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

THE OHIO STATE UNIVERSITY

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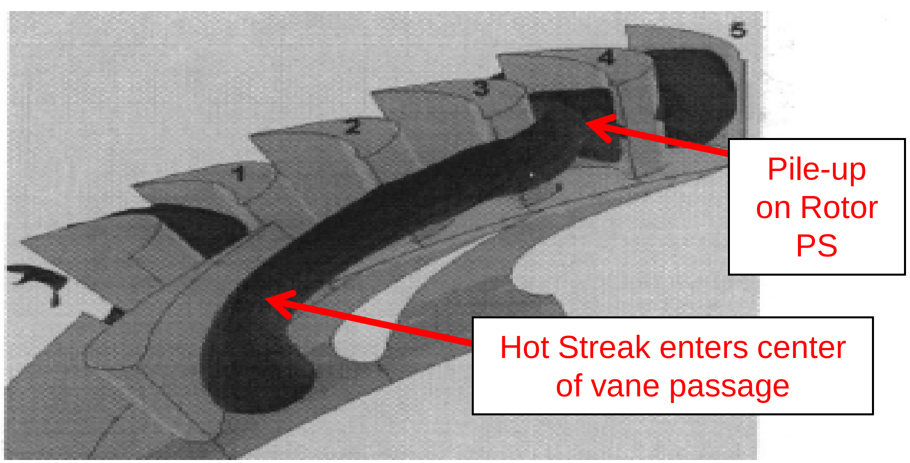
MOTIVATION

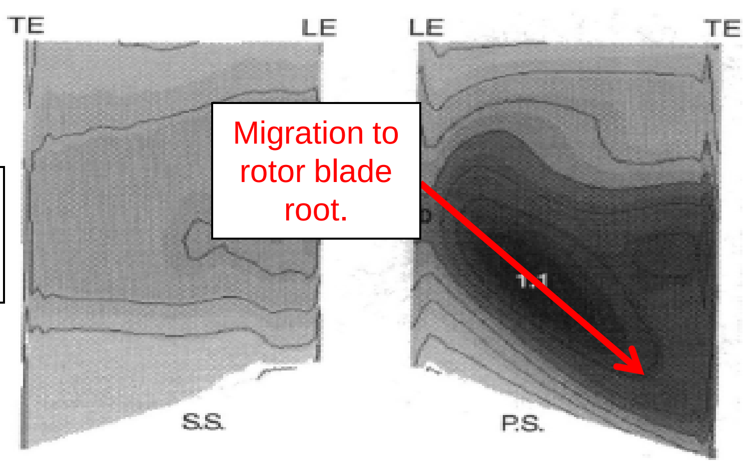
- Future gas turbines operating with HHC fuels will have higher turbine inlet temperatures relative to natural gas operation.

- 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)



