EFFECTS OF HOT STREAK AND PHANTOM COOLING ON HEAT TRANSFER IN A COOLED TURBINE STAGE INCLUDING PARTICULATE DEPOSITION

THE OHIO STATE UNIVERSITY

Robin Prenter, Daniel Zagnoli, Steven Whitaker,
Ali Ameri, Jeffrey Bons

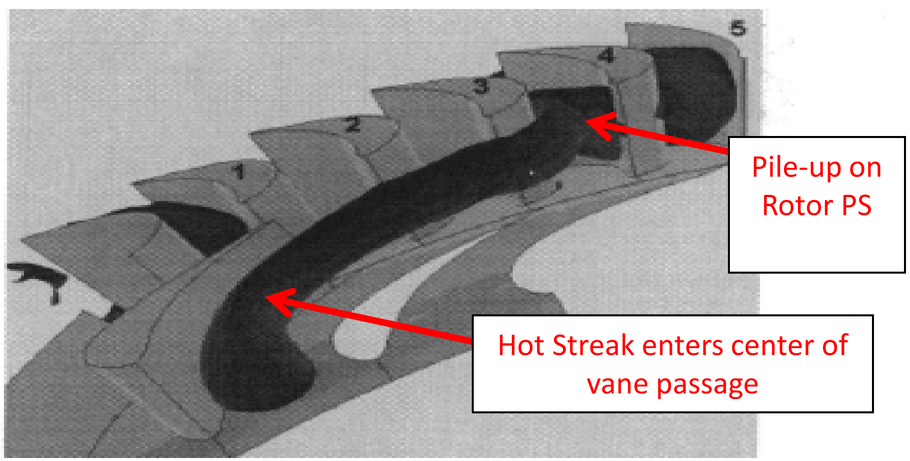
2014 UTSR Workshop – 21 Oct. 2014

MOTIVATION

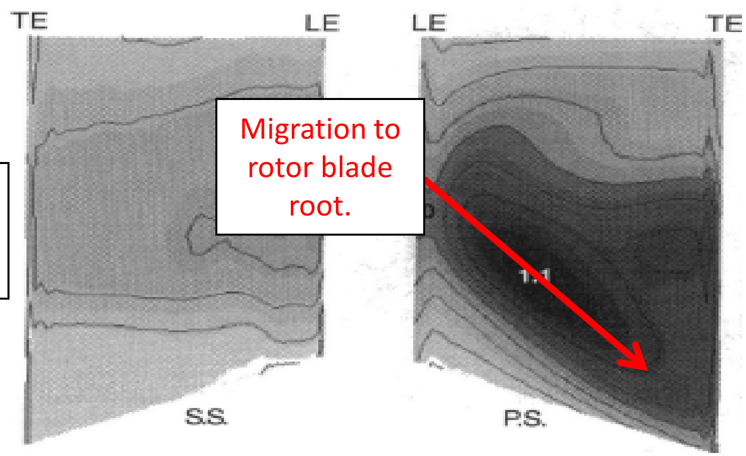
• Future gas turbines operating with HHC fuels will have higher turbine inlet temperatures relative to natural gas operation.

• Increased temperatures require better materials and more efficient cooling schemes. Increased cooling is unacceptable, so coolant must be used smarter and more sparingly.

• Requires better prediction of combustor exit temperature distribution (pattern factor) and migration of high temperature core (hot streak) through high pressure turbine.



Prediction of hot streak migration in uncooled turbine stage using <u>inviscid</u>, <u>unsteady</u> simulation. (Shang & Epstein, JTurbo 1997)



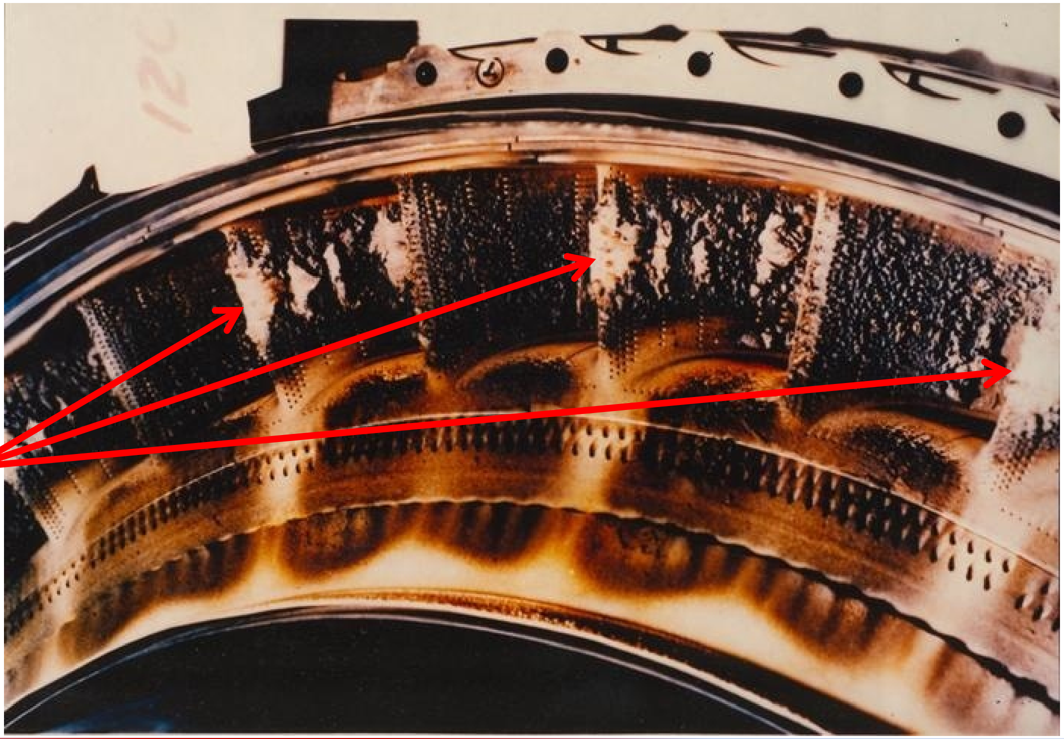
Time averaged surface temperature on rotor suction (left) and pressure (right) surfaces.

MOTIVATION

•HHC fuels may contain airborne ash particulate that then deposits in the turbine – degrading performance. Hot streaks will result in preferential deposition. Predictive tools for modeling the combined effect of hot streaks and deposition are necessary for risk assessment and mitigation.

First stage nozzle volcanic ash deposition from RB211 following Mt Gallungung eruption, 24 June 1982 (Chambers)

Elevated ash deposition aligned with fuel nozzle locations - evident every other NGV



CRITICAL NEED

Additional research is NEEDED to…

- **model hot streak migration in a modern, cooled first stage turbine**
- **model effect of hot streak on coolant flow (phantom cooling)**
- **model deposition in HHC, elevated temperature environment**
- **validate models with steady (stator) and unsteady (rotor) experimental data**

OBJECTIVES

• The objective of this work is to develop a validated modeling capability to characterize the effect of hot streaks on the heat load of a modern gas turbine.
• As a secondary objective the model will also be able to predict deposition locations and rates.

This will be accomplished for a cooled turbine stage (stator and rotor)
AND
will be validated with experimental data from facilities at OSU.

The effort includes both experimental and computational components, with work divided into three phases of increasing complexity:

1) Uncooled Vane
2) Cooled Vane
3) Cooled Vane + Rotor

RESEARCH TEAM

TEAM LEAD
Focus: Experimental Heat Transfer and Deposition Measurements in OSU Hot Cascade Facility

Dr. Jeffrey Bons
Professor
Department of Mechanical and Aerospace Engineering
Ohio State University
Columbus, OH

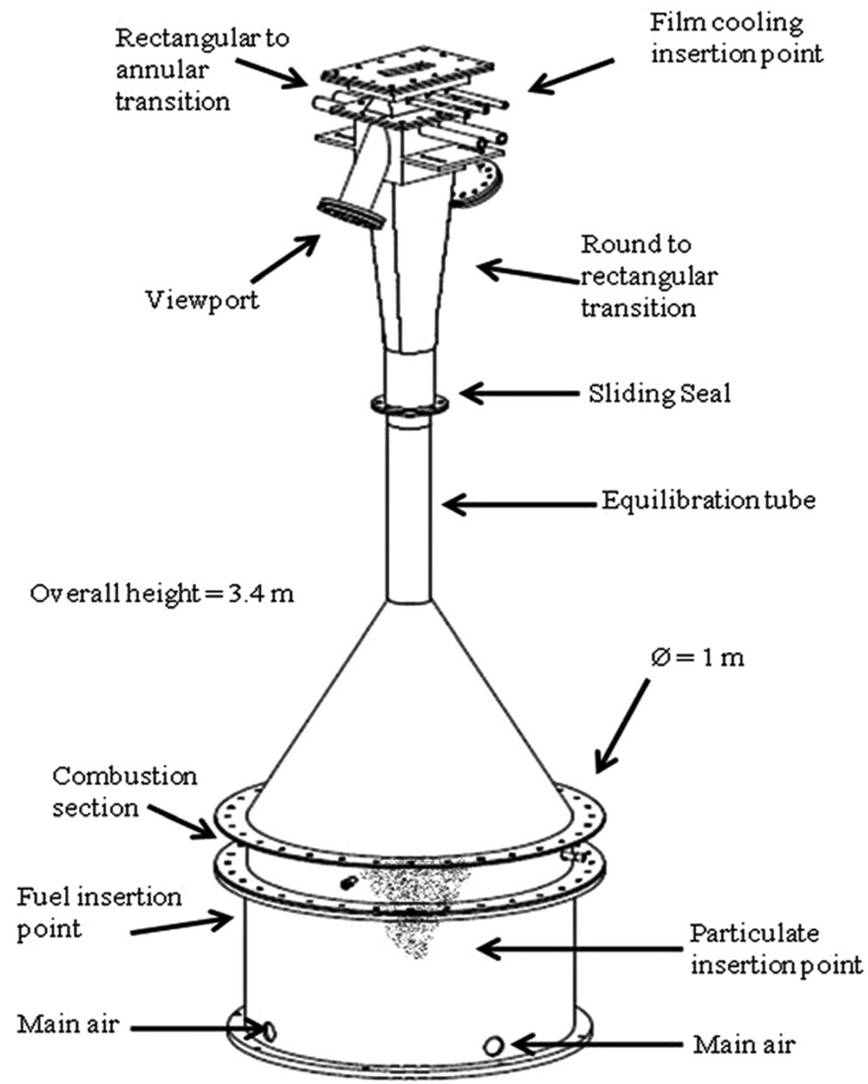
Co-PI
Focus: Deposition Model Development and Heat Transfer CFD

Dr. Ali Ameri
Research Scientist
Department of Mechanical and Aerospace Engineering
Ohio State University
Columbus, OH

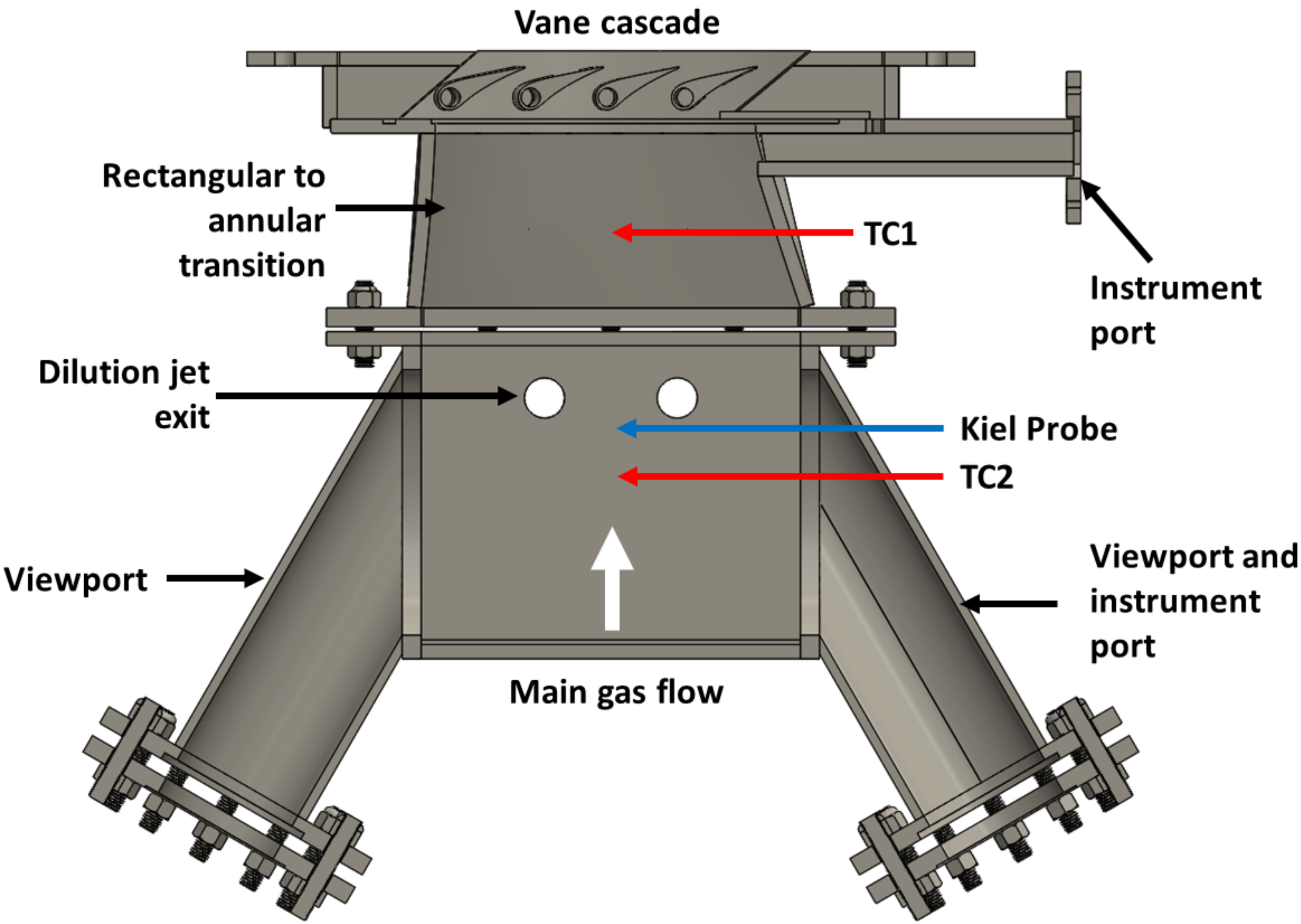
External Deposition on a Cooled Nozzle Guide Vane with Non-Uniform Inlet Temperatures

Experimental Facility - TuRFR

- Turbine Reacting Flow Rig – TuRFR
- Simulates hot section of gas turbine
    - Natural gas combustor
    - Max temperature ~ 1365 K
    - Inlet Mach ~ 0.1
- Ash injected in combustion chamber
- Vane housing enables integration of actual engine hardware
- Film cooling and hot streak capabilities

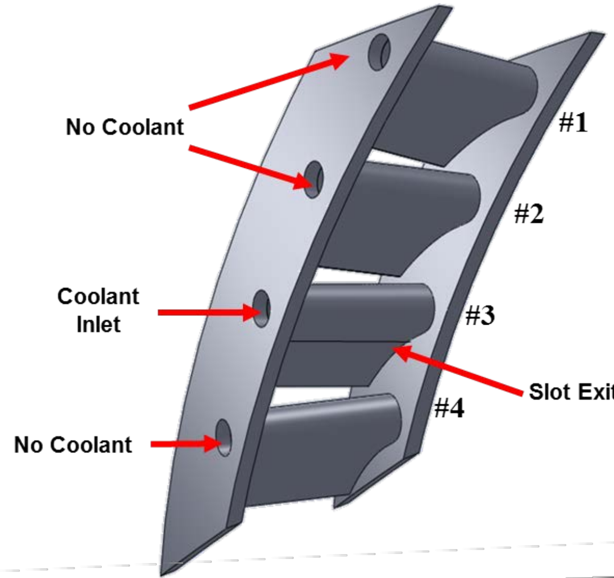


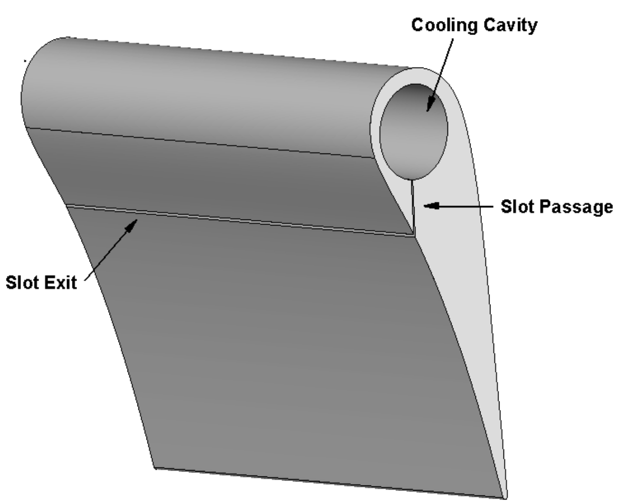
Experimental Facility – TuRFR Test Section

