# Simulating Particle Deposition and Mitigating Deposition Degradation Effects in Film Cooled Turbine Sections

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

# Gas turbine needs

- IGCC power plants utilize coal- or biomass-derived synthetic gas ("syngas") to fuel power generation gas turbines with readily available, stable fuel supplies.
- Syngas tends to be less clean than natural gas, resulting in more significant deposits of contaminants on turbine surfaces.
- Depositions on turbine component surfaces result in decreased film cooling performance and less efficient plant operation.
- Consequently there is a need to:
  - better understand how contaminant deposition effects film cooling performance.
  - develop film cooling designs that are less sensitive to the adverse effects of contaminant depositions.

# Project Objectives

- Develop techniques for deposition of contaminant particles on wind tunnel models similar to deposition on actual turbine components.
- Evaluate performance of the shallow trench film cooling configurations when subjected to dynamic deposition of contaminants.
- Develop new trench configurations or other film cooling configurations that maximize film cooling performance under contaminated conditions, and minimize deposition of contaminates.

## Project Objectives, continued

- Quantify and understand contaminant particle transport for a flow in a first vane passage.
- Determine how the placement of film-cooling holes on a flat endwall can alleviate particle deposition.
- Determine how a contoured endwall configuration combined with film-cooling could be used to alleviate and mitigate particle deposition effects on the cooling of an endwall

# Summary of research at University of Texas at Austin

# Simulation of depositions on turbine components

*Basic concept:* Depositions occur because particles are molten and they solidify on the cooled airfoils and endwalls.

➢ **This is simulated in our wind tunnel facilities using molten wax particles.**

***Schematic of the wax spray device at UT:***

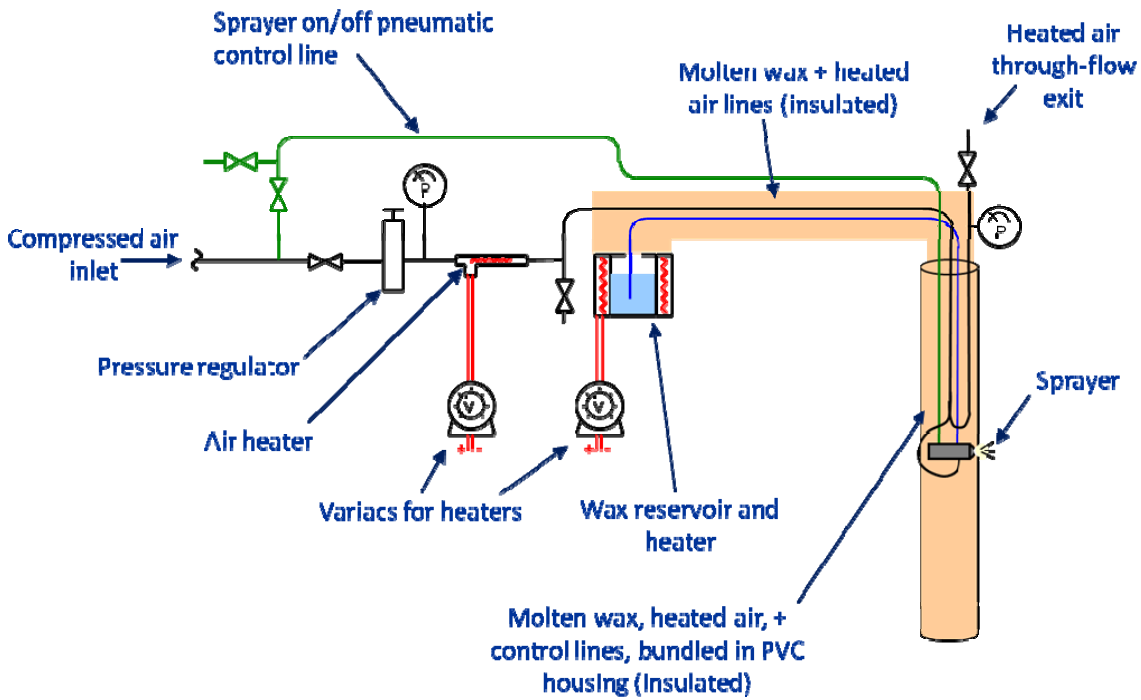



***Photo of wax spray device in turbulence grid:***

# Wax particles were sized to match the Stokes number at engine conditions

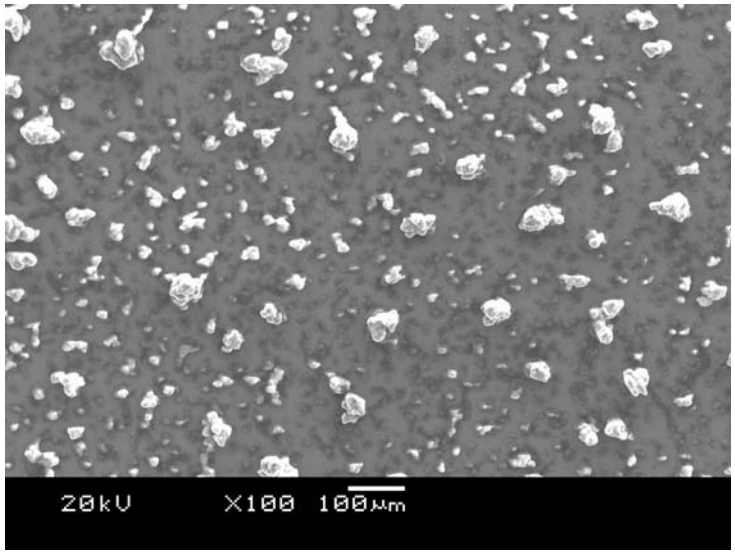
For a spherical particle in flow: $$Stk = \frac{\tau}{l_c / U_c} = \frac{\rho_p d_p^2 U_c}{18\, l_c \mu_g}$$

Coal ash in engine: $d_{p,max}$ = 1-10 μm

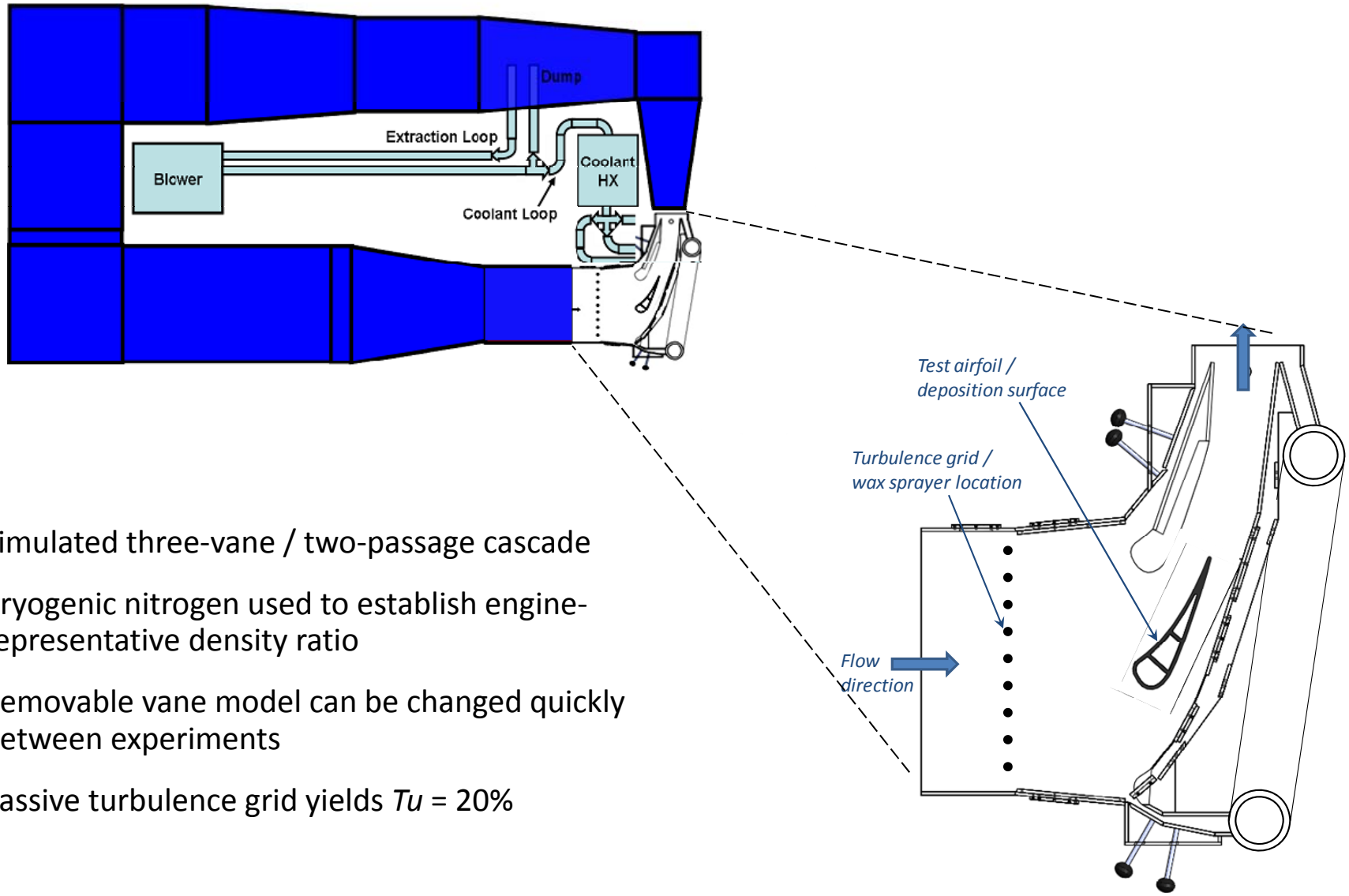
Wax in wind tunnel : $d_{p,max}$ = 8-80 μm

} $Stk$ = 1-100

***SEM image of wax particles sample:***



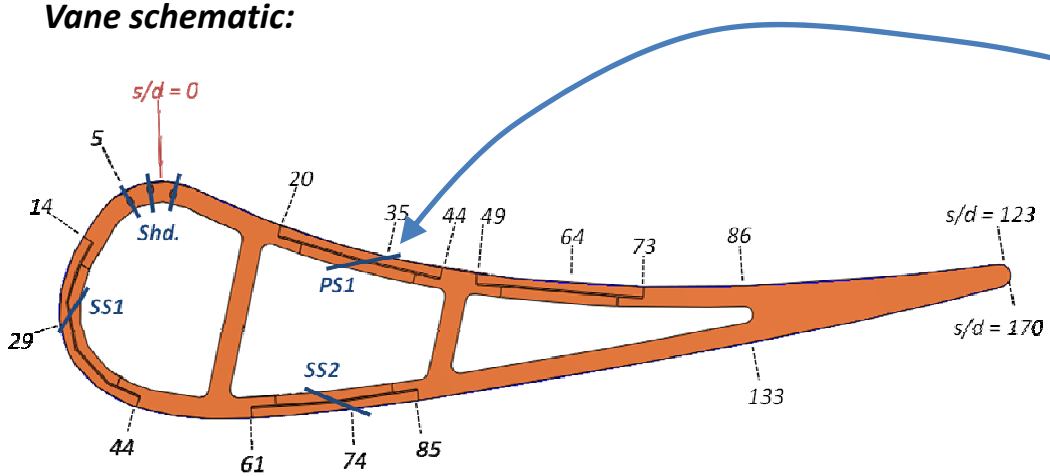
# UT wind tunnel facility used for vane film cooling and deposition testing



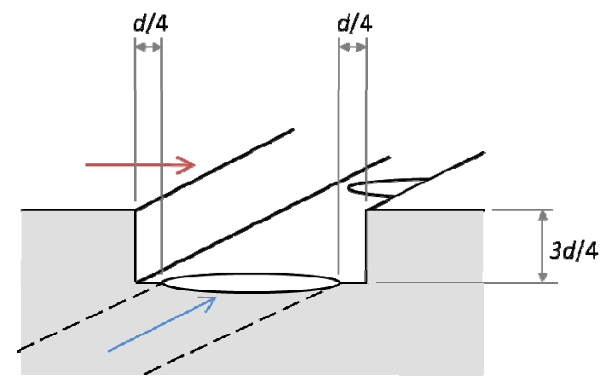

- Simulated three-vane / two-passage cascade
- Cryogenic nitrogen used to establish engine-representative density ratio
- Removable vane model can be changed quickly between experiments
- Passive turbulence grid yields *Tu* = 20%

# UT vane model and film cooling description

*Vane schematic:*




*PS trench schematic:*




- **Cooling hole geometry:**

  **All holes:** $d$ = 4.22 mm

  **3-row showerhead:** round holes, $p/d$ = 5.55, surface angle = 25°, compound angle = 90°

  **PS row:** 1 row, round & trenched holes, $p/d$ = 3, surface angle = 30°, compound angle = 0°

  **SS rows:** 2 rows, round holes, $p/d$ = 3, surface angle = 30°-40°, compound angle = 0°

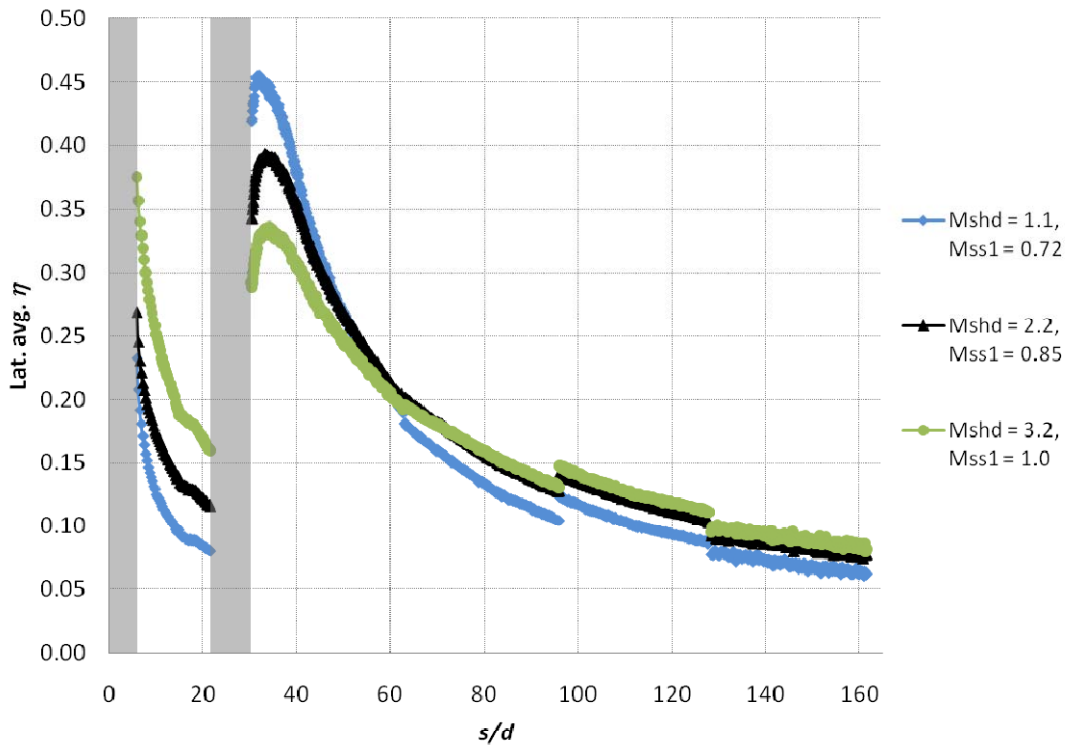
- **Experimental flow conditions:**

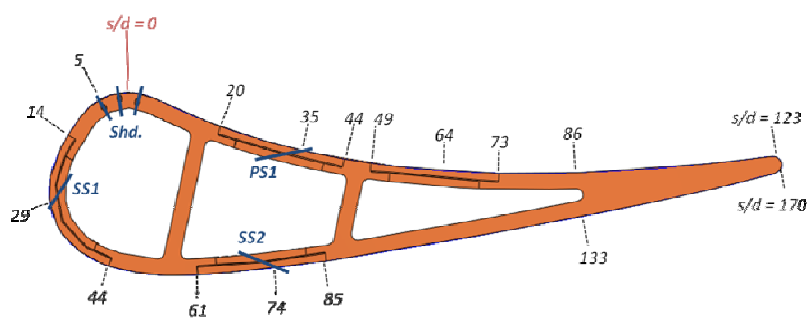
  **PS tests:** $DR$ = 1.4 ($T_\infty$ = 305 K, $T_c$ = 220 K)