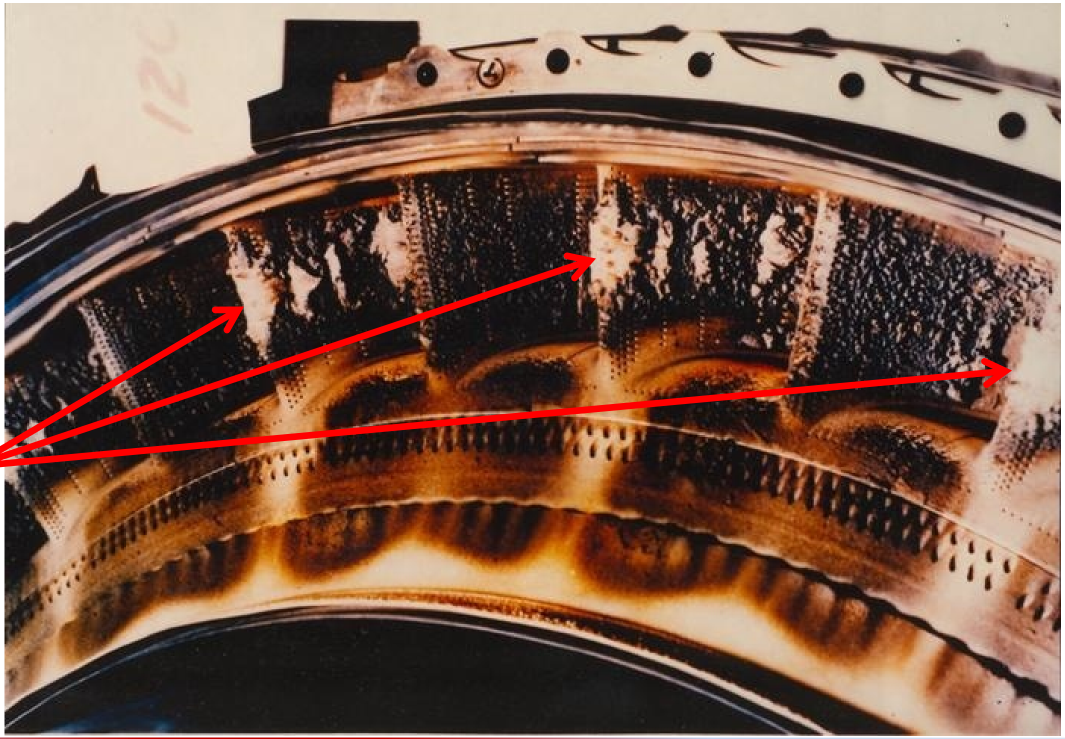
Time averaged surface temperature on rotor suction (left) and pressure (right) surfaces.

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) Uncooled/Cooled Rotor

RESEARCH TEAM

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

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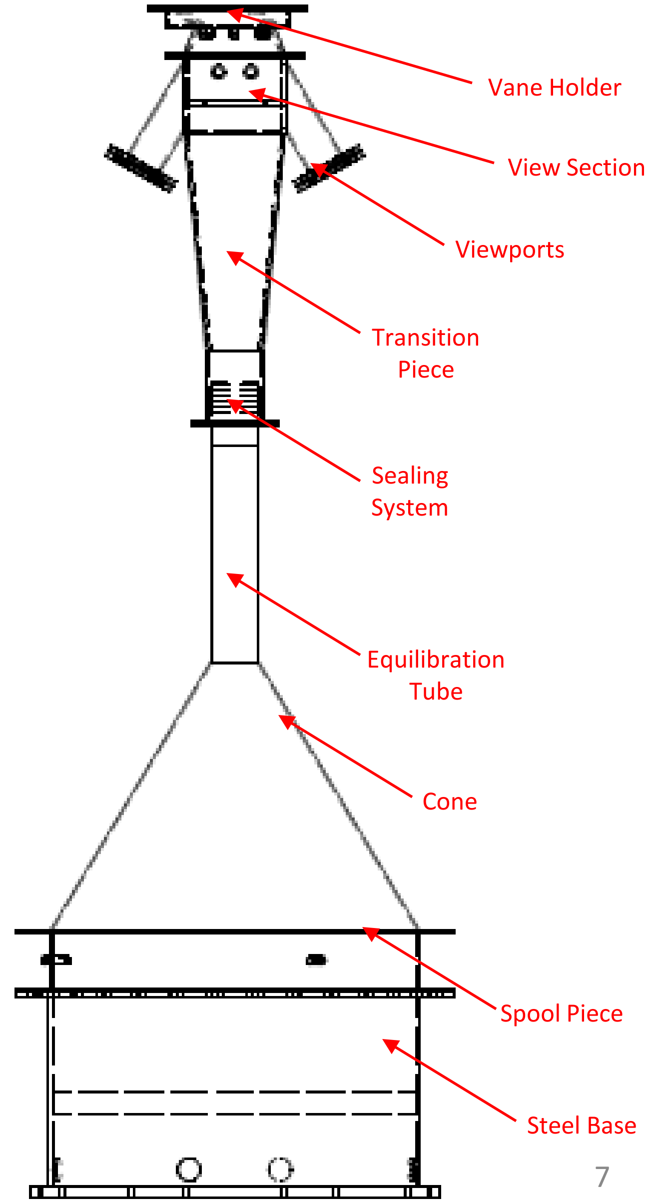