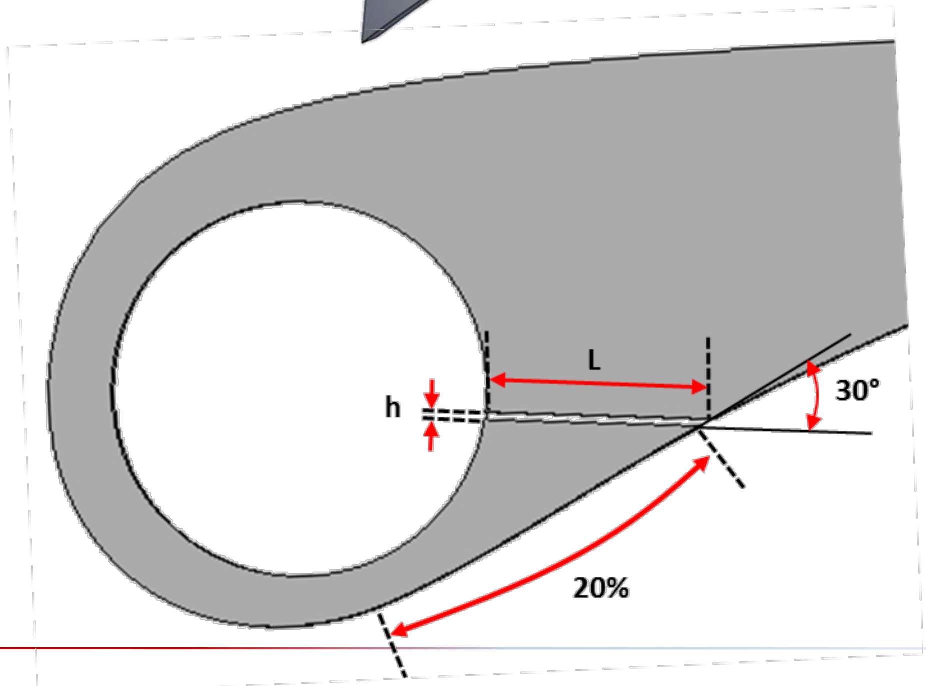


Experimental Test Piece

- Simple geometry
  - Rolls Royce 2D research profile
  - Extruded profile with flat endwalls
  - Four vanes, one cooled
- A single span-wise slot used as cooling scheme
  - Easy to model
  - Fundamental effects
  - Ease of manufacturing



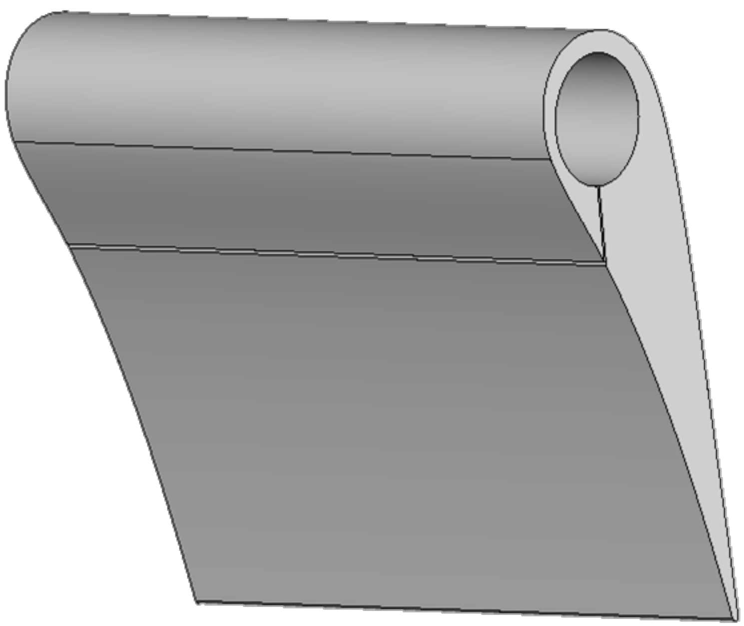




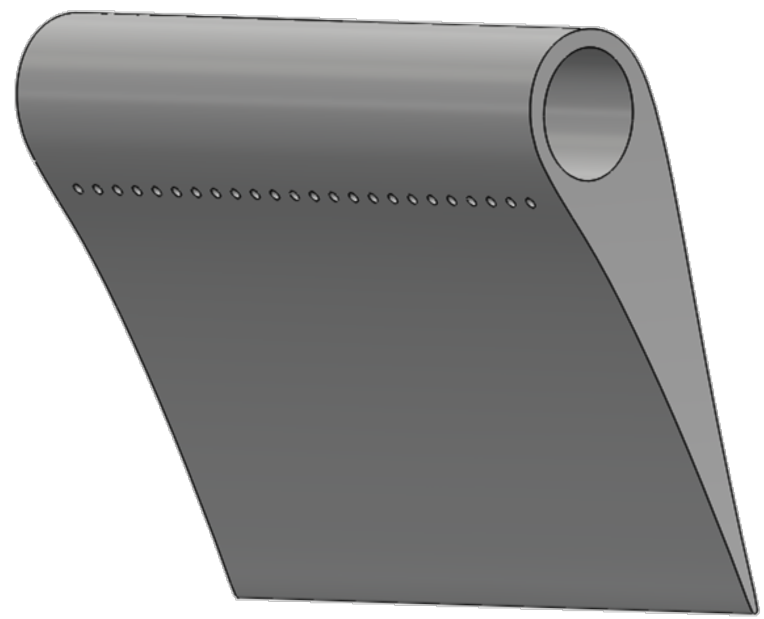
Experimental Facility - TuRFR

Exit area of slot

Exit area of a typical row of film cooling holes



$\approx$



Test Conditions

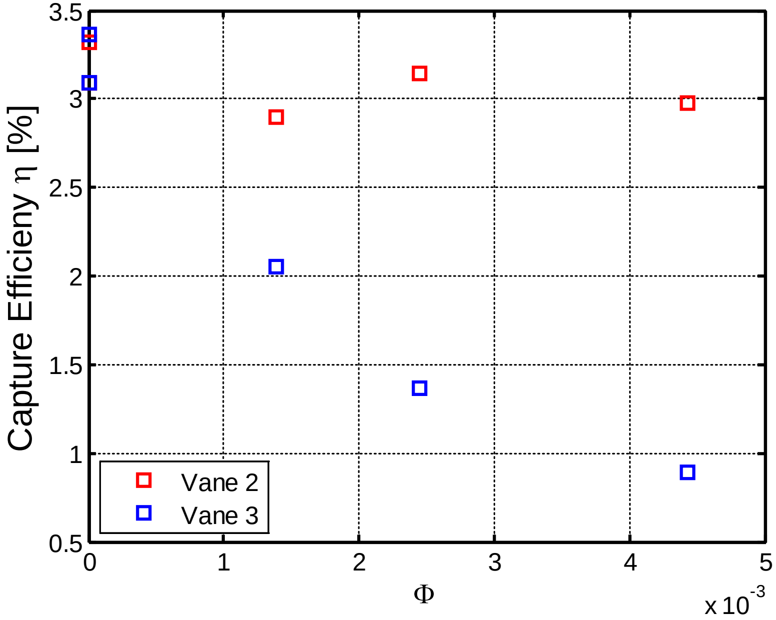
Test	Hot Streak	Film Cooling	$T_{upstream}$	M_{inlet}	$\dot{m}_{dil}/\dot{m}_{inlet}$
B	○	○	1340 K	~0.1	0
HS	●	○	1375 K	~0.1	7.2%
FC	○	●	1375 K	~0.1	0
HS+FC	●	●	1375 K	~0.1	7.2%

$\frac{\dot{m}_c}{\dot{m}_p}$[%]	$T_{c,i}$ [K]	Re_h	DR	M
0.62	926	200	1.54	1.35
0.88	834	296	1.74	1.88
1.27	705	453	2.13	2.78

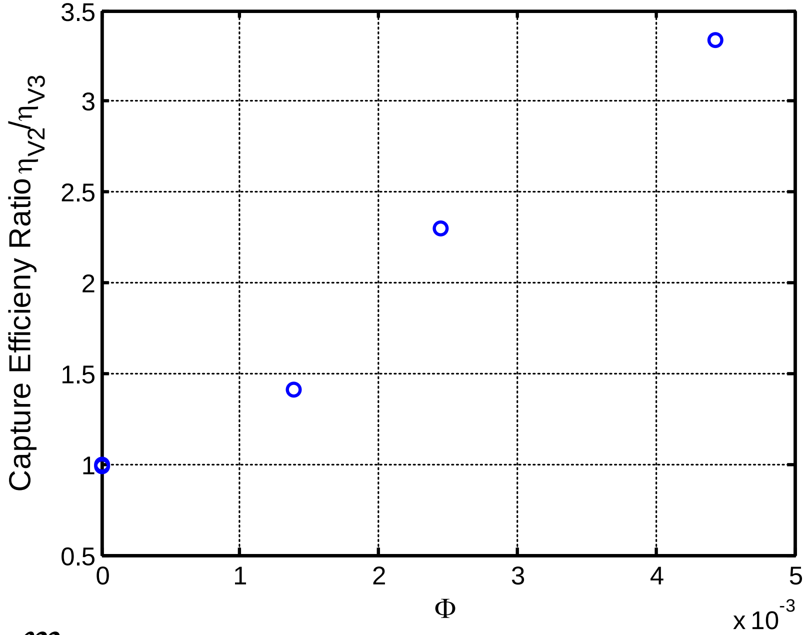
Film Cooling-Only Tests

Film Cooled-Only Tests

Capture Efficiencies



Capture Efficiency Ratios

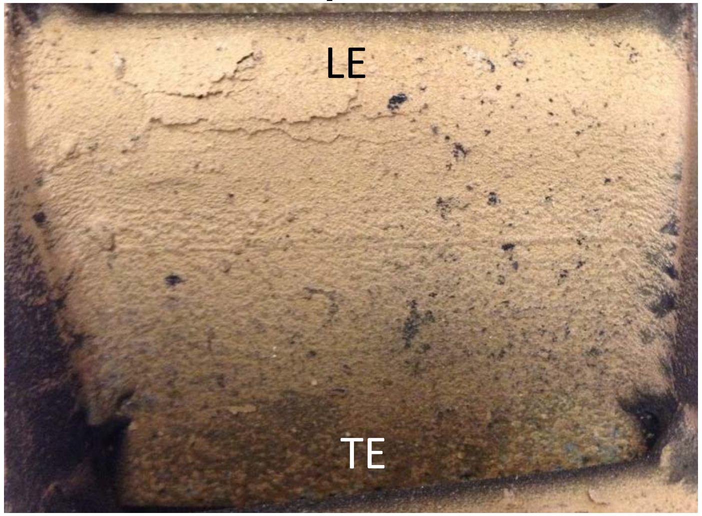


$$\eta_{v,i} = N \frac{m_{v,i}}{m_t}$$

- Capture efficiency for uncooled vane relatively consistent (~3%)
- Capture efficiency for cooled vane reduced with higher cooling levels
    - Almost **70%** reduction at the highest cooling level.

Film Cooled-Only Tests

$$\frac{\dot{m}_c}{\dot{m}_p}[\%] = 0$$



$$\frac{\dot{m}_c}{\dot{m}_p}[\%] = 0.62$$

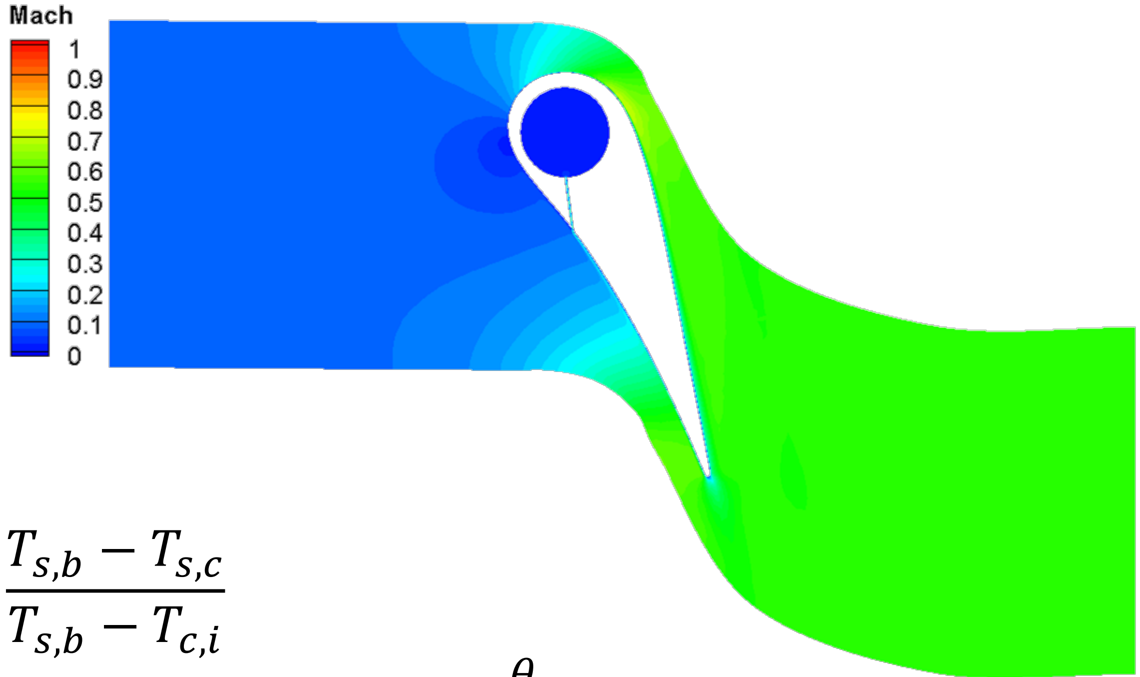
$$\frac{\dot{m}_c}{\dot{m}_p}[\%] = 0.88$$

$$\frac{\dot{m}_c}{\dot{m}_p}[\%] = 1.27$$

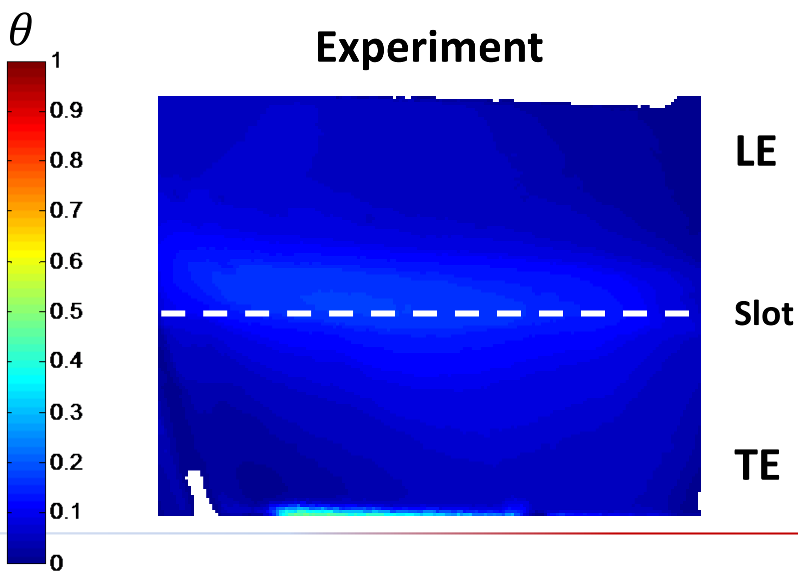
Computational Details

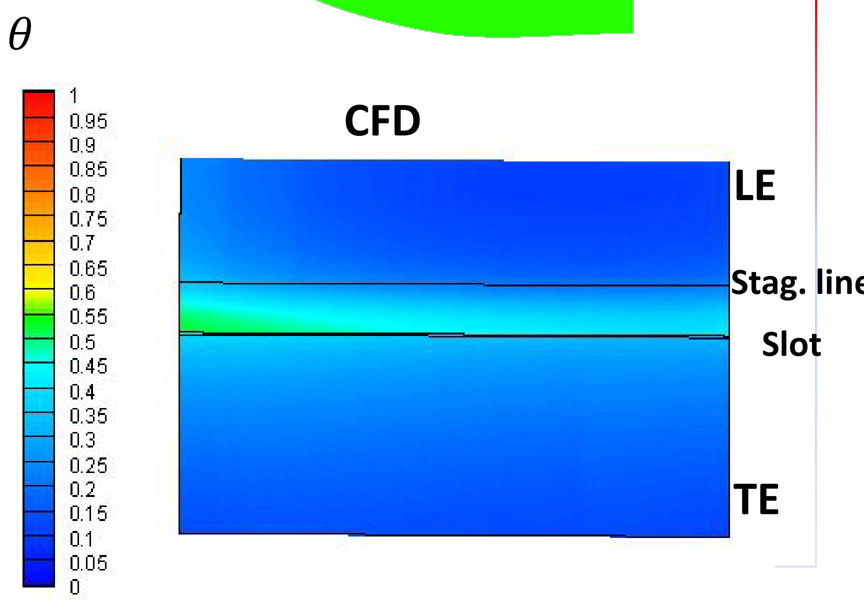
- Commercial finite volume code ANSYS FLUENT 13.0
- 3D RANS simulation
- Boundary conditions set to match experimental values
  - Mass flow rate, total temperature and turbulence intensity set at main and coolant inlets
  - Static pressure specified at outlet
  - Coupled vane walls for conjugate heat transfer
  - Endwalls set as adiabatic
- k-ω SST Turbulence model
- Temperature dependent polynomials for thermal properties of air and Inconel