  **SS tests:** $DR$ = 1.2 ($T_\infty$ = 305 K, $T_c$ = 255 K)

# Vane SS film effectiveness: Effect of blowing ratio

***Plot of laterally-averaged $\eta$ when Showerhead + SS1 holes active:***



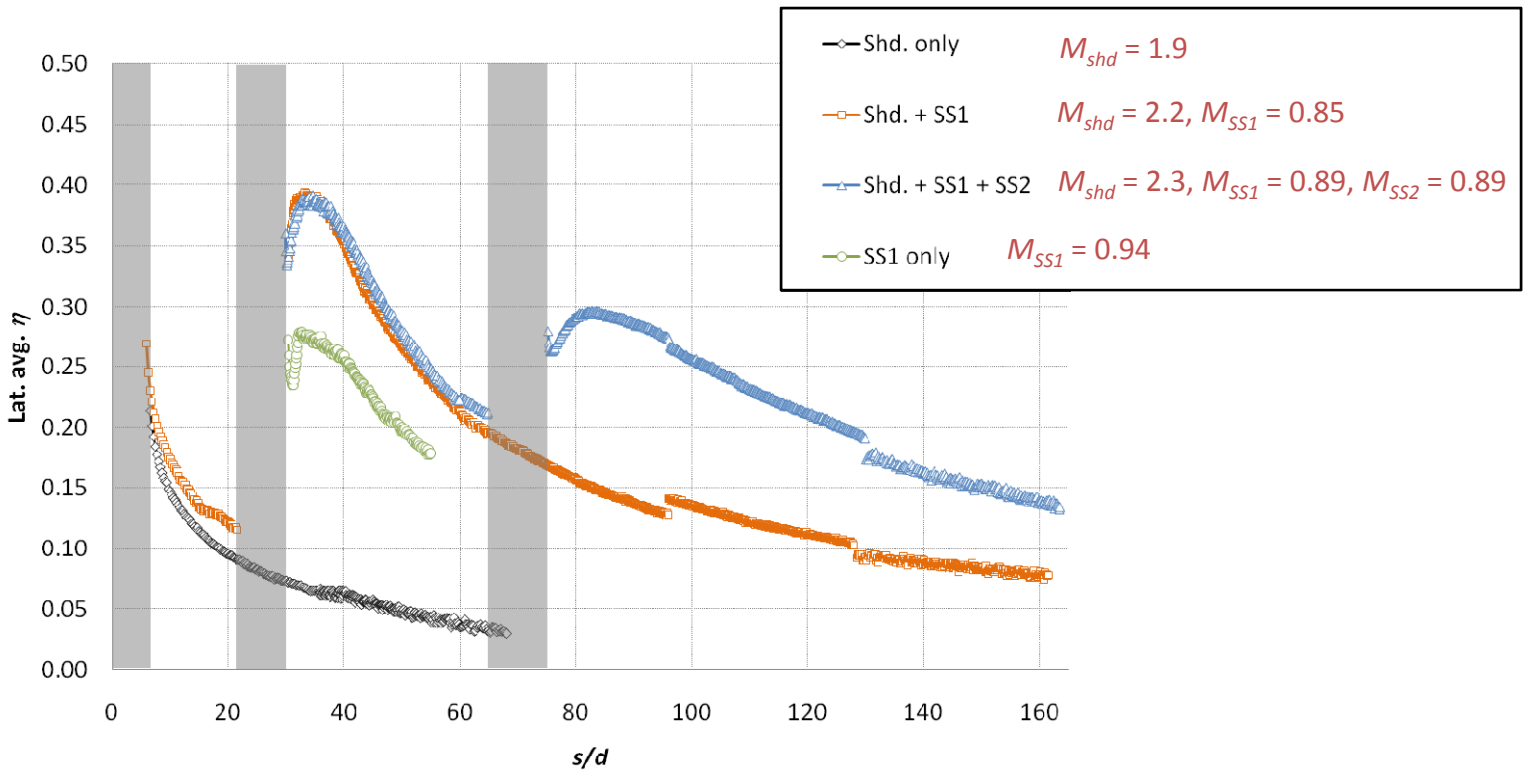

Other conditions

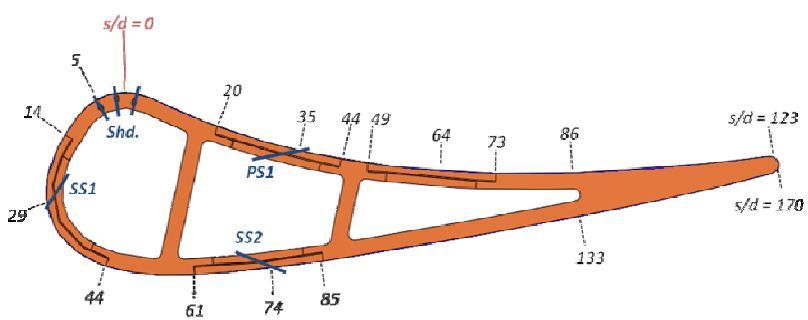
*DR* = 1.2

*Tu* = 20%

# Vane SS film effectiveness: Various film rows active

***Plot of laterally-averaged $\eta$ with various rows of cooling holes active:***




Other conditions

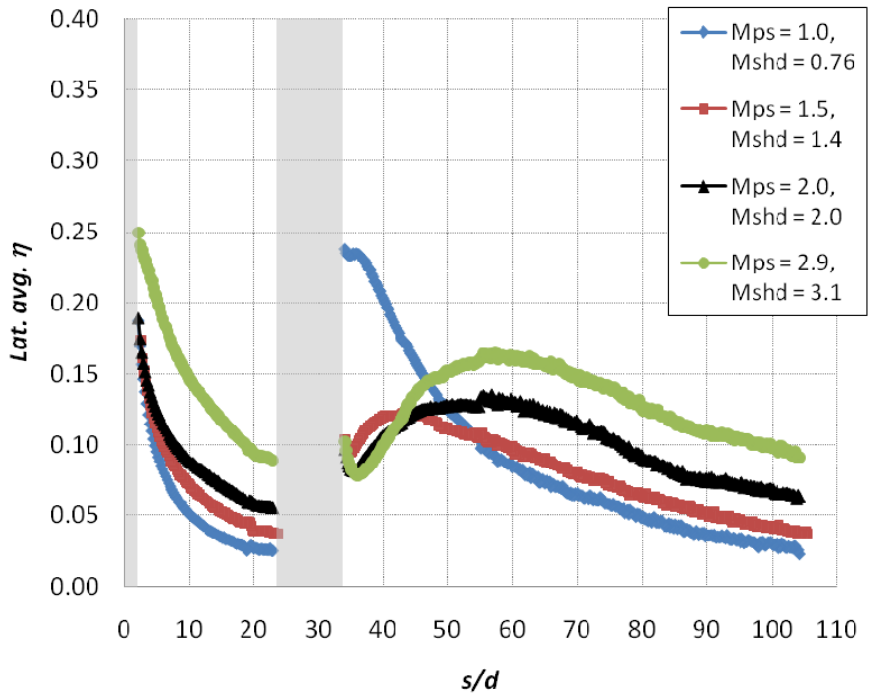
*DR* = 1.2

*Tu* = 20%

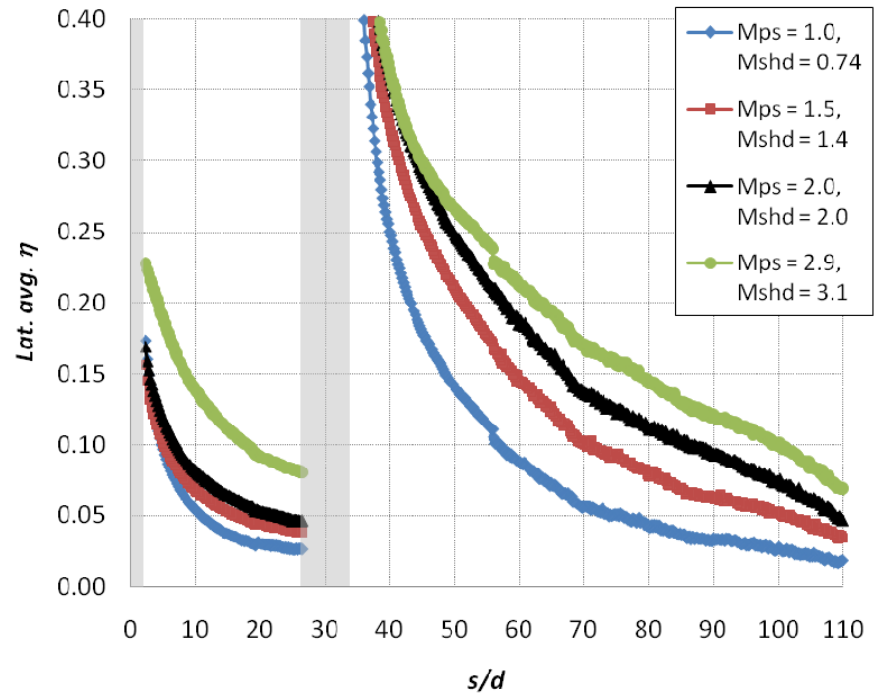
# Vane PS film effectiveness: Baseline vs. Trenched holes

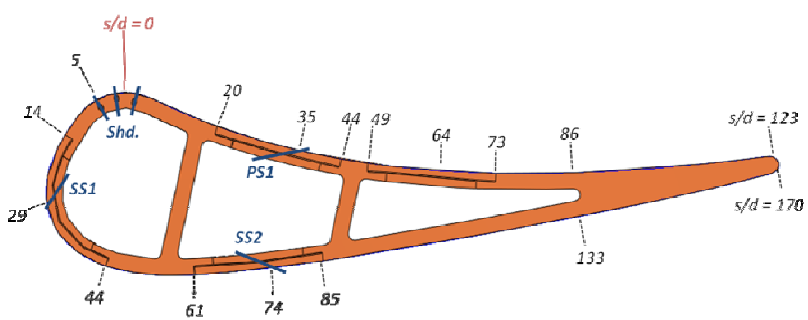
***Plots of laterally-averaged $\eta$:***

**Baseline** PS holes + showerhead




**Trenched** PS holes + showerhead




Other conditions

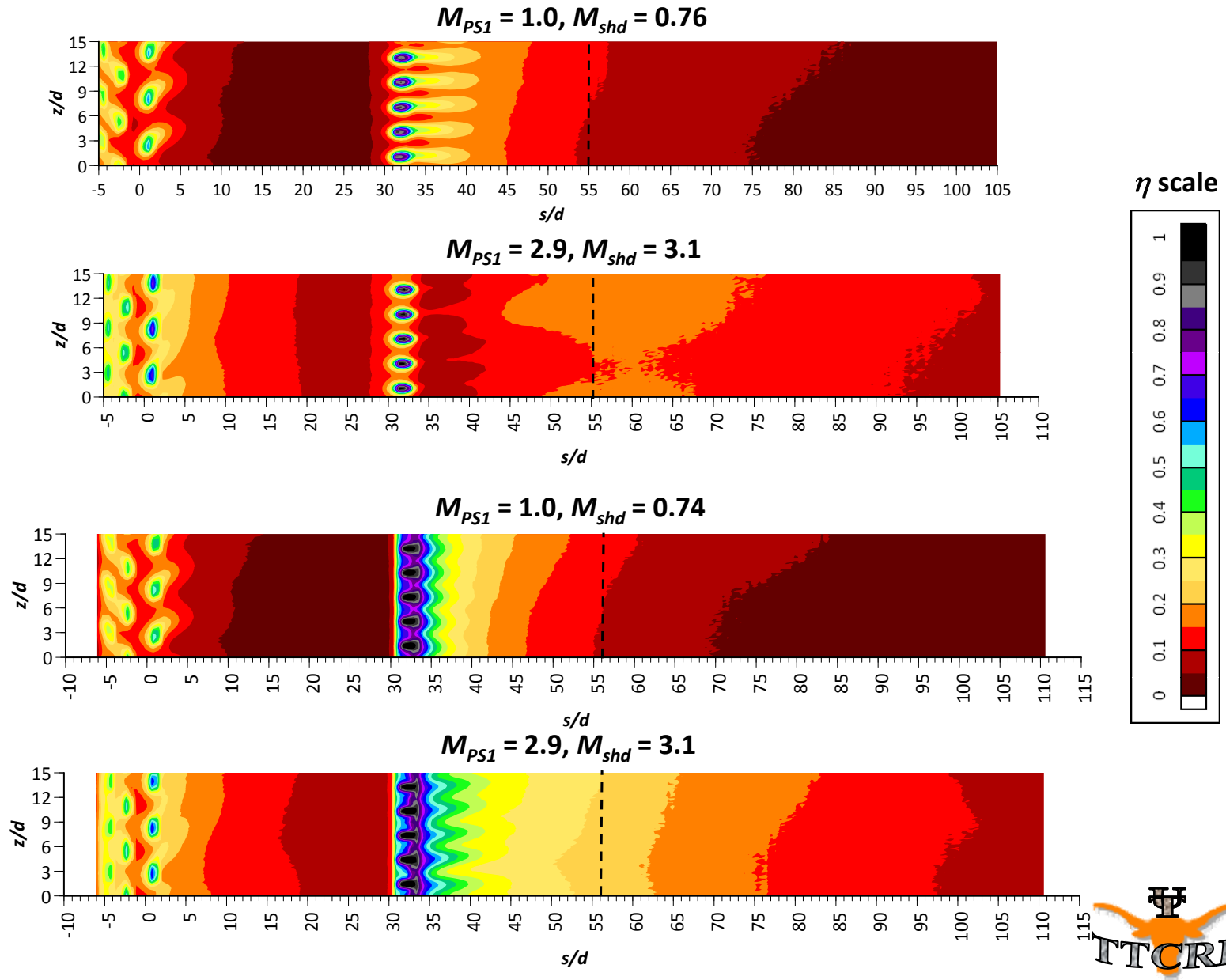
*DR* = 1.4

*Tu* = 20%

# Vane PS film effectiveness: Baseline vs. Trenched holes

**Baseline**
**PS holes + showerhead**

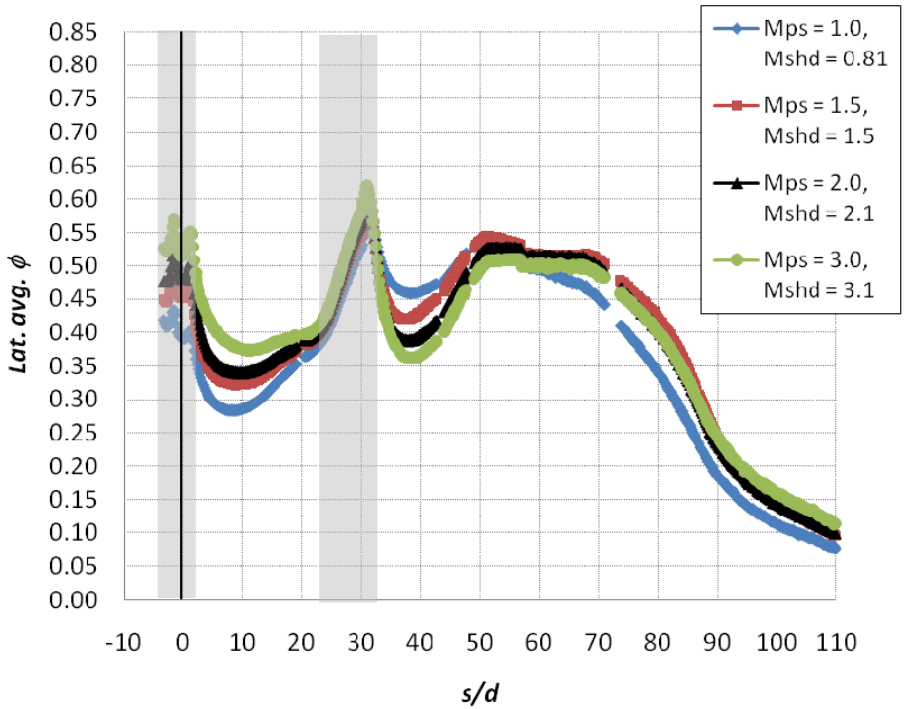
**Trenched**
**PS holes + showerhead**



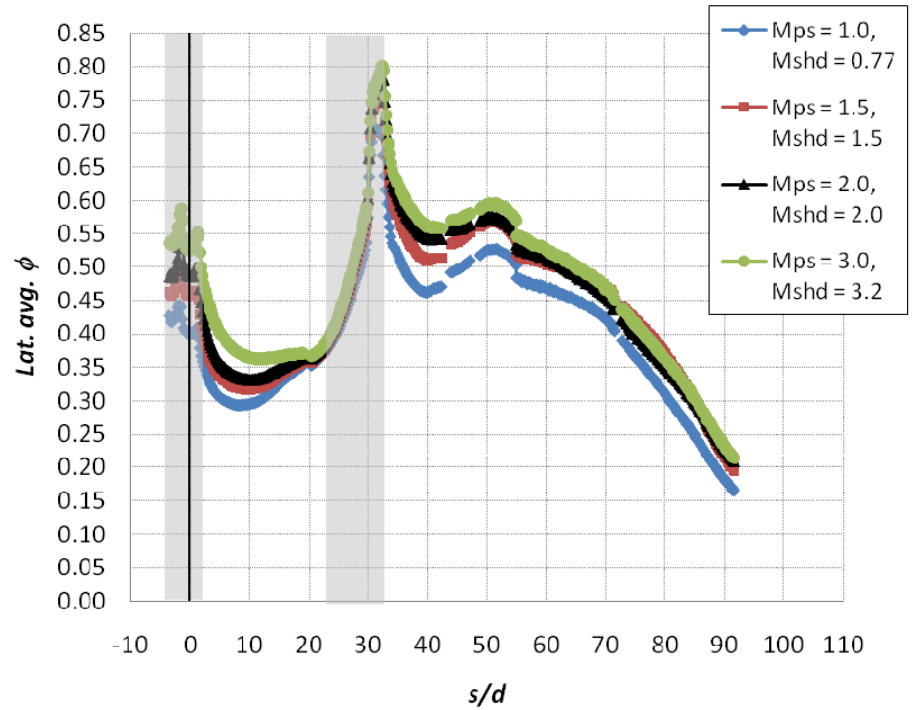
# Vane PS overall effectiveness: Baseline vs. Trenched holes

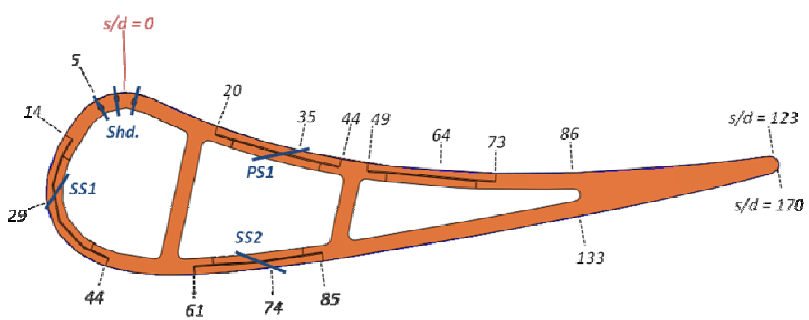
***Plots of laterally-averaged $\phi$:***

