Improving Durability of Turbine Components Through Trenched Film Cooling and Contoured Endwalls

DOE Award Number DE-FE0005540
UTSR Project Number 07-01-SR127

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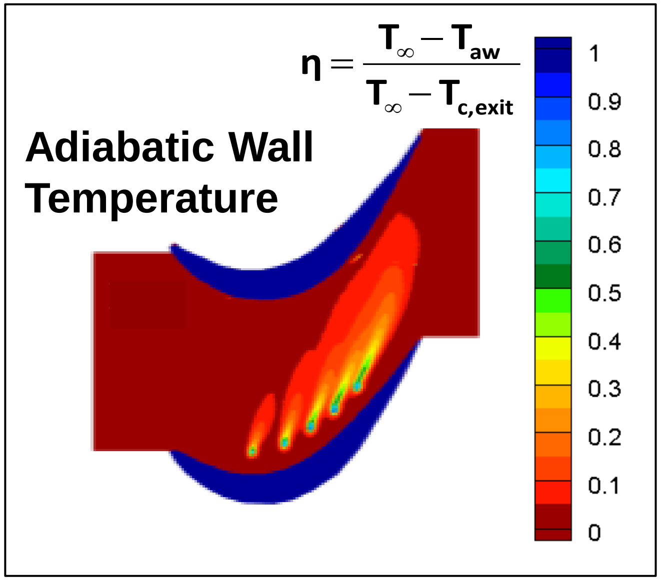
Background image: [Hamed, A., Tabakoff, W., and Wenglarz, R., 2006]

PSU Completed Milestones:
DOE Award DE-FE0005540, UTSR Project 07-01-SR127

Flat Endwall	Measure Endwall Overall Effectiveness	Completed Q8
	Measure Endwall Overall Effectiveness with Deposits	Completed Q10
	Measure Endwall Overall Effectiveness with TBC	Completed Q11
	Computational Predictions of Conjugate Heat Transfer, with and without TBC	Completed Q12
Contoured	Measure Overall Effectiveness with Optimized Endwall Design (Contoured)	Completed Q13
	Measure Contoured Endwall Overall Effectiveness with TBC	Completed Q14
	Measure Velocity Fields with and without Film Cooling	Completed Q14
	Computational Predictions of Contoured Endwall Conjugate Heat transfer, with and without TBC	Completed Q16

Supplementary Tasks (not in original proposal)

Better understanding of endwall cooling and its interaction with endwall contouring is needed to predict performance



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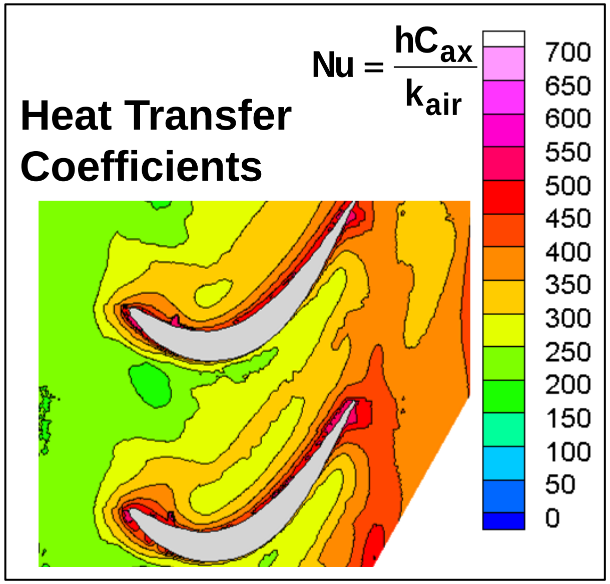
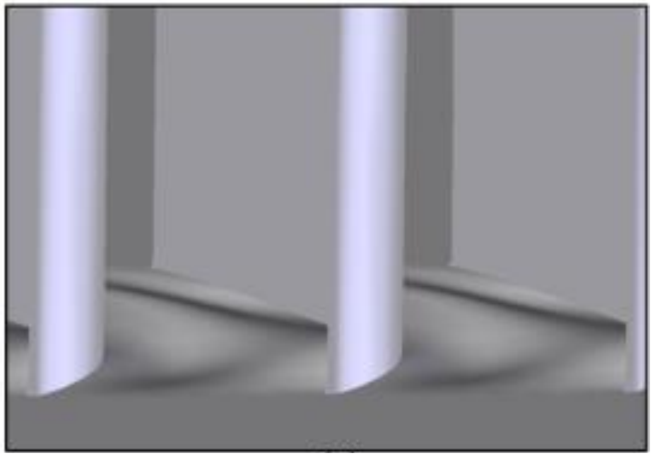


Design Codes → **Metal Temp.**

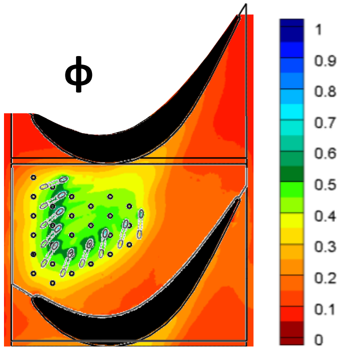
Lynch et al. [2011]

Praisner et al. [2007] – Pack-B contour



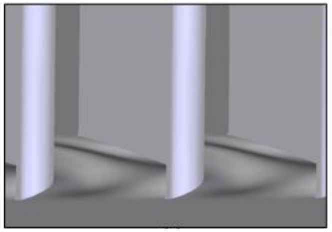
Conjugate heat transfer measurements and predictions of flat and contoured endwalls will be presented

Flat Endwall Overall Effectiveness

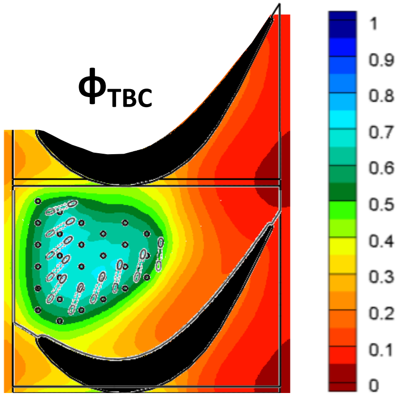


Overall Effectiveness with Deposition

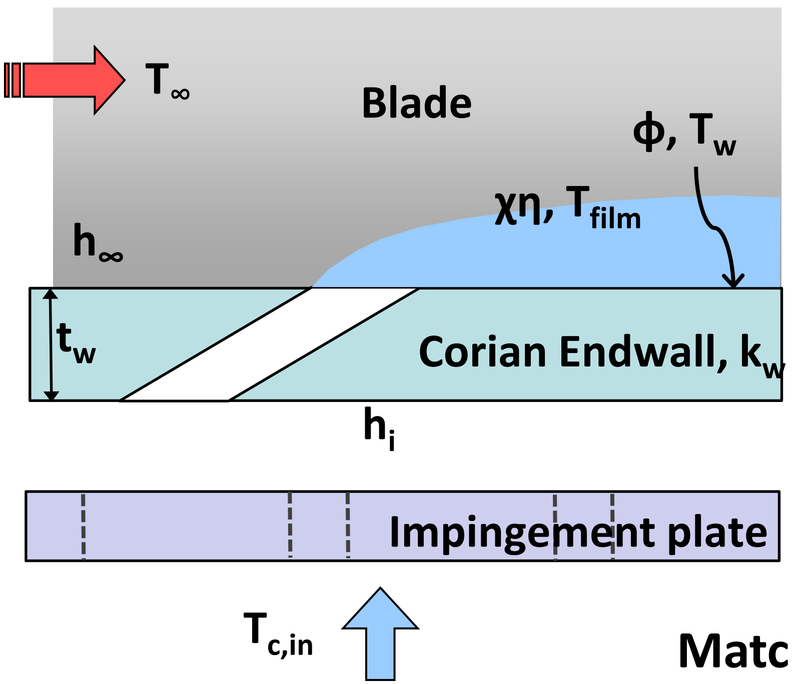
Contoured Endwall Effectiveness and Flow Measurements



Endwall Effectiveness with TBC



Matching the geometry, Biot number and h_∞/h_i to engine conditions allows direct measurement of metal temperature



Overall effectiveness (metal temperature)

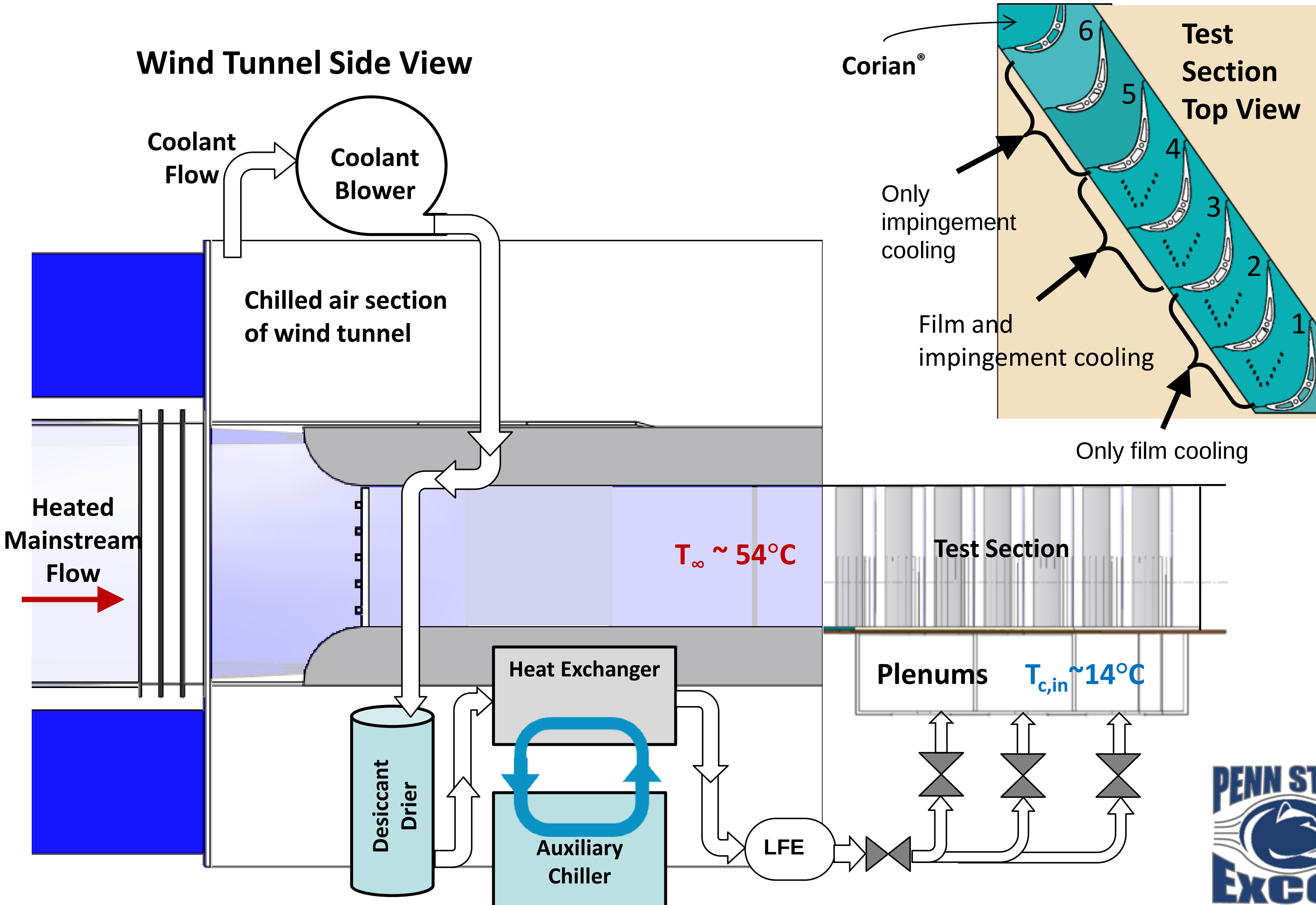
$$\boxed{\phi = \frac{T_\infty - T_w}{T_\infty - T_{c,in}} = \frac{1 - \chi\eta}{1 + Bi_\infty + h_\infty / h_i} + \chi\eta}$$

$$\chi\eta = f(Re, M, geometry)$$

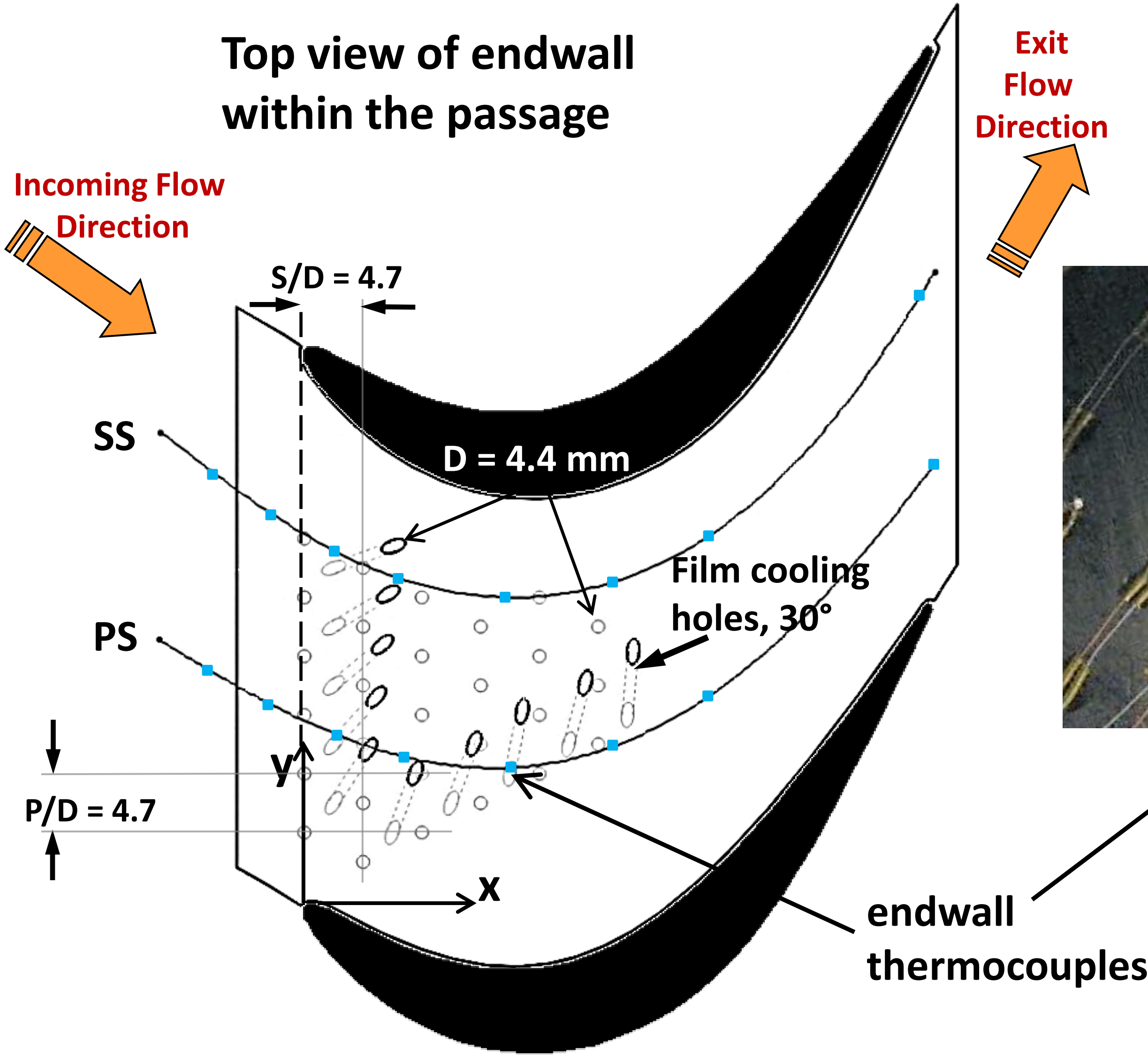
Matched Parameters	Typical Engine	Model
$Re_{\infty,in}$ (C_{ax})	1.25×10^5	1.25×10^5
h_∞/h_i	1	0.5 - 2.3
$M = (\rho_c U_c/\rho_\infty U_\infty)$	1 – 2	0.6, 1, 2
$Bi_\infty = h_\infty t/k_w$	0.27	0.30 - 0.77