Computational Results



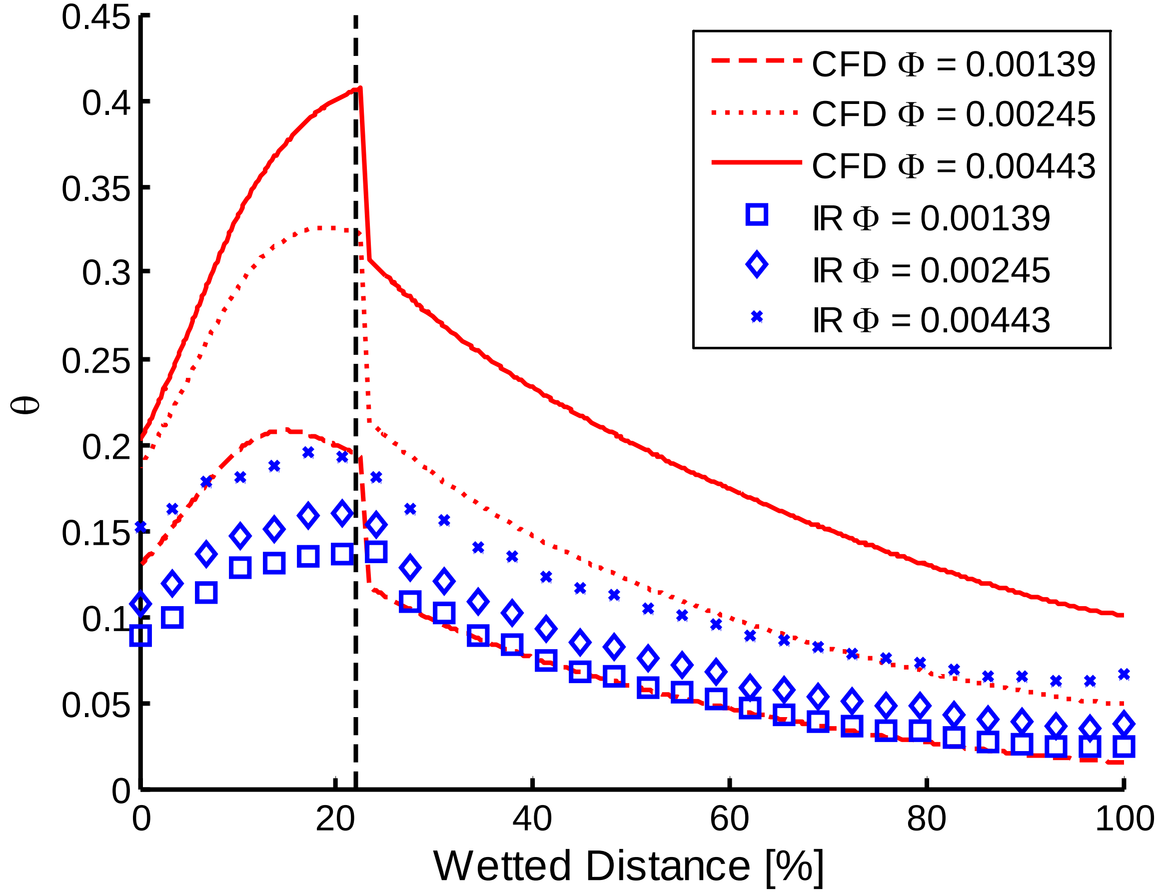
$$\theta = \frac{T_{s,b} - T_{s,c}}{T_{s,b} - T_{c,i}}$$





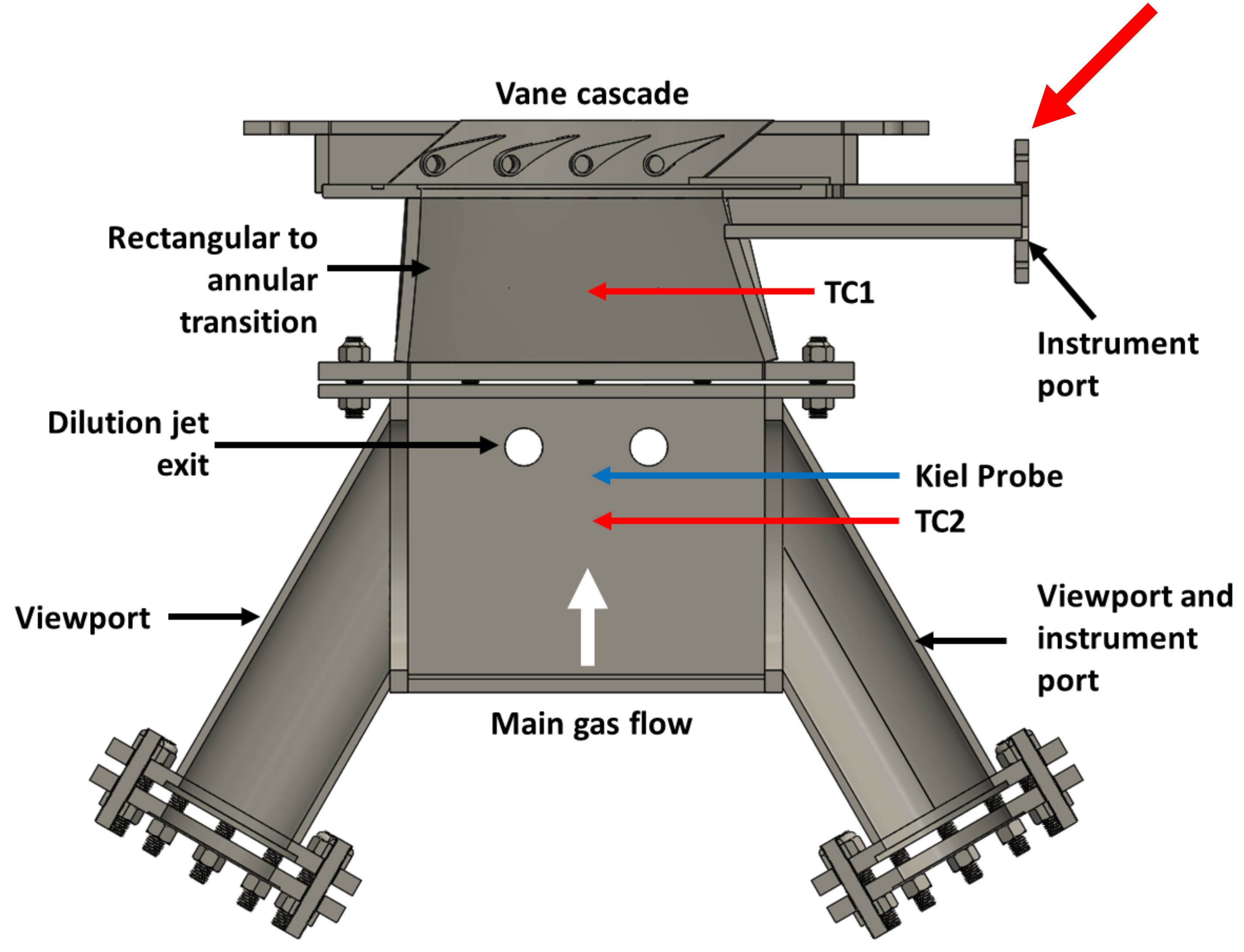
Conjugate Heat Transfer Results

- High cooling effectiveness upstream of the slot
  - High L/h ratio
- Qualitatively similar to experimental
  - High effectiveness upstream of slot
  - Effectiveness decreases towards TE
- CFD over predicts cooling effectiveness
  - Especially in region upstream of slot

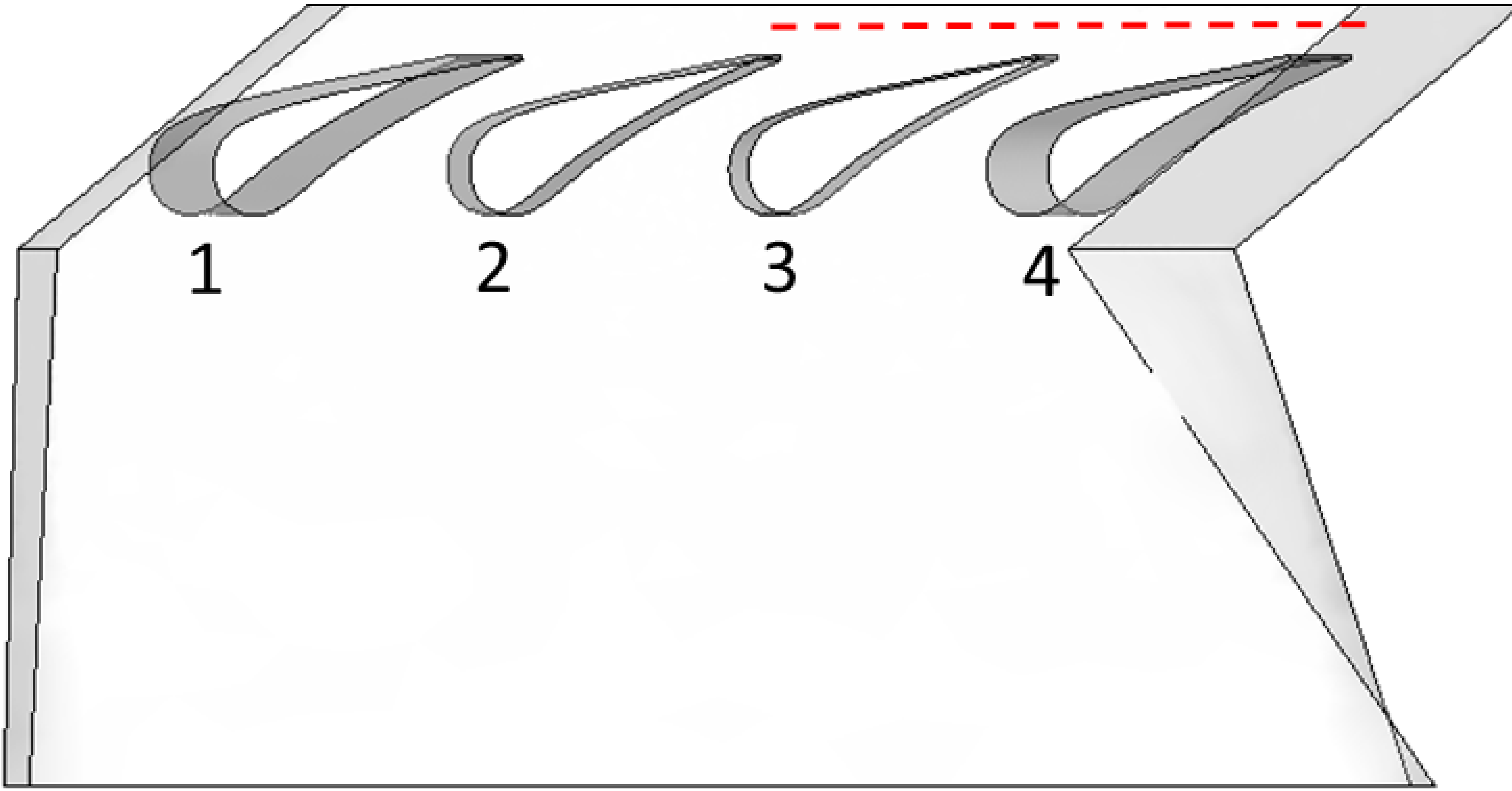


Hot Streaks and Film Cooling

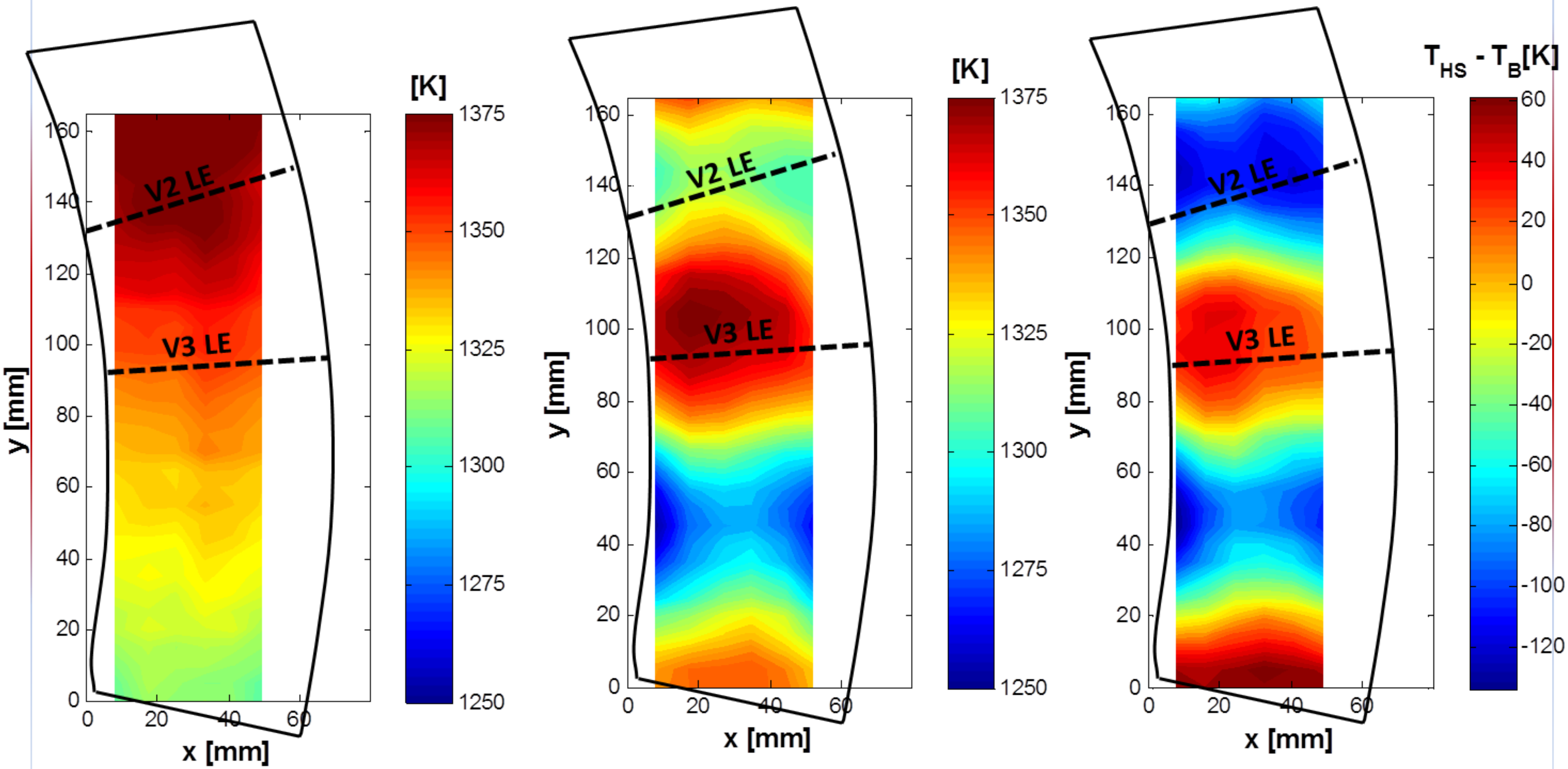
Hot Streaks and Film Cooling



Hot Streaks and Film Cooling –Inlet Characterization



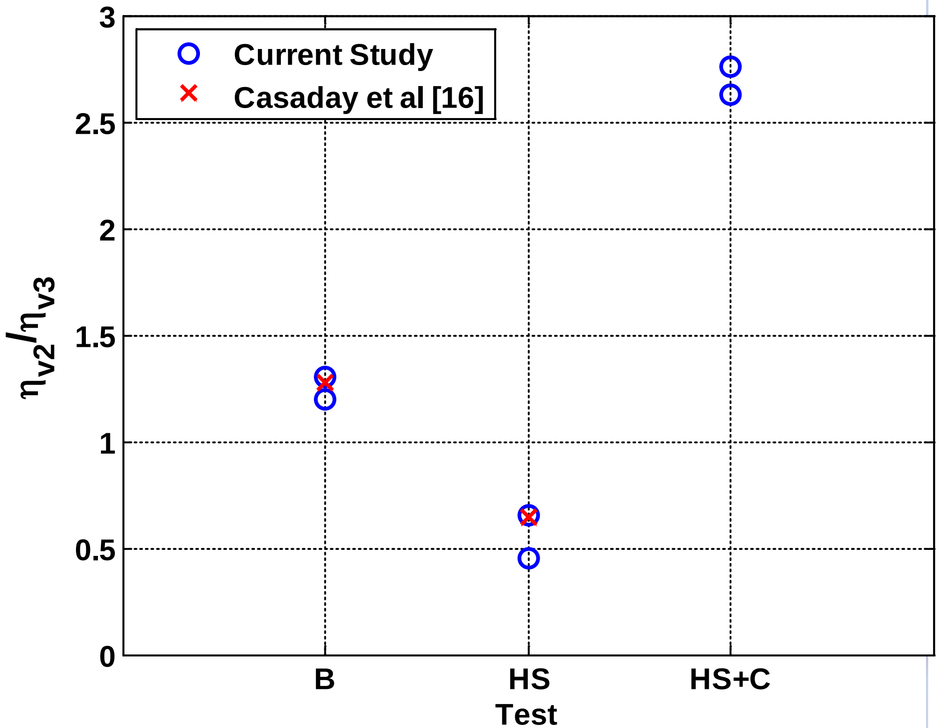
Hot Streaks and Film Cooling –Inlet Characterization



Baseline **Hot Streak** **Difference = T_{HS} - T_B**

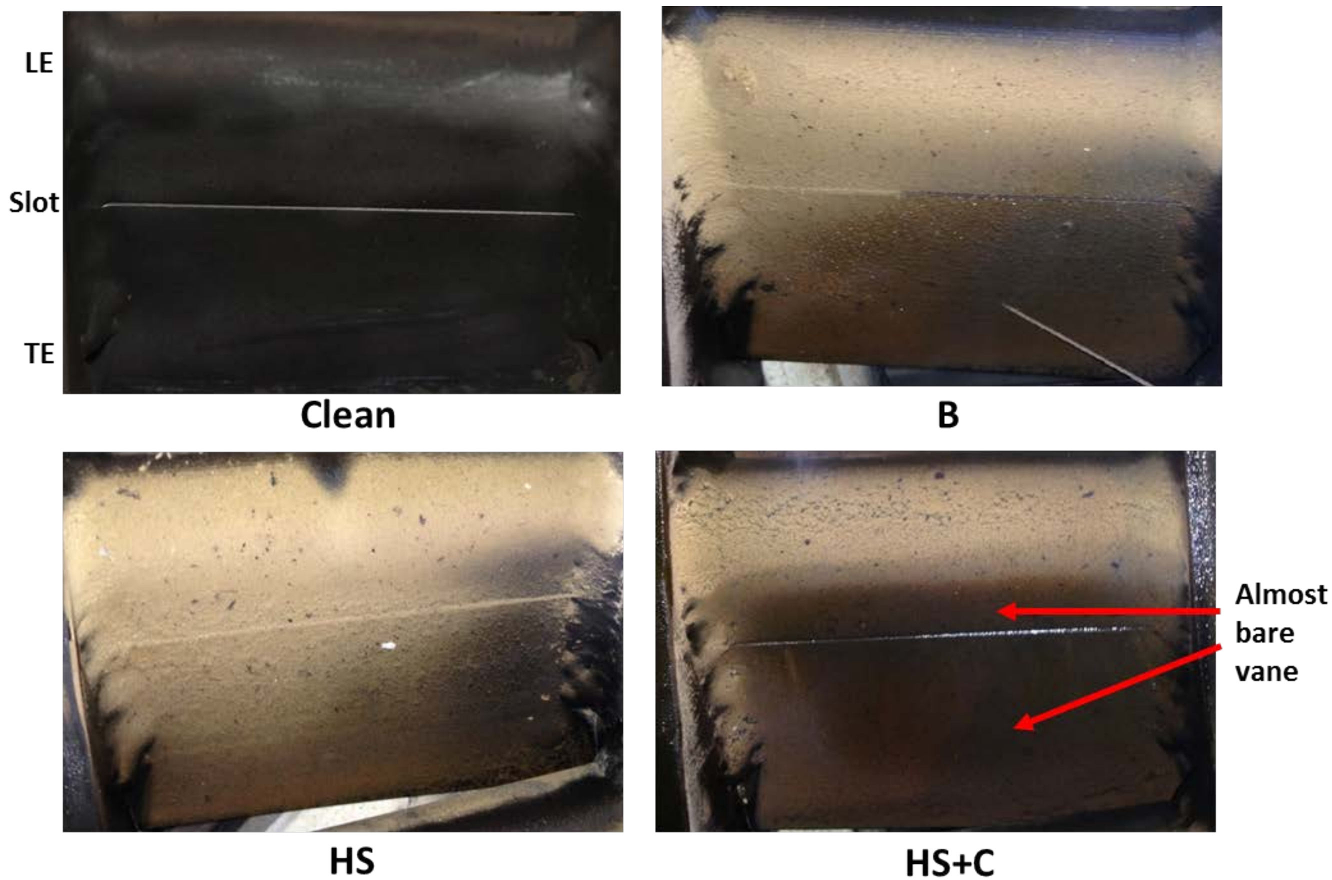
Hot Streaks and Film Cooling – Deposition Tests