**Baseline** PS holes + showerhead




**Trenched** PS holes + showerhead




Other conditions

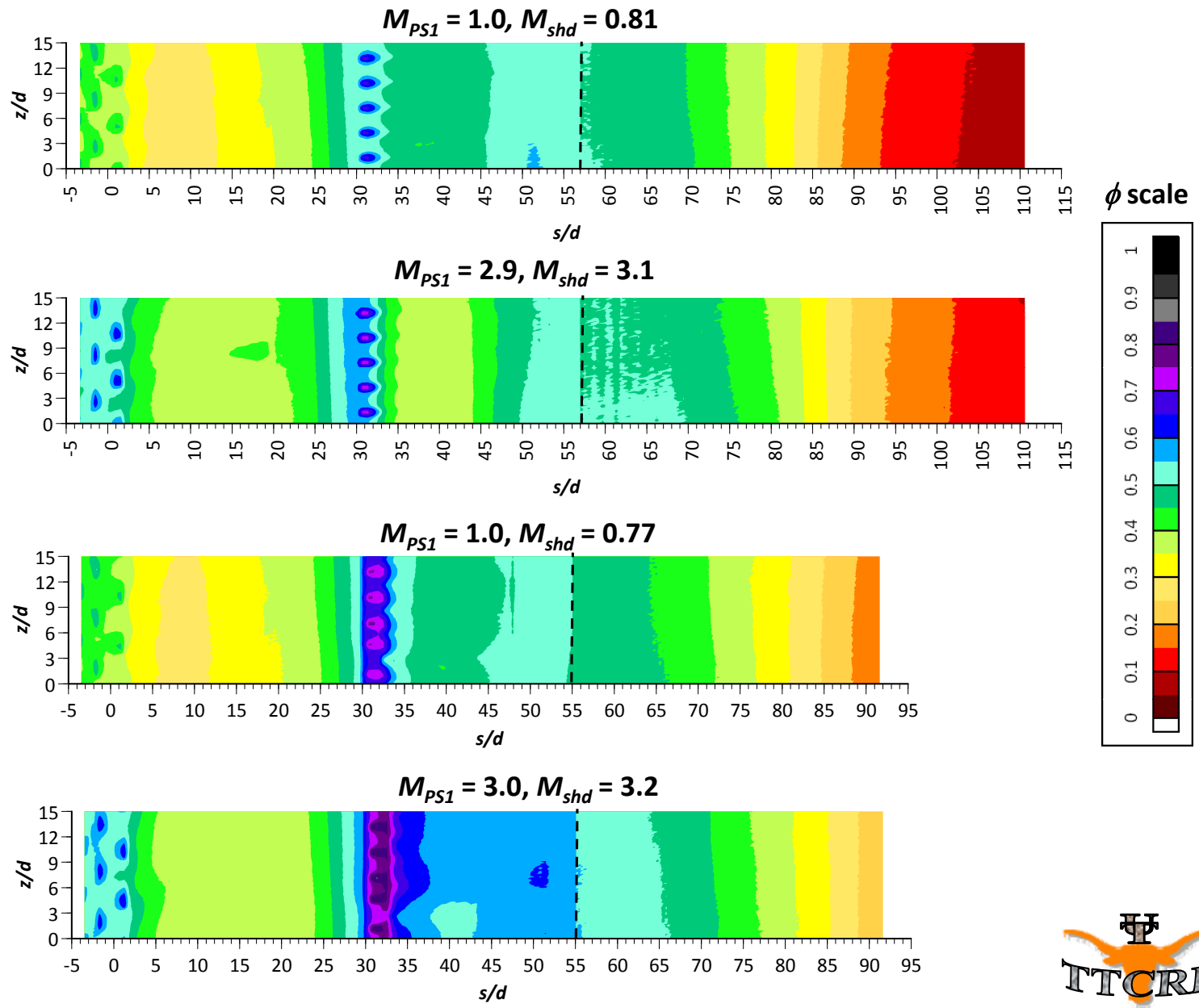
*DR* = 1.4

*Tu* = 20%

# Vane PS overall effectiveness: Baseline vs. Trenched holes

**Baseline**
**PS holes + showerhead**

**Trenched**
**PS holes + showerhead**

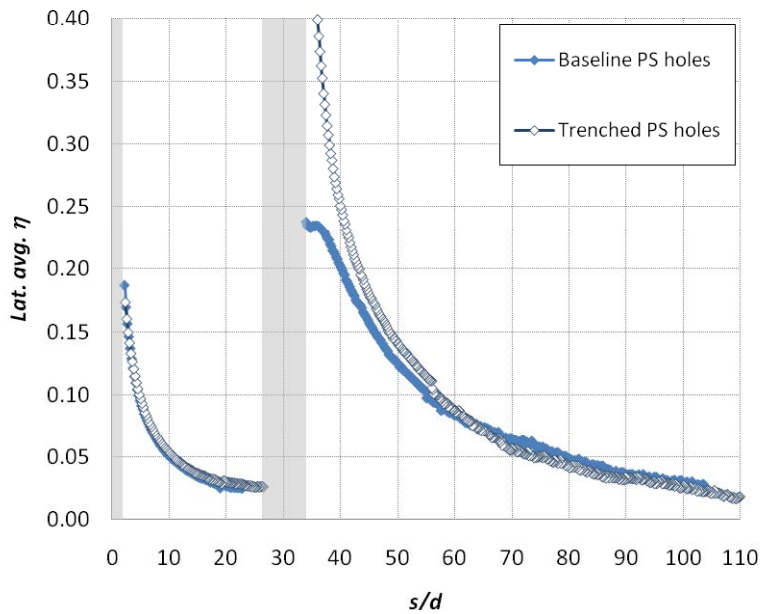


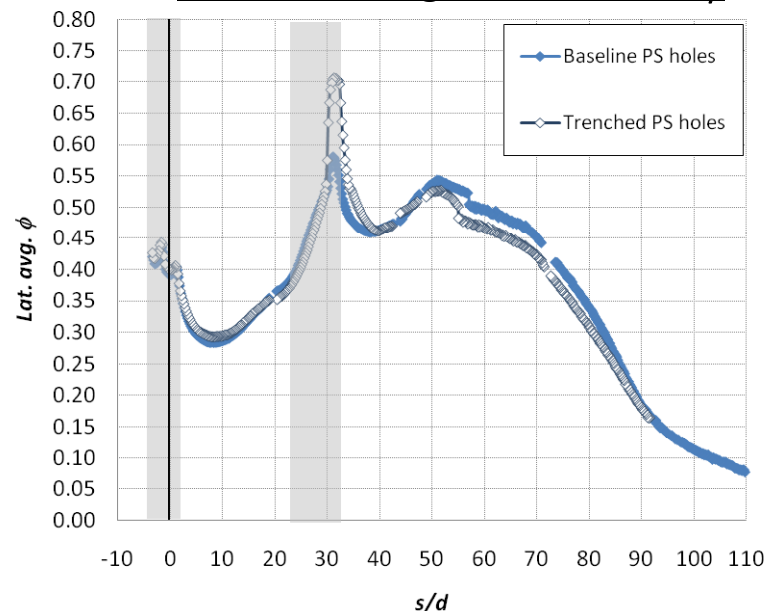
# Vane PS $\eta$ and $\phi$: Baseline vs. Trenched holes

**Adiabatic film effectiveness, $\eta$**

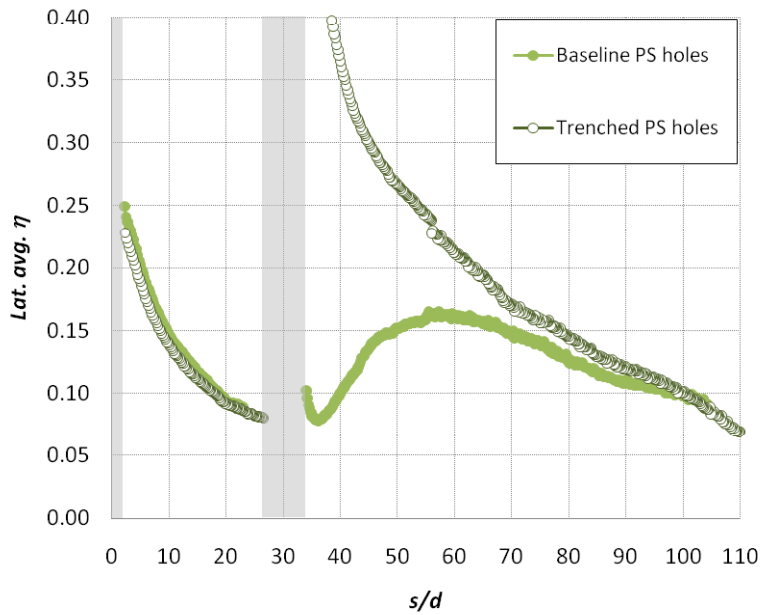
**Overall cooling effectiveness, $\phi$**

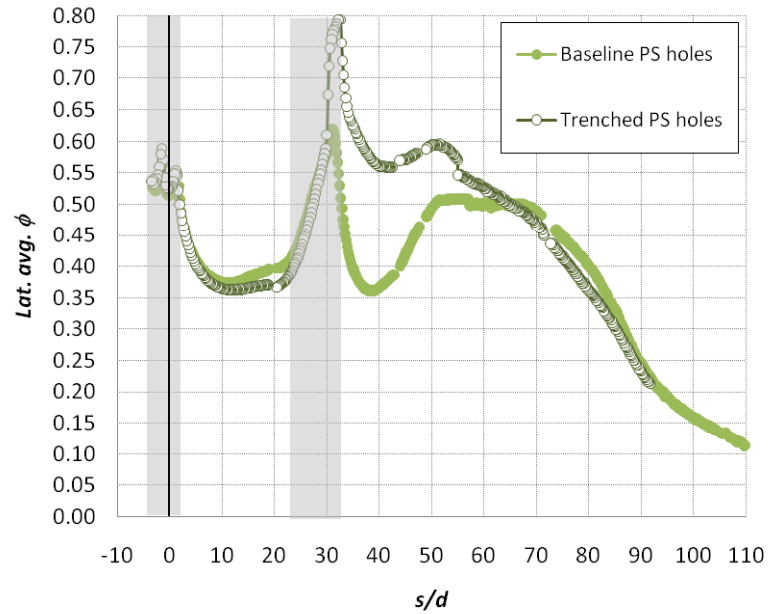
$M_{ps}$ = 1.0
($M_{shd}$ = 0.8)




$M_{ps}$ = 3.0
($M_{shd}$ = 3)

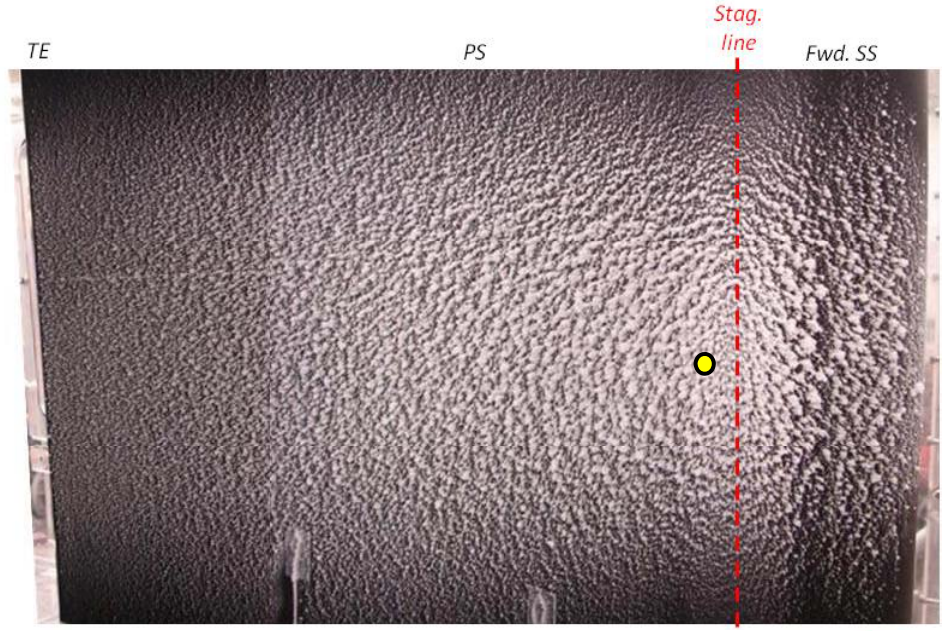


# Vane PS deposits: Effect of surface temperature

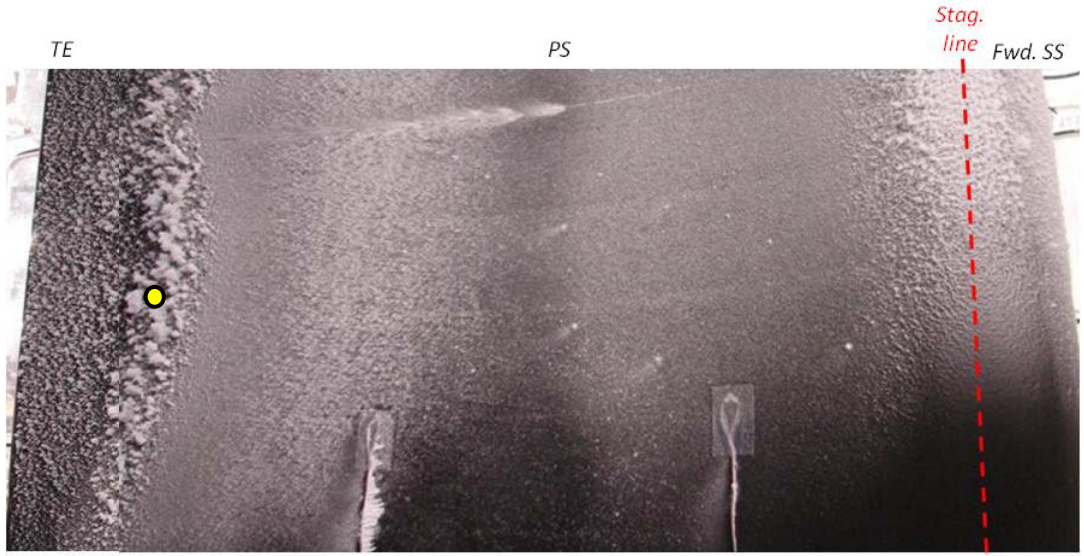
Matched-*Bi* model
No film cooling
**Isothermal**
$T_\infty = T_{cool} = 305$ K

**max. $t_{dep}$ = 3.1 mm**




Matched-*Bi* model
No film cooling
**Internally cooled**
$T_\infty = 305$ K, $T_{cool} = 220$ K

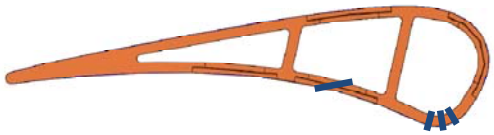
**max. $t_{dep}$ = 5.3 mm**

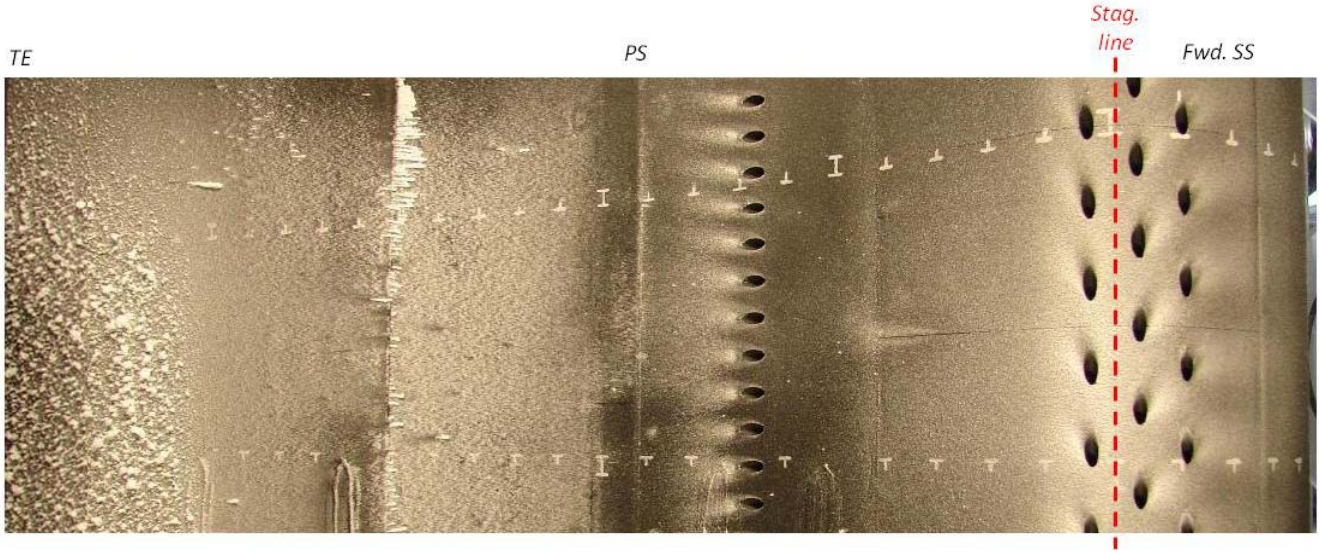



***Common conditions:*** **$T_{wax,melt}$ = 315 K**

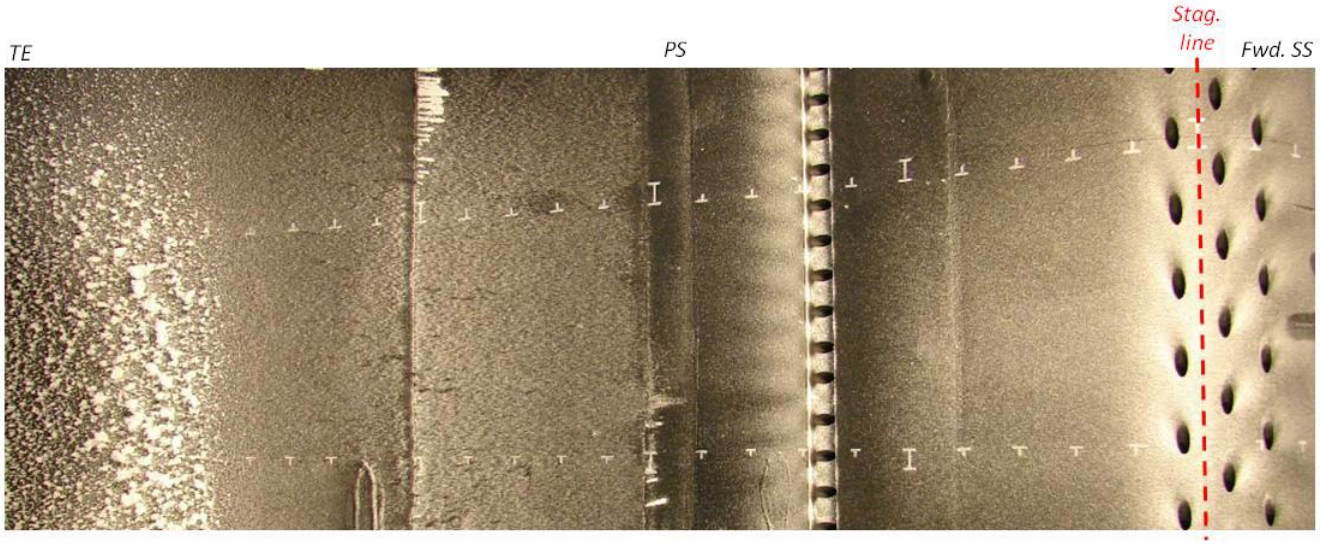
# Vane PS deposits: Baseline vs. Trenched holes

Matched-*Bi* model
**Baseline PS film cooling**
$M_{PS}$ = 2.0, $M_{Shd}$ = 2.0





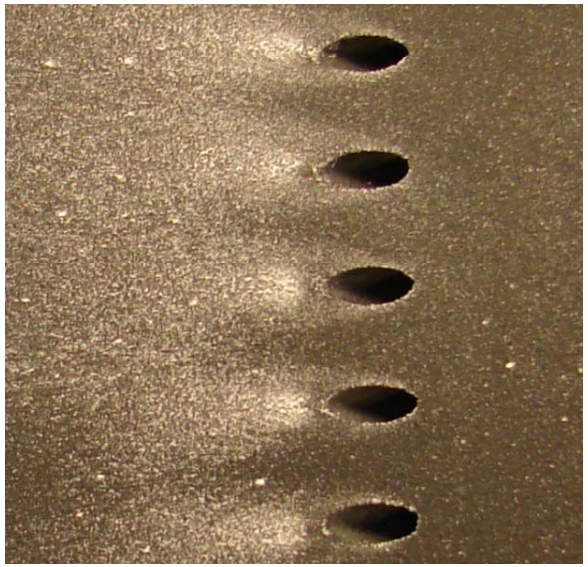

Matched-*Bi* model
**Trenched PS film cooling**
$M_{PS}$ = 2.0, $M_{Shd}$ = 2.0



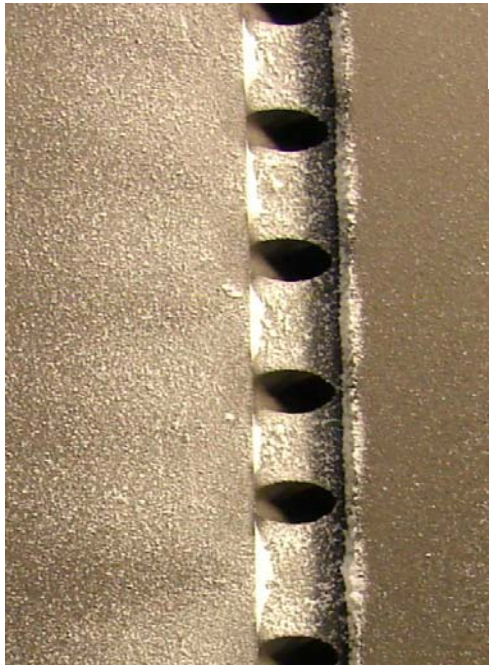

*Common conditions:* $DR$ = 1.4 ($T_\infty$ = 305 K, $T_{cool}$ = 220 K), $T_{wax,melt}$ = 315 K