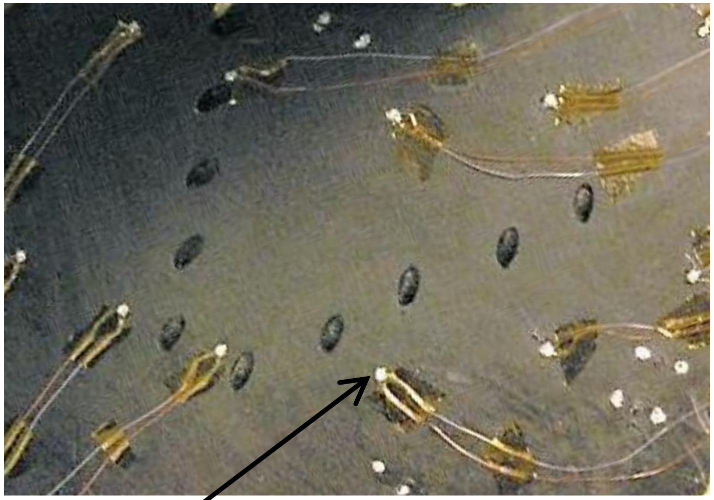
PENN STATE ExCCL

Mainstream flow is heated, and coolant flow is chilled to maximize driving $\Delta T = T_{\infty} - T_{c,internal}$

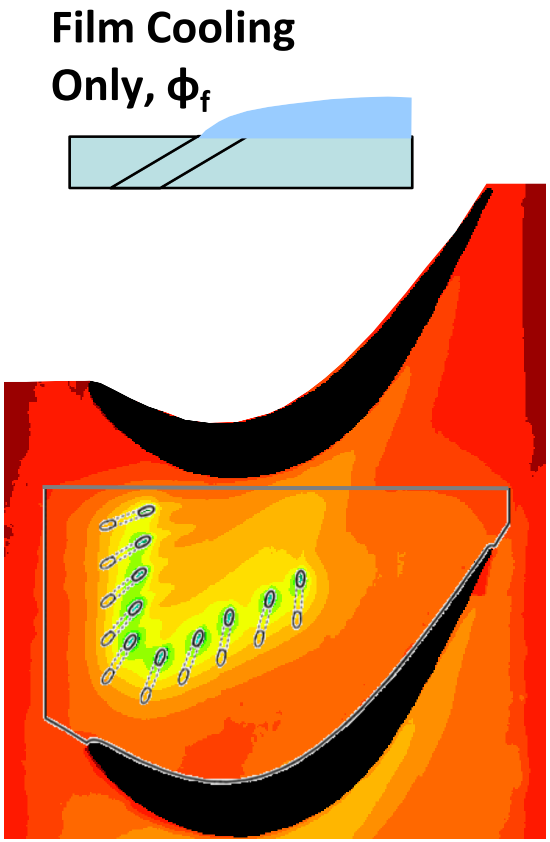


Thermocouples were installed on the endwall surface under the TBC to measure ϕ_{TBC} along two streamlines

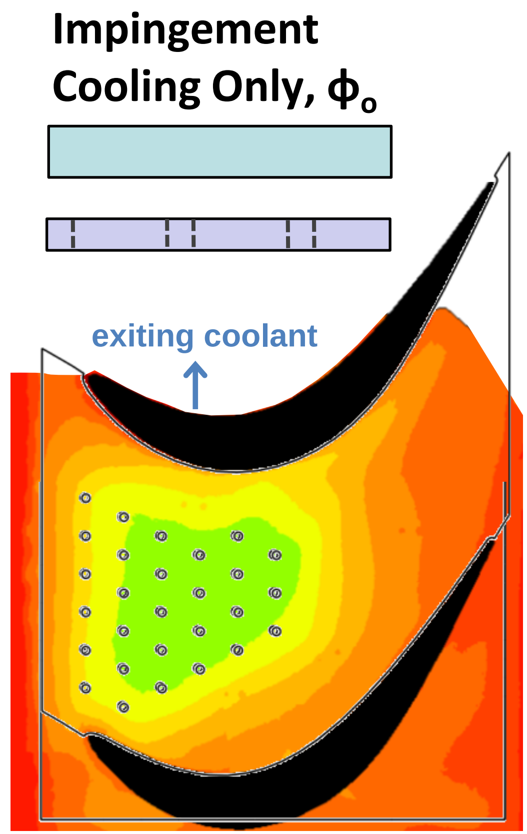




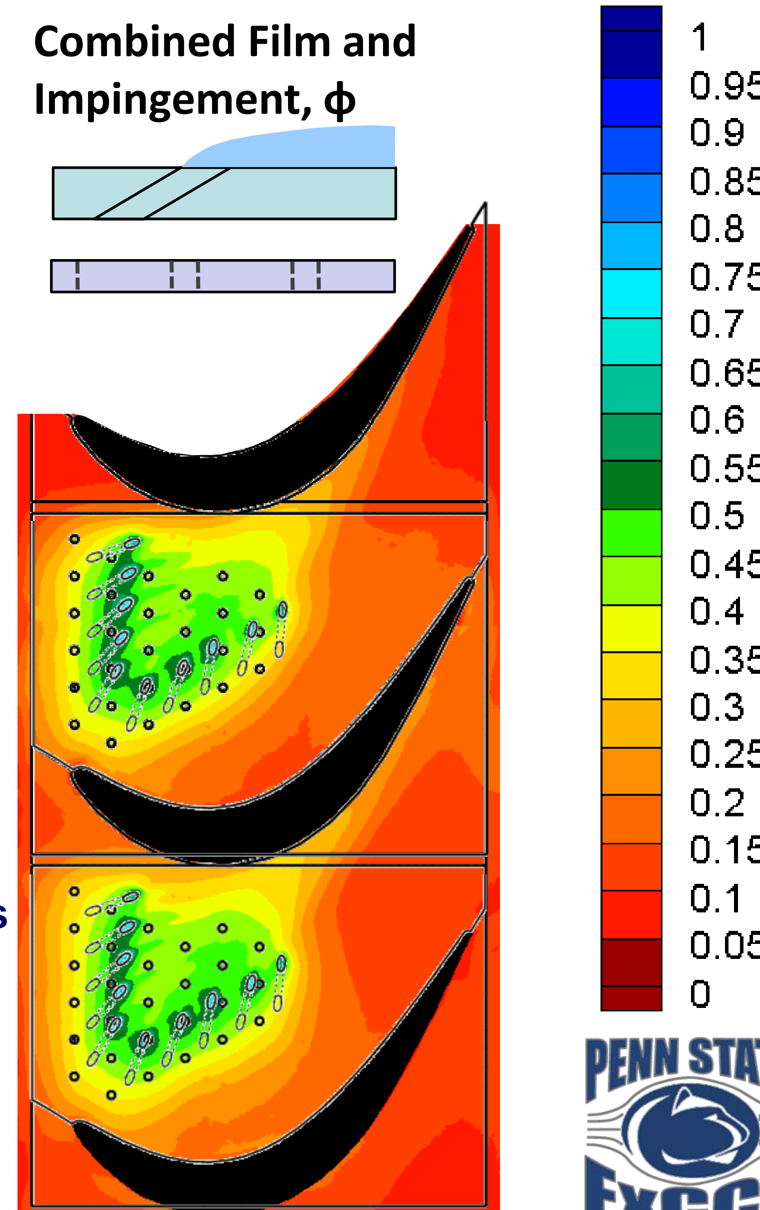
The measurements of overall effectiveness demonstrated the key features of film cooling and internal impingement



in-hole convection



uniform high effectiveness



$M_{avg} = 2.0$

$$\phi = \frac{T_\infty - T_w}{T_\infty - T_{c,in}}$$

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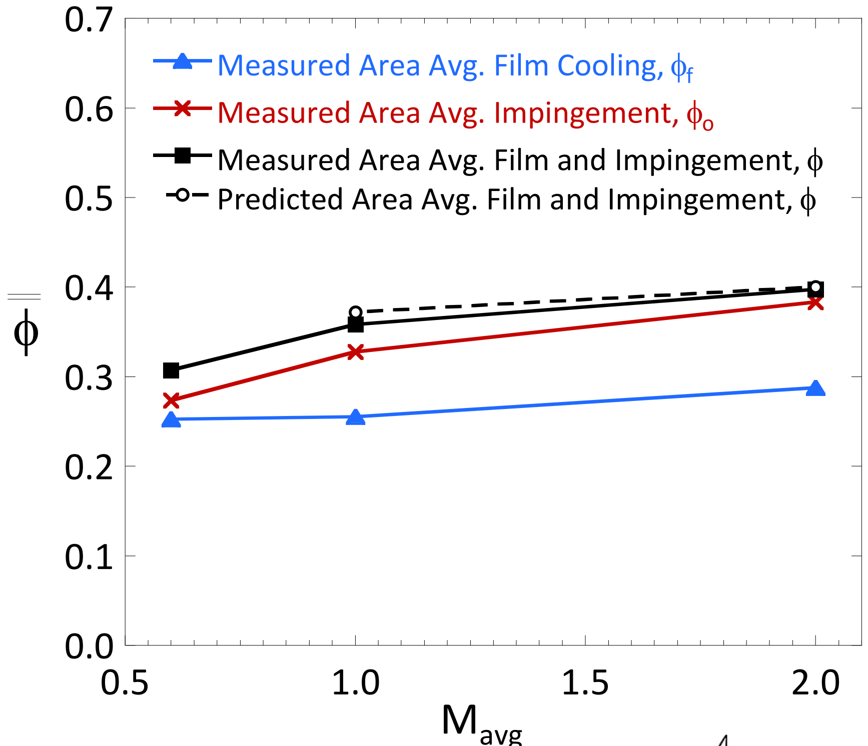
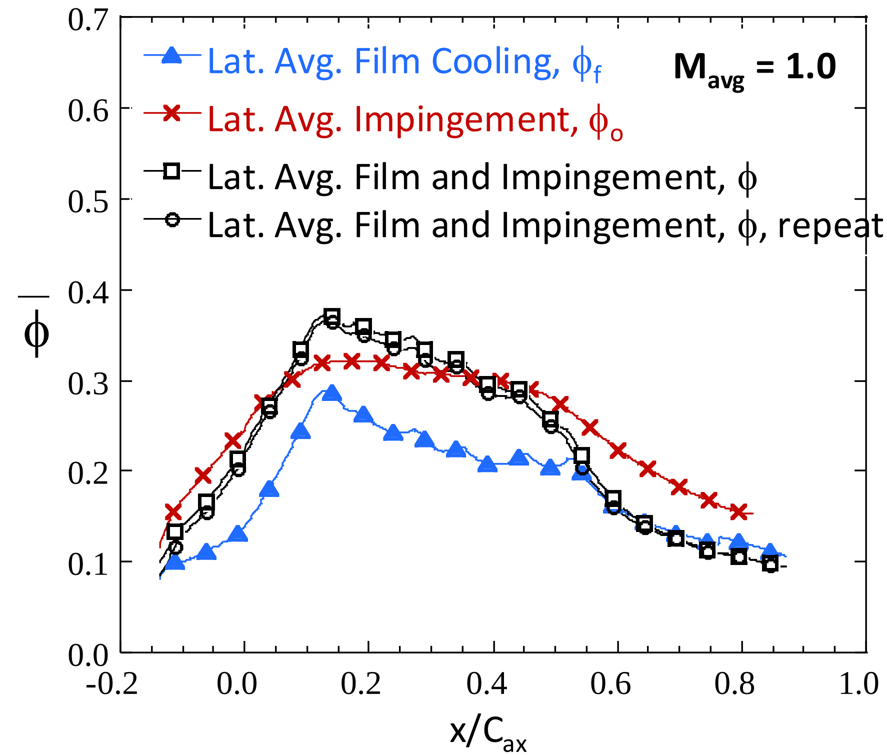
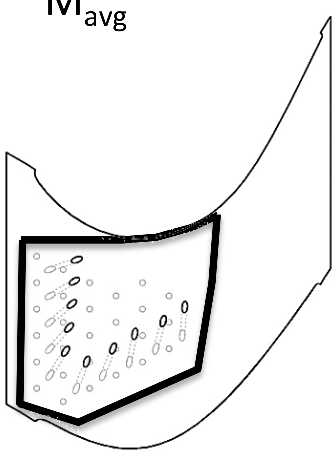
Increasing blowing ratio improved average ϕ for impingement more than for film cooling

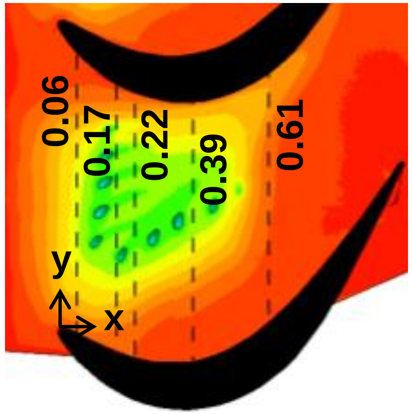




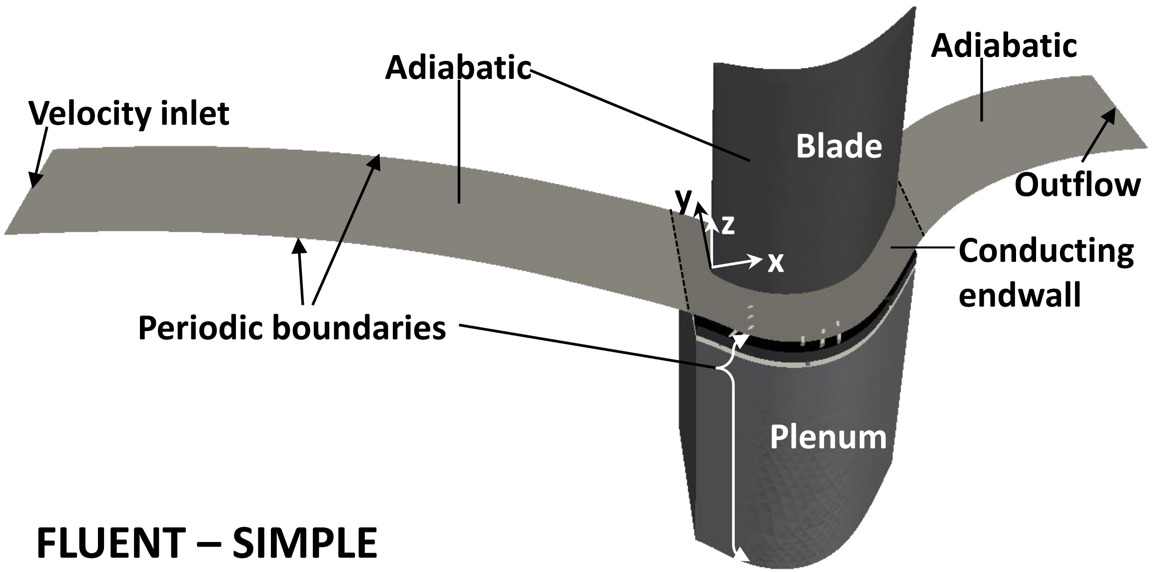
Area Averaged

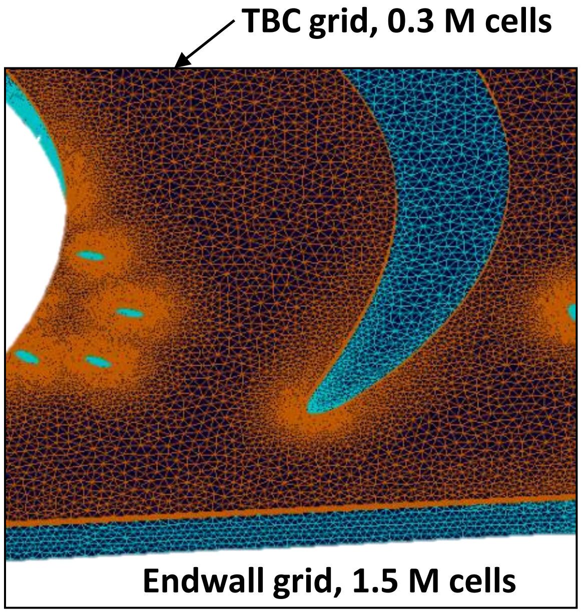


x/C_{ax} =



Conjugate RANS simulations used the SST k-ω model and an unstructured computational grid with wall prism layers