Test	m_t	$\eta_{v,2}$	$\eta_{v,3}$	$\eta_{v,2}/\eta_{v,3}$
B1	74.87g	7.05%	5.88%	1.20
B2	81.77g	6.24%	4.79%	1.30
HS1	76.43g	3.40%	7.48%	0.45
HS2	85.78g	3.92%	6.07%	0.65
HS+C1	63.03g	4.38%	1.59%	2.76
HS+C2	75.98g	3.74%	1.42%	2.63

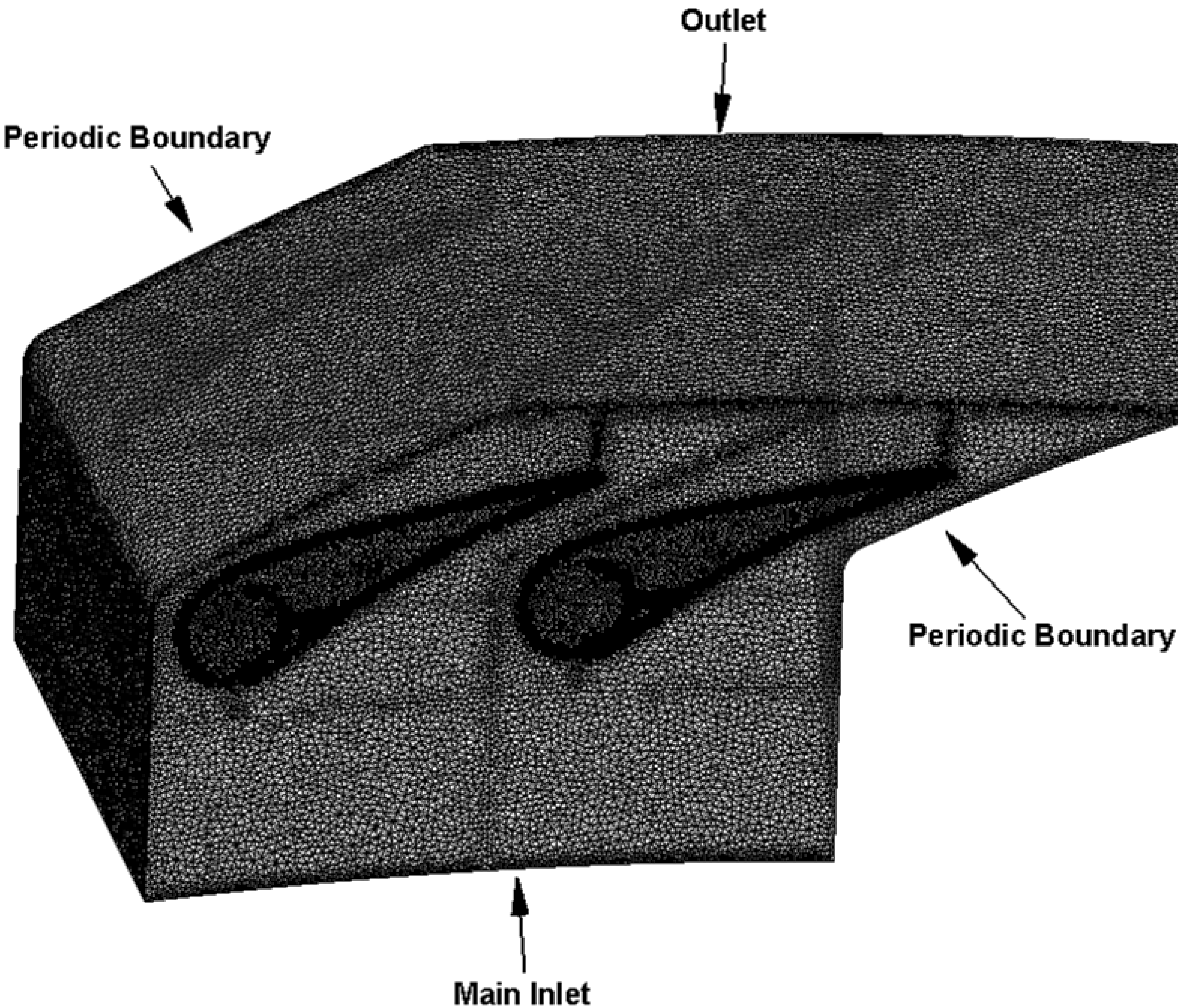


- HS trends match those of previous TuRFR HS study
- Slot film cooling leads to significant reduction in CE, even in presence of HS

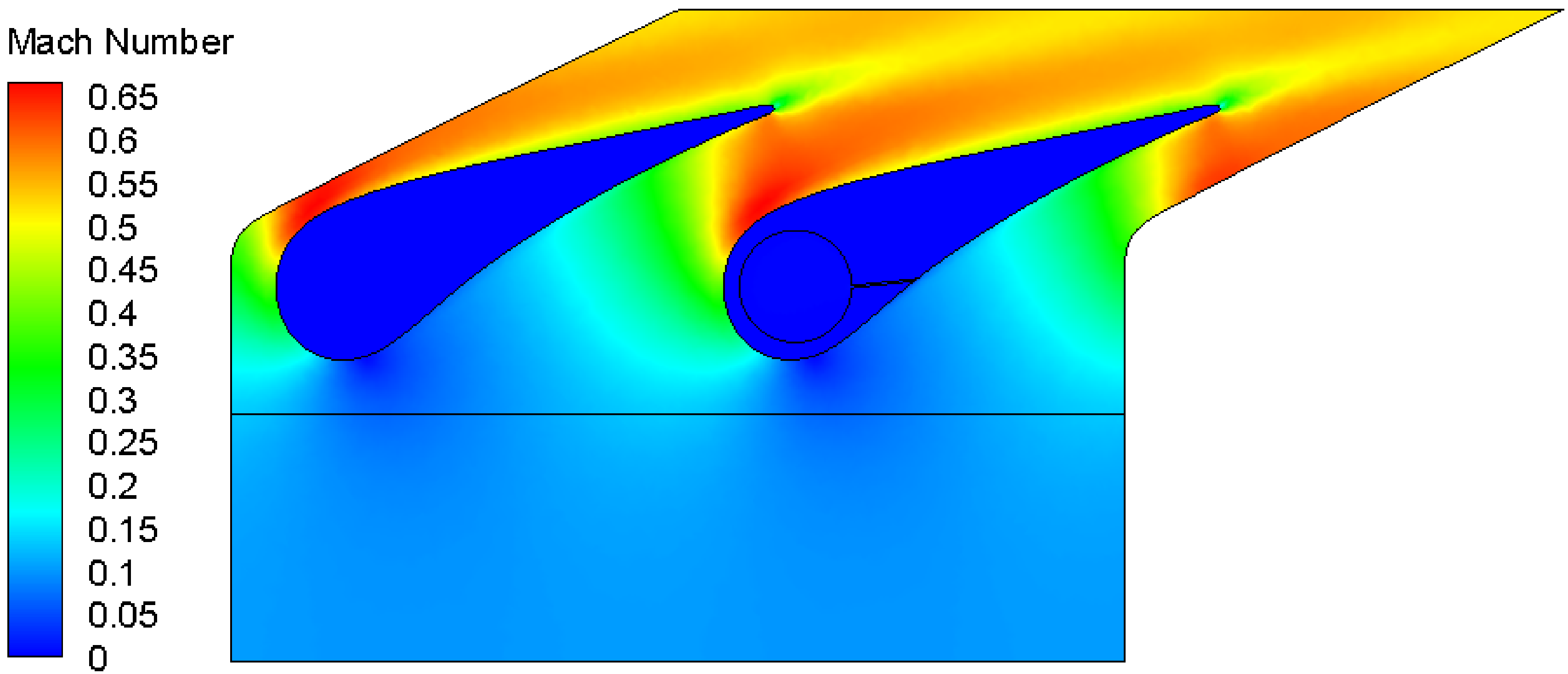
Hot Streaks and Film Cooling – Deposition Tests



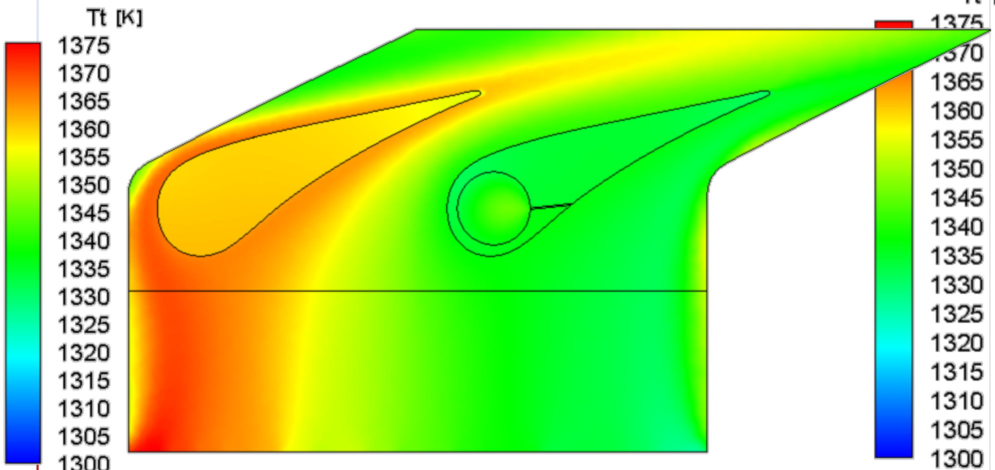
Hot Streaks and Film Cooling - Computational



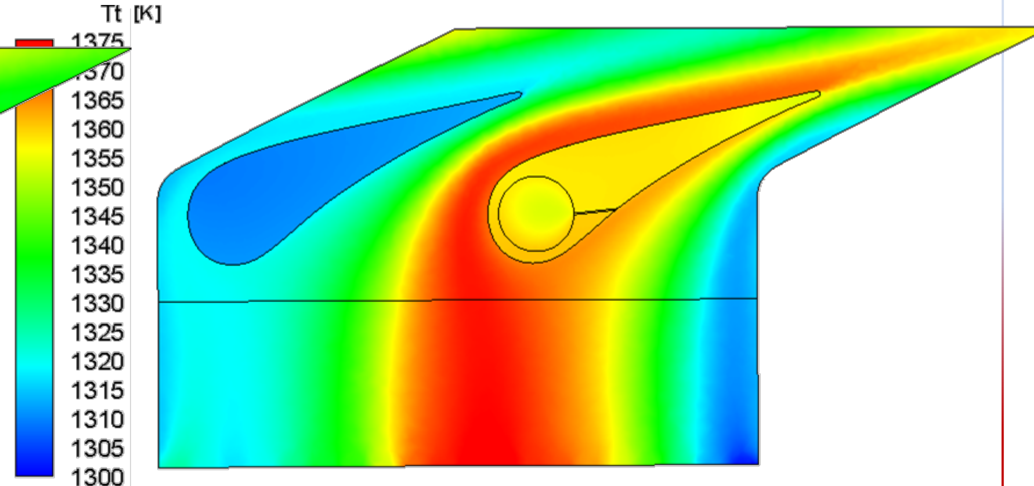
Hot Streaks and Film Cooling - Computational



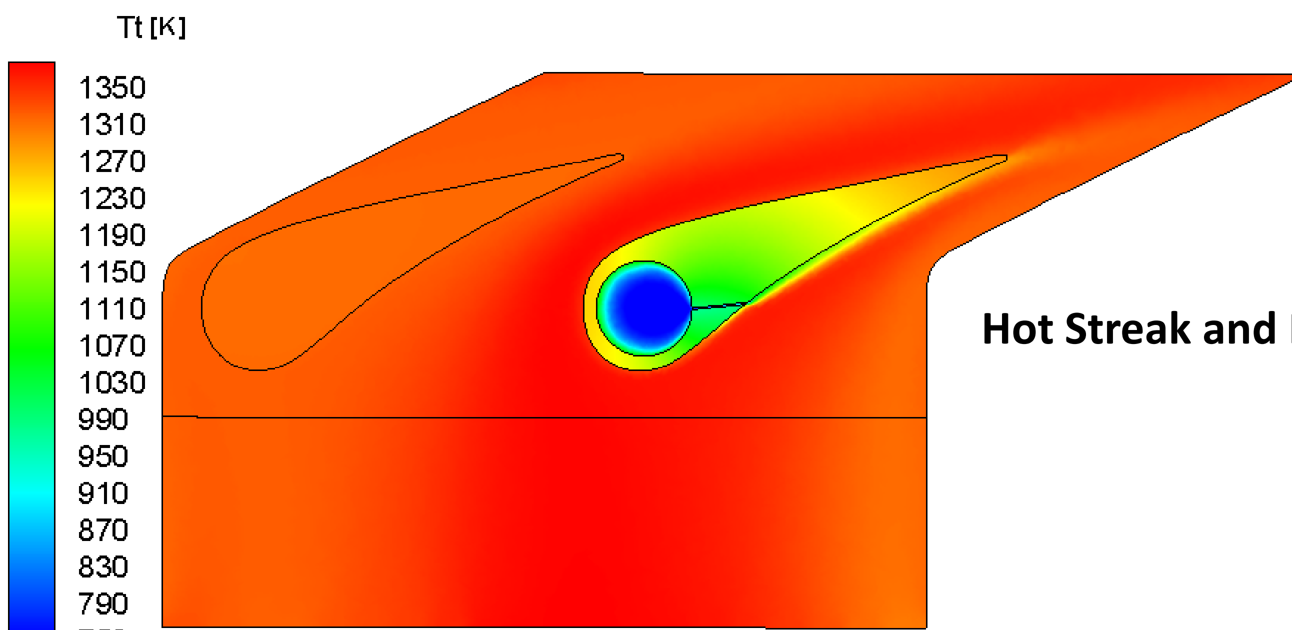
Hot Streaks and Film Cooling - Computational