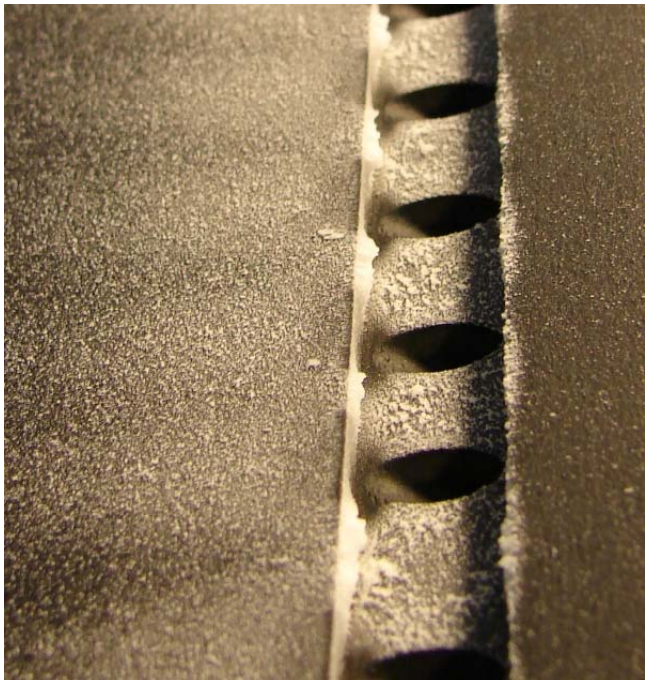
# Vane PS deposit details: Baseline vs. Trenched holes

Matched-*Bi* model
**Baseline PS film cooling**
$M_{PS}$ = 2.0, $M_{Shd}$ = 2.0



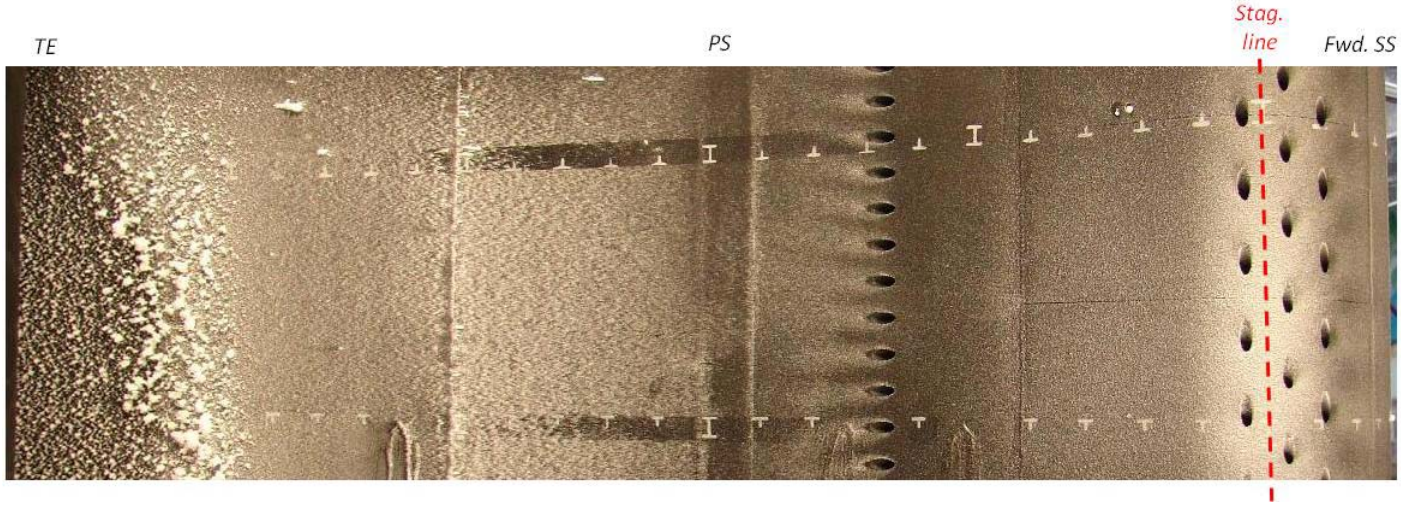
Matched-*Bi* model
**Trenched PS film cooling**
$M_{PS}$ = 2.0, $M_{Shd}$ = 2.0

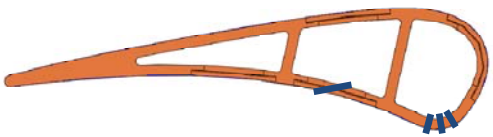




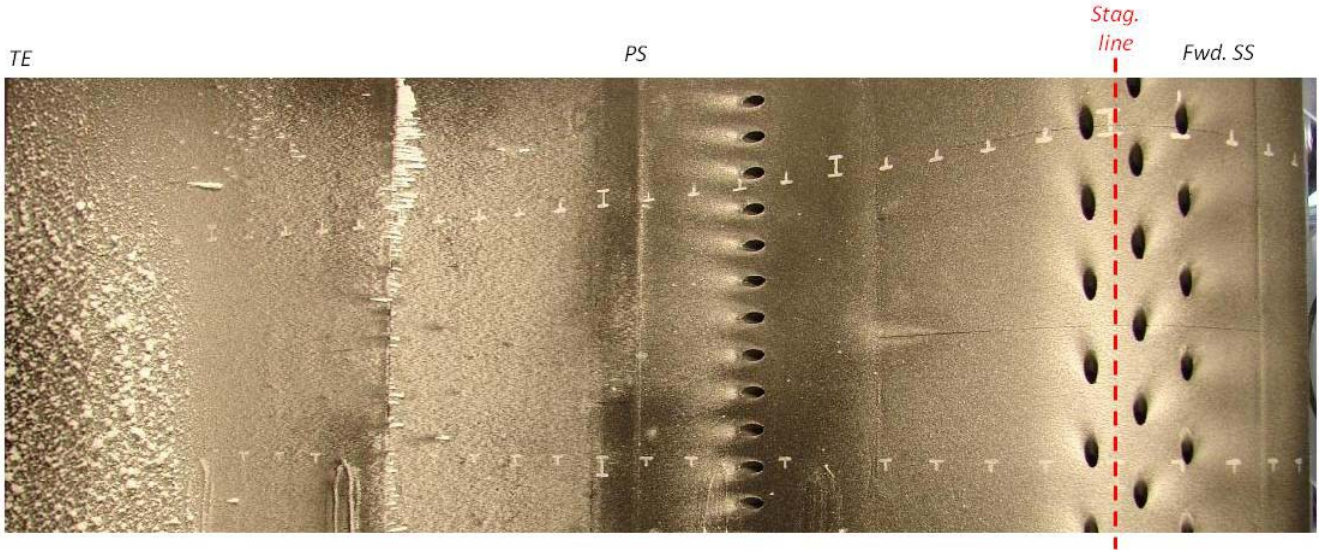
# Vane PS deposits: Effect of blowing ratio

Matched-*Bi* model
Baseline PS film cooling
$M_{PS}$ = 1.0, $M_{Shd}$ = 0.75



Matched-*Bi* model
Baseline PS film cooling
$M_{PS}$ = 2.0, $M_{Shd}$ = 2.0



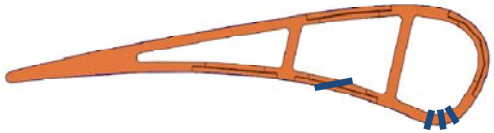

*Common conditions:* $DR$ = 1.4 ($T_\infty$ = 305 K, $T_{cool}$ = 220 K), $T_{wax,melt}$ = 315 K

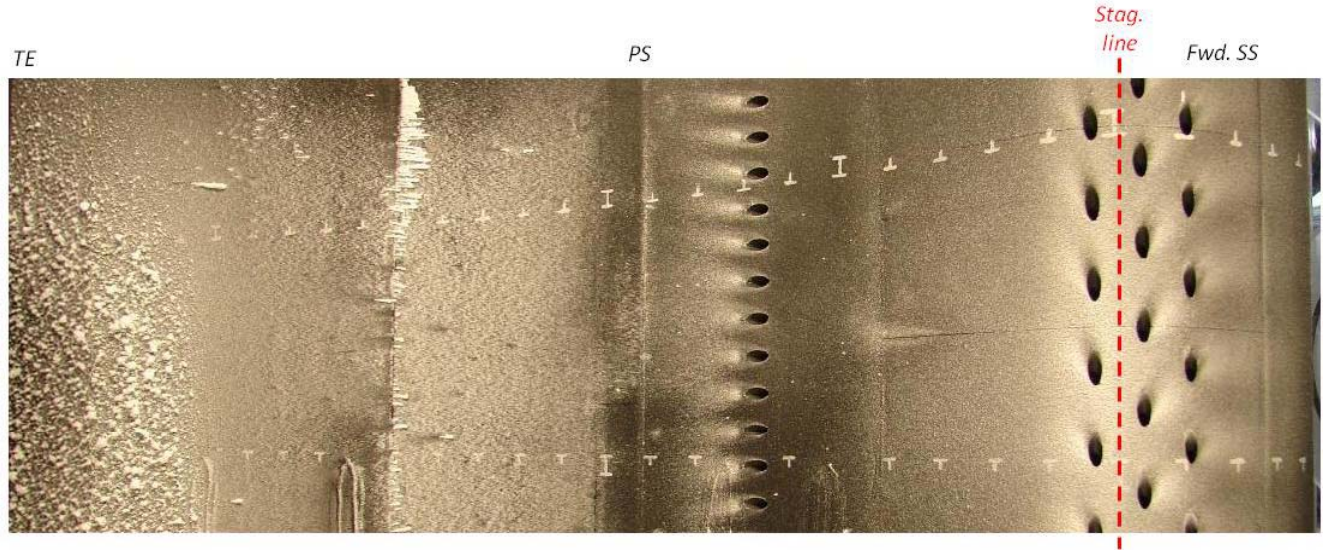
# Vane PS deposits: Effect of surface temperature

**Matched-*Bi* model**

Baseline PS film cooling

$M_{PS}$ = 2.0, $M_{Shd}$ = 2.0

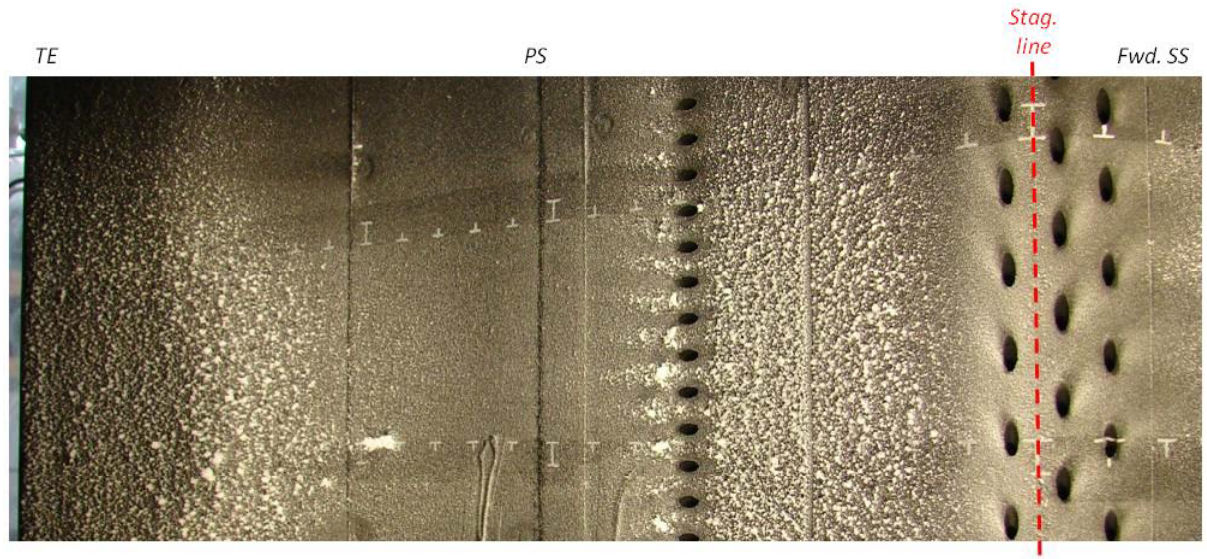





**Adiabatic model**

Baseline PS film cooling

$M_{PS}$ = 2.0, $M_{Shd}$ = 2.0



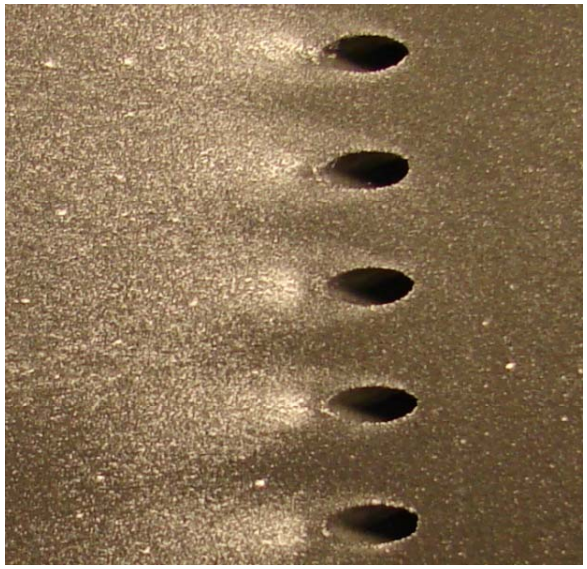

*Common conditions:* $DR$ = 1.4 ($T_\infty$ = 305 K, $T_{cool}$ = 220 K), $T_{wax,melt}$ = 315 K

# Vane PS deposit details: Effect of surface temperature

**Matched-*Bi* model**

Baseline PS film cooling

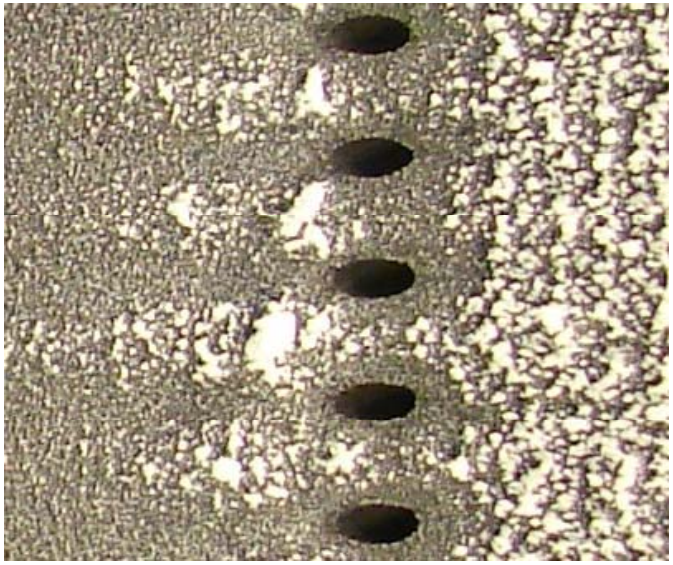
$M_{PS}$ = 2.0, $M_{Shd}$ = 2.0



**Adiabatic model**

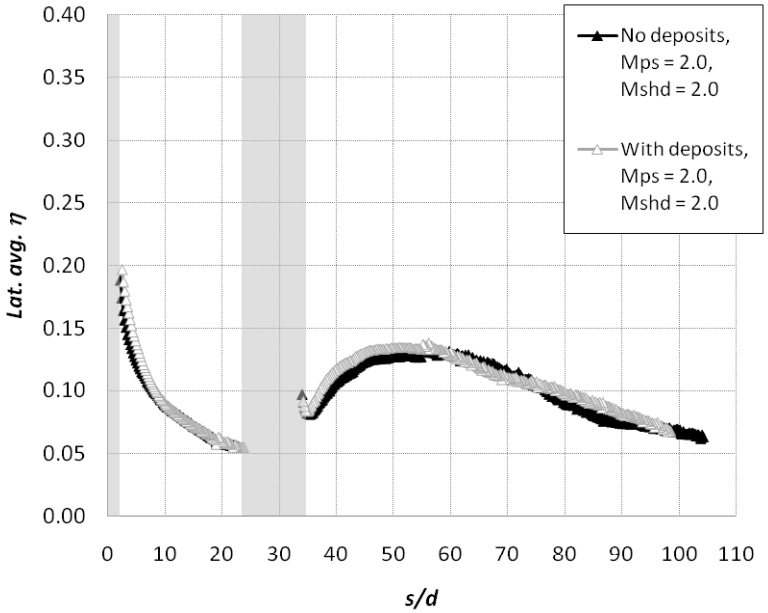
Baseline PS film cooling

$M_{PS}$ = 2.0, $M_{Shd}$ = 2.0

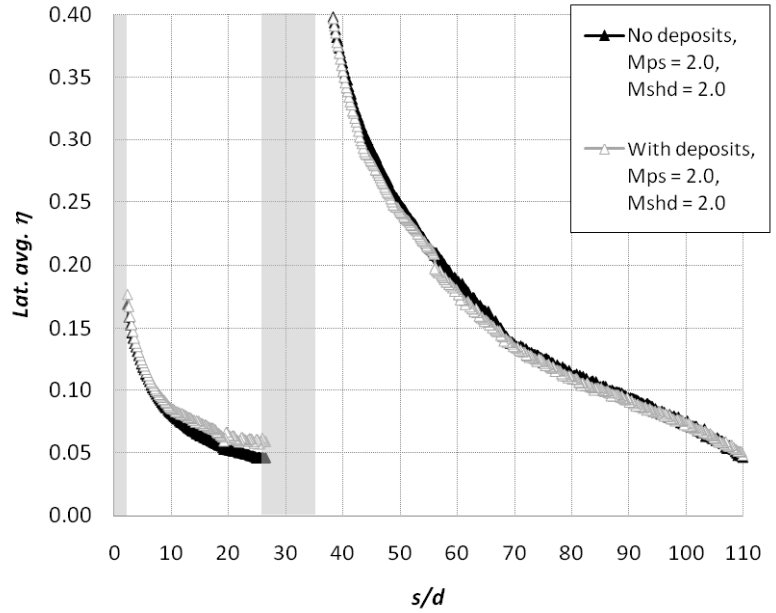


# Effect of simulated depositions on PS film effectiveness

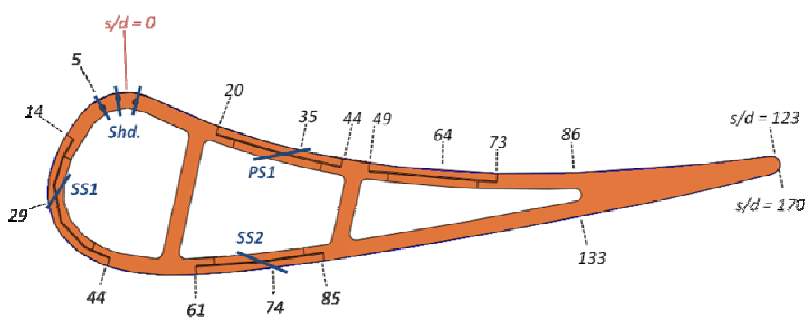
**Baseline** PS holes + showerhead




**Trenched** PS holes + showerhead




- **The deposit roughness has a minor effect on the film cooling performance.**
- **The strong trip caused by showerhead likely overwhelms the surface roughness.**