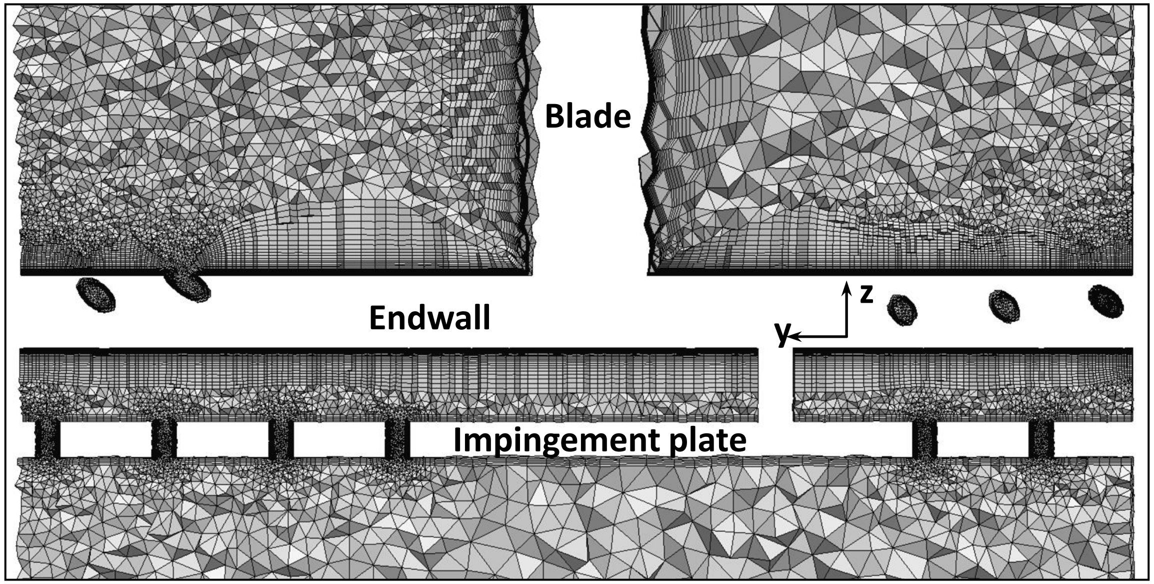


FLUENT – SIMPLE

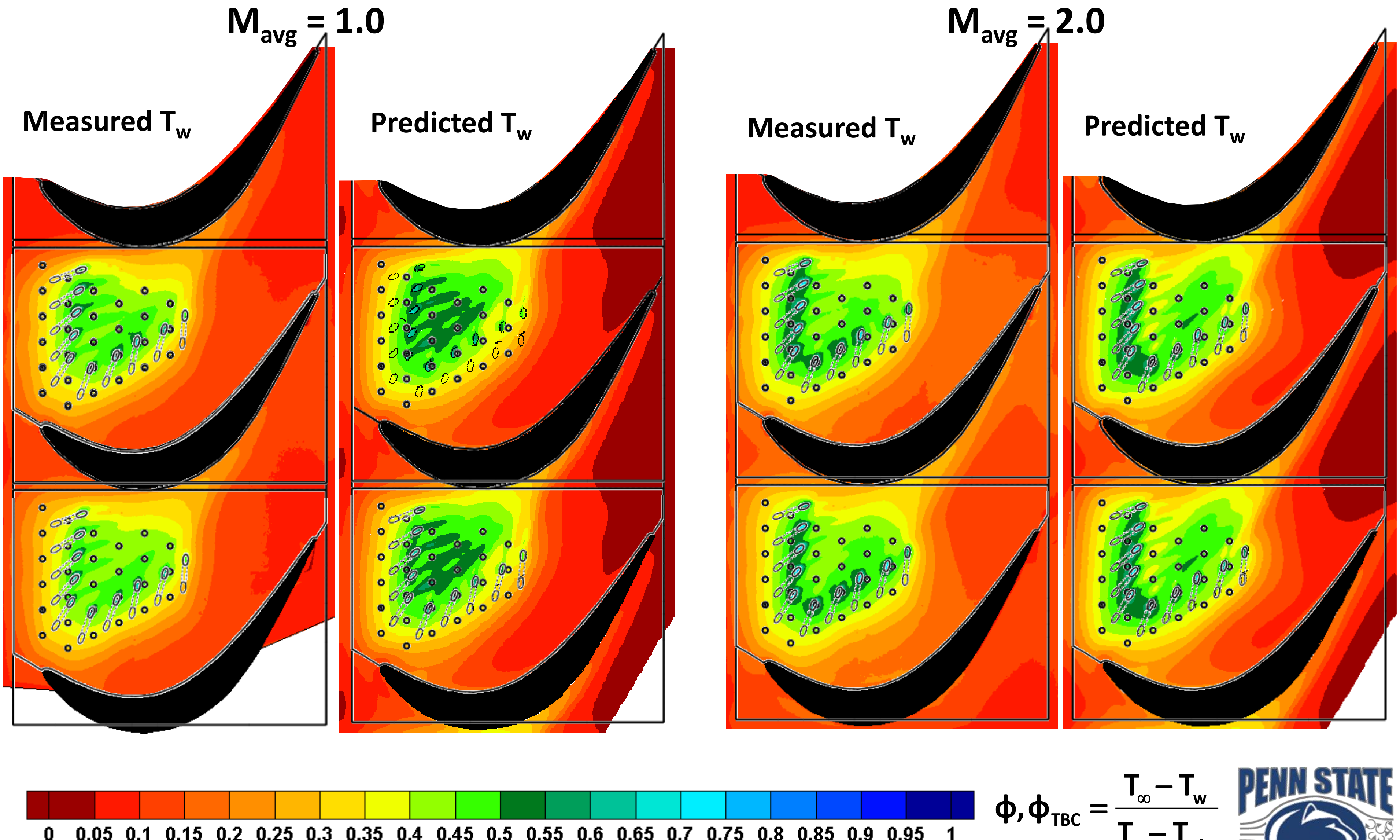
RANS, SST k-ω, & energy – 2nd order

Flow grid – 9.8 M cells
$y^+ < 1$

Flow and solid domains thermally coupled



There is good overall agreement between the measured and predicted ϕ, except for the attachment of the jets



$$\phi, \phi_{TBC} = \frac{T_\infty - T_w}{T_\infty - T_{c,in}}$$

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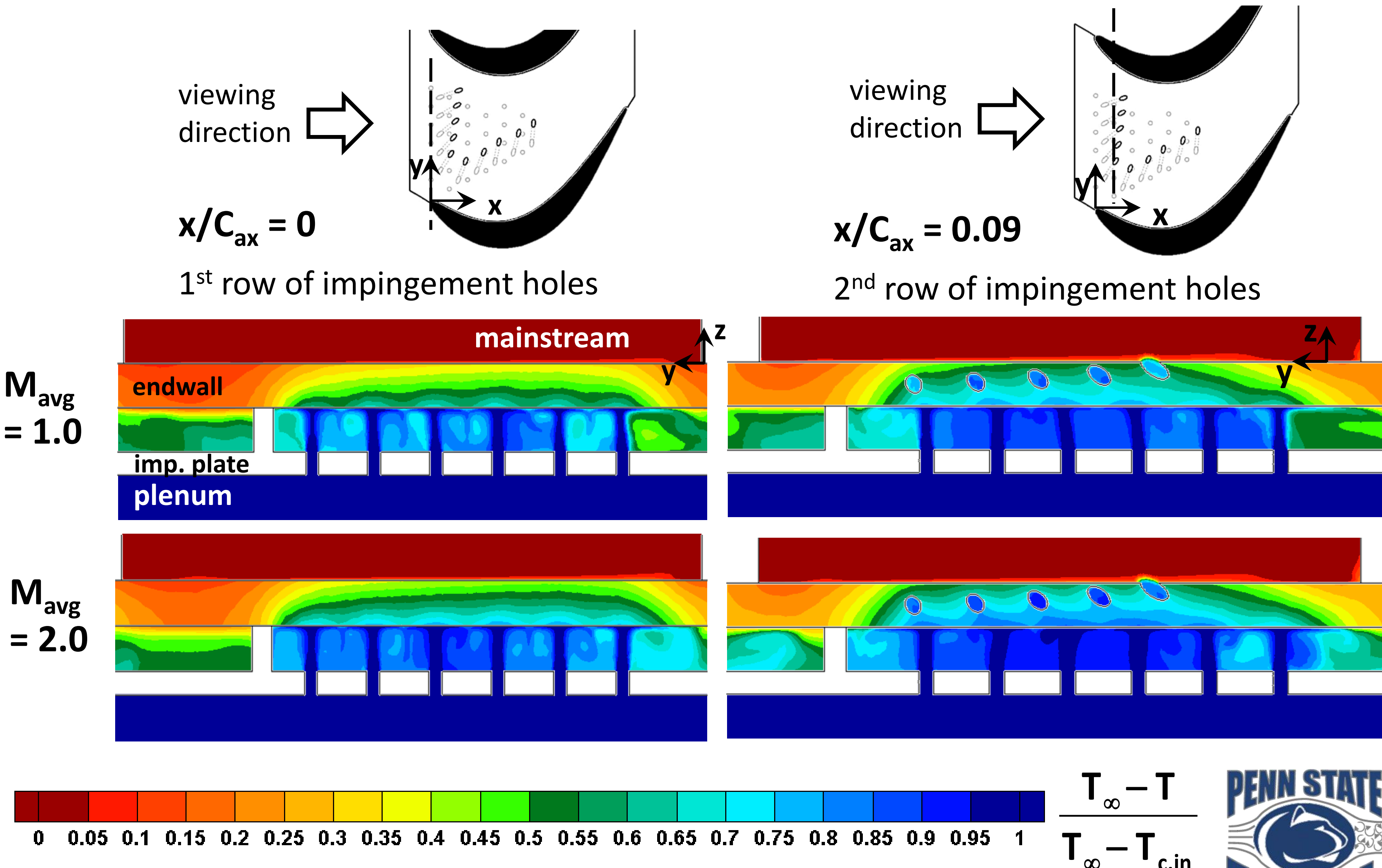
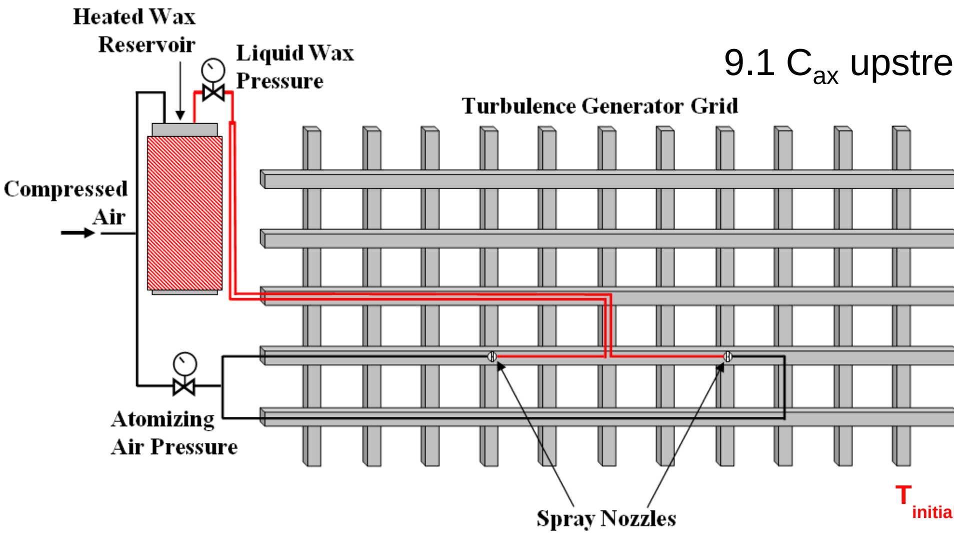
CFD temperature results show the three-dimensional conduction and steep gradients within the endwall



We simulated deposition with wax, matching the Stokes number, Thermal Scaling Parameter and conductivity ratio



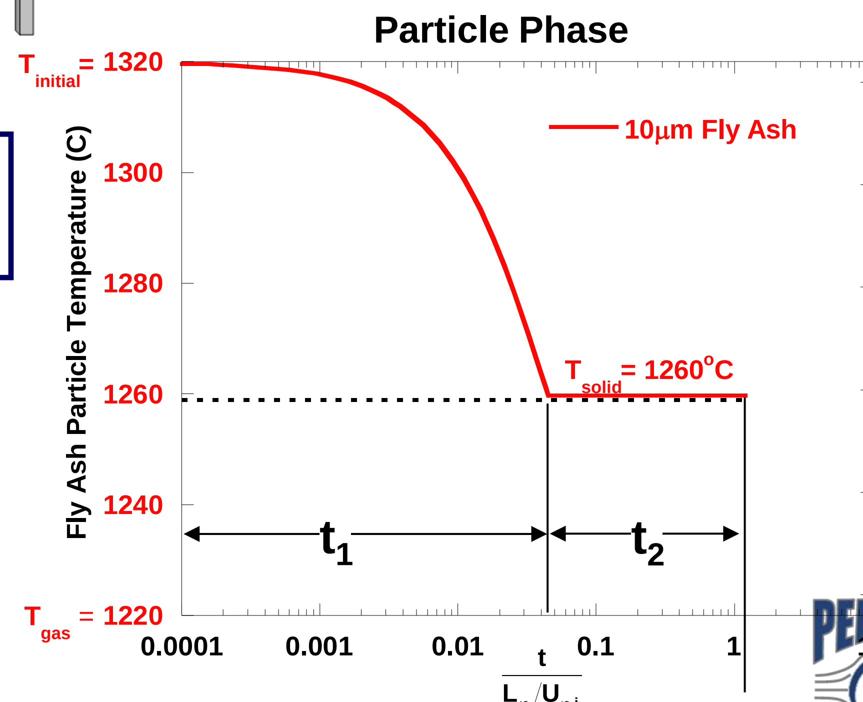
9.1 C_{ax} upstream

$$Stk = \frac{\text{particle relaxation time}}{\text{fluid time scale}} = \frac{\rho_p d_p^2 U_p}{18 \mu L_c} = 6.54$$

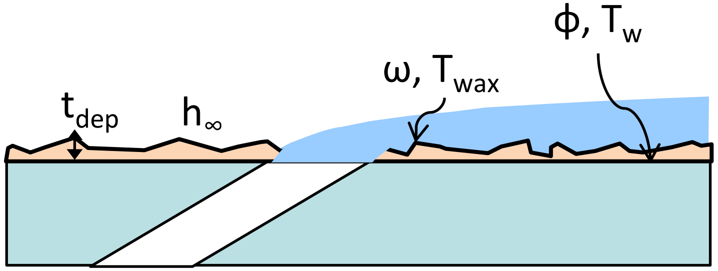
$$TSP = \frac{t_1 + t_2}{L_\infty / U_{\infty,i}} = 0.3$$

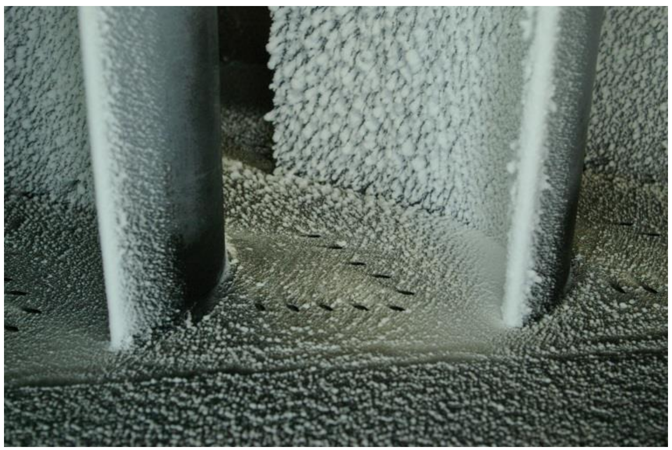
TSP < 1 Solid
TSP > 1 Molten

$$\frac{k_{deposit}}{k_{wall}} = 0.069 \qquad \frac{k_{wax}}{k_{Corian}} = 0.11$$