Baseline

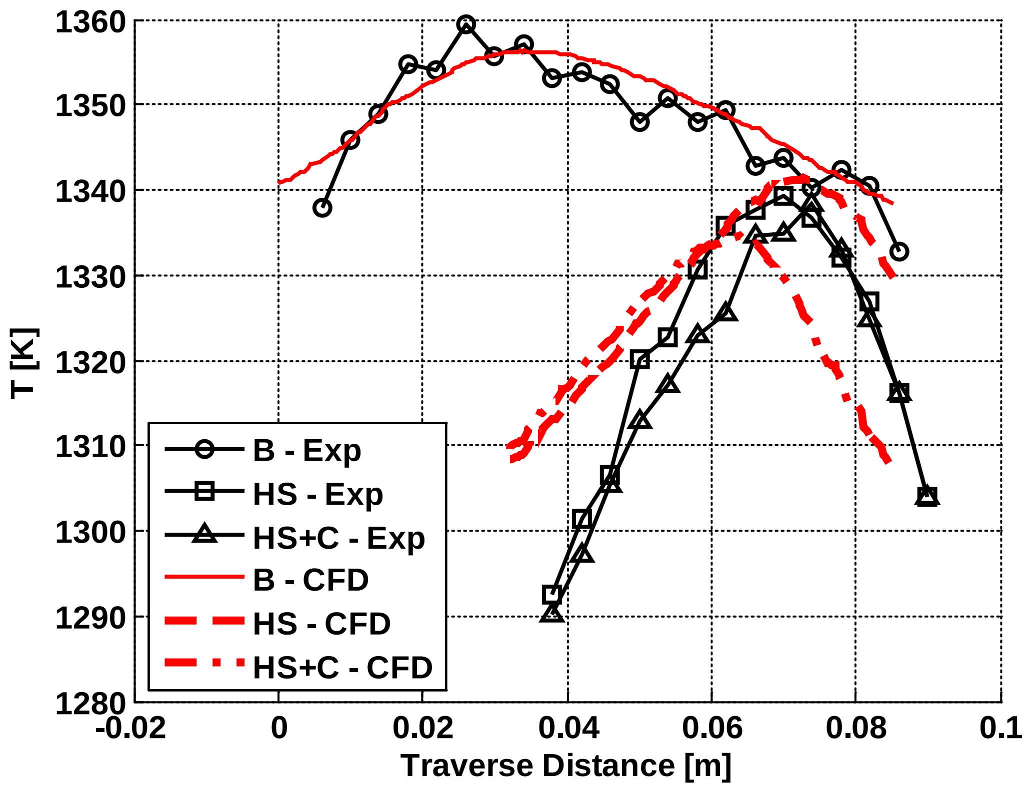


Hot Streak

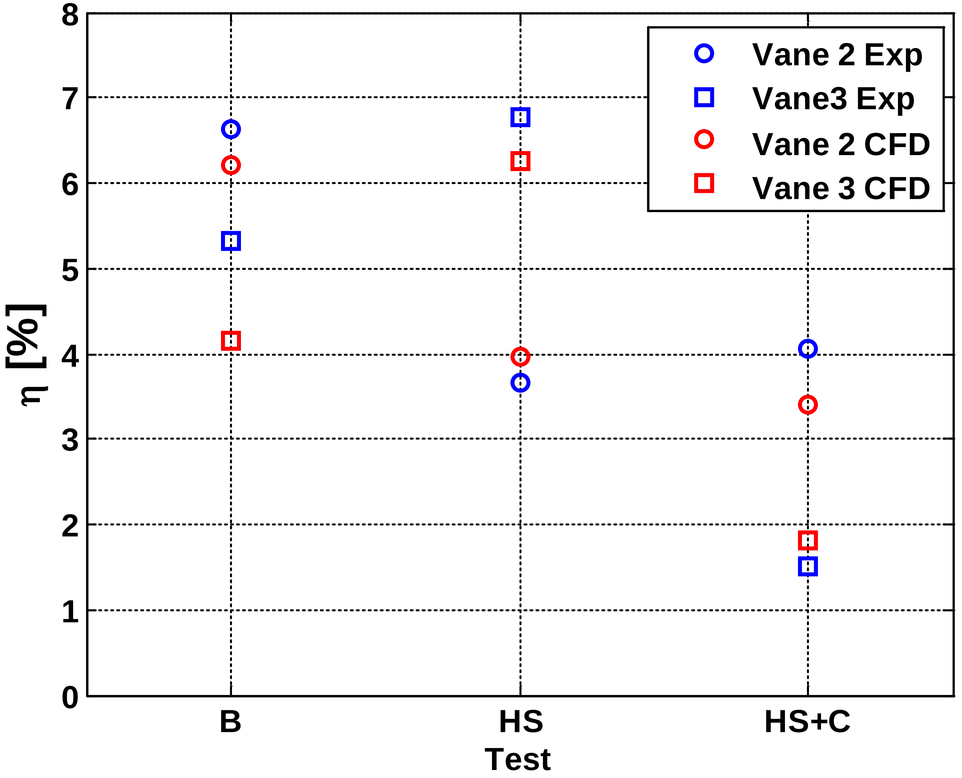


Hot Streak and Film Cooling

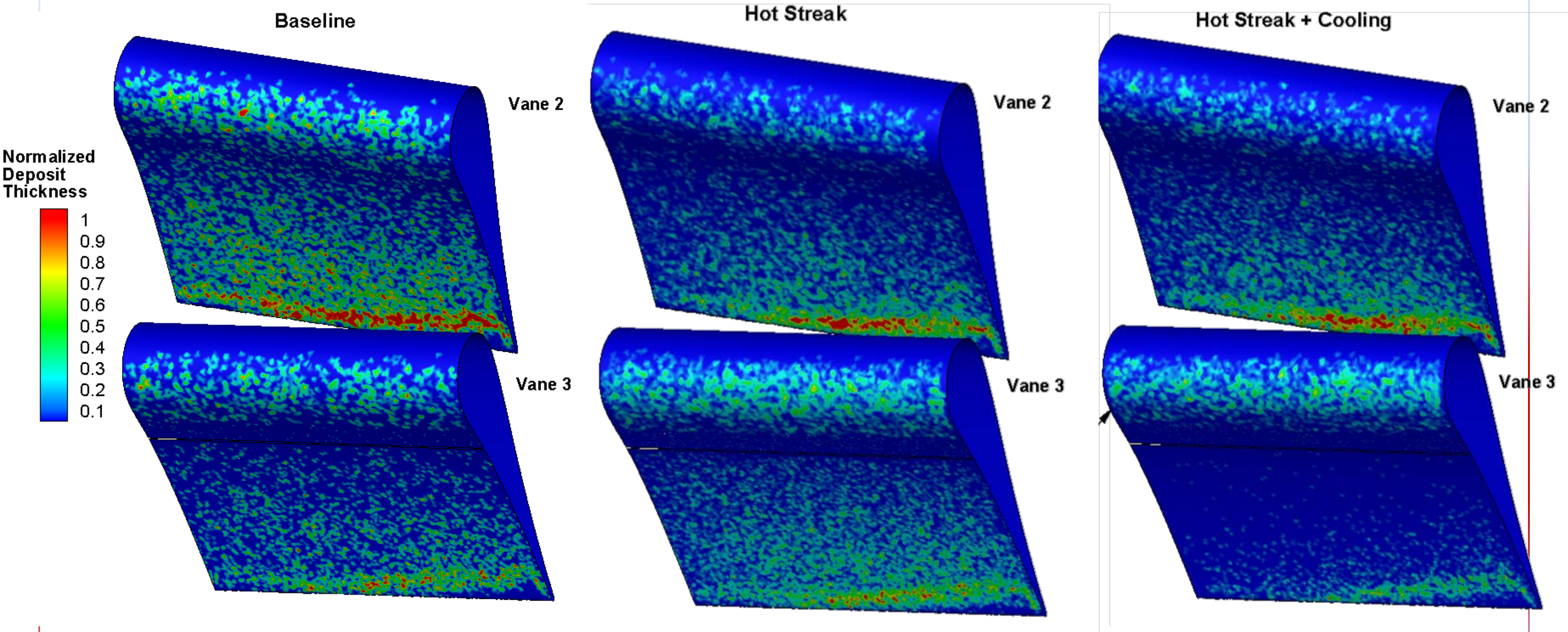
Hot Streaks and Film Cooling – Exit T Traces



Hot Streaks and Film Cooling
Computational Deposition Simulations

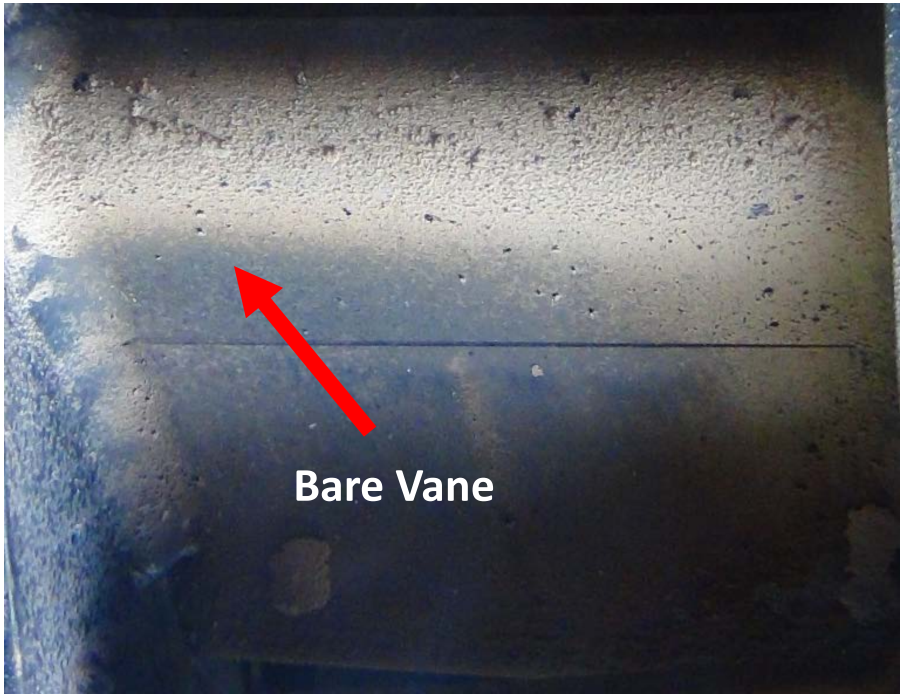


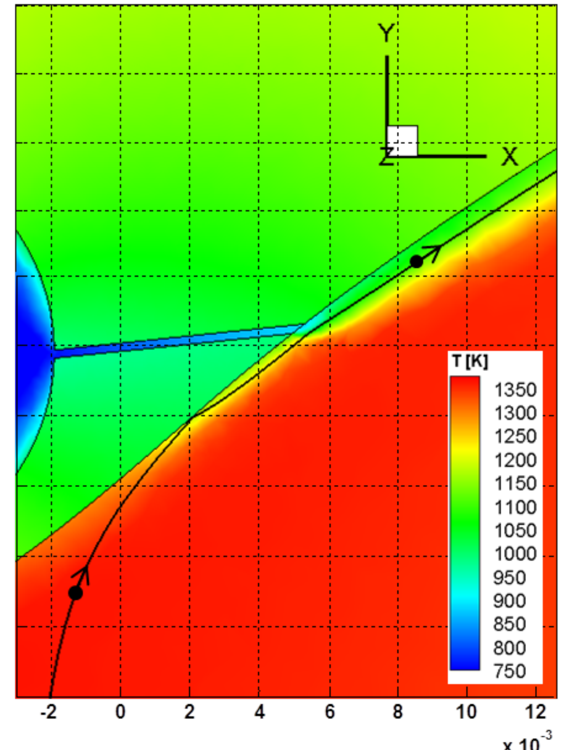
Computational Deposition Simulations

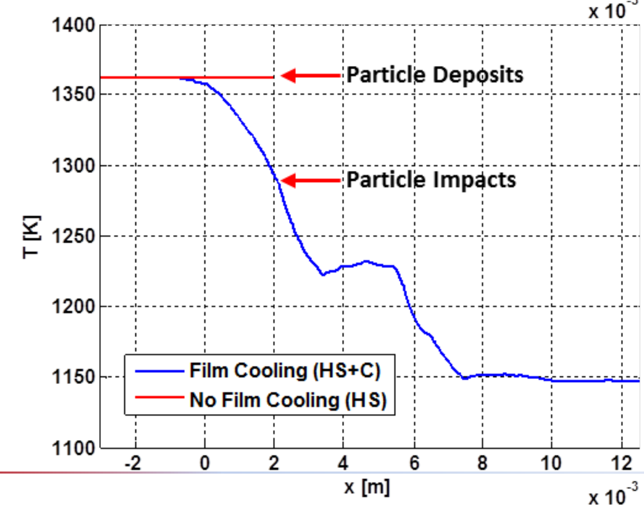


- Large amounts of deposition on LE in all cases – matches exp.
- Reduction in deposition down stream of slot in HS+C case – matches exp.
- Trailing edge deposition over predicted – no dependency on local flow shear rate in model

Hot Streaks and Film Cooling - Computational







- Particle cools in thermal BL
  - Temperature reduced by 70K for this case
- Reduction in sticking probability
- Does not rule out surface temperature effects (if any)

Fundamental Deposition Modeling

Fundamental Deposition Modeling Roadmap and Progress

- There are many impact models that include elastic and plastic deformation, as well as effects from adhesion.

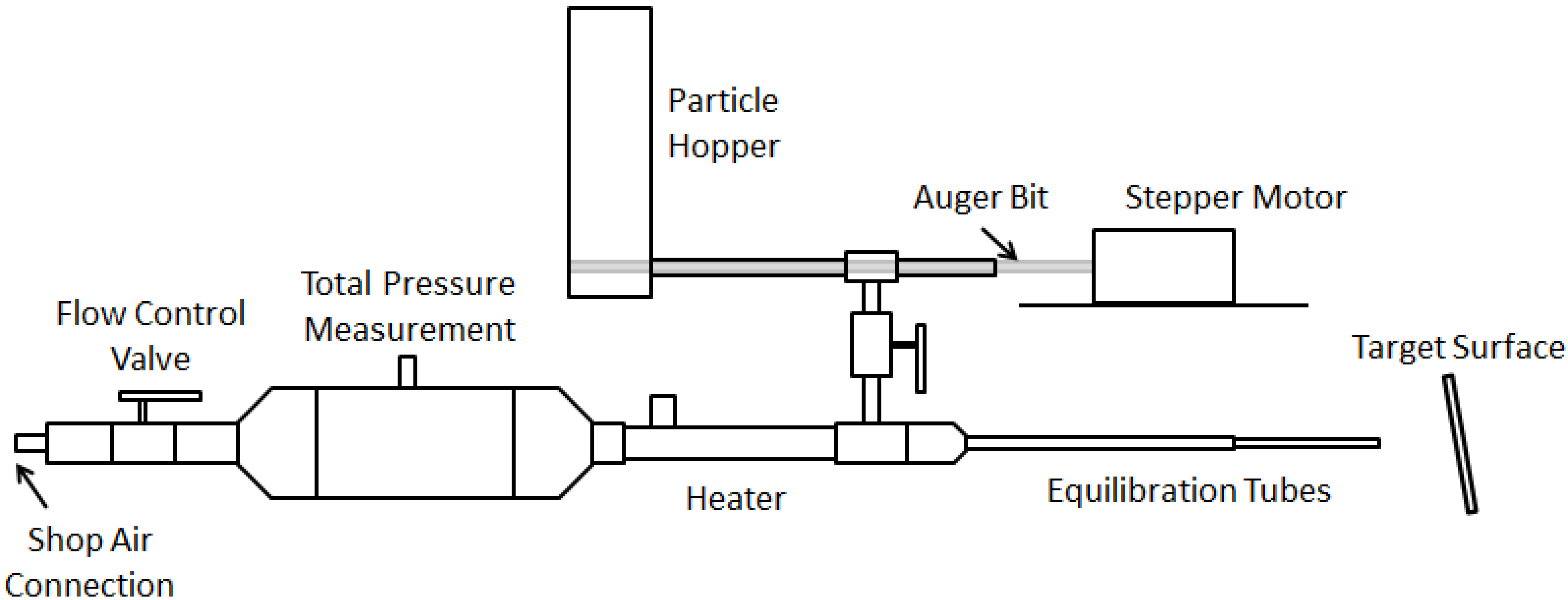
- These models require knowledge of ash properties:
  - Mechanical properties (Young's Modulus, yield strength, Poison's ratio)
  - Surface energy adhesion parameter
  - Almost every impact model uses these properties.

Not well known for fly ash.

- Often models neglect the effects of local flow shear rate.

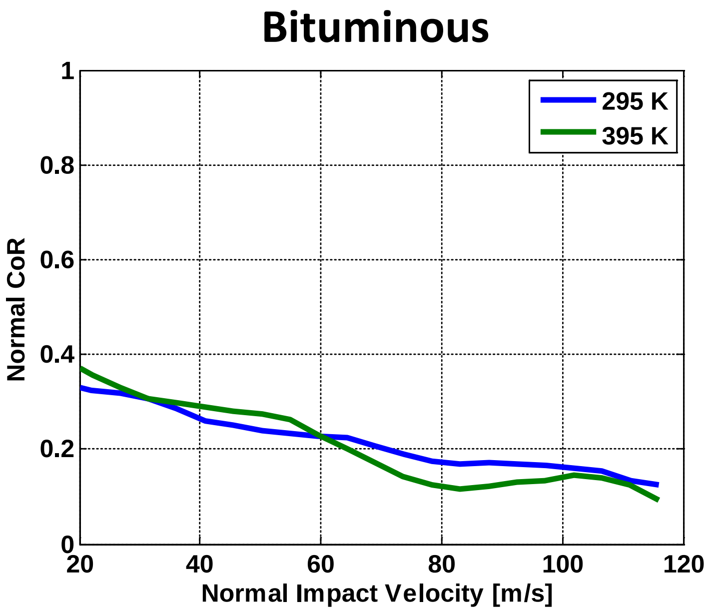
- Need to determine:
  - Are impact models valid for ashes (which are non-homogenous materials)?
    - Need mechanical properties
  - Surface energy parameter, important effect?
  - Effect of local flow shear rate?