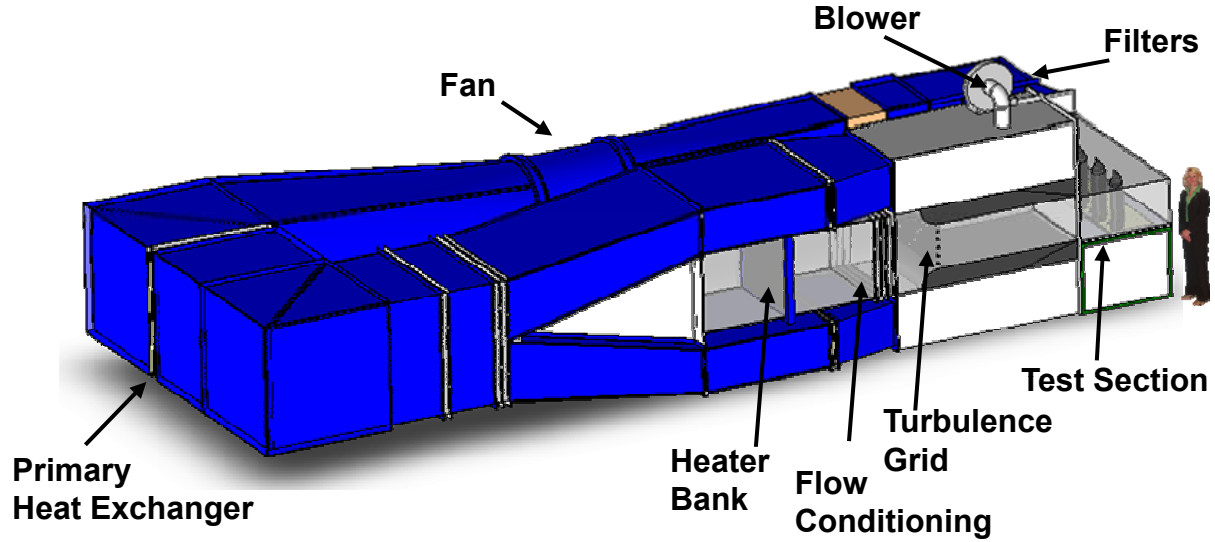

Other conditions

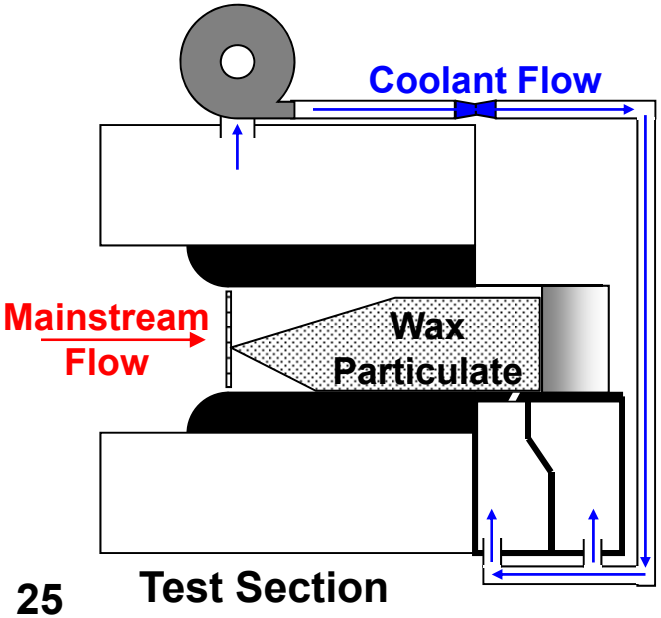
*DR* = 1.4

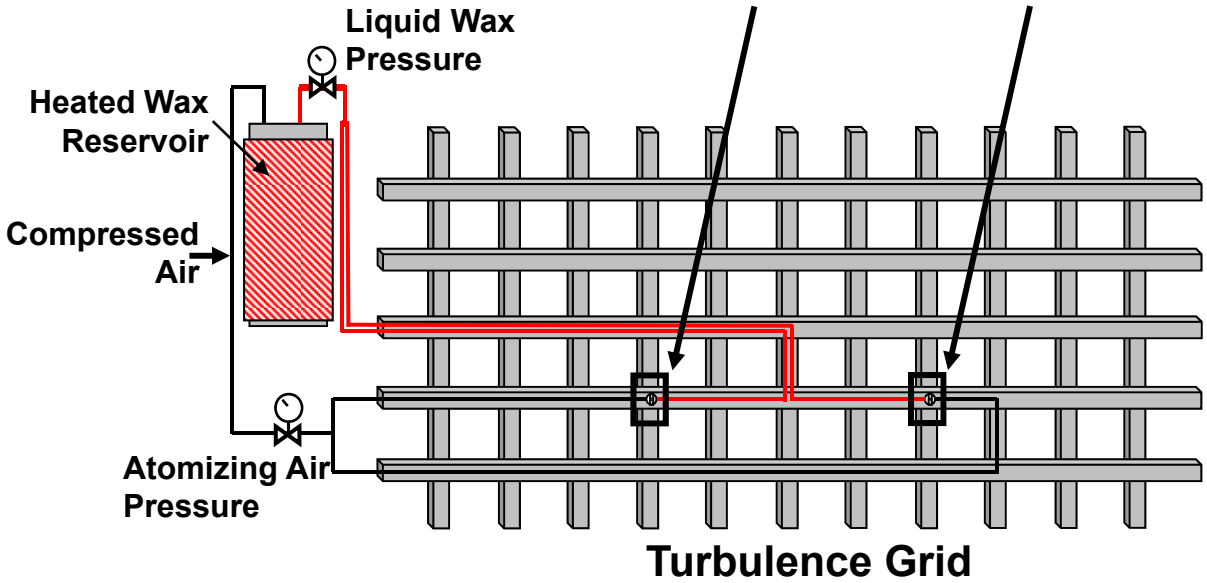
*Tu* = 20%

# Summary of research at Pennsylvania State University

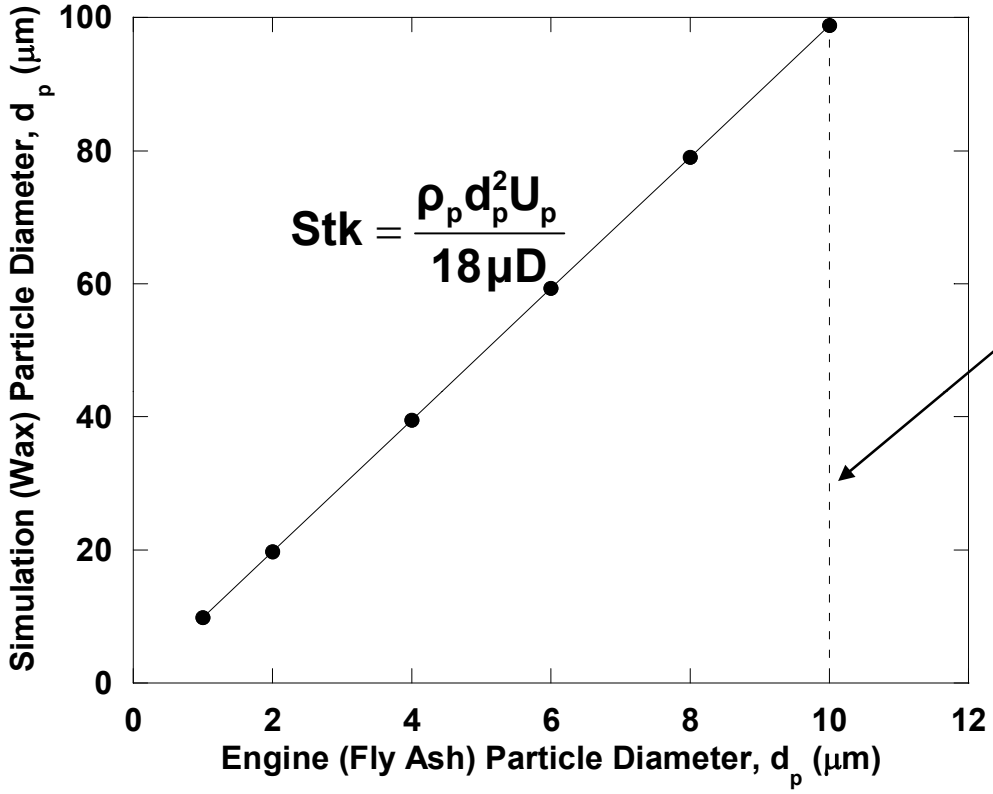
# Experiments at PSU were conducted in a large scale closed loop wind tunnel





# A Stokes analysis was performed to determine the wax particle size needed to simulate engine particles



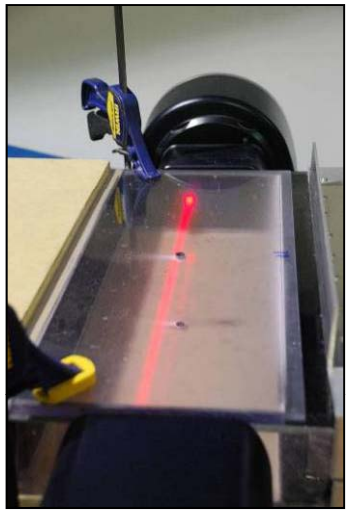

**Fly ash maximum particle diameter**

**[Bons et al., 2007]**

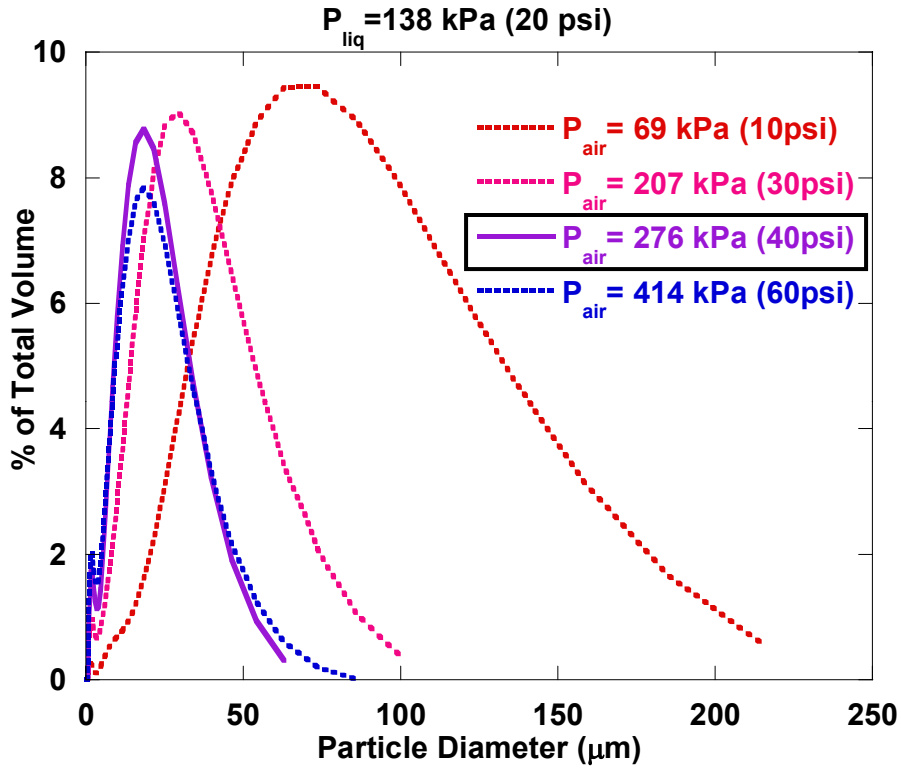
| | Engine (Fly Ash) | Laboratory (Wax) |
|---|---|---|
| Particle Diameter, $d_p$ (μm) | 0.1 - 10 | 1 - 100 |
| Particle Density, $\rho_p$ (kg/m$^3$) | 1980 | 800 |
| Gas Viscosity, μ (kg/m-s) | 5.55 x 10-5 | 1.82 x 10-5 |
| Particle Velocity (Mainstream Velocity), $U_\infty$ (m/s) | 93 | 6.3 |
| Film Cooling Hole Diameter, D (mm) | 0.5 | 4.6 |
| Stokes number, Stk | 0.004 - 40 | 0.004 - 40 |

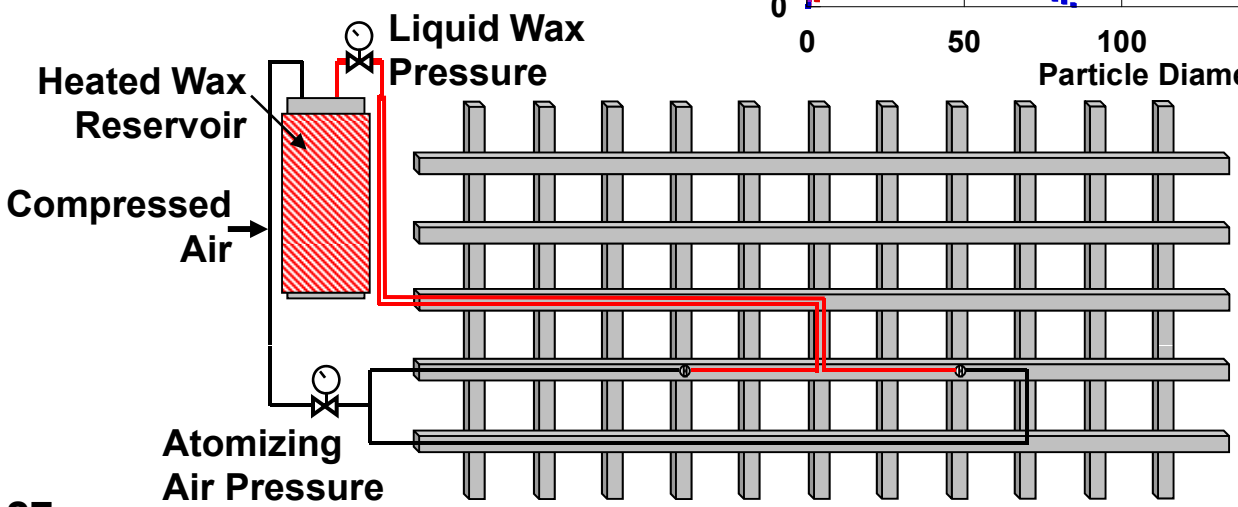
[Bons et al. 2007, Dennis et al. 2007, Johnson 2006]

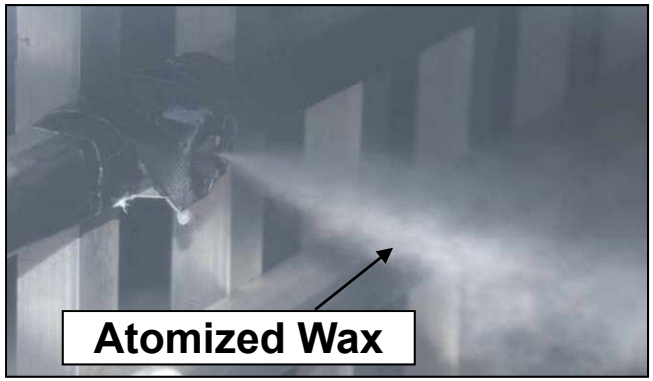
# A Malvern particle analyzer was used to measure particle sizes at various atomizing air pressures



Malvern Particle Analyzer
PSU MNE Gas Dynamics Lab
http://www.mne.psu.edu/psgdl/



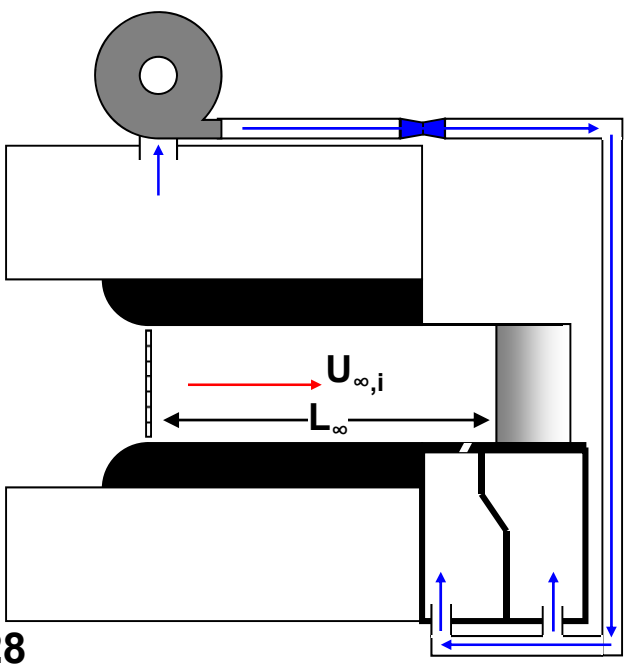
# A thermal scaling parameter was developed to scale the particle phase upon reaching the test section

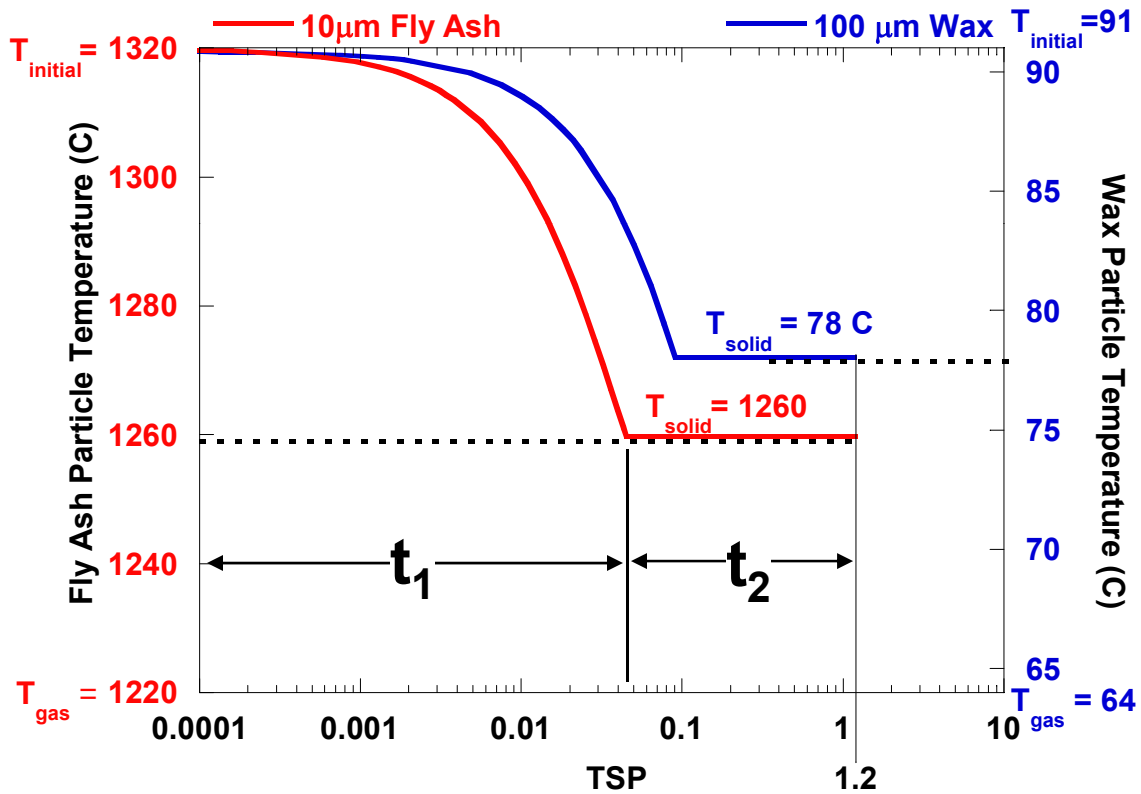
$$T_p = \left(T_{p,i} - T_\infty\right) e^{\left(\frac{-hA_p}{\rho_p C_p V_p} t\right)} + T_\infty$$

$$t_1 = -\frac{\rho_p C_p V_p}{hA_p} \ln\left[\frac{T_{p,s} - T_\infty}{T_{p,i} - T_\infty}\right] \quad t_2 = \frac{\Delta H_{fus}}{hA_p\left(T_{p,s} - T_\infty\right)}$$