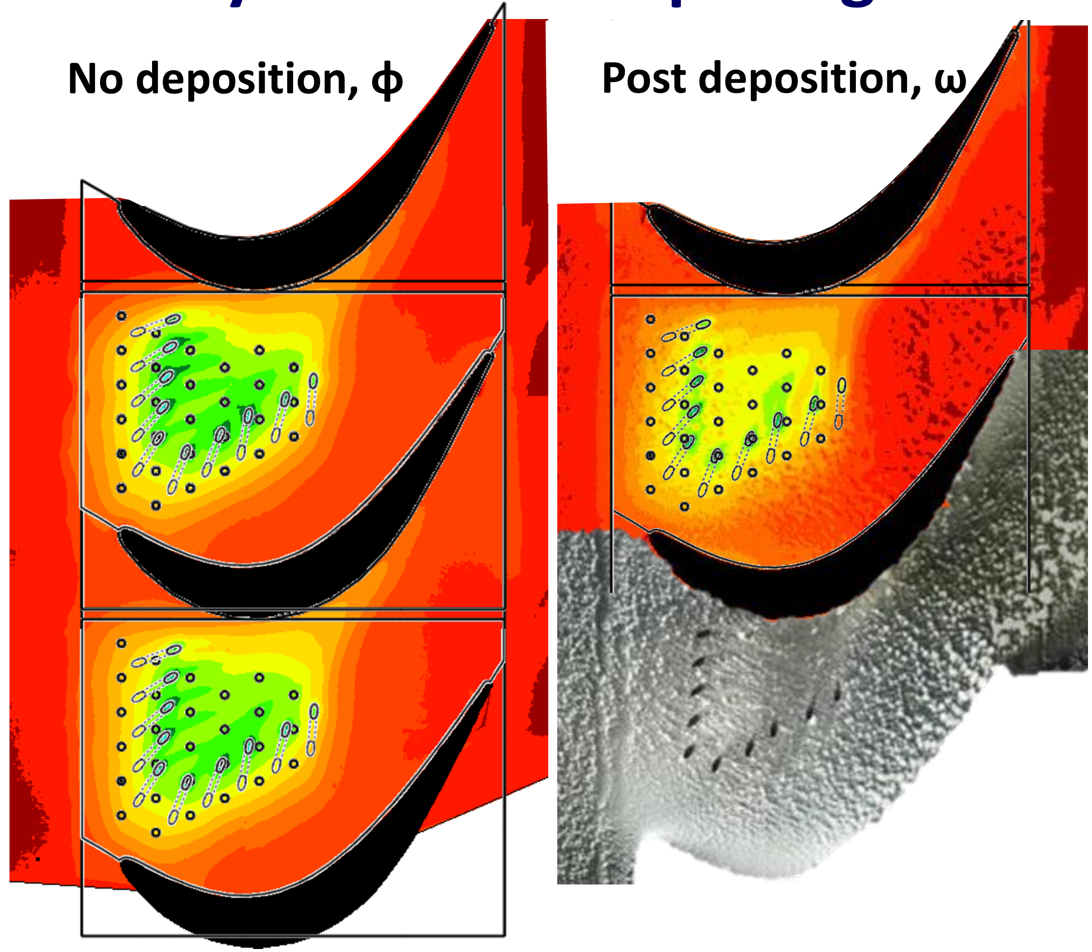


The cooling systems mitigated some deposition, but effectiveness was reduced everywhere in the passage



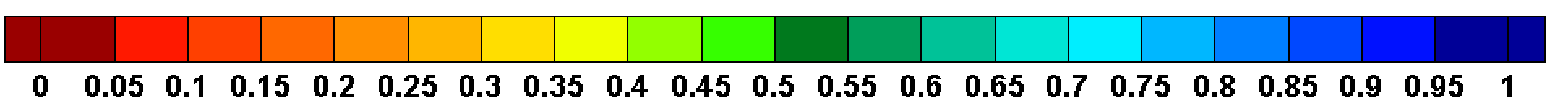


Passage inlet



$$\phi = \frac{T_\infty - T_w}{T_\infty - T_{c,in}} \; or \quad \omega = \frac{T_\infty - T_{wax}}{T_\infty - T_{c,in}}$$

$M_{avg} = 1.0$



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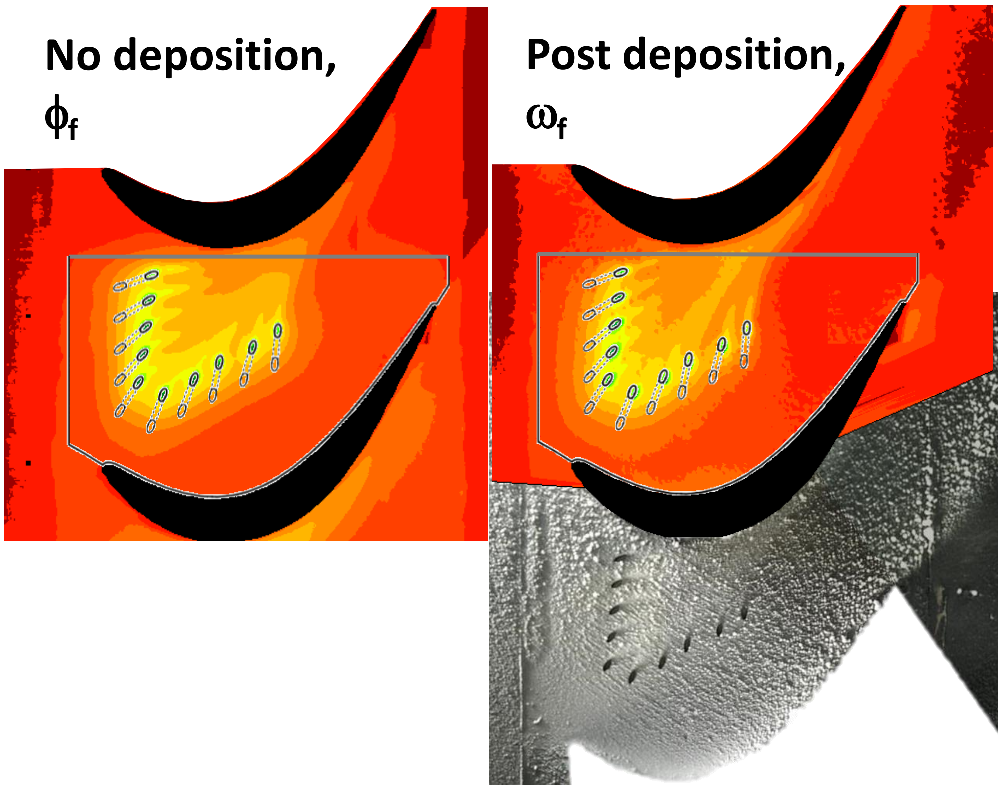
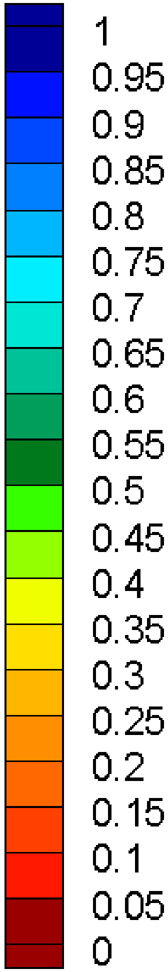
We observed clear areas due to the film cooling jets, and deposition on the blade from the passage vortex

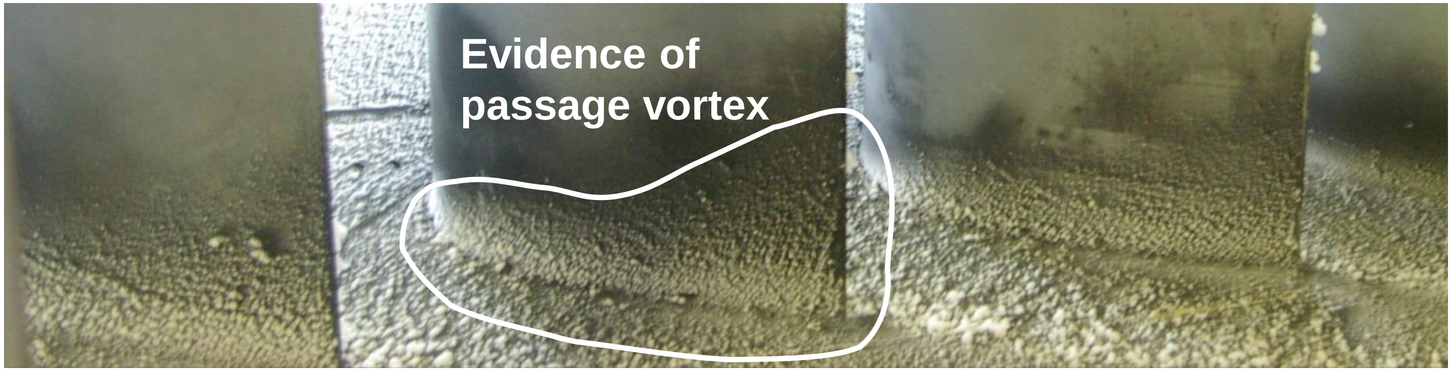


$$\phi_f = \frac{T_\infty - T_{w,f}}{T_\infty - T_{c,int}}$$

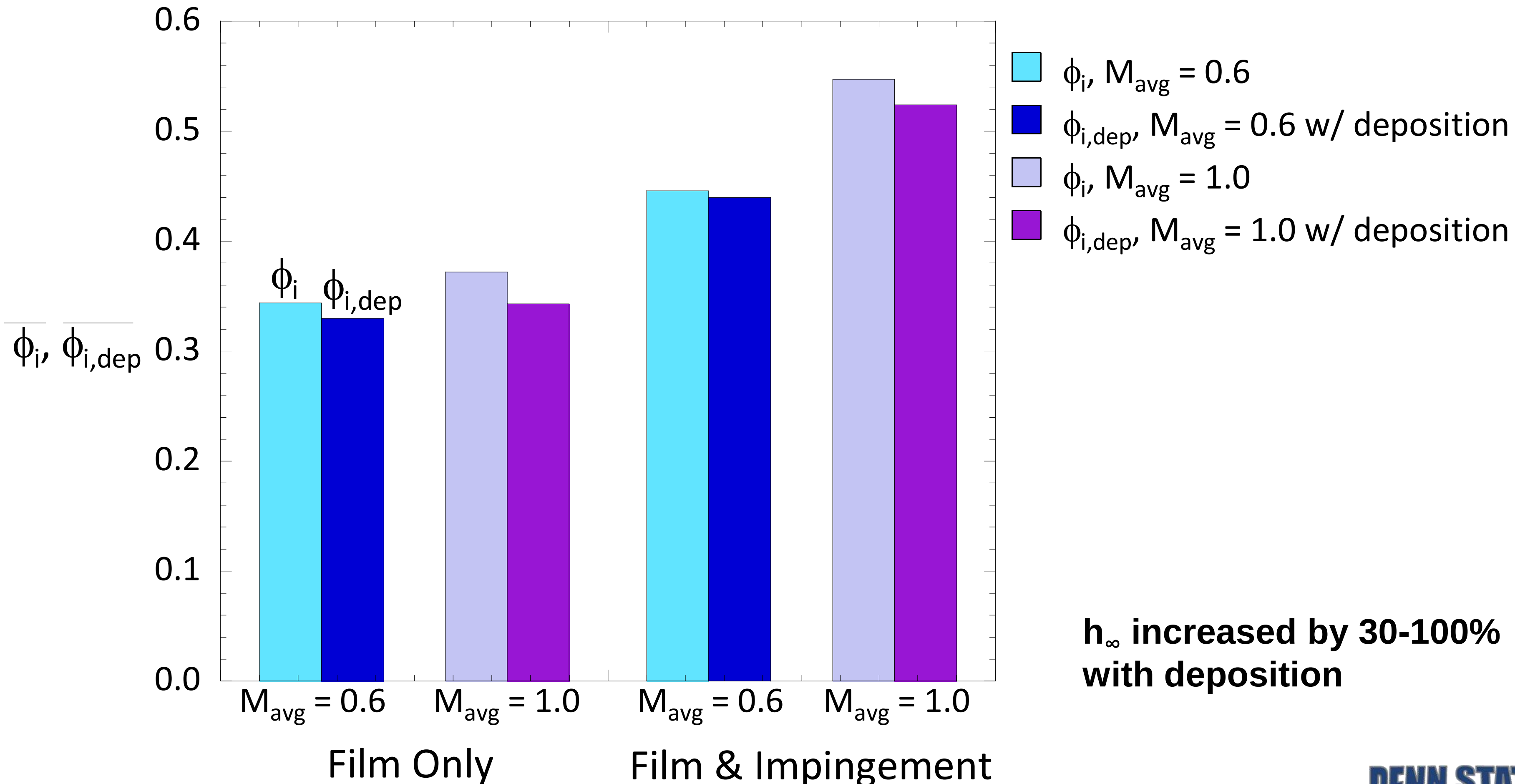
$$\omega_f = \frac{T_\infty - T_{wax,f}}{T_\infty - T_{c,int}}$$



$M_{avg} = 1.0$

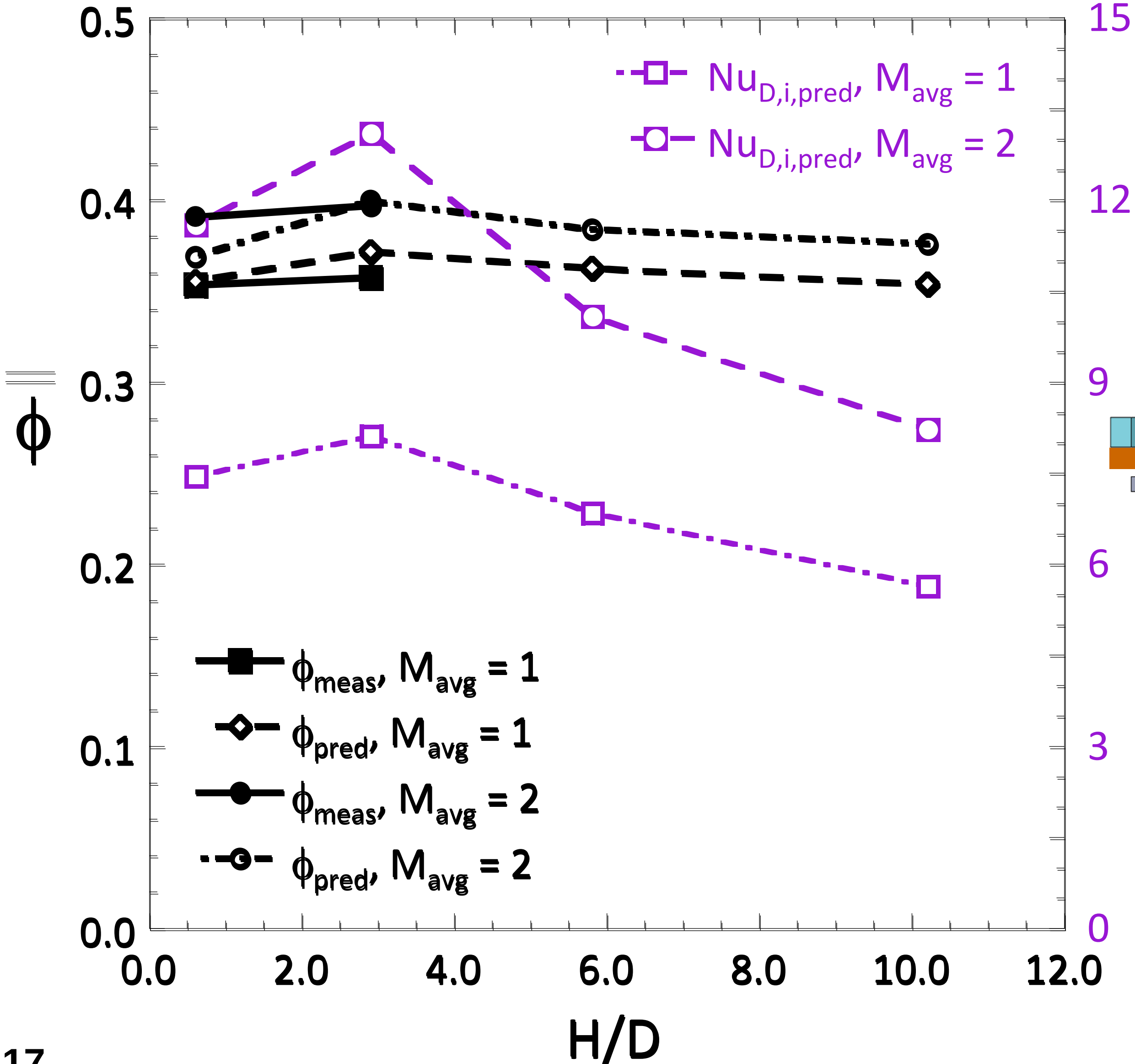


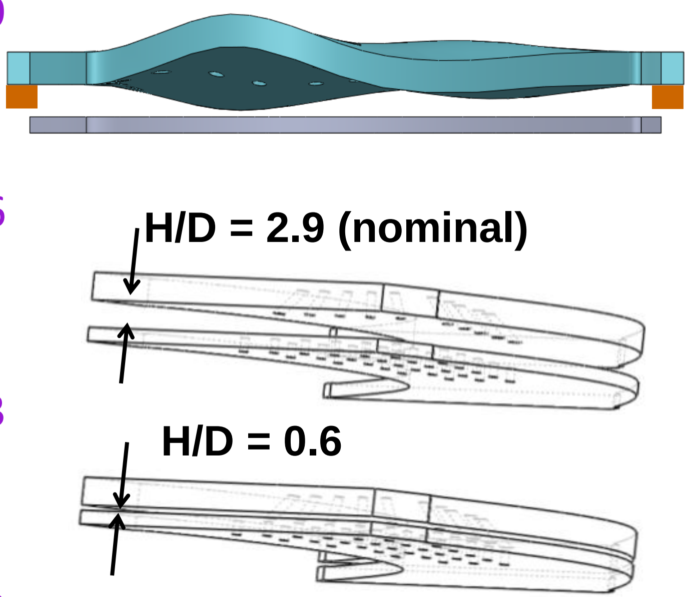
Roughness from the deposition degrades the cooling performance, resulting in higher endwall temperatures



