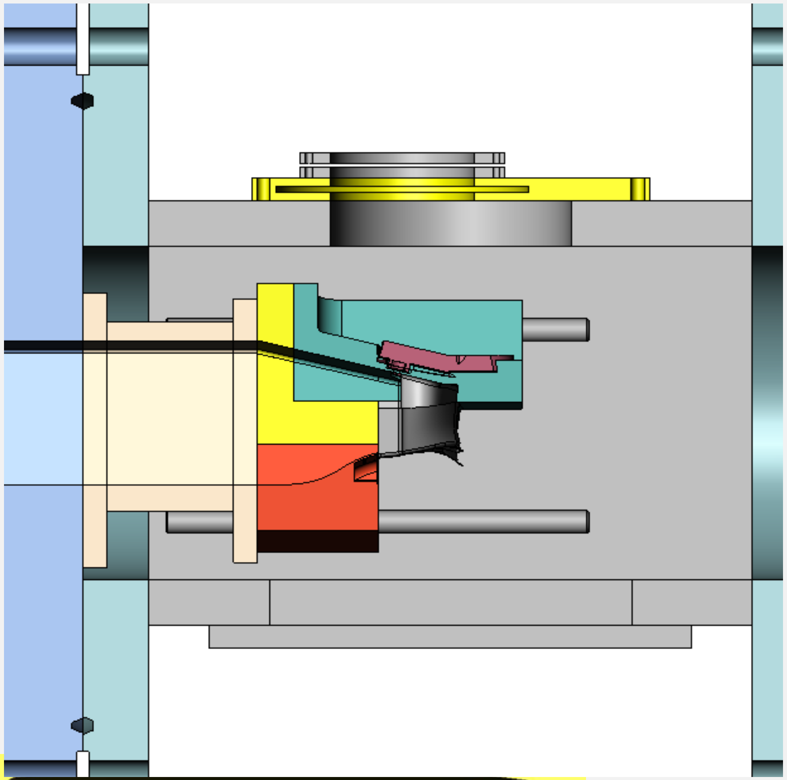
- **Flow field and heat transfer measured in atmospheric blade cascade facility with 3D non-axisymmetric endwall**
  - **Passage vortex clearly reduced by contouring**
  - **Nusselt numbers are reduced upstream of throat region and pitchwised averaged reduction can be as much as 15%.**
  - **Total pressure losses are reduced significantly across the passage (~40%).**
  - **Higher blowing ratio (~2) is advantageous in terms of smaller pressure coeff at exit (higher total pressure) and higher adiabatic film cooling effectiveness.**

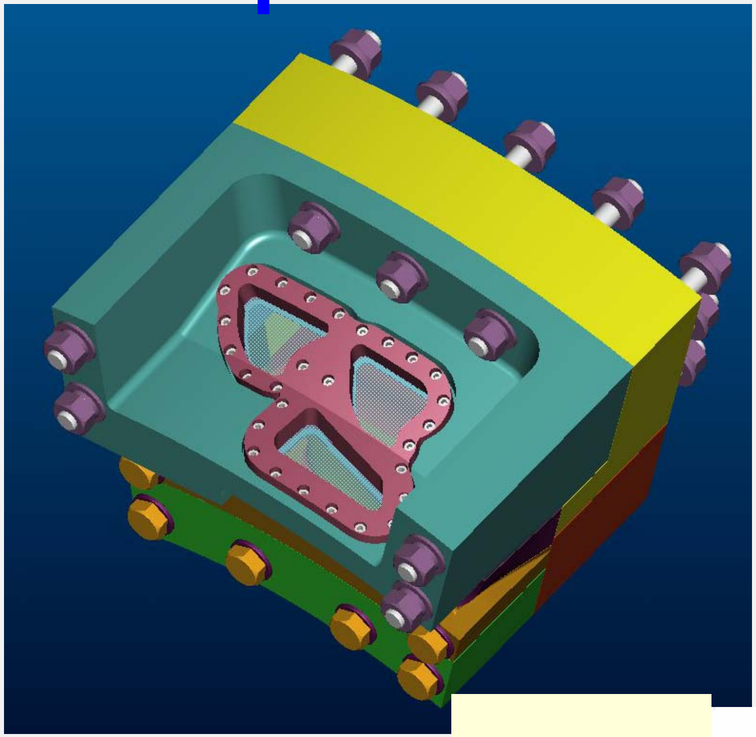

LSU
Questions??
LSU

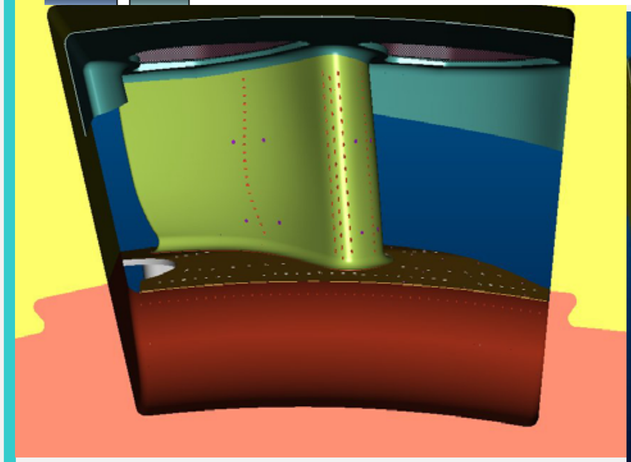
Hot Cascade

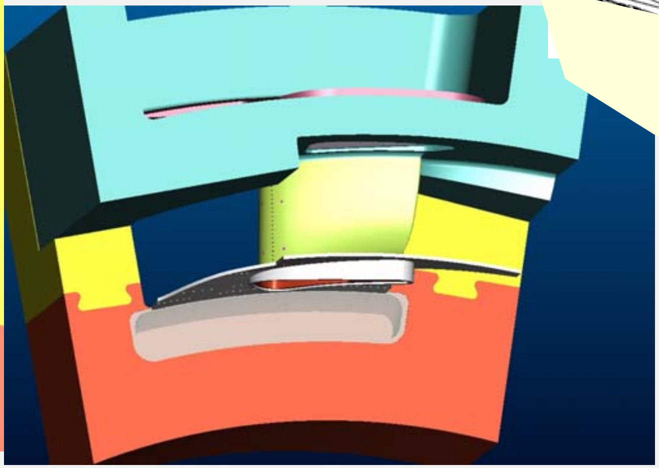


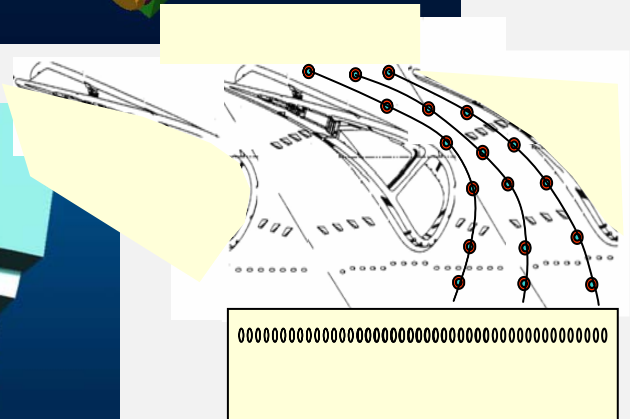
Hot Cascade Components











Transition duct