**Thermal Scaling Parameter (TSP)**

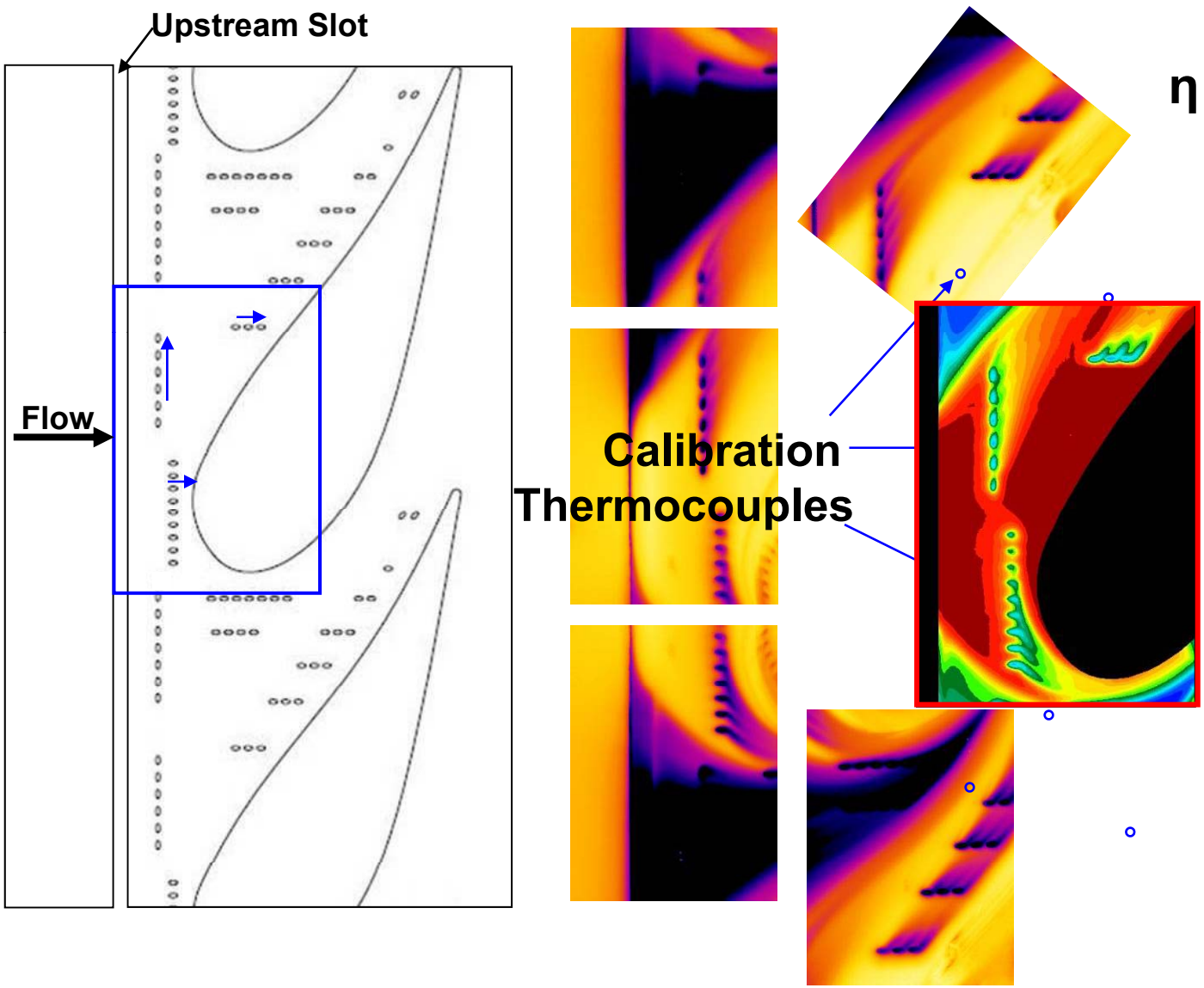
$$TSP = \frac{t_1 + t_2}{L_\infty / U_{\infty,i}}$$



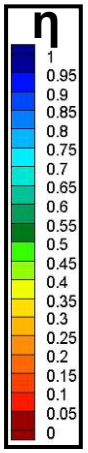




**TSP < 1 Solid (S)**
**TSP > 1 Molten (M)**

# A spatially resolved IR thermography method was used to measure endwall adiabatic effectiveness

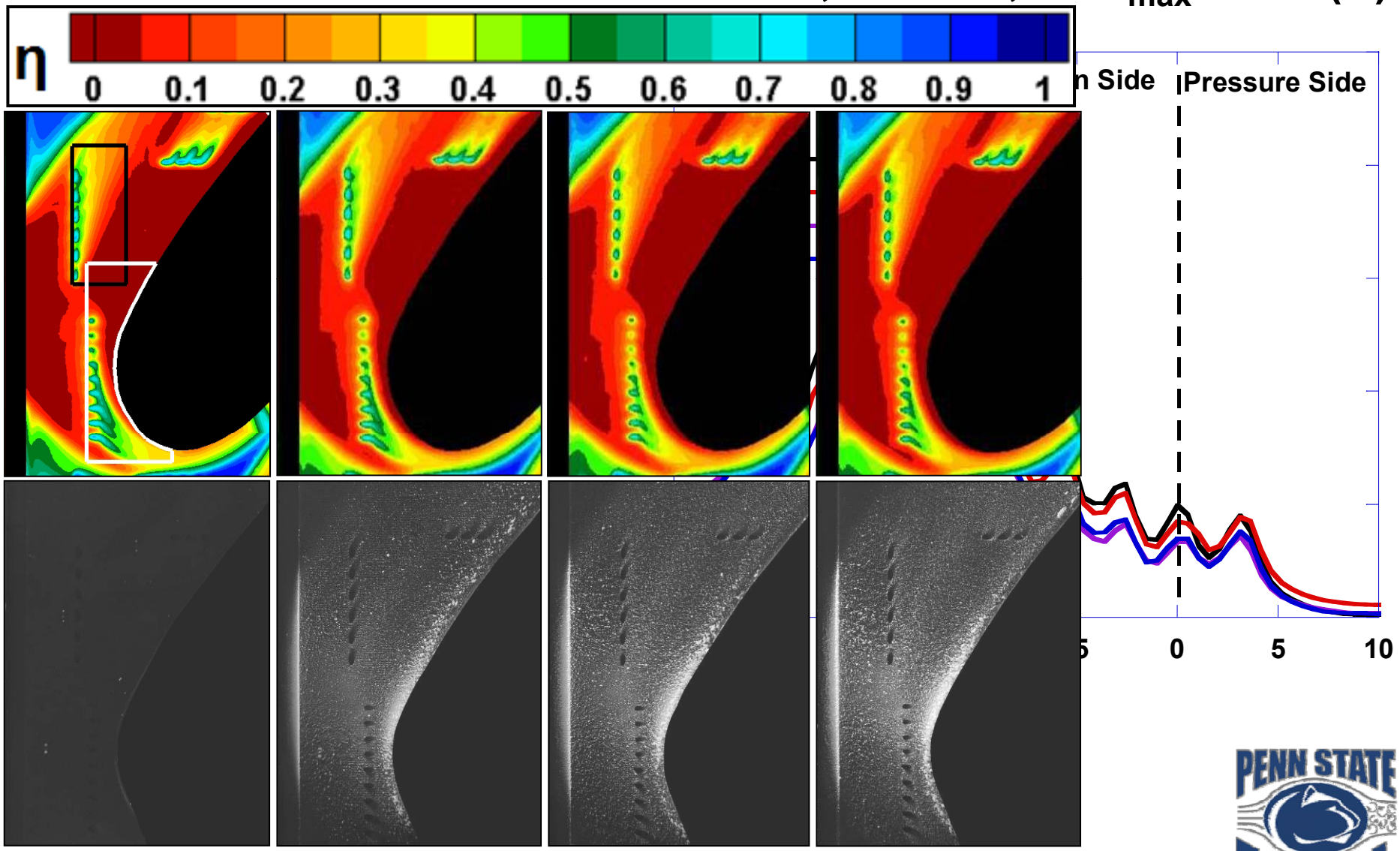



$$\eta = \frac{T_\infty - T_{aw}}{T_\infty - T_j}$$



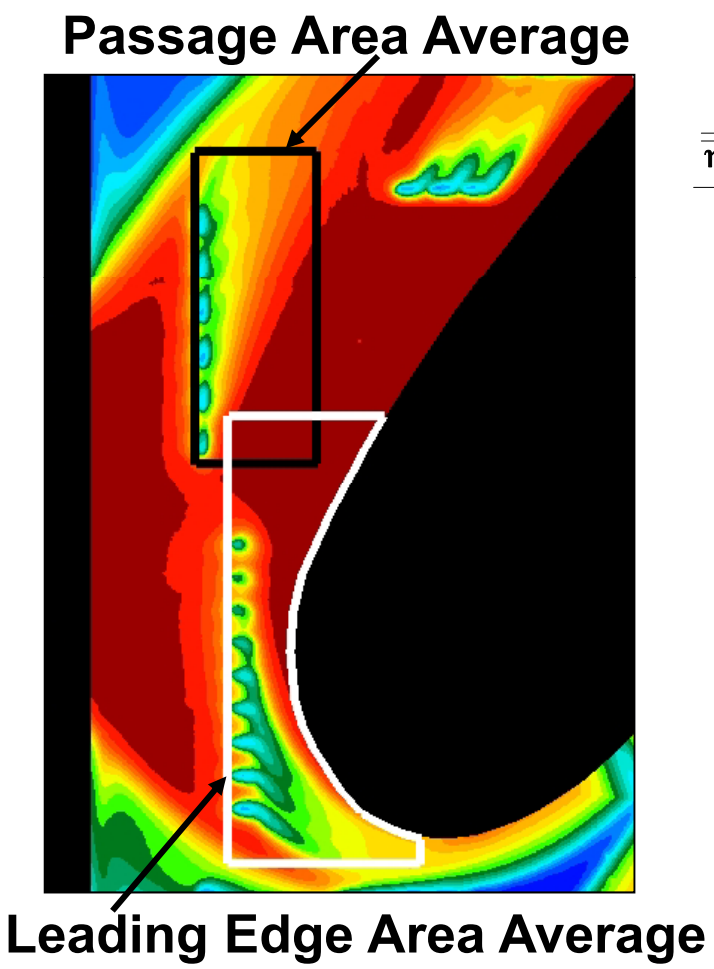
# Effectiveness reached an equilibrium state after 900g of wax injection

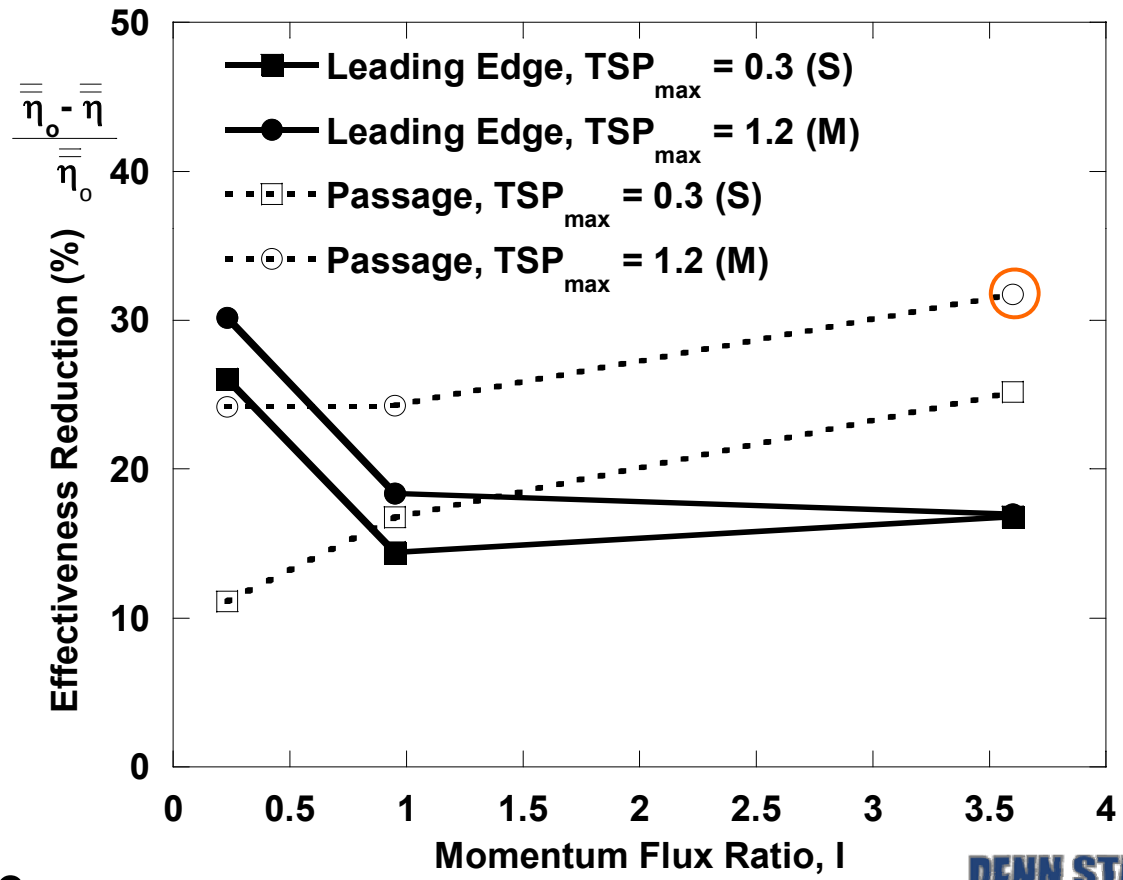
$I = 0.23$, $M = 0.5$, $TSP_{max} = 0.3$ (S)



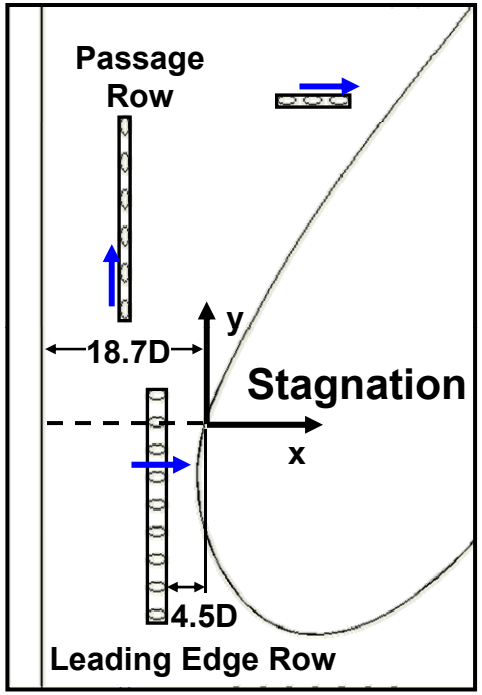

Baseline 300g 600g 900g

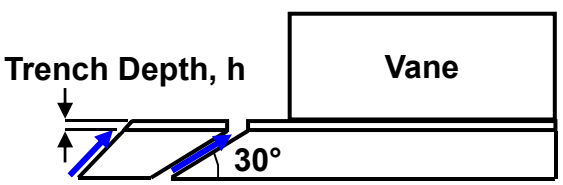
# Effectiveness reduction was as high as 30% for passage cooling holes at I = 3.6 and $TSP_{max}$ = 1.2