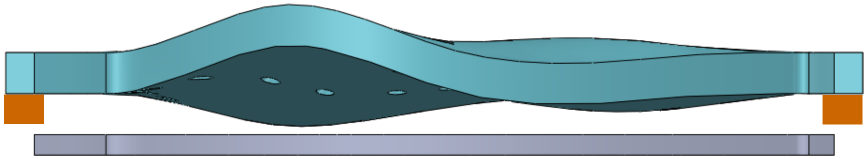
h_∞ increased by 30-100% with deposition

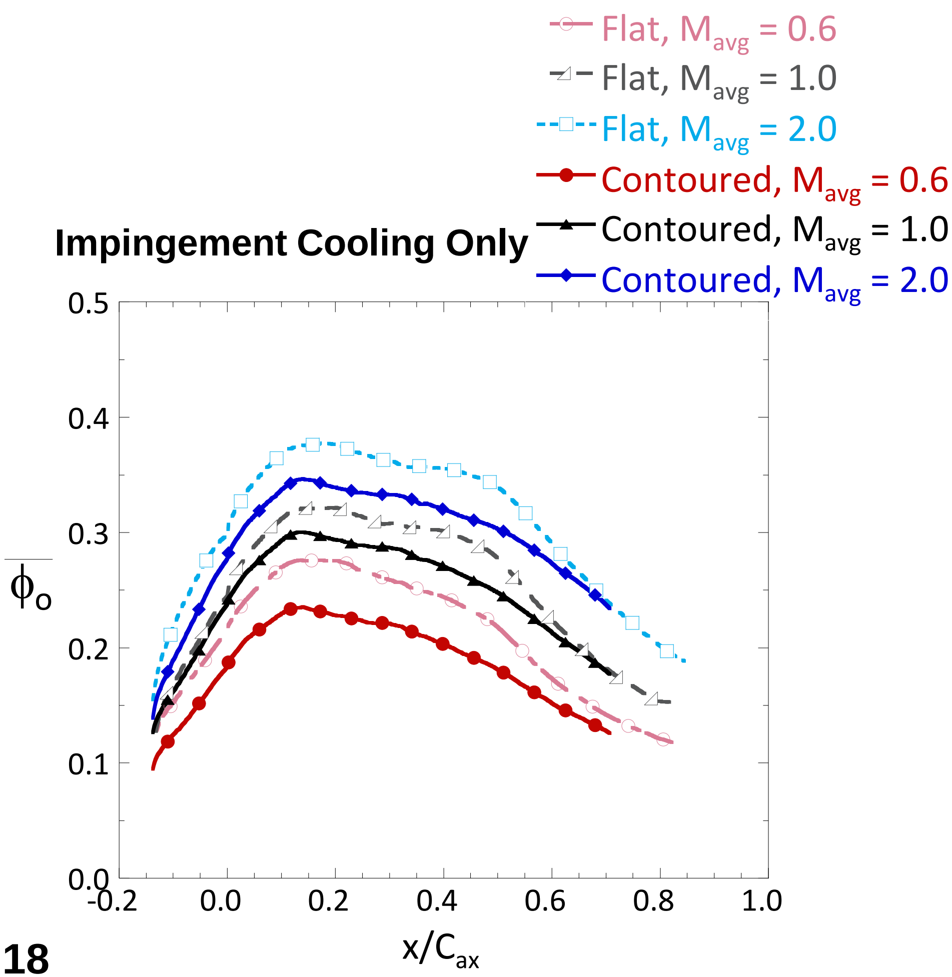
Although the Nu peaks at H/D = 2.9, the area averaged ϕ, with film and impingement, is relatively insensitive to H/D

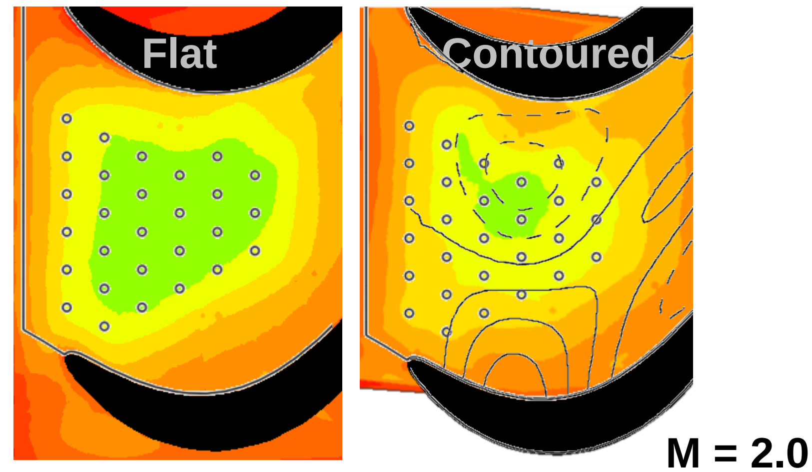


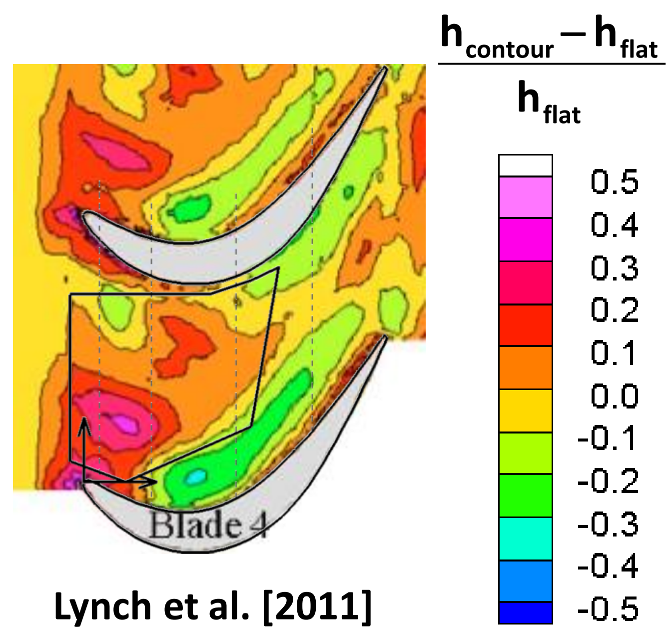


Contouring reduces effectiveness for impingement only, since h_i decreases and h_∞ increases from the flat endwall





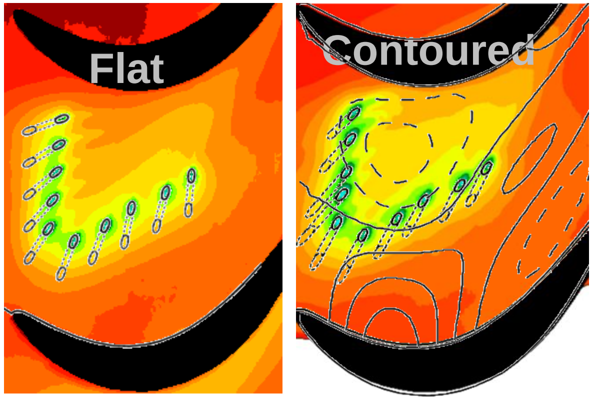


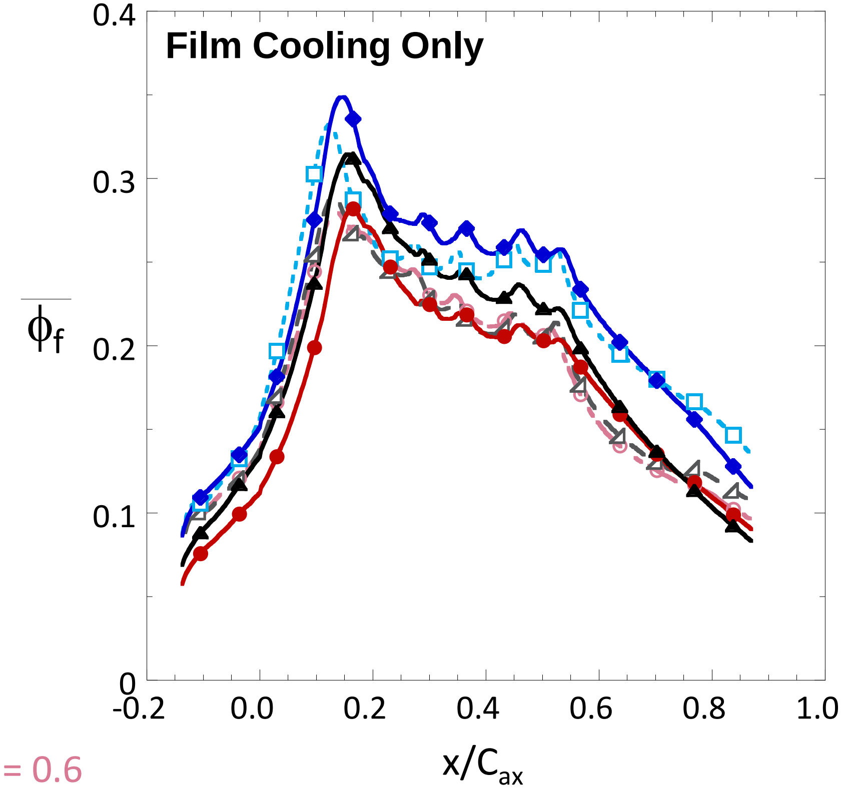


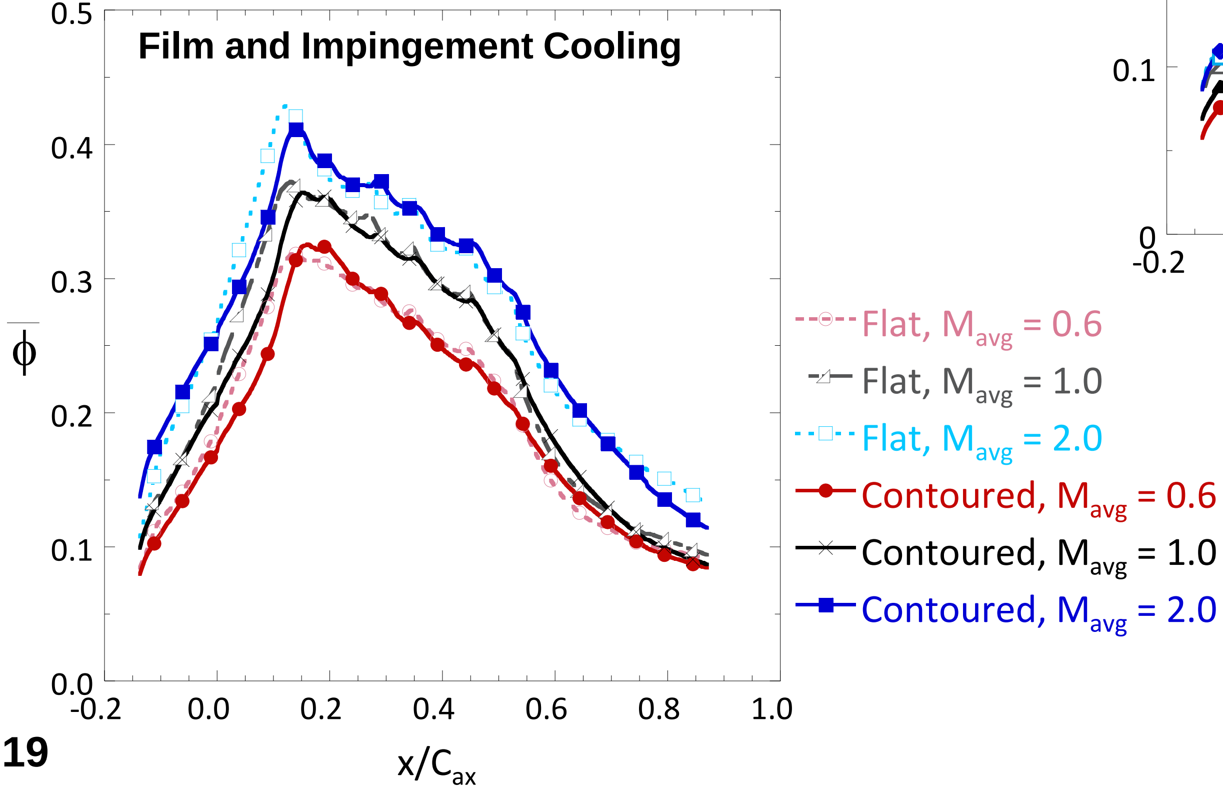
Lynch et al. [2011]

Overall effectiveness does not change much between the flat and contoured endwall with film cooling

Film Cooling Only, M = 2.0







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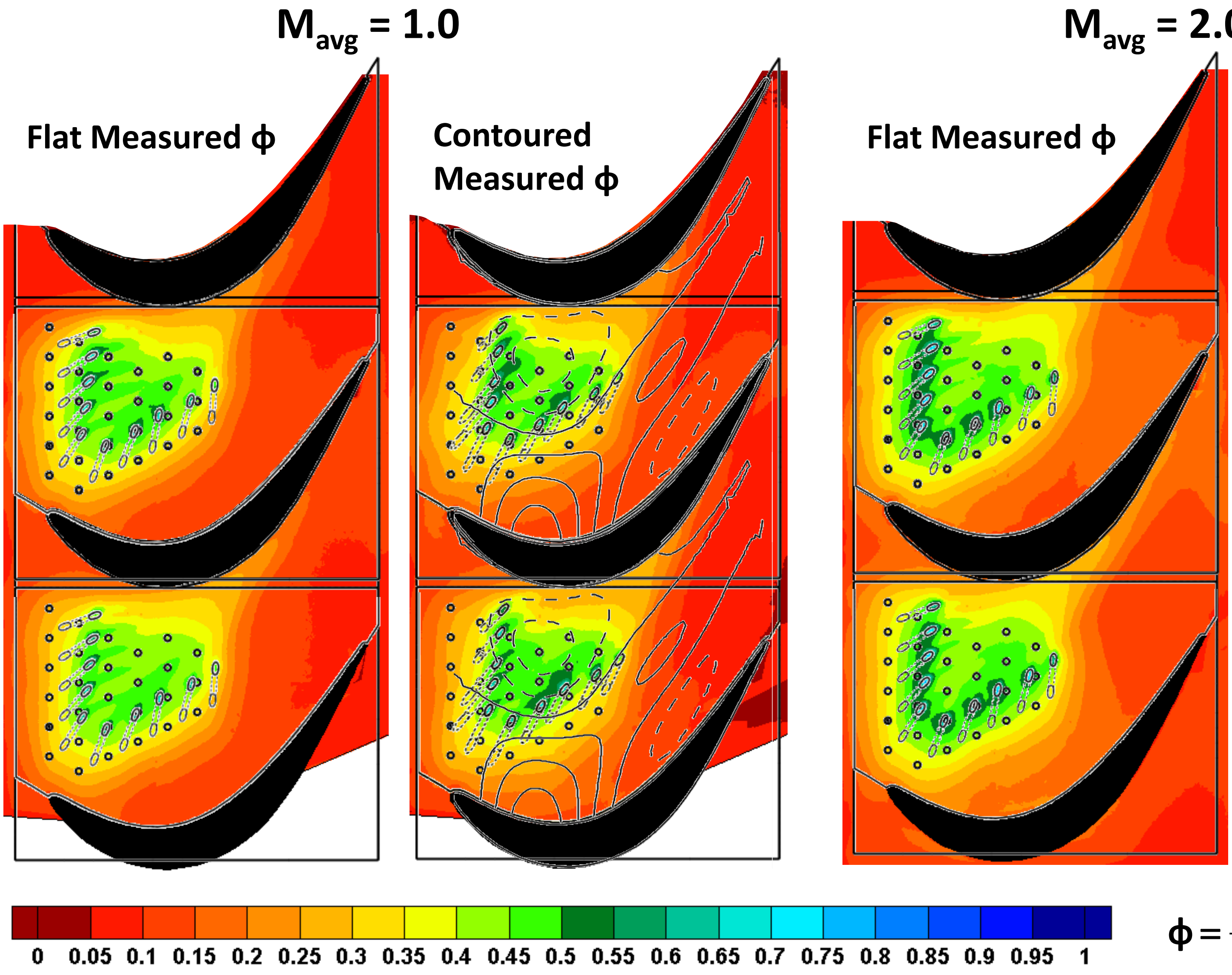
Although the average overall effectiveness is the same for the flat and contoured endwall, there are local differences