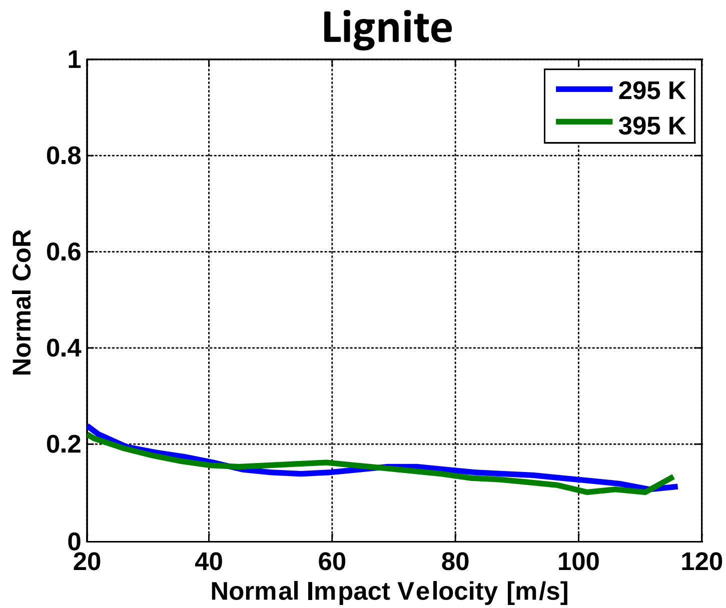
Evaluation of Elastic-Plastic Rebound Properties of Coal Fly Ash

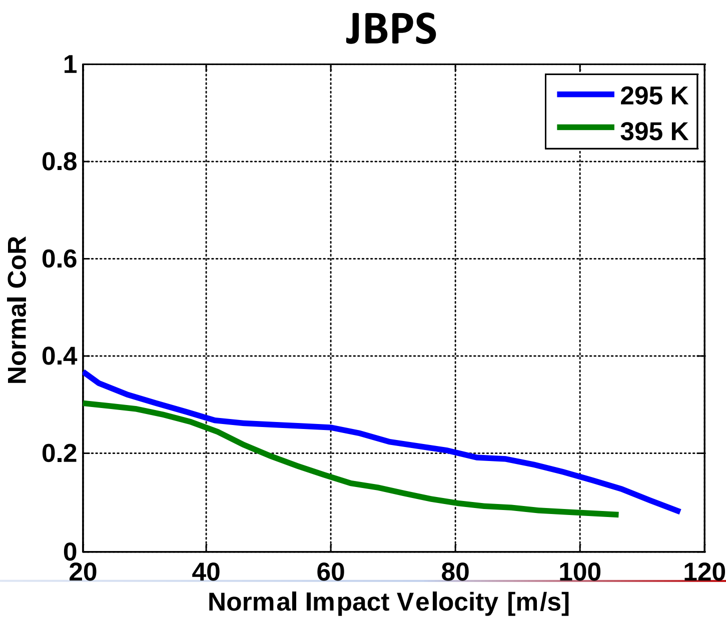


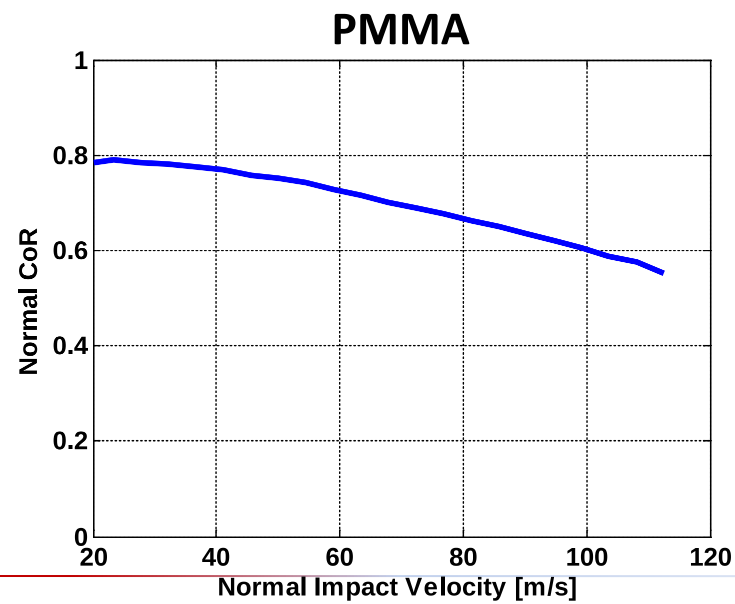
- CoR measured using Particle Shadow Velocimetry (PSV)
  - LED, High speed camera
- Three ash types tested
  - Bituminous, Lignite, JBPS
- Polymer tested
  - PMMA

Evaluation of Elastic-Plastic Rebound Properties of Coal Fly Ash









Evaluation of Elastic-Plastic Rebound Properties of Coal Fly Ash

- Several impact models evaluated so far
  - Bitter (Hertzian Impact Model)
  - Weir and McGavin (Plastic – JKR Impact Model)
  - Wu et al. (FE Model)

- Mechanical properties unknown
  - Law of mixtures

- Comparison of CoR results to impact models
  - Hertzian Impact Model – over predict V_y
  - Plastic – JKR Impact Model – over predict V_y
  - FE Model – good estimation of V_y for PMMA

Determining surface energy of fly ash particles using CoR measurements

A Mathematical Model of the Impact and Adhesion of Microspheres

Brach, R. M., and Dunn, P. F., *Journal of Aerosol Science and Technology*, 1992

Classical Impact Theory:

Approach phase:

$$-mv_n = P_D{}^A + \cancel{P_E{}^A}$$

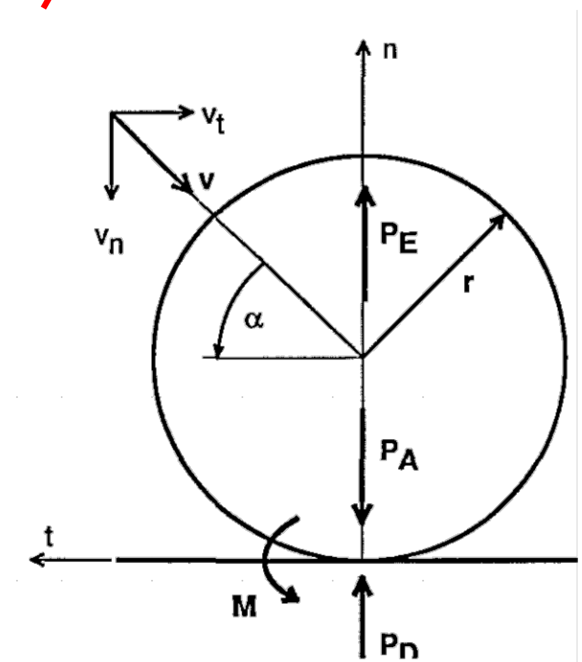
Rebound phase:

$$mV_n = P_D{}^R + \cancel{P_E{}^R} - P_A$$

$$mV_n - mv_n = P_D - P_A$$

Define $R = \frac{P_{D,R}}{P_{D,A}} = \frac{V_n}{v_n} =$ CoR when adhesion negligible

$\Longrightarrow$ **High impact velocities**



Determining surface energy of fly ash particles using CoR measurements

Work done by an impulse:

$$W = P(v_n + V_n)/2 \qquad \Longrightarrow \quad W_A$$

Kinetic energy loss from an impact:

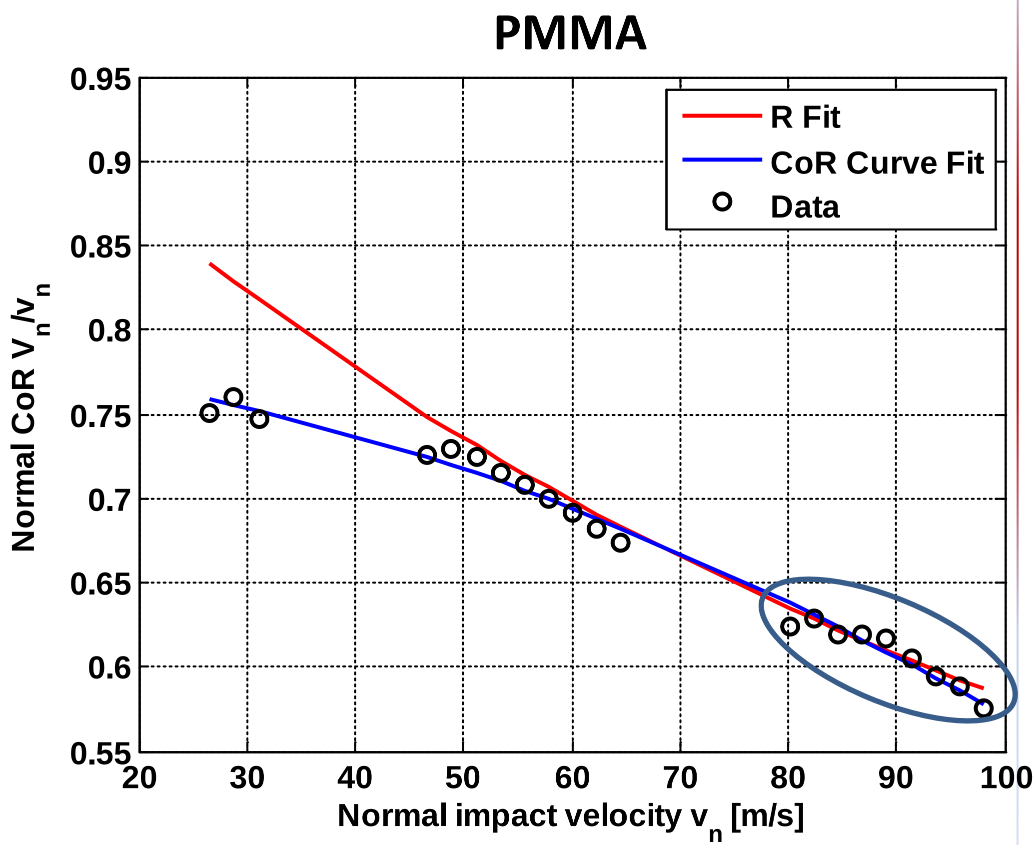
$$T_L = \frac{1}{2}m\left(V_n{}^2 - v_n{}^2\right) = -W_A + \frac{1}{2}mv_n{}^2[1 - R^2]$$

$$\boxed{W_A = \frac{1}{2}mv_n{}^2\left[\frac{V_n{}^2}{v_n{}^2} - R^2\right]}$$

Determining surface energy of fly ash particles using CoR measurements

Obtain curve fit for R using experimental data with high impact velocities:

$$R = \left[\frac{V_n}{v_n}\right]_{High\,Vel} = \frac{k}{k + {v_n}^p}$$



Determining surface energy of fly ash particles using CoR measurements

Hertzian Theory:

Idealized line force to represent adhesion force:

$$F_A = 2\pi a f_0$$

$$W_A = \frac{-2{a_m}^2 F_A}{3r} \qquad a_m = \left[\frac{15\pi}{8}(k_1 + k_2) r^2 \frac{1}{2} m {v_n}^2\right]^{1/5}$$

Work of adhesion force set to JKR surface adhesion energy, then surface energy adhesion parameter becomes:

$$\gamma = \frac{2F_A}{3\pi r}$$

$$\Longrightarrow \quad \boxed{W_A = -\left[\frac{5}{4}\rho \pi^{9/2}(k_1 + k_2)\right]^{2/5} \gamma r^2 {v_n}^{4/5}}$$

Determining surface energy of fly ash particles using CoR measurements

$$W_A = \frac{1}{2} m {v_n}^2 \left[\frac{{V_n}^2}{{v_n}^2} - R^2 \right] \qquad\qquad W_A = -\left[\frac{5}{4} \rho \pi^{9/2} (k_1 + k_2) \right]^{2/5} \gamma r^2 {v_n}^{4/5}$$

$$\frac{1}{2} m {v_n}^2 \left[\frac{{V_n}^2}{{v_n}^2} - {\frac{k}{k + {v_n}^p}}^{2} \right] = -\left[\frac{5}{4} \rho \pi^{9/2} (k_1 + k_2) \right]^{2/5} \gamma r^2 {v_n}^{4/5}$$

$$\boxed{\gamma = -\frac{1}{2} r^{-2} m {v_n}^{6/5} \left[\frac{{V_n}^2}{{v_n}^2} - {\frac{k}{k + {v_n}^p}}^{2} \right] \left[\frac{5}{4} \rho \pi^{9/2} (k_1 + k_2) \right]^{-2/5}}$$

Fundamental Deposition Modeling – Moving Forward

- ORNL to conduct high temperature tests to determine mechanical properties
- Obtain adhesion parameter by curve fitting CoR data together with impact model
- Currently developing an experiment to investigate role of local flow shear rate

FULL TURBINE STAGE SIMULATIONS

URETI /GTL's Stage

- Experiments on single stage HP turbines were conducted at OSU GTL under URETI program.
- Both uncooled vane and cooled vane were used.
- Inlet Temperature Distributions:
  - **Uniform Distribution**
  - Radial Distribution
  - Hot Streak targeted at mid-pitch or vane leading edge
- Hot Streak intensity varied
- Cooling rate varied
- Q_{wall} measured

GTL's Relevant Cases

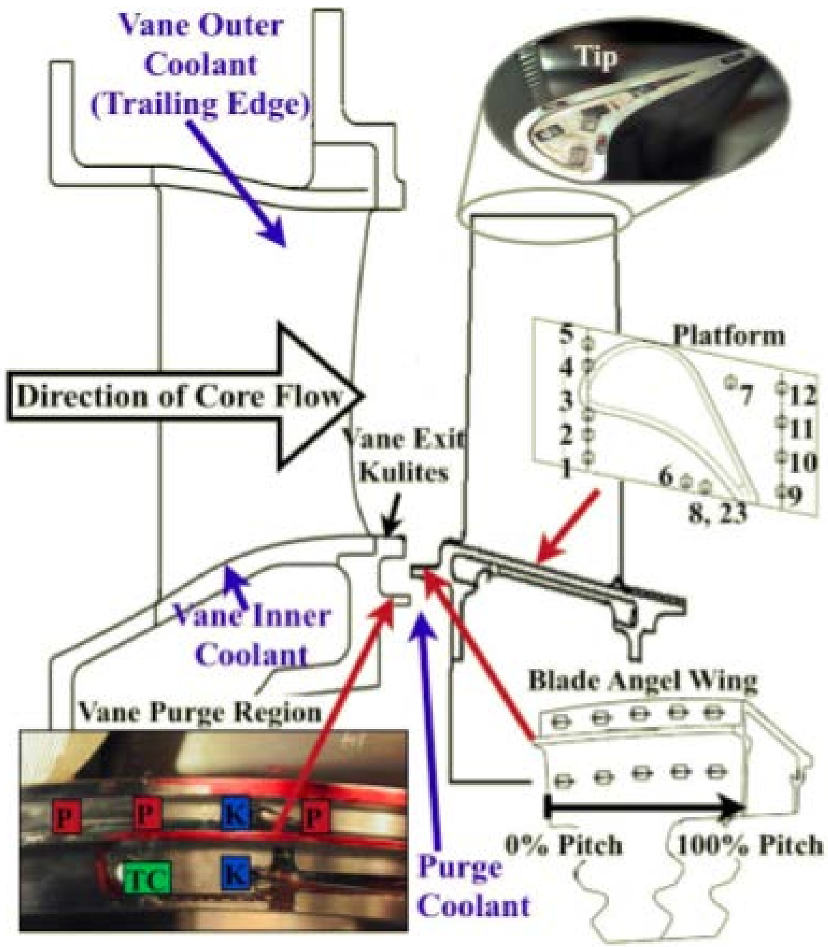


Figure 1. Schematic of instrument locations (not to scale)

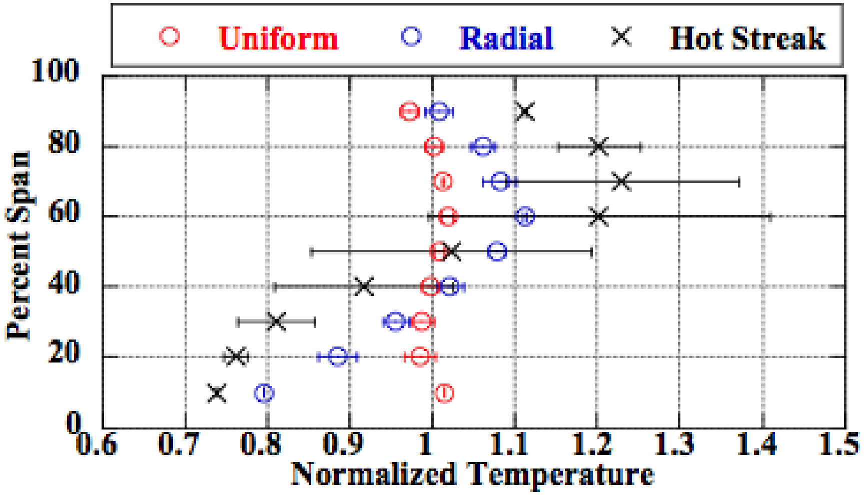
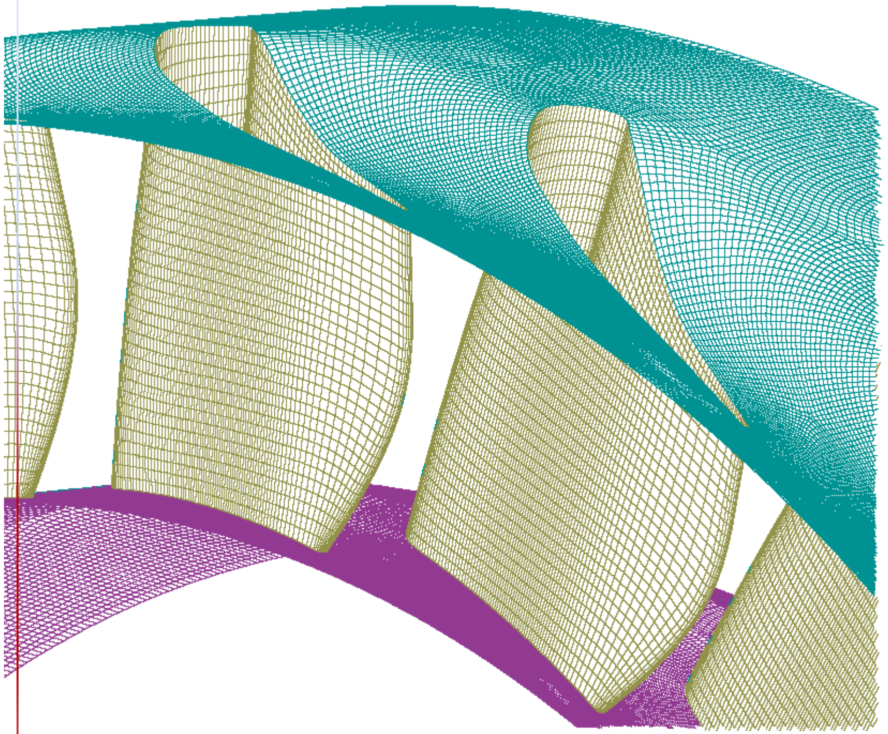
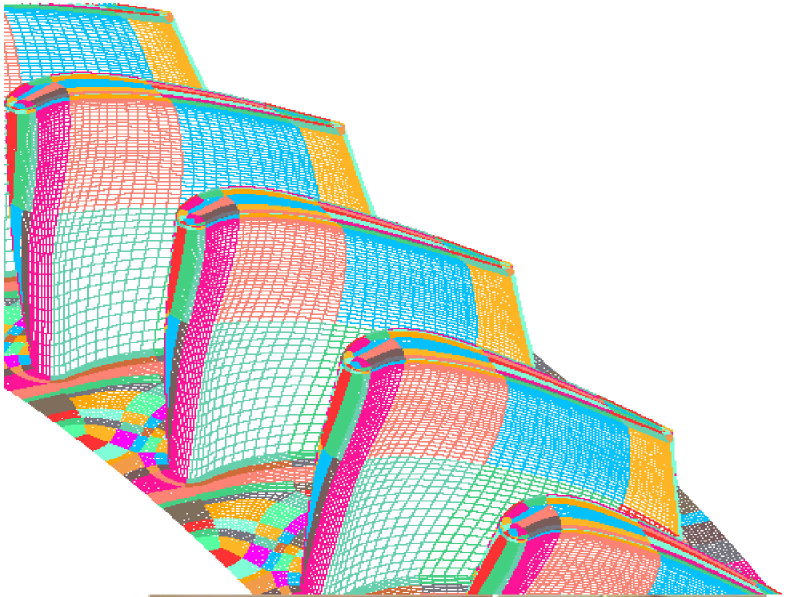
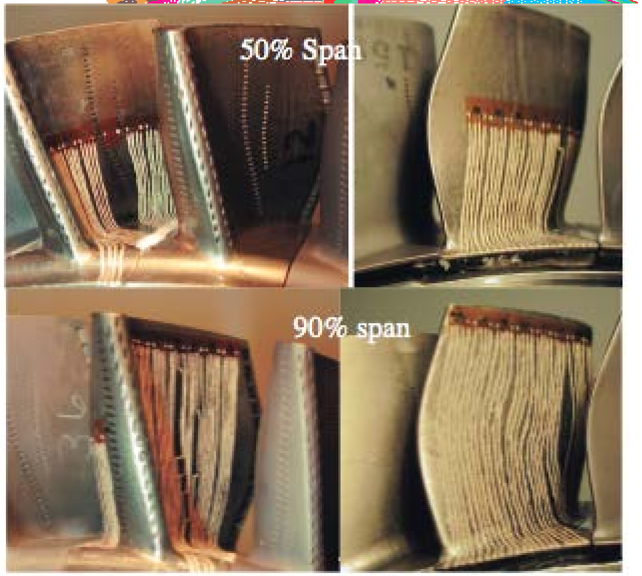