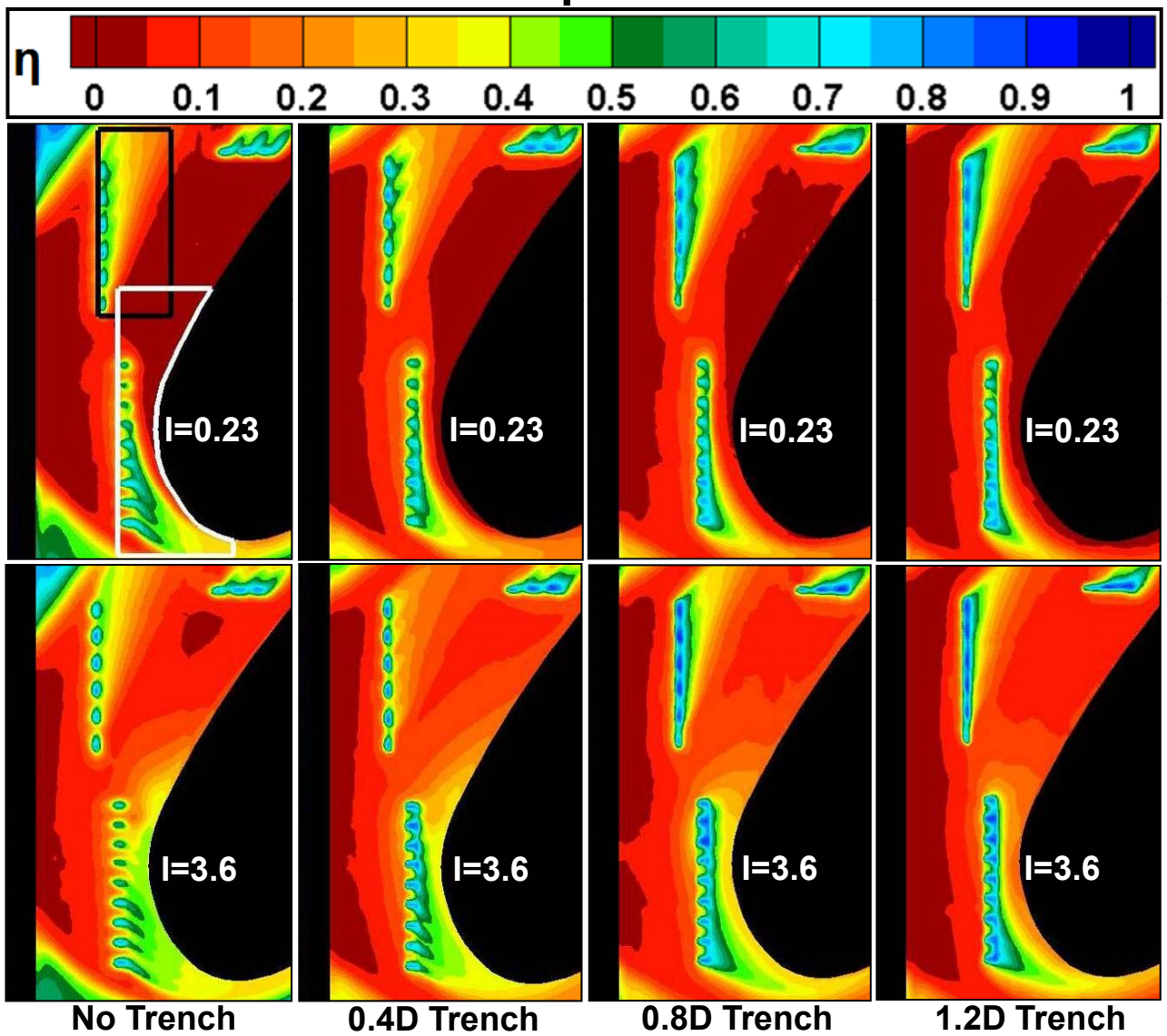


# Endwall cooling rows were embedded in transverse trenches with depths of 0.4D, 0.8D, and 1.2D

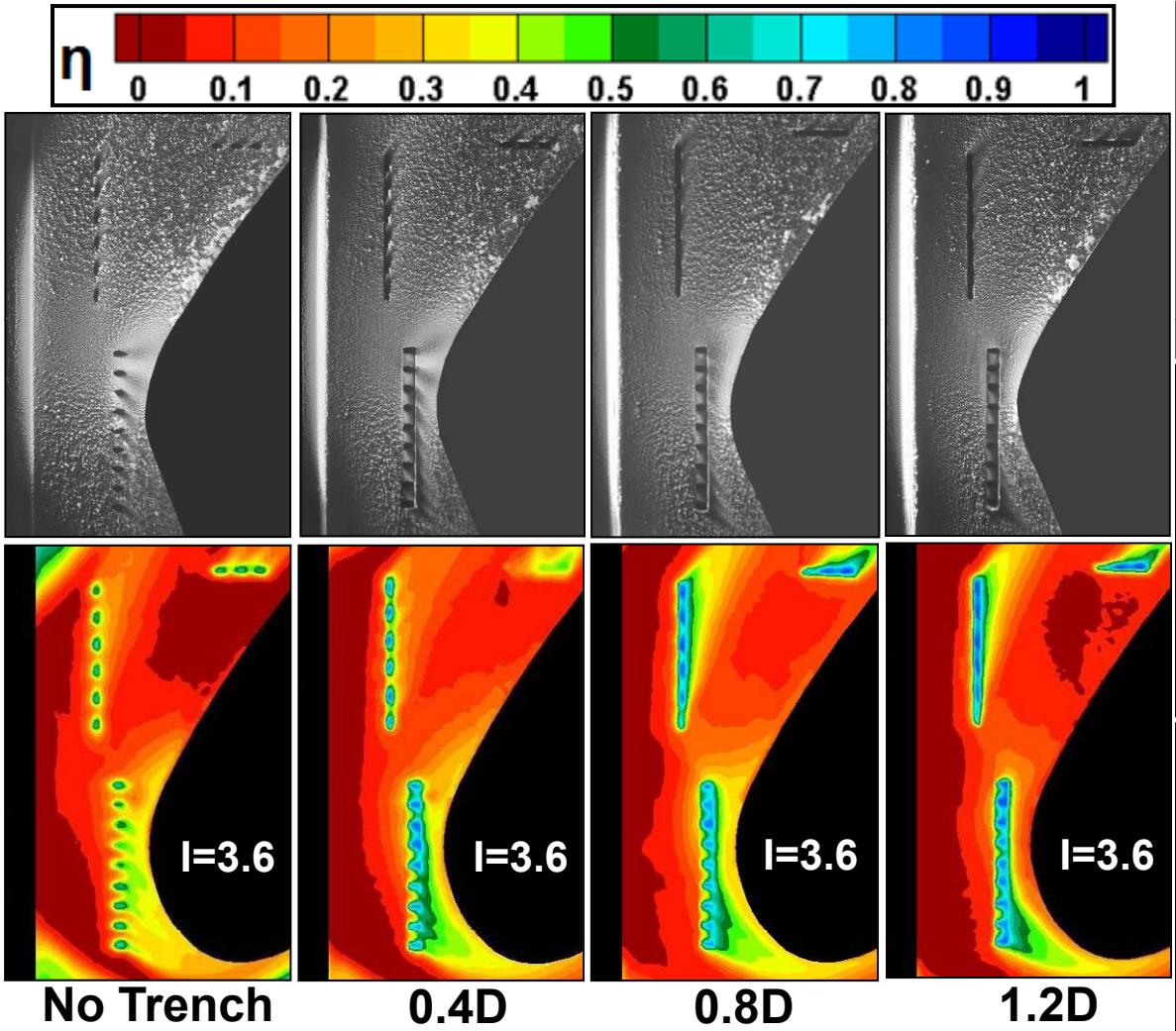


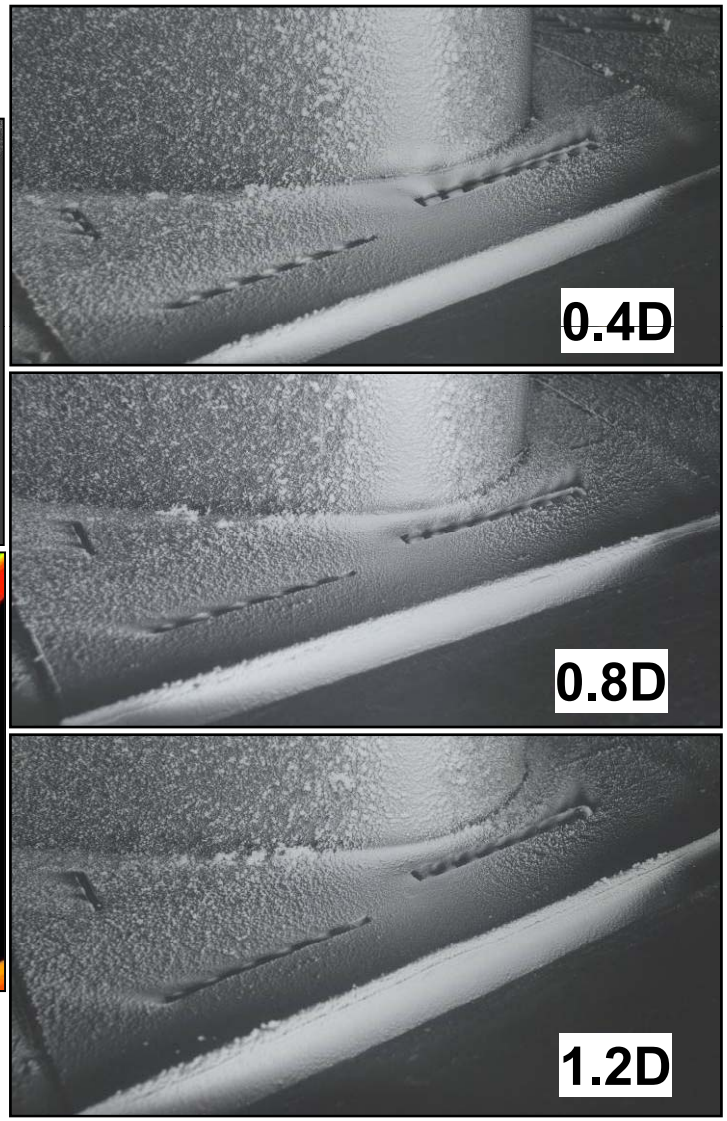



# Deposition patterns were sensitive to trench depth having a strong correlation with coolant patterns

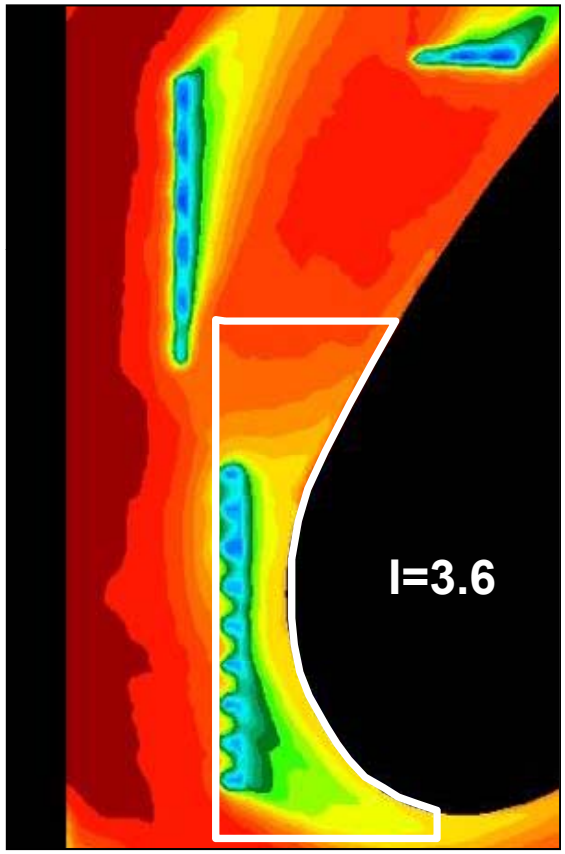
$TSP_{max}$ = 1.2 (m)



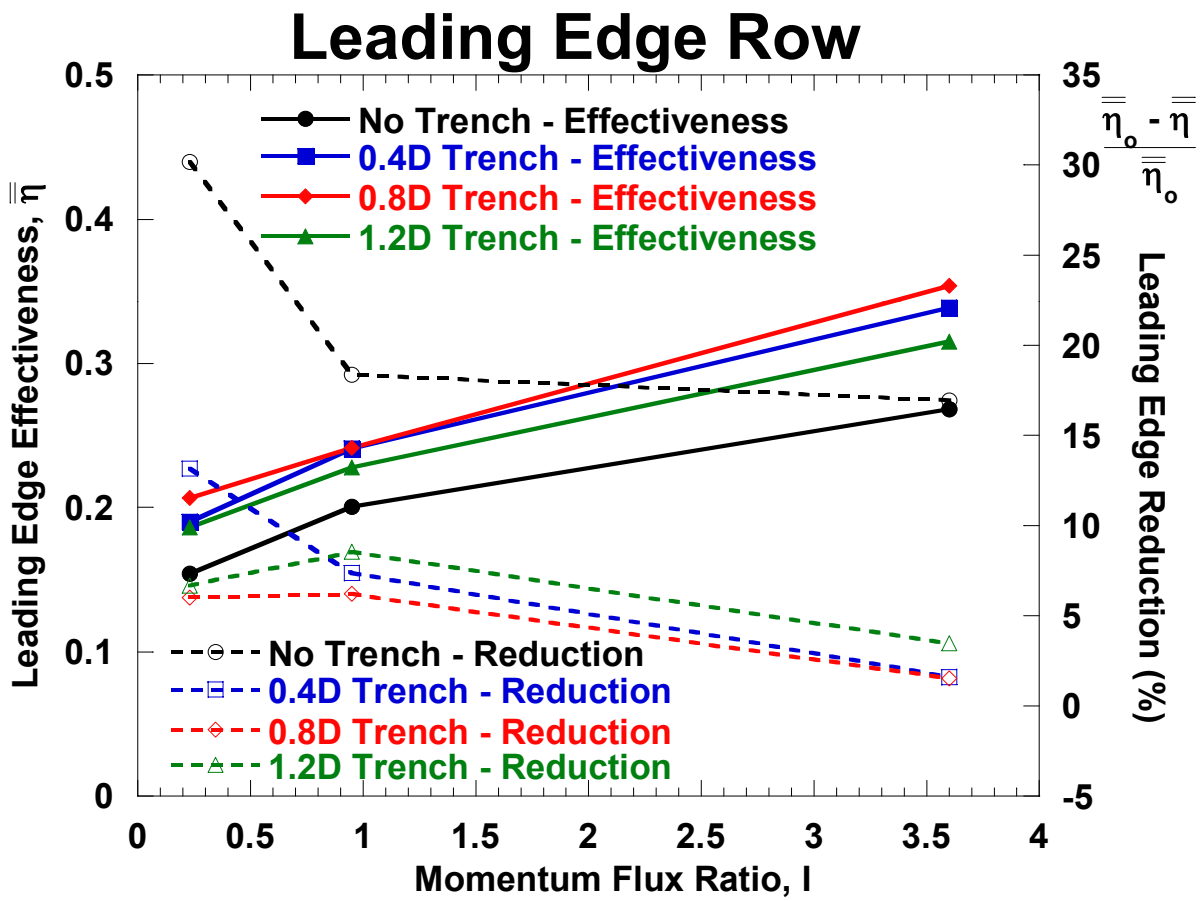

I = 3.6



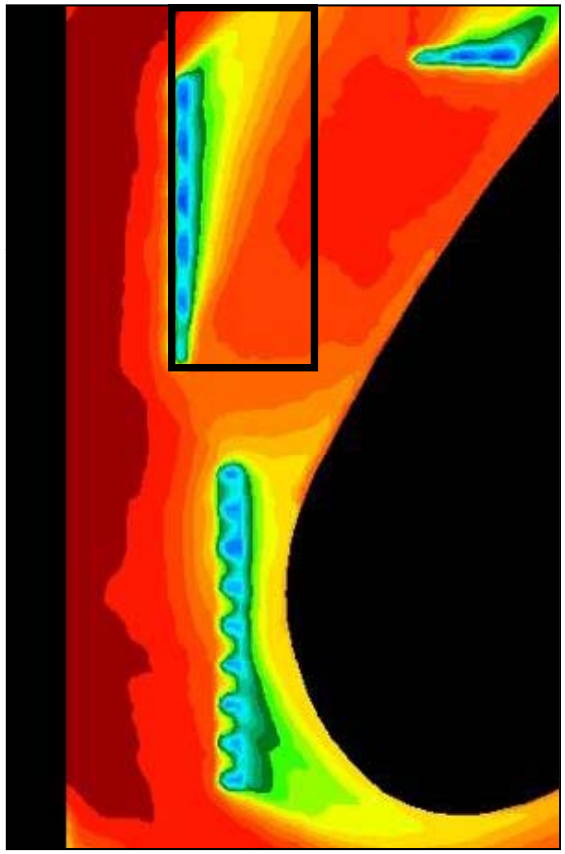
# All three trench depths reduced the negative impact of deposition on leading edge cooling effectiveness

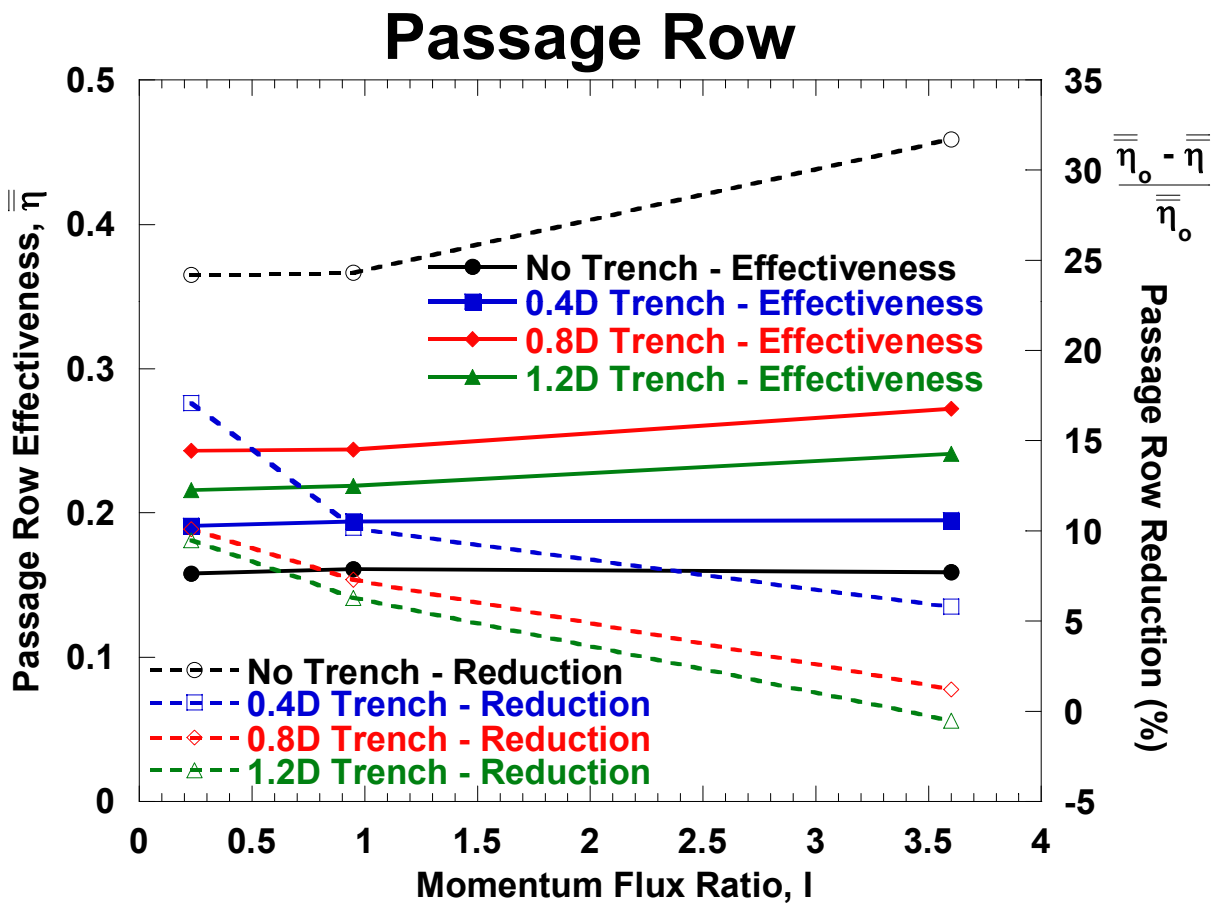



0.8D Trench



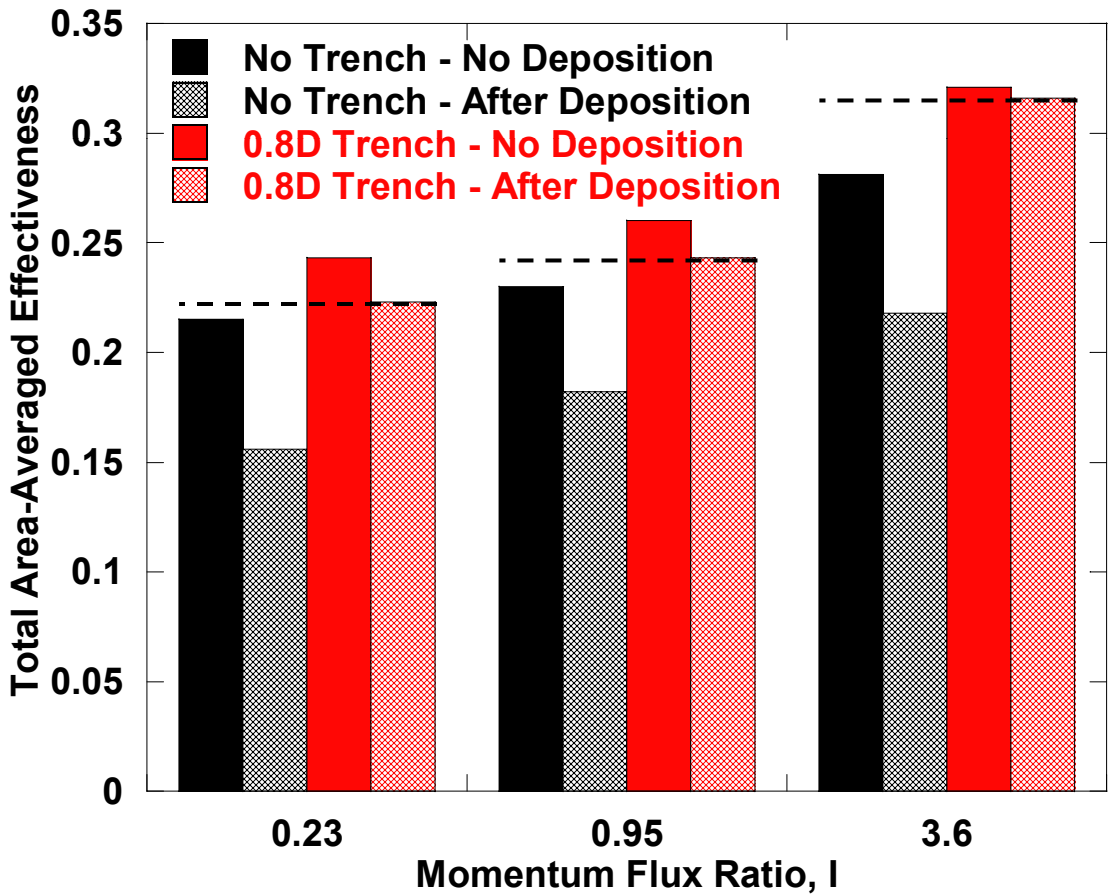
# Passage row effectiveness was maximized when the 0.8D trench was employed