$$\phi = \frac{T_\infty - T_w}{T_\infty - T_{c,in}}$$

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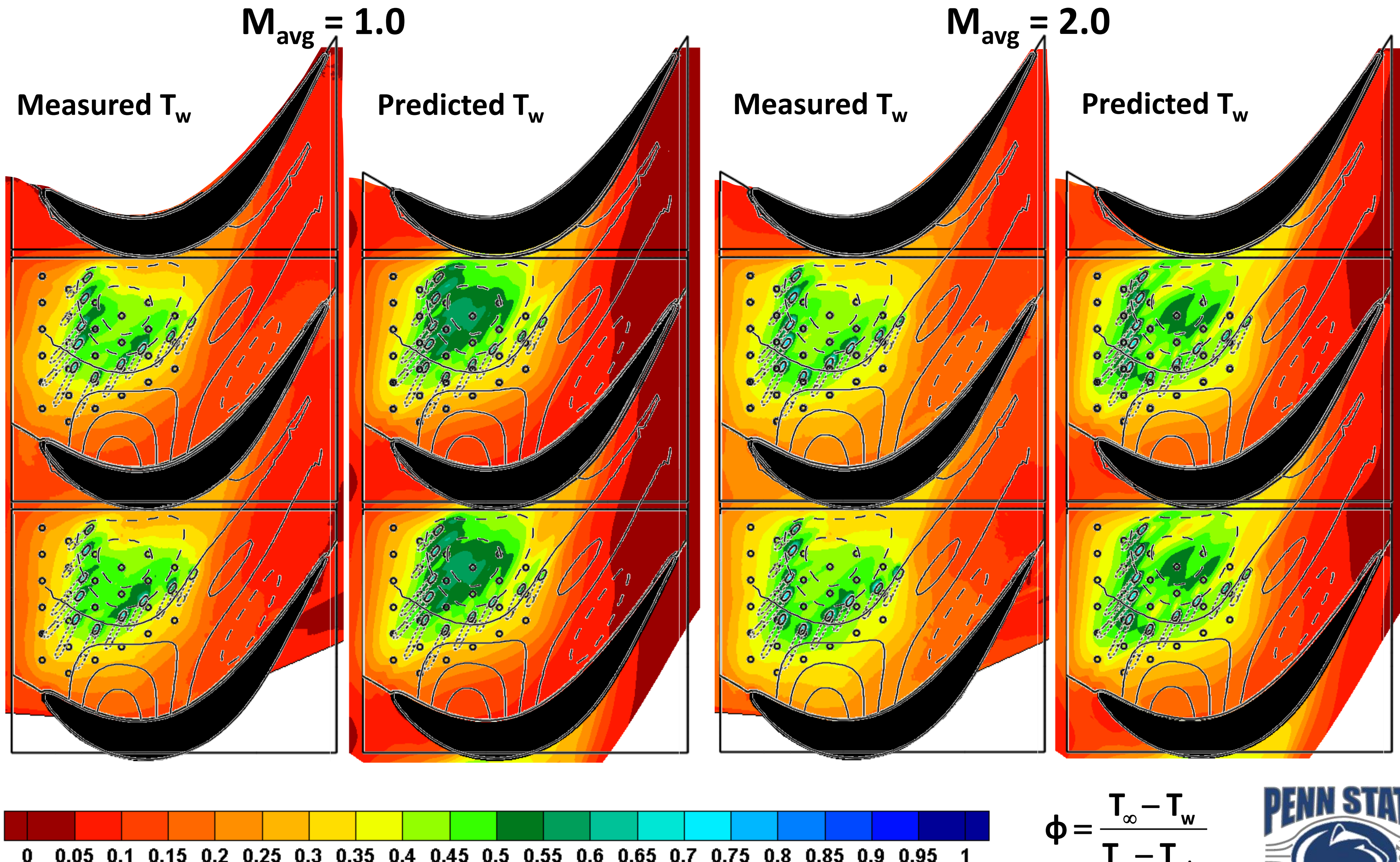
Other than film attachment, the contoured endwall simulations predict the same trends as the measurements



$$\phi = \frac{T_\infty - T_w}{T_\infty - T_{c,in}}$$

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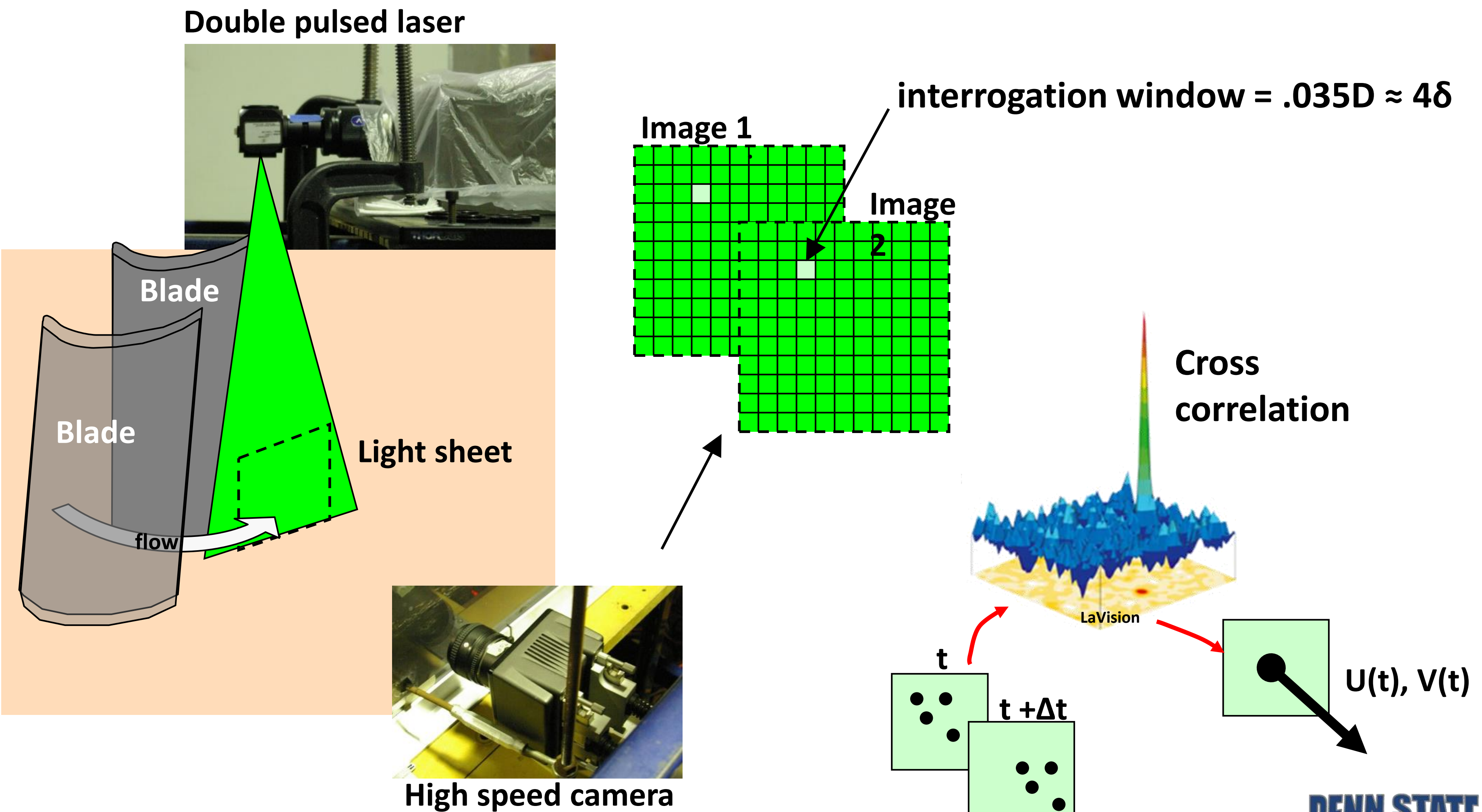
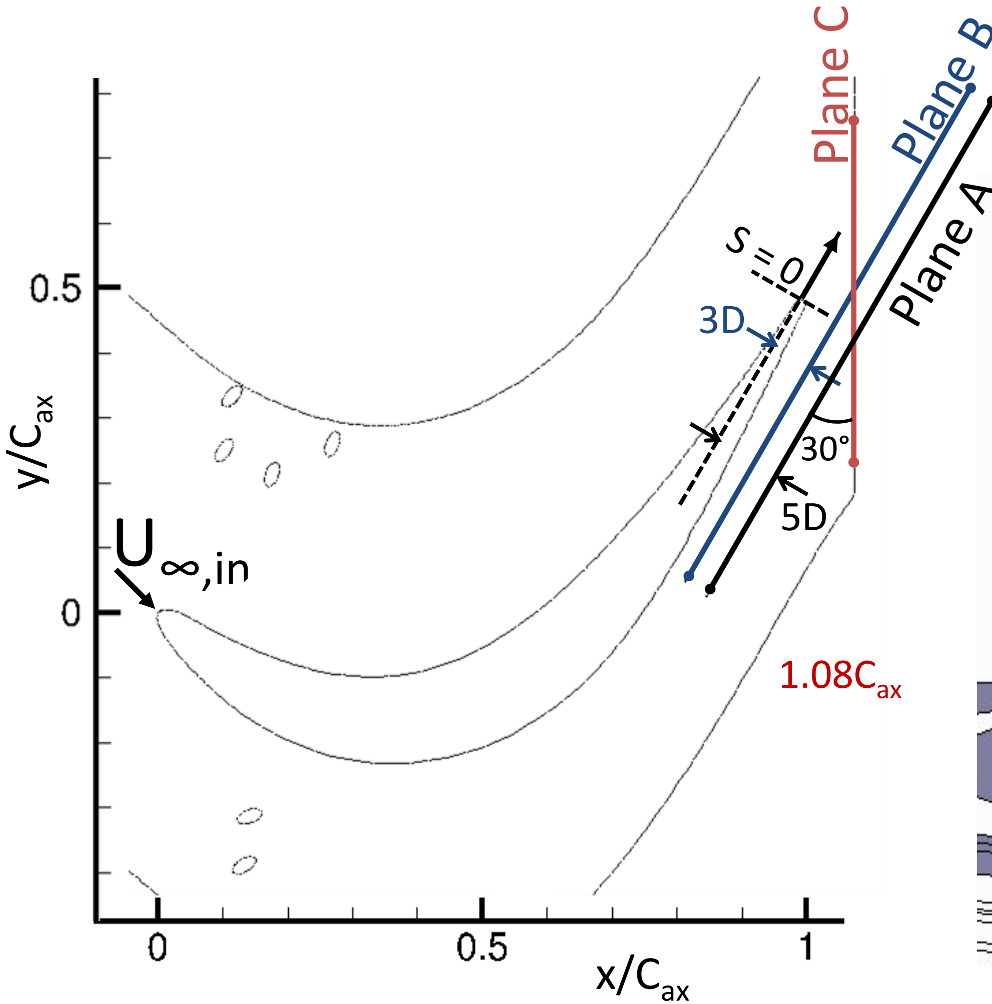
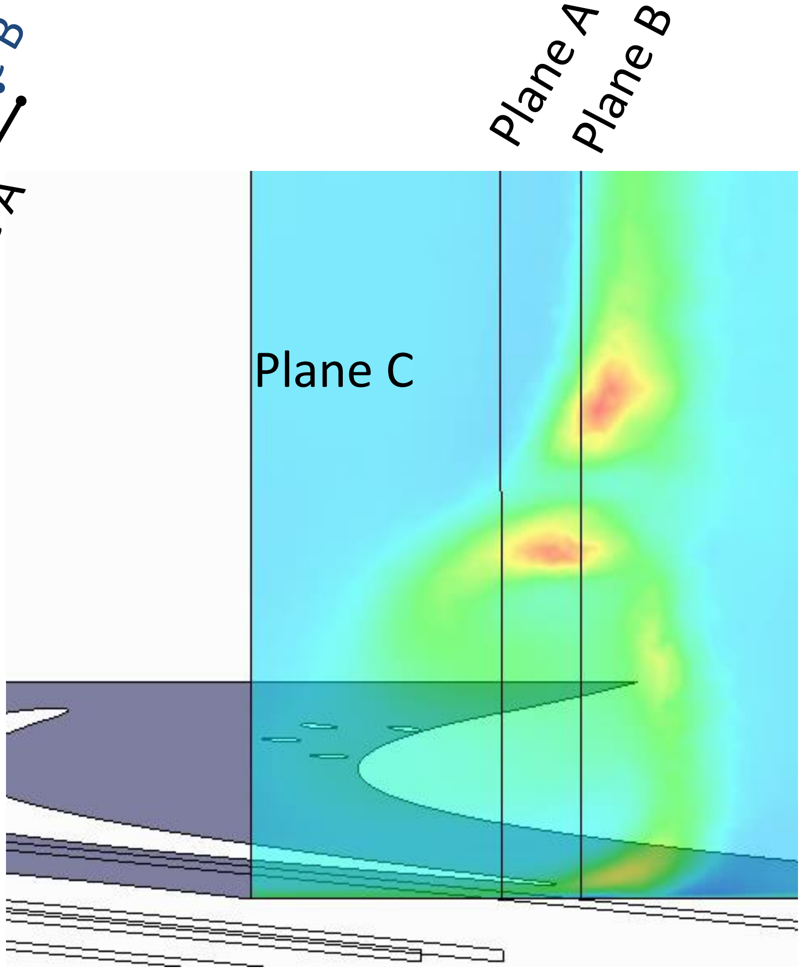
The trailing edge flowfield was measured using a time resolved particle image velocimetry (PIV) system



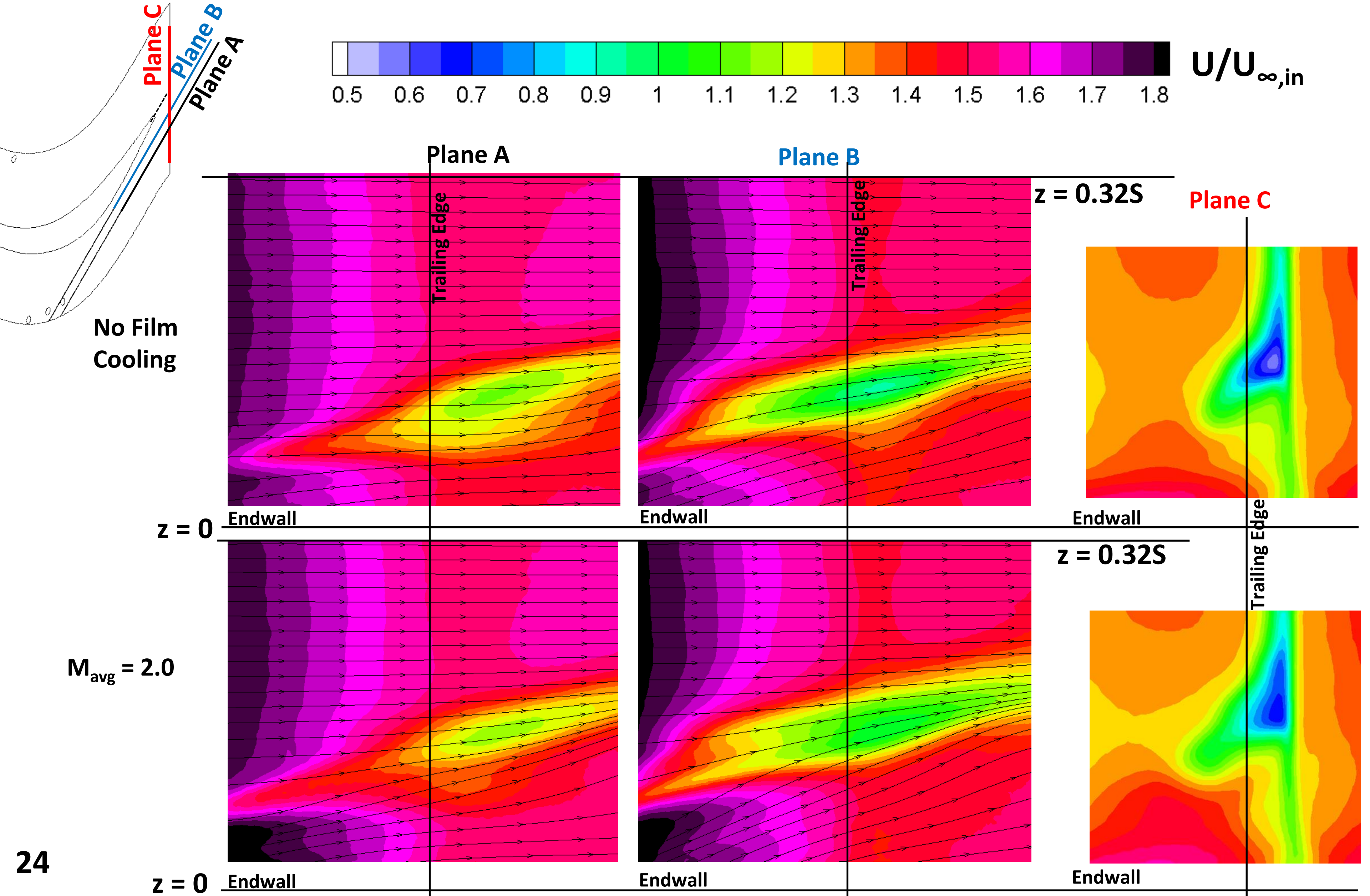
Flowfield was sampled for 3000 or 6000 images at $\Delta t = \delta/U_\infty$