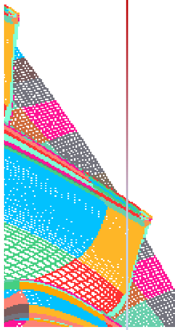
Figure 2. Comparison of inlet temperature profile shapes for runs without cooling

URETI Experiments (Hot Streak)

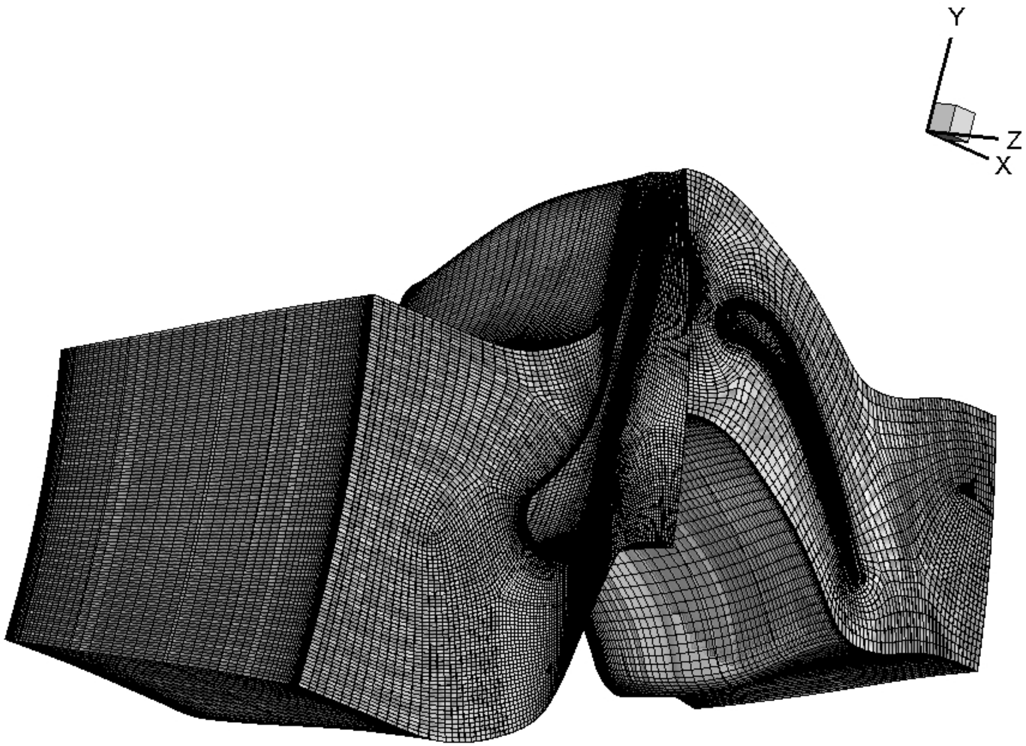






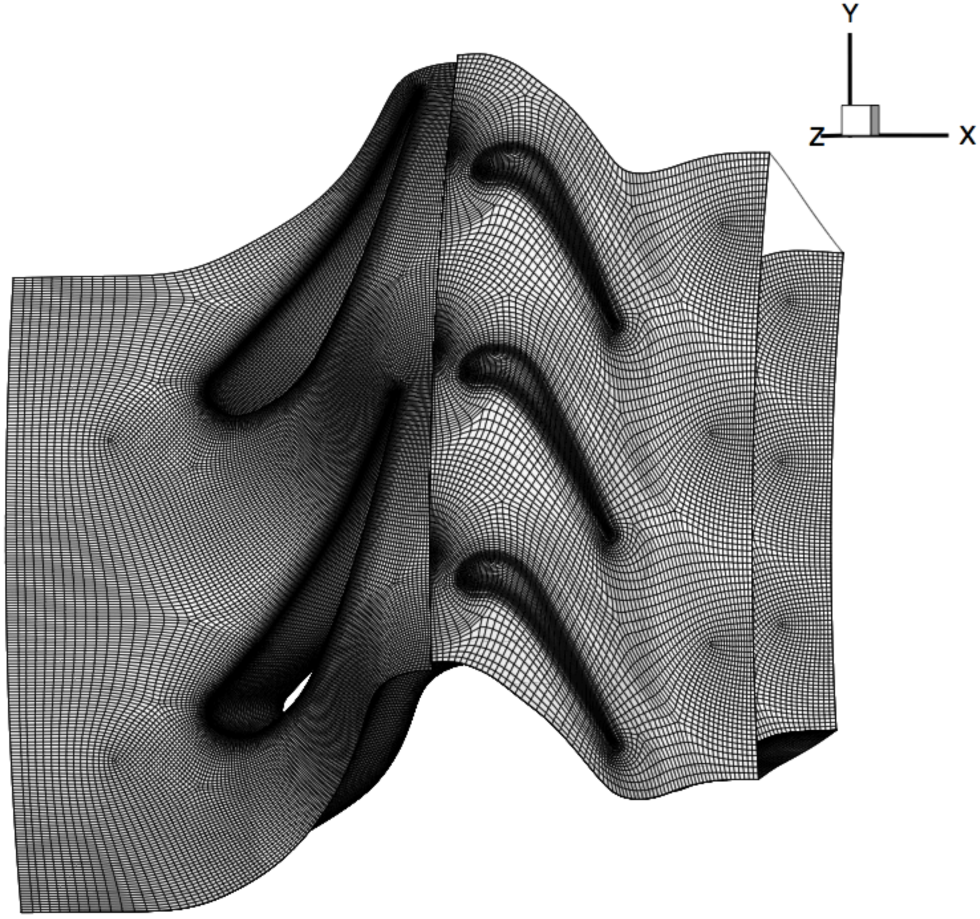


Steady Mesh



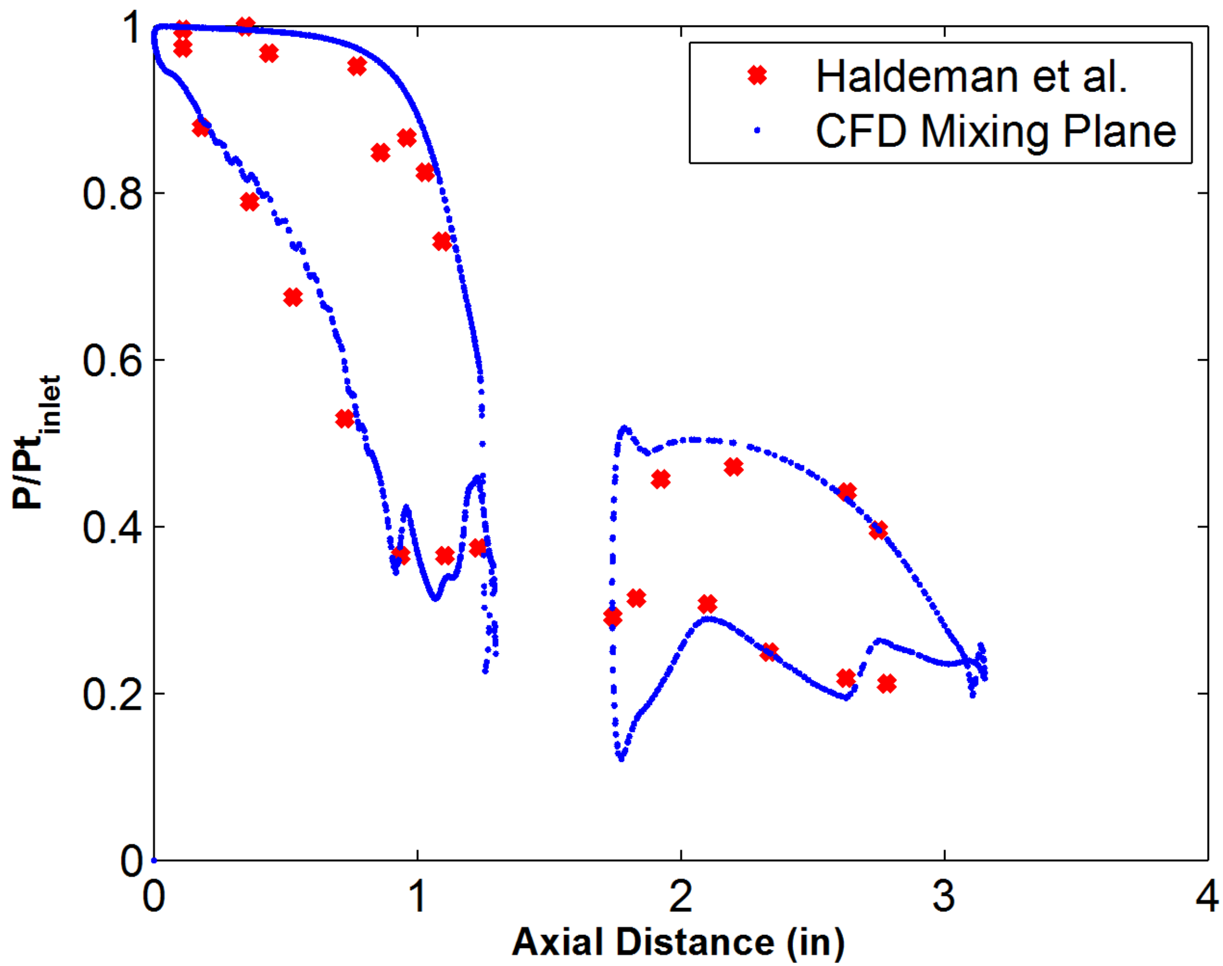
Mesh	Number of Cells
Medium 1/1	1,621,783
Medium 2/3	3,658,637
Fine 1/1	3,212,240
Fine 2/3	7,431,764

Unsteady Mesh

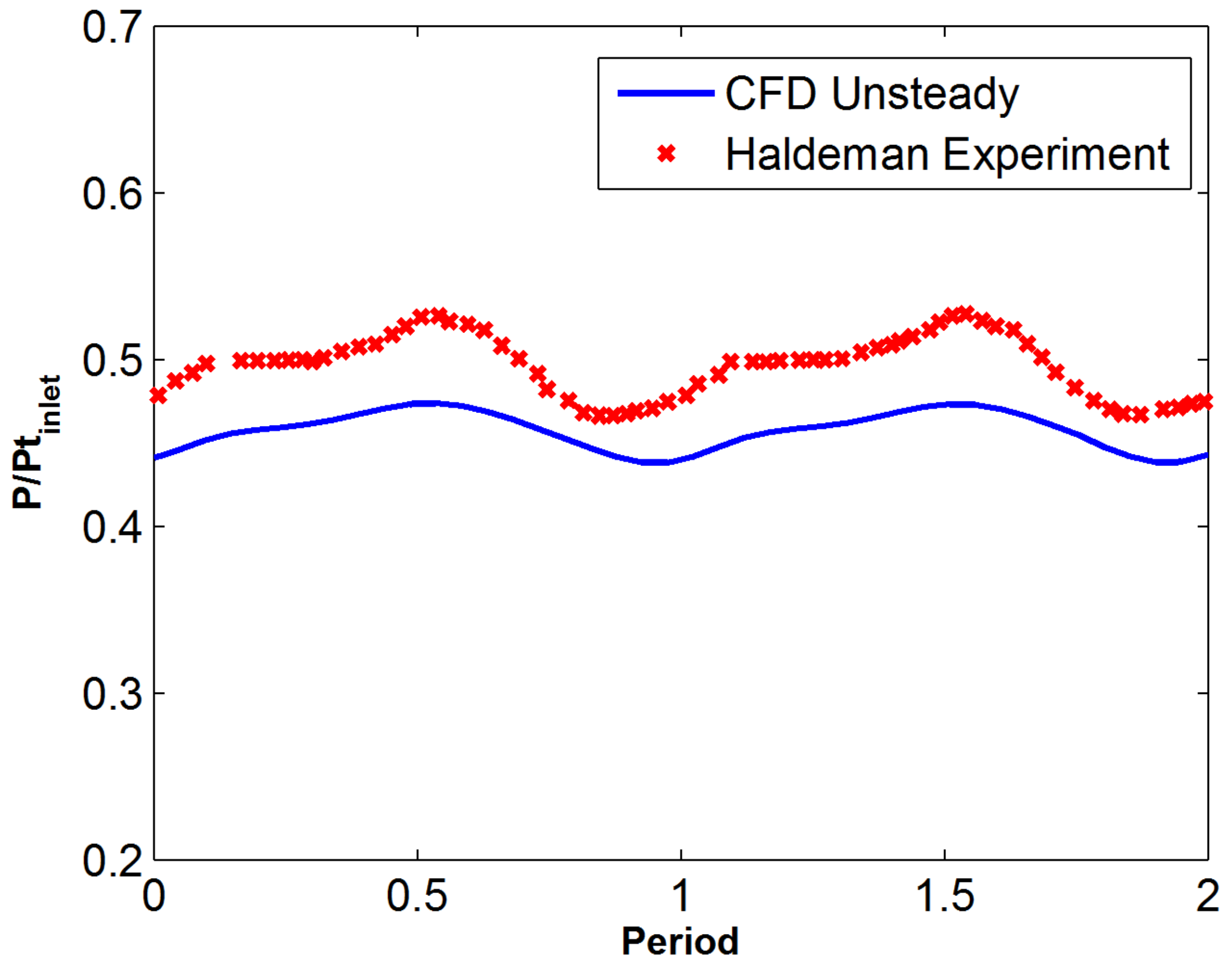


Mesh	Number of Cells
Medium 1/1	1,621,783
Medium 2/3	3,658,637
Fine 1/1	3,212,240
Fine 2/3	7,431,764