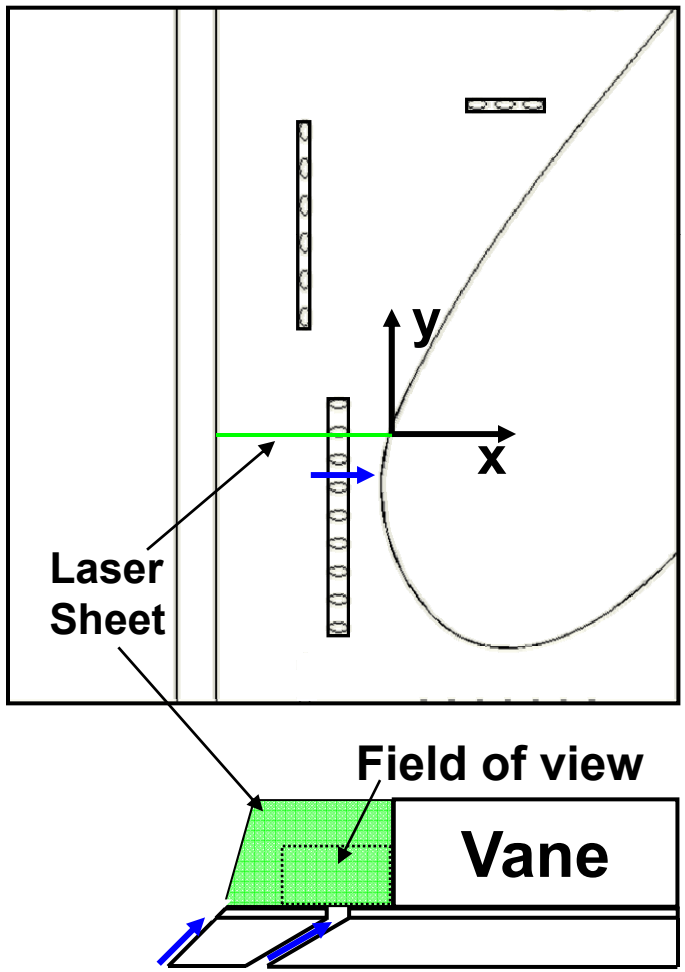
# Even with deposition, the 0.8D trench performed better than the baseline with no deposition

$$\bar{\bar{\eta}}_{total} = \frac{A_{passage}\bar{\bar{\eta}}_{passage} + A_{LE}\bar{\bar{\eta}}_{LE}}{A_{passage} + A_{LE}}$$

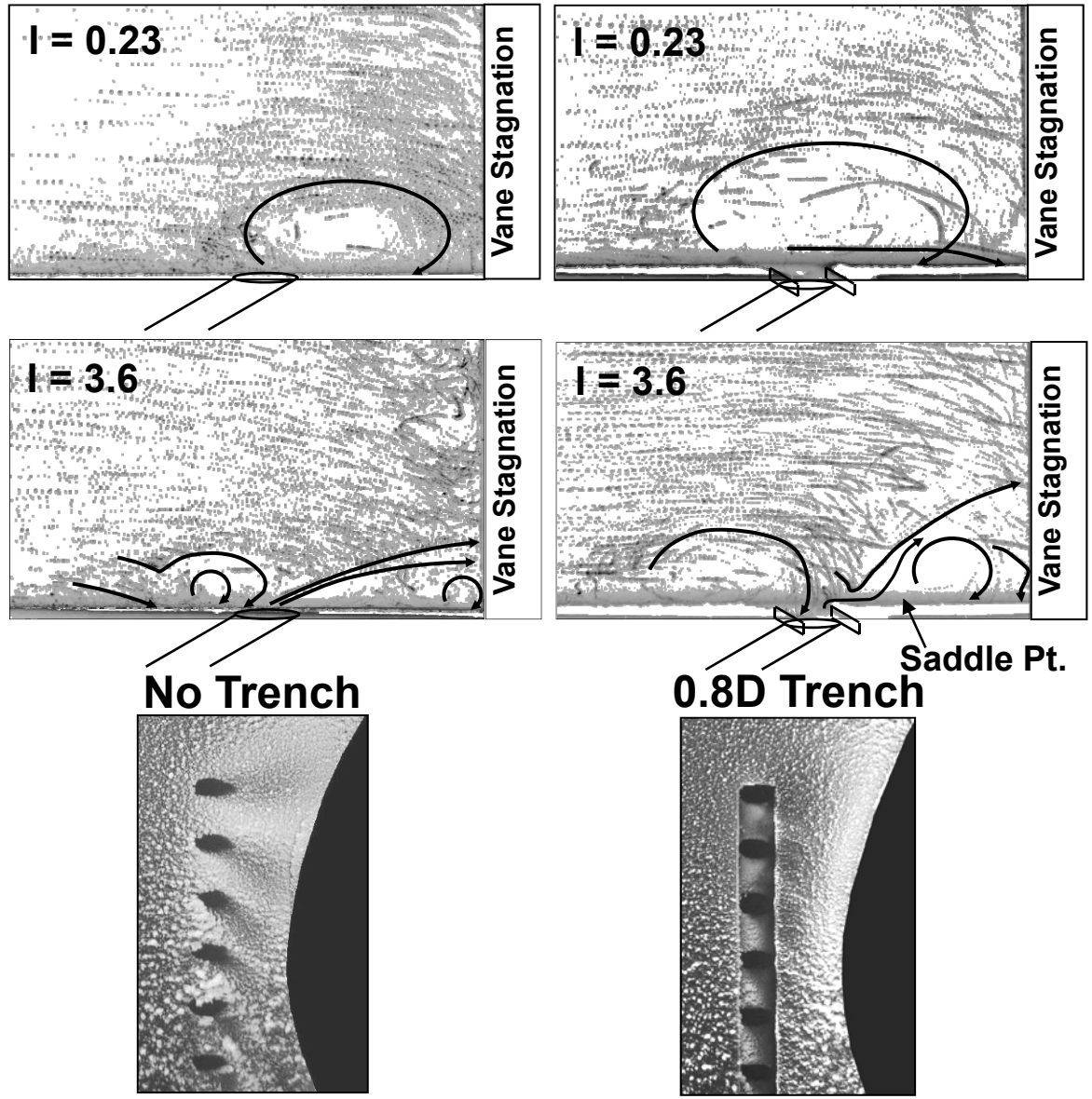


# Flow visualization was performed with a high speed camera and Nd:YLF pulsed laser

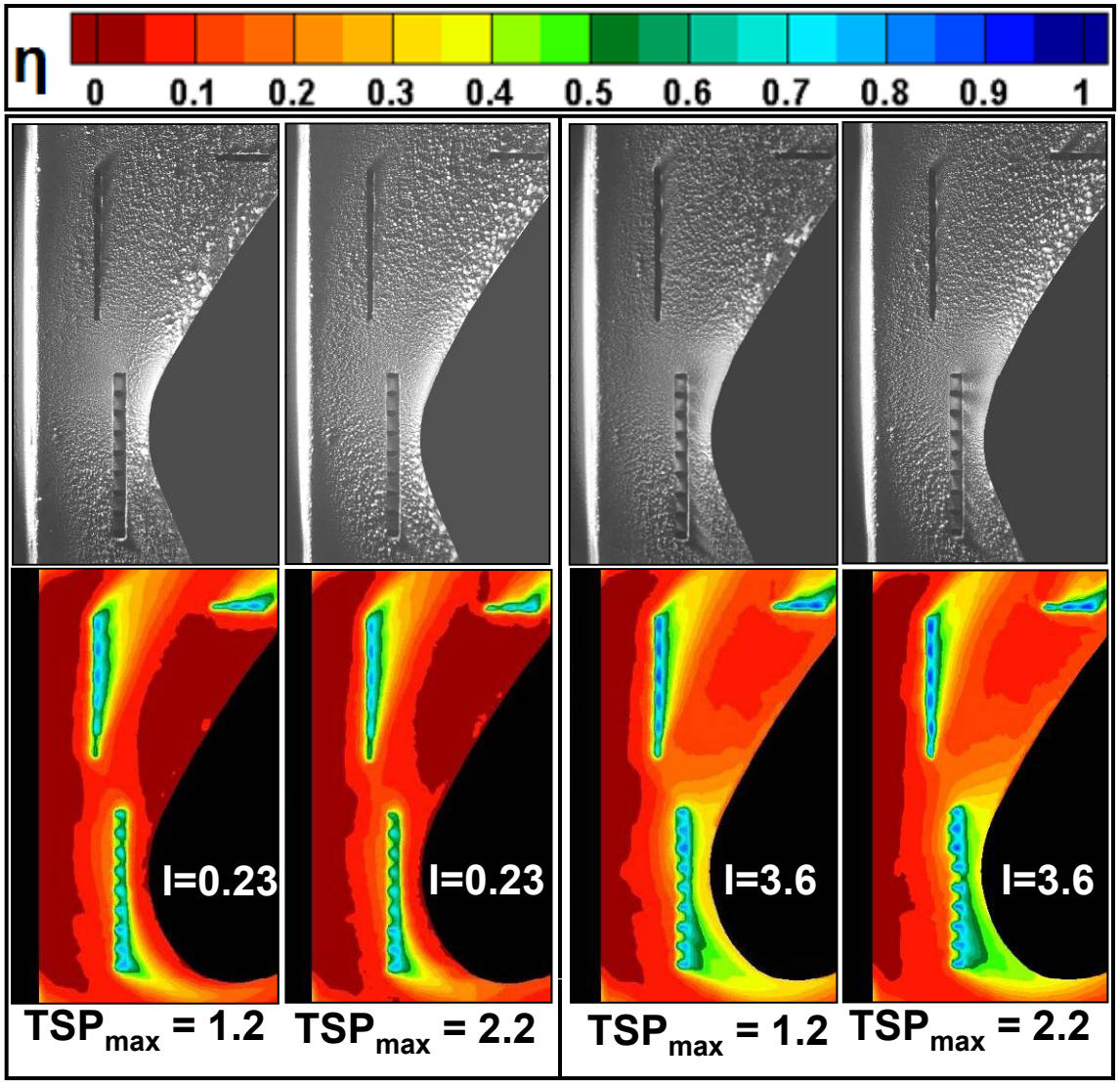
Laser Frequency ~ 6kHz
Camera Speed = 2 kHz

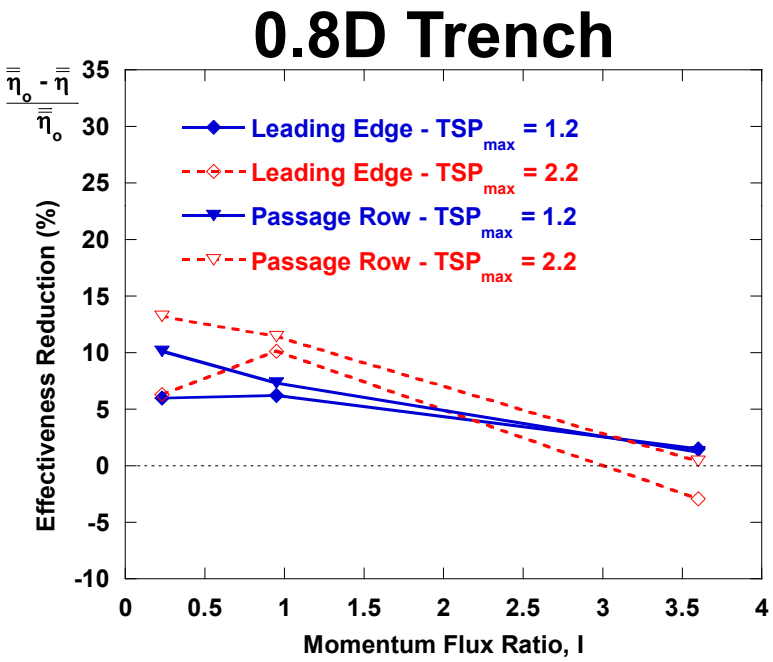



Composite images ~ 20 Frames (0.01s)

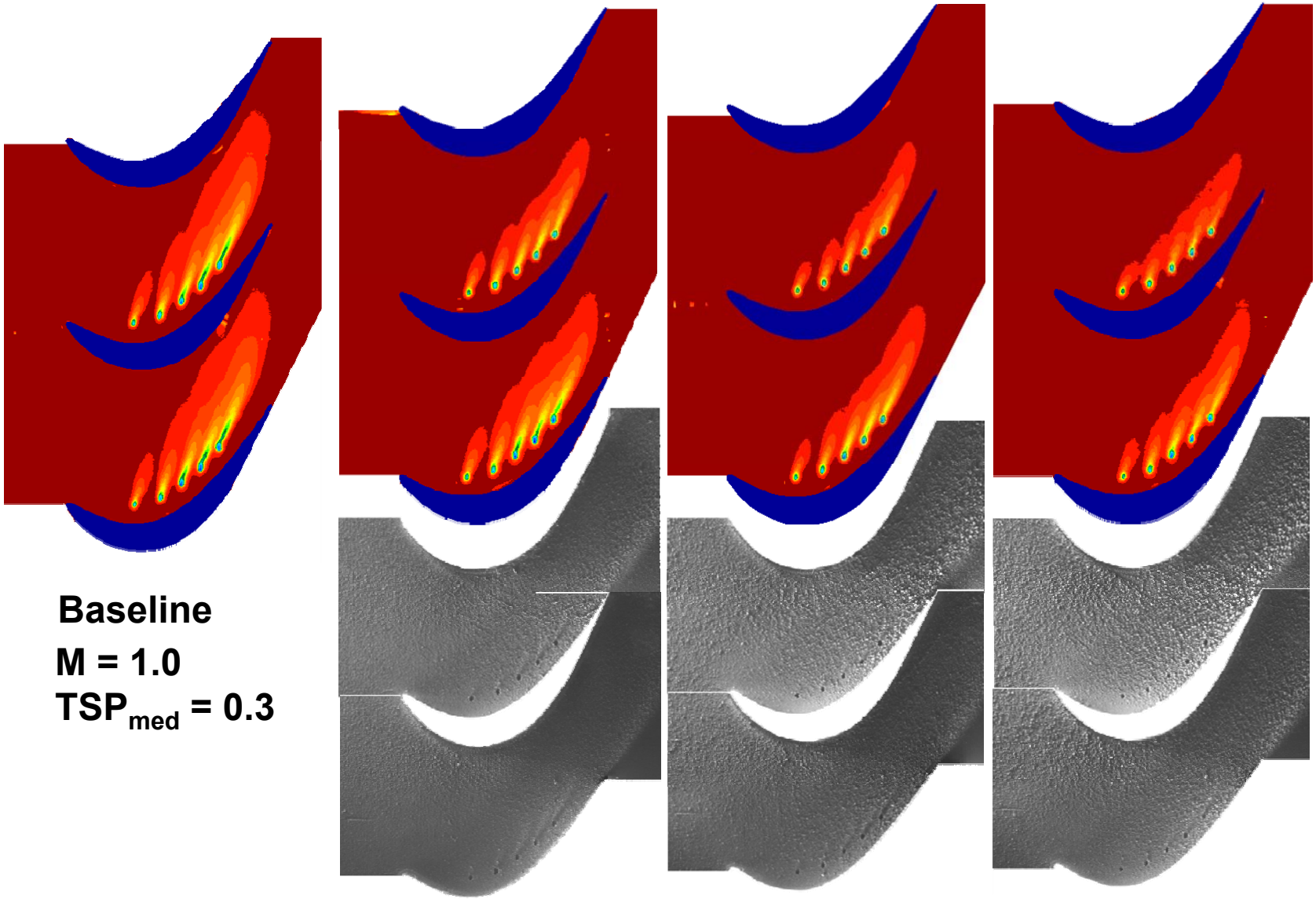


# Deposition tests at TSP = 1.2 and 2.2 showed that TSP had a small effect on cooling effectiveness



# The effects of deposition on film-cooling with and without contours is currently being explored



Baseline

M = 1.0

$TSP_{med}$ = 0.3

300g

600g

900g

# Conclusions

*UT vane study:*

- **Trenched holes had better film performance ($\eta$ and $\phi$) than baseline holes, except at low *M* and far downstream of the holes.**

- **Deposition was strongly influenced by surface temperature and film cooling design. The trenched holes were fairly insensitive to deposits.**

*PSU endwall study:*

- **Deposition can decrease endwall cooling effectiveness by up to 30% depending on endwall location and cooling operating conditions.**

- **Placing endwall cooling rows in a transverse trench mitigates the negative effects of deposition on film-cooling.**