The trailing edge flowfield was measured for three vertical planes to capture the passage vortex development

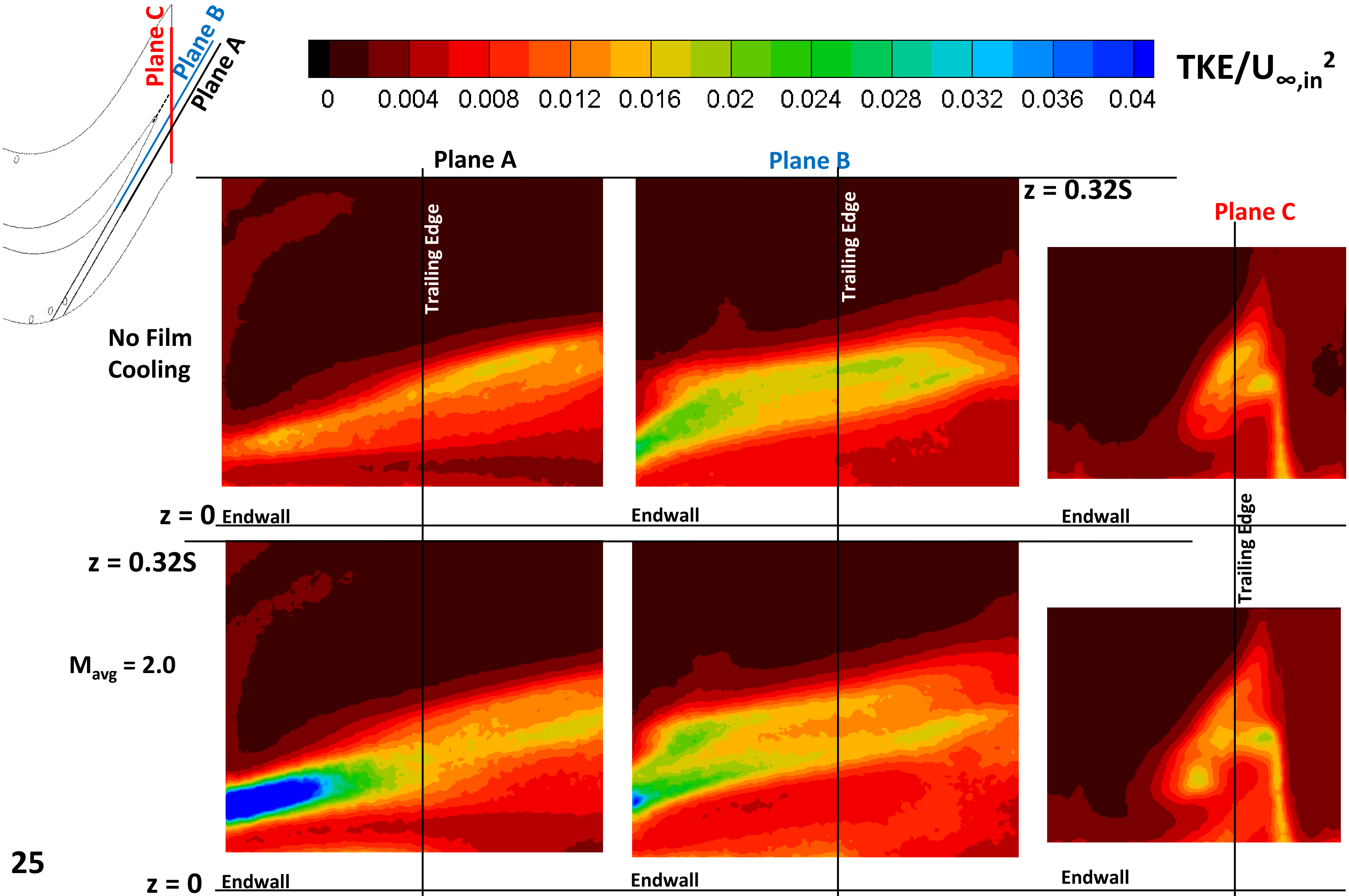




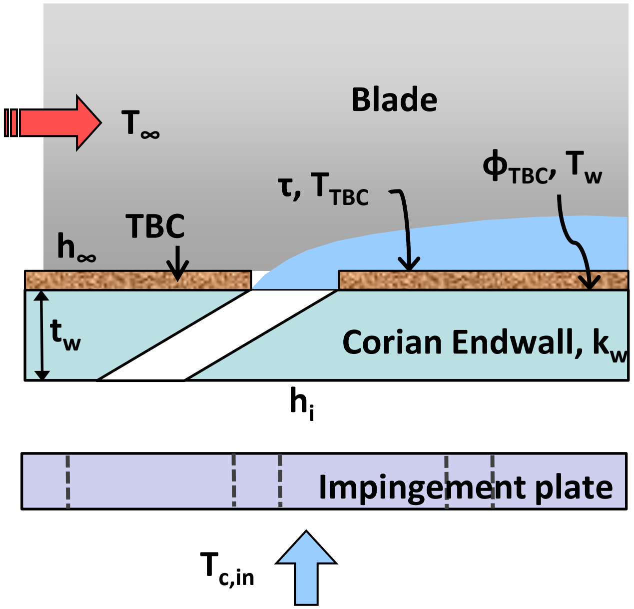
The passage vortex, indicated by the low velocity region, moves farther away from the wall with film cooling



Contours of turbulent kinetic energy show two bands of peak tke, indicating the presence of two vorticies



To accurately quantify the thermal effect of TBC, the thermal resistance was scaled to match the engine



Overall effectiveness with TBC

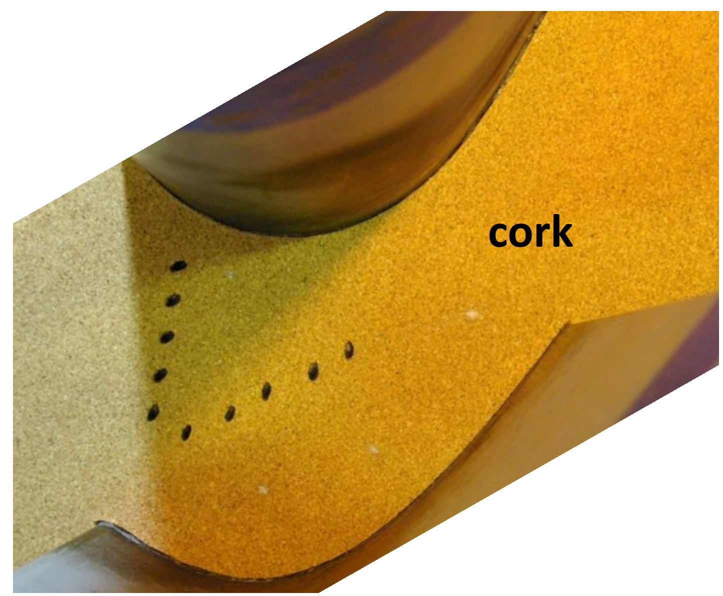
$$\phi_{TBC} = \frac{T_\infty - T_w}{T_\infty - T_{c,in}} = \frac{1 - \chi\eta}{1 + \dfrac{Bi_\infty + h_\infty / h_i}{Bi_\infty \left(R_{TBC} / R_w\right) + 1}} + \chi\eta$$

TBC effectiveness

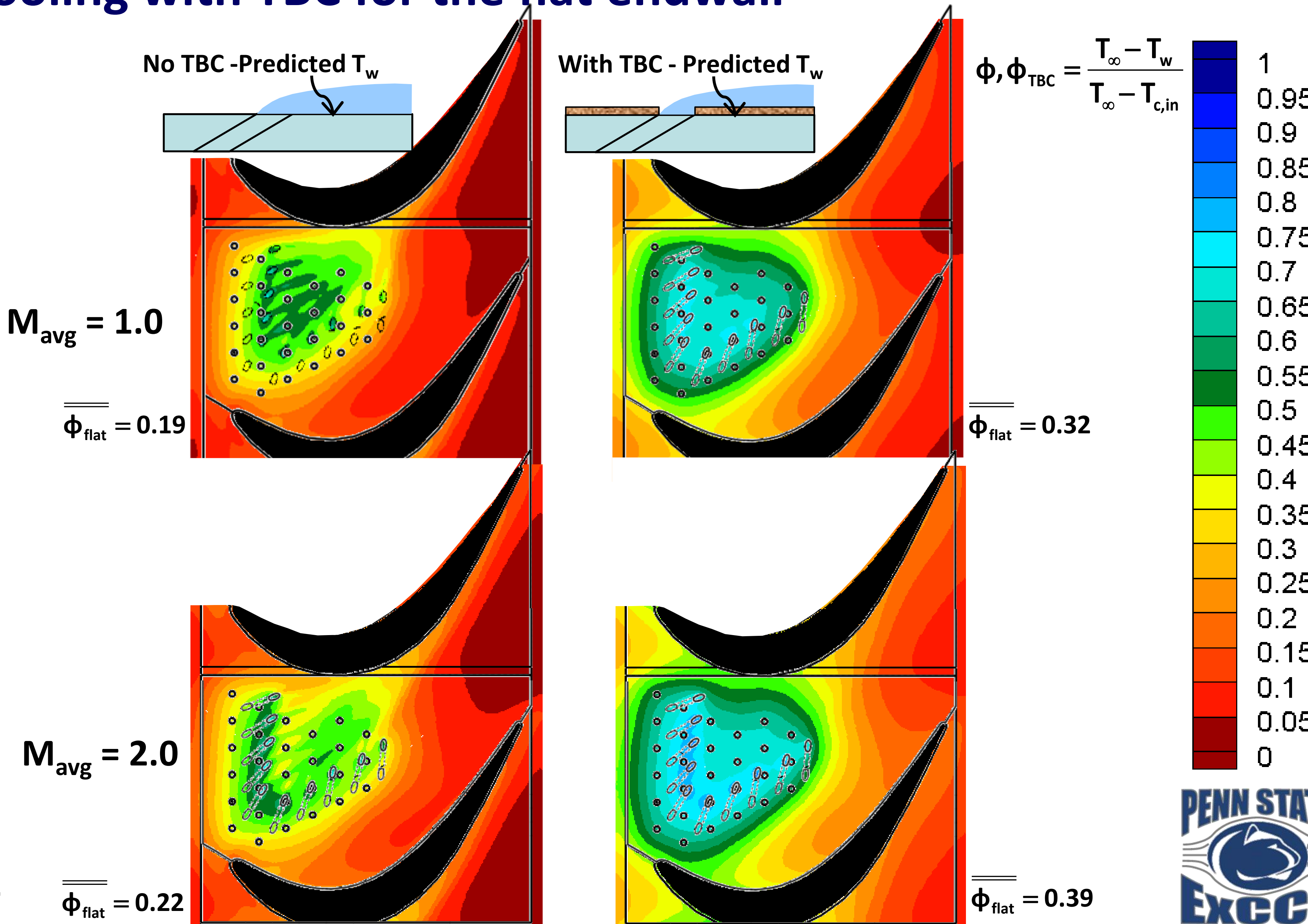
$$\tau = \frac{T_\infty - T_{TBC}}{T_\infty - T_{c,in}}$$

$$\chi\eta = f\left(Re_\infty, M, \text{geometry}\right)$$

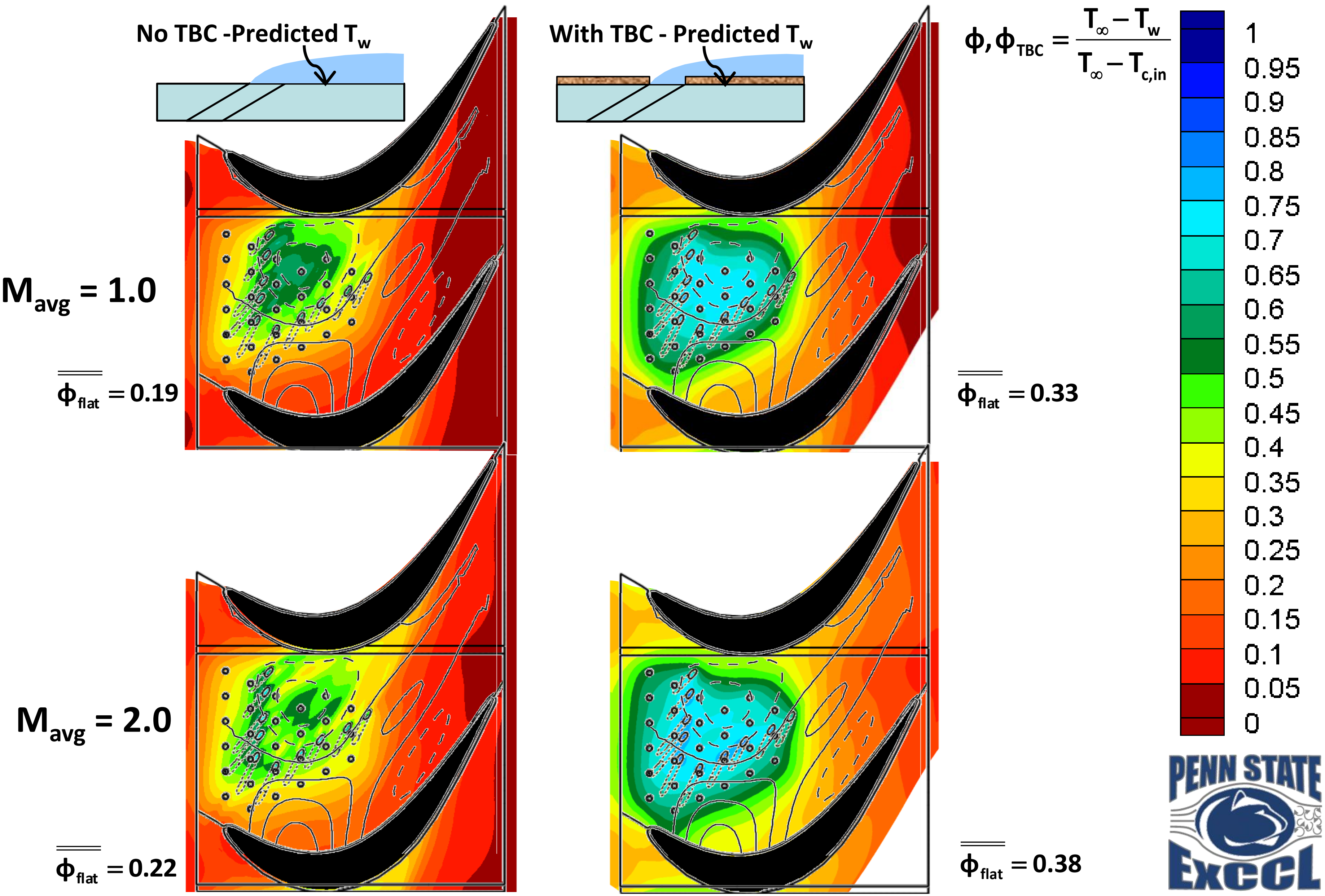
Matched Parameters	Typical Engine	Model
$Re_{\infty,in}$ (C_{ax})	1.25×10^5	1.25×10^5
h_∞/h_i	1	0.5 - 2.3
$M = (\rho_c U_c/\rho_\infty U_\infty)$	1 – 2	0.6, 1, 2
$Bi_\infty = h_\infty t/k_w$	0.27	0.30 - 0.77
$\dfrac{R_{TBC}}{R_w} = \dfrac{t_{TBC} k_w}{t_w k_{TBC}}$	0.6–9.3	2.5