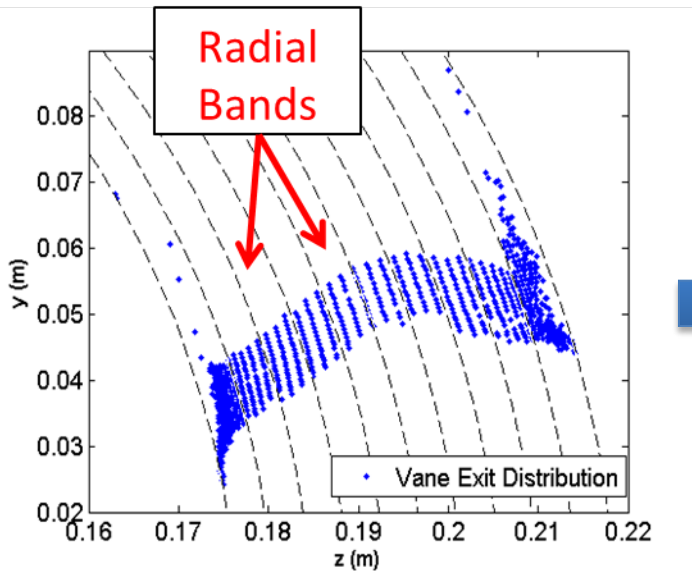
Uniform Inlet Steady Pressures: Midspan

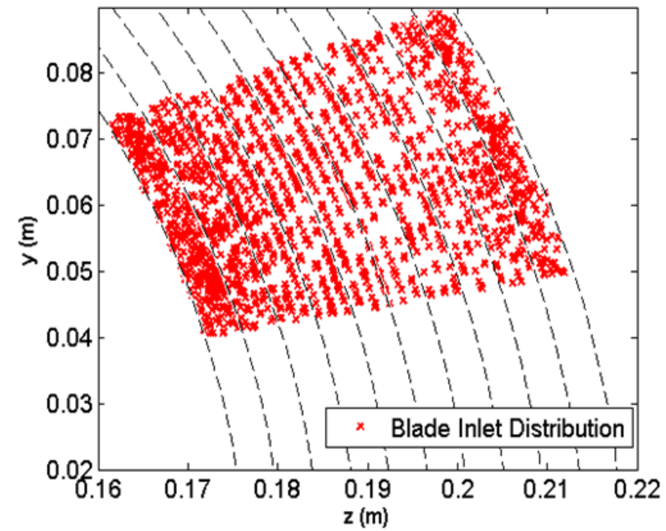


Uniform Inlet Unsteady Pressures: -27% WD Pressure Surface



Mixing Plane Method





Vane Outlet Positions

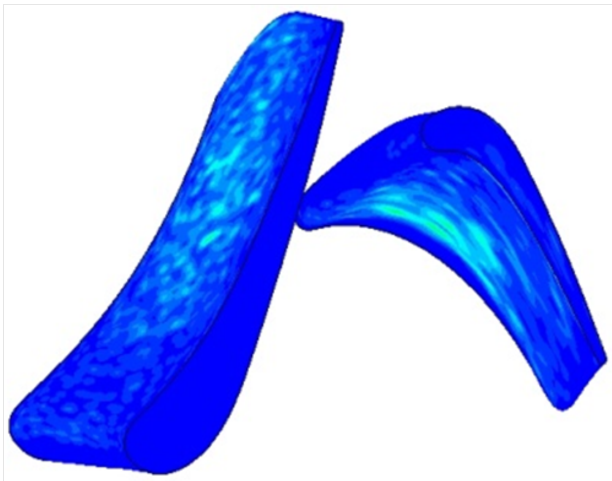
Randomize Circumferentially

Blade Inlet Positions

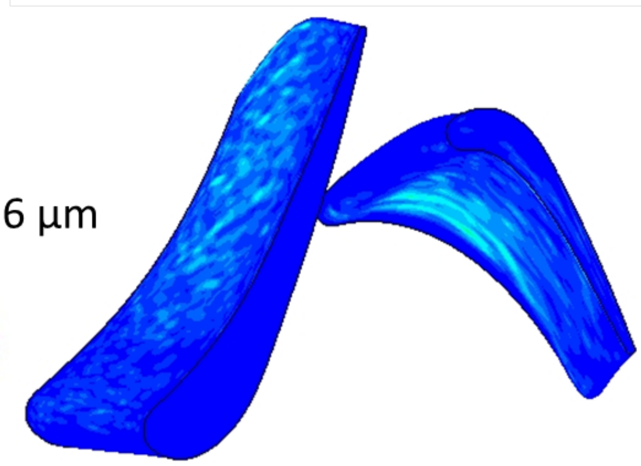
Averaged vs. Preserved Method

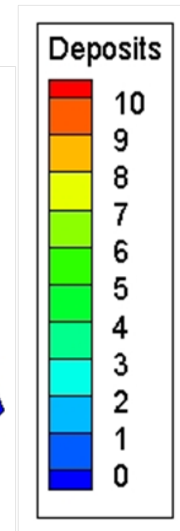
AVERAGED

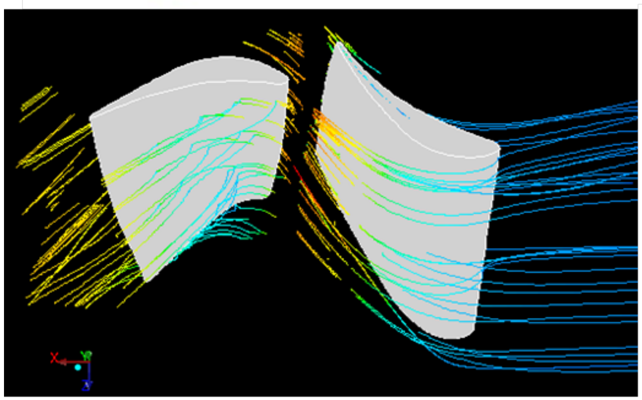
PRESERVED

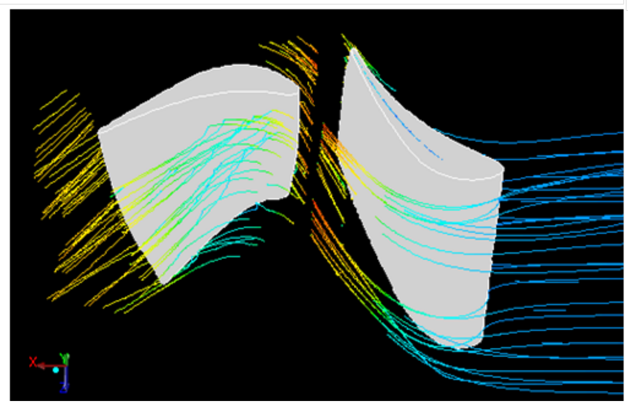


6 µm



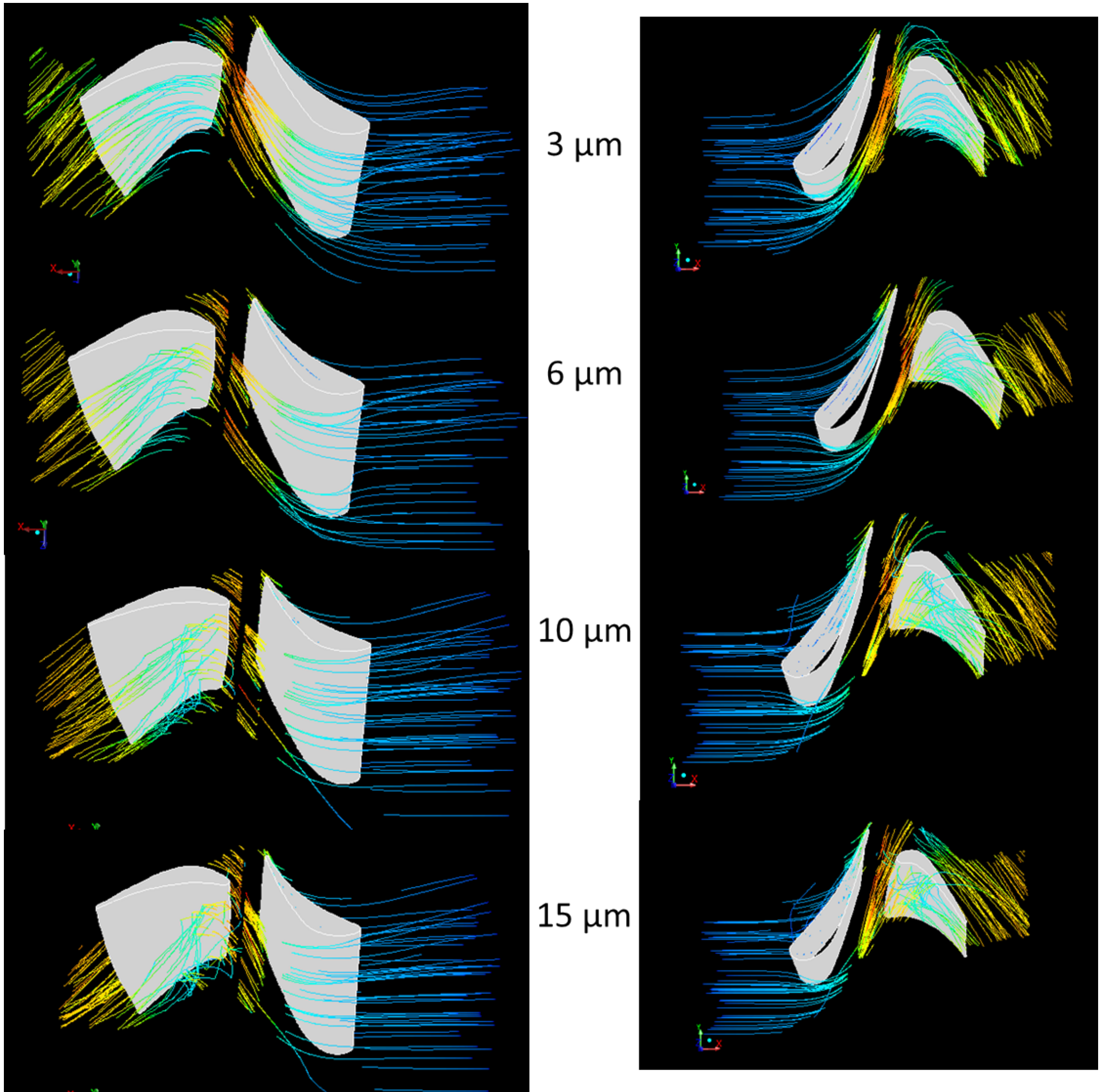






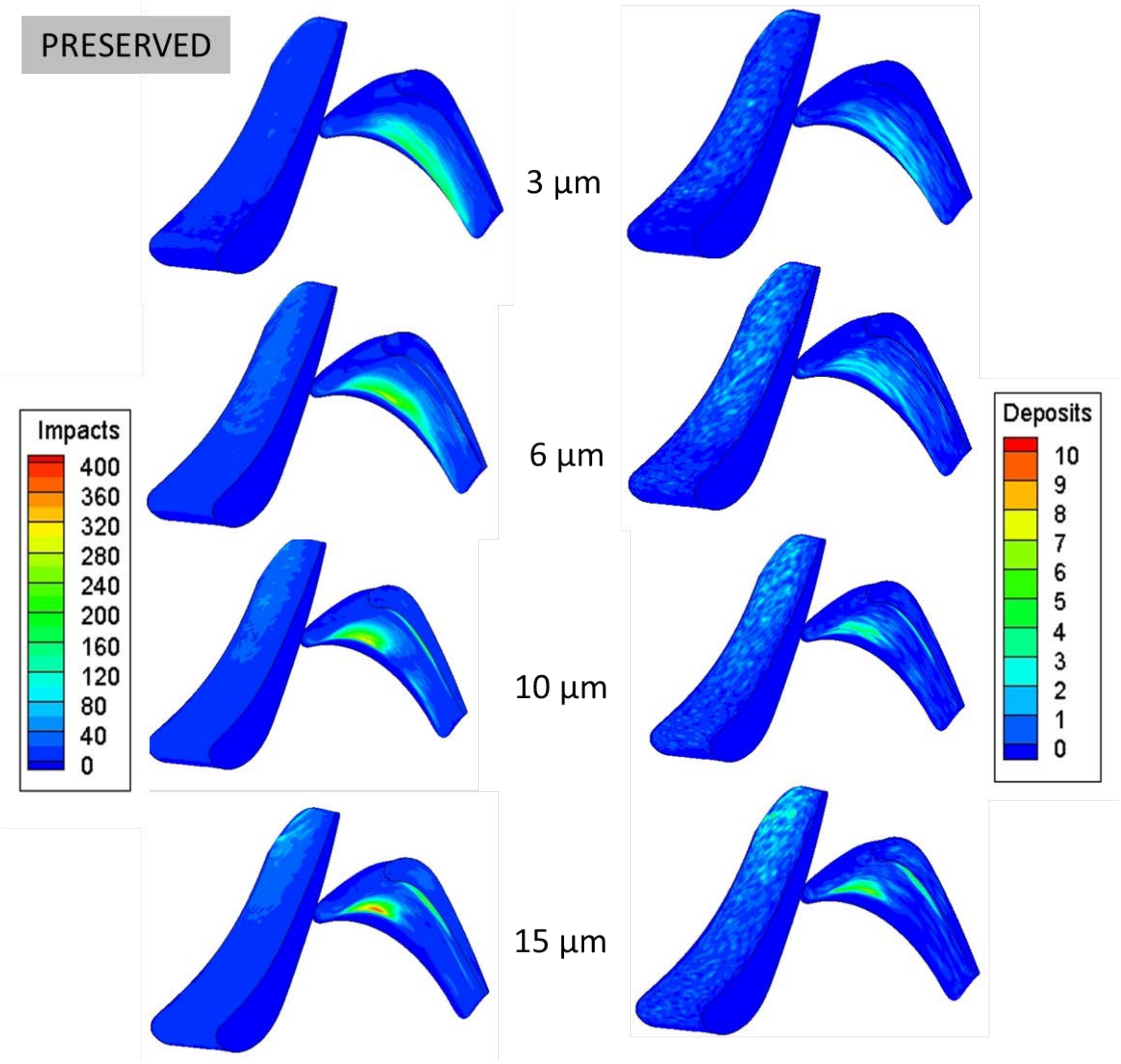
Particle Tracks: Preserved

Case Towards Bottom

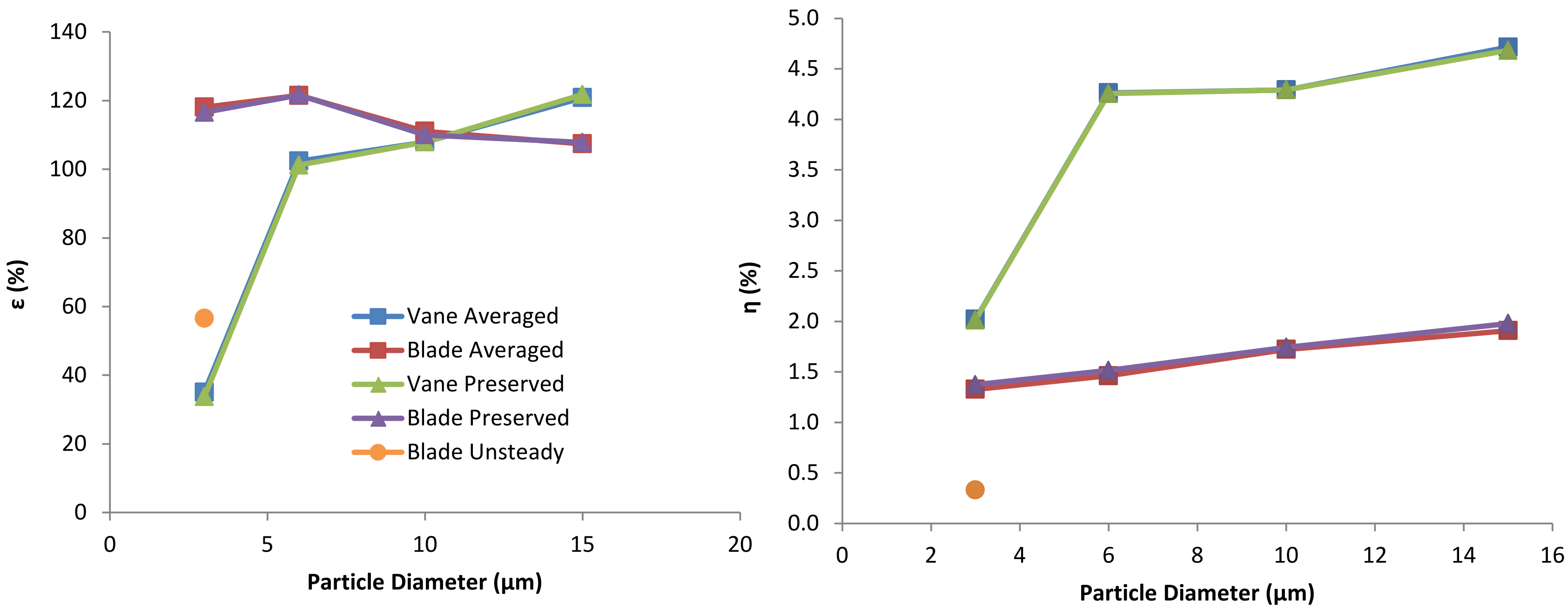


Colored by Velocity Magnitude

Impact and Deposit Distributions



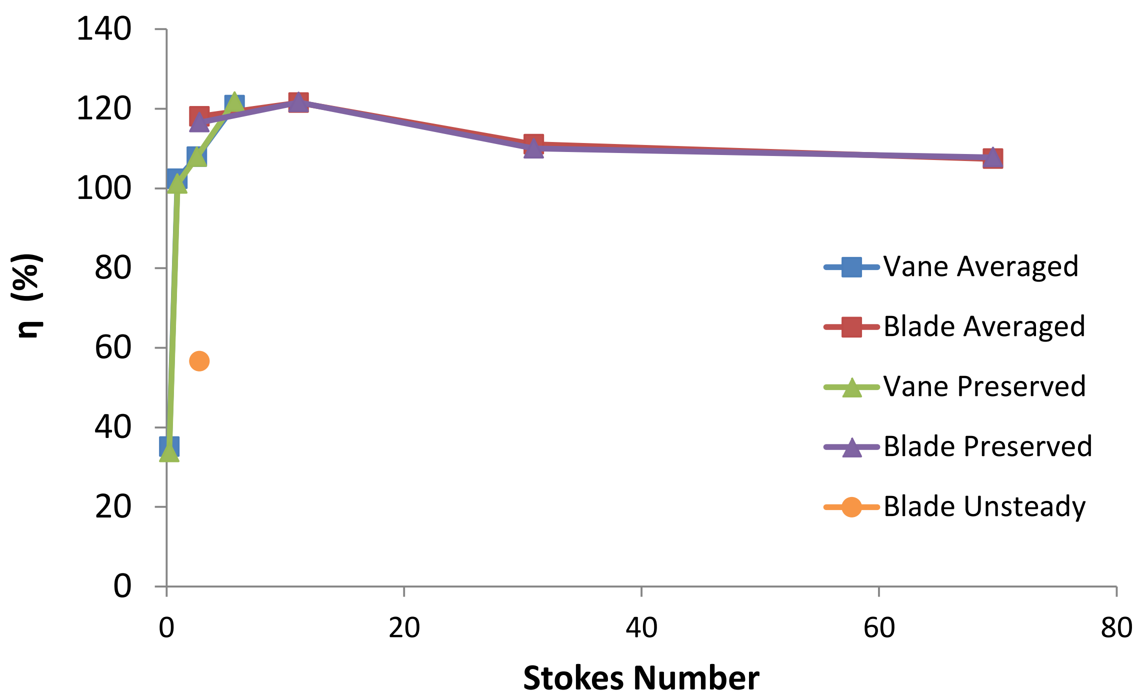
Impact and Capture Efficiencies



$$\varepsilon_v = \frac{N_{i,v}}{N_{inj,v}} \quad , \quad \varepsilon_b = \frac{N_{i,b}}{N_{inj,b}} \qquad (3)$$

$$\eta_v = \frac{N_{d,v}}{N_{inj,v}} \quad , \quad \eta_b = \frac{N_{d,b}}{N_{inj,b}} \qquad (4)$$

Impact Efficiencies vs. Stokes



D (μm)	$St_{k,\ vane}$	$St_{k,\ blade}$
3	0.2	2.8
6	0.9	11.1
10	2.5	30.9
15	5.7	69.6

$$St_k = \frac{\rho_p d_p^2 V_i}{18 \mu_{T_p} l_c}$$

URETI Stage Plan

- Have the tools we need to perform deposition modeling with mixing plane method. We are honing our tools for unsteady simulations.
- A case with radial profile and hot streak will be performed next to be able to compare the results.
- Will perform unsteady modeling of hot streak through a stage and effect of phantom cooling from vane coolant will be performed.