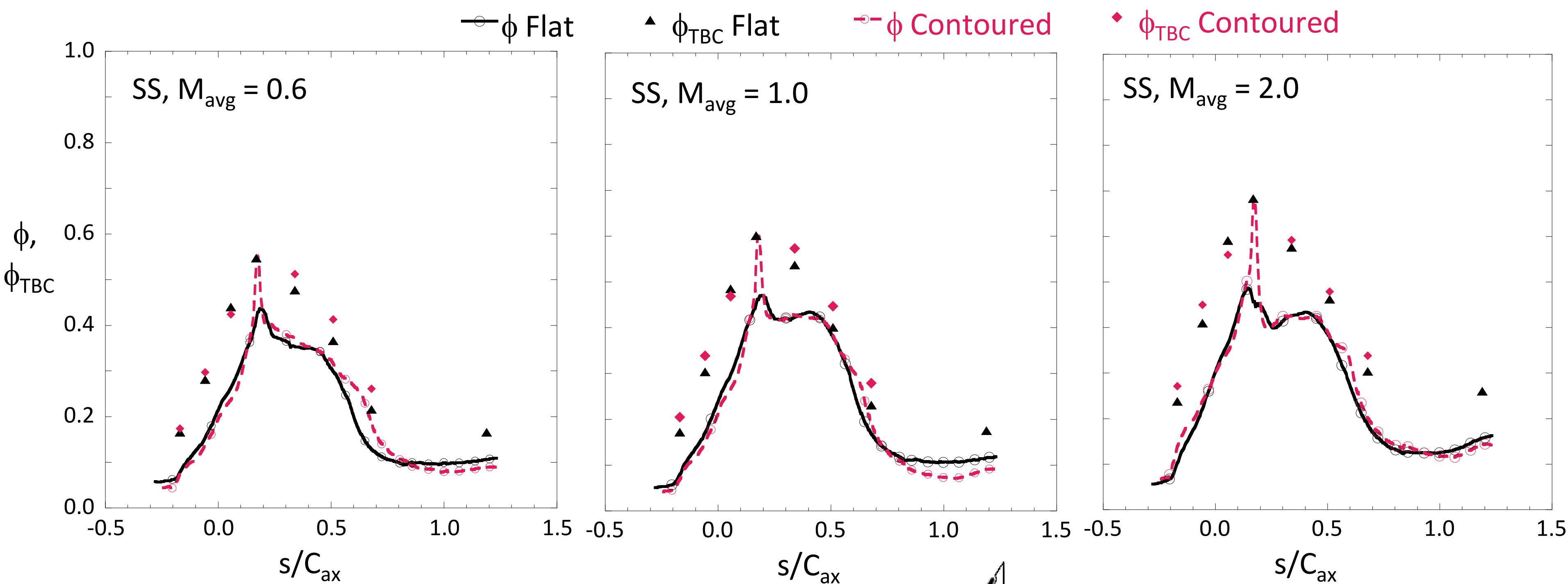
The conjugate simulations predict significant and uniform cooling with TBC for the flat endwall

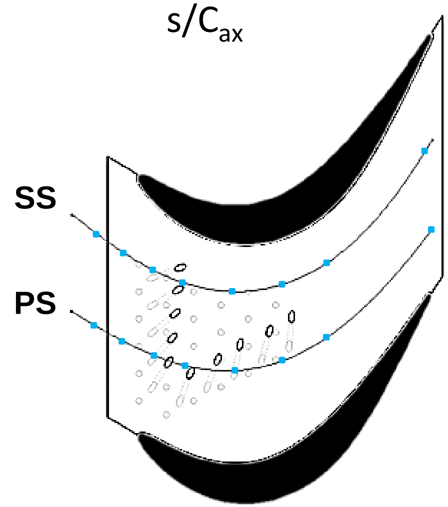


The conjugate simulations predict similar improvements with TBC for the contoured endwall with small differences



Endwall contouring measurements along the streamlines are similar to the flat endwall, with and without TBC





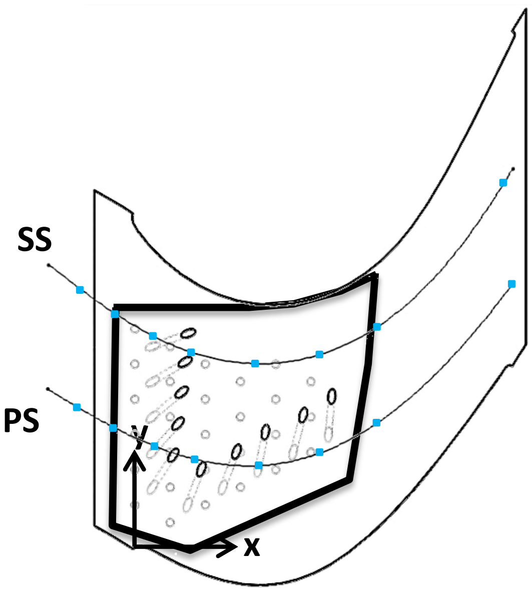
Adding TBC improves ϕ more than an increase in blowing ratio because TBC reduces heat transfer

$$\overline{\overline{\Delta\phi_M}} \approx 0.05$$

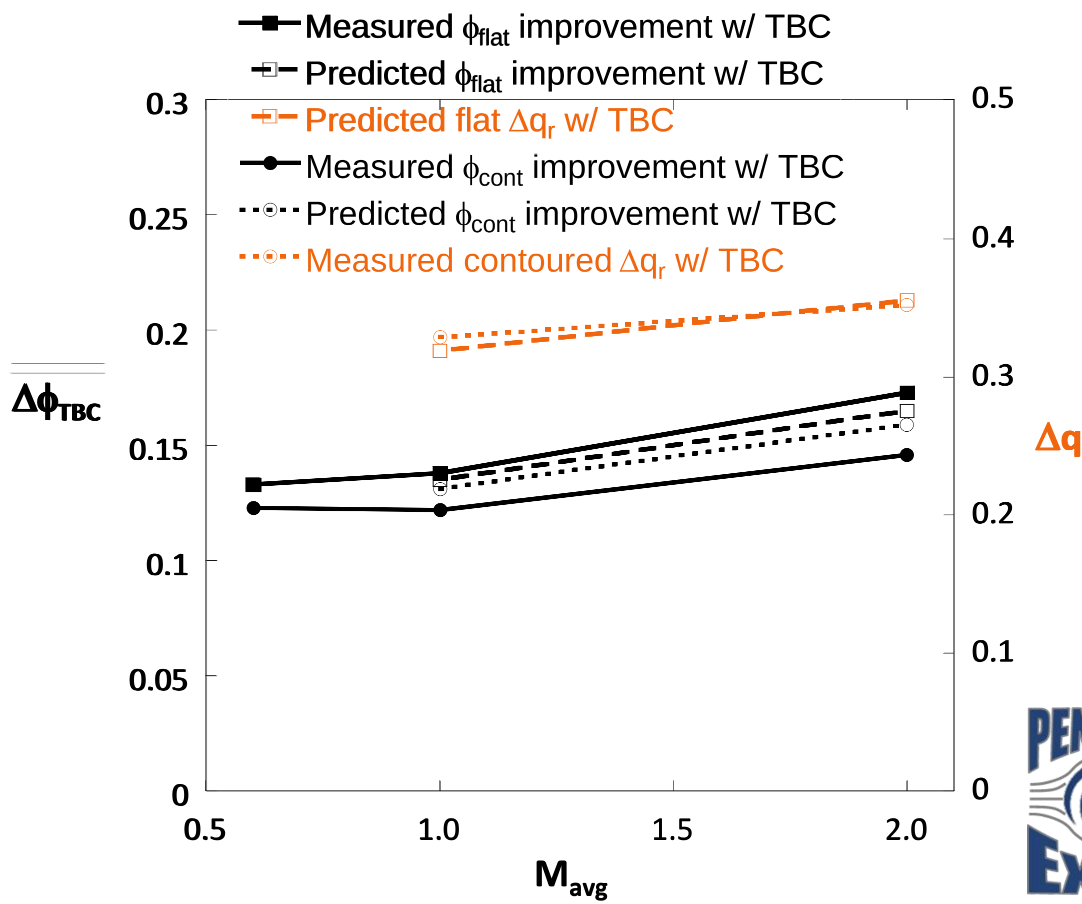
$$\overline{\overline{\Delta\phi_{TBC}}} = \overline{\overline{\phi_{TBC} - \phi}} \approx 0.15$$

Net Heat Flux Reduction – outer endwall surface

$$\Delta q_r = \frac{q_w - q_{w,TBC}}{q_w}$$

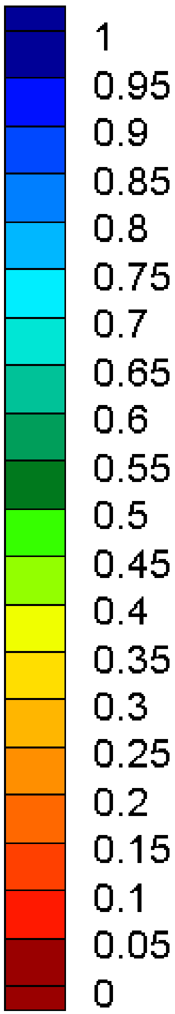


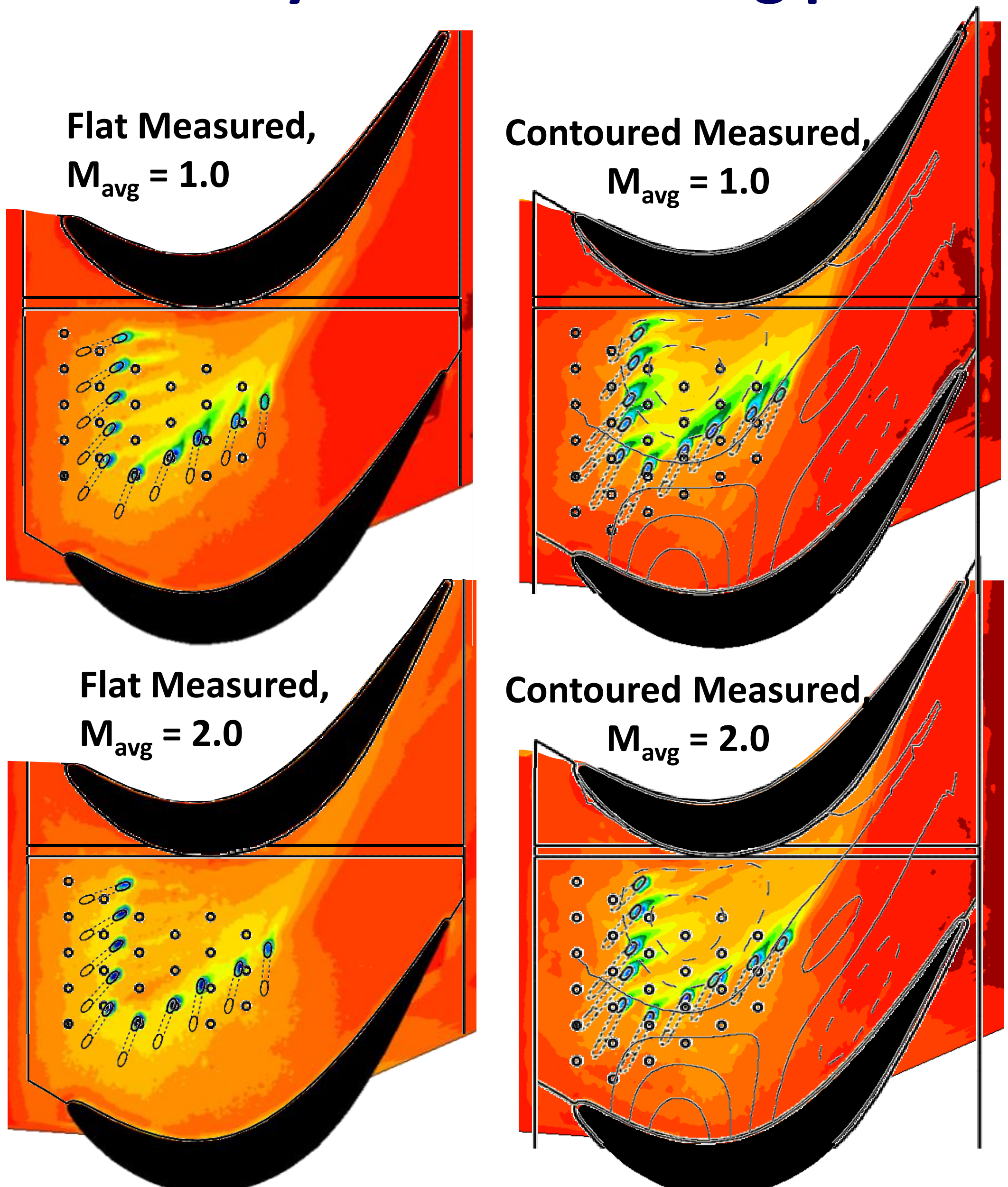
$\overline{\overline{\Delta\phi_{TBC}}}$ **also increases with M**

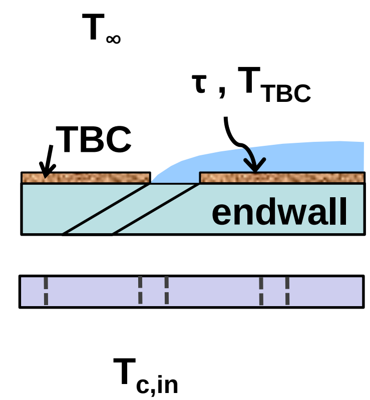


TBC temperature is less affected by the internal cooling and more affected by the film cooling performance

$$\tau = \frac{T_\infty - T_{TBC}}{T_\infty - T_{c,in}}$$

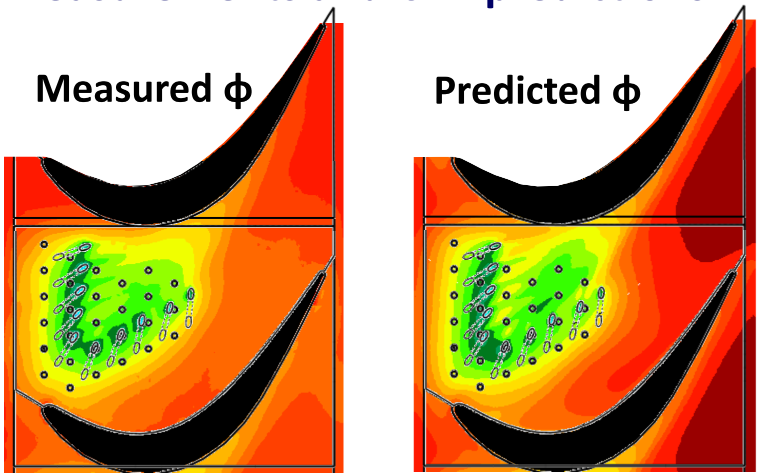




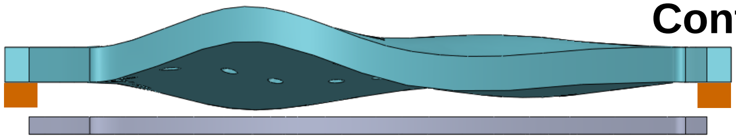


This study demonstrates conjugate heat transfer trends for gas turbine endwalls and the secondary flow effects

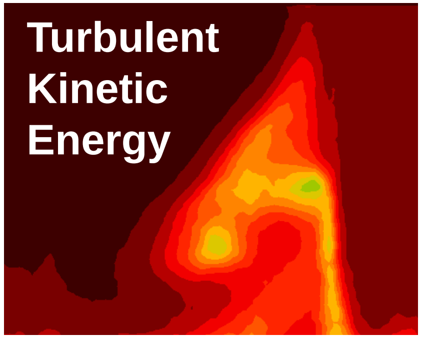
Good agreement between conjugate measurements and CFD predictions



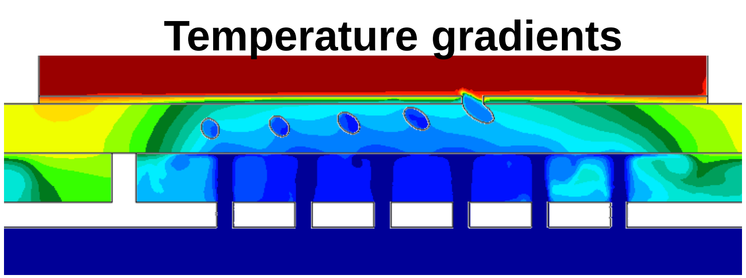
Demonstrate trends for:



Unique flowfield measurements demonstrate interactions between passage vortex and film cooling



with film cooling



with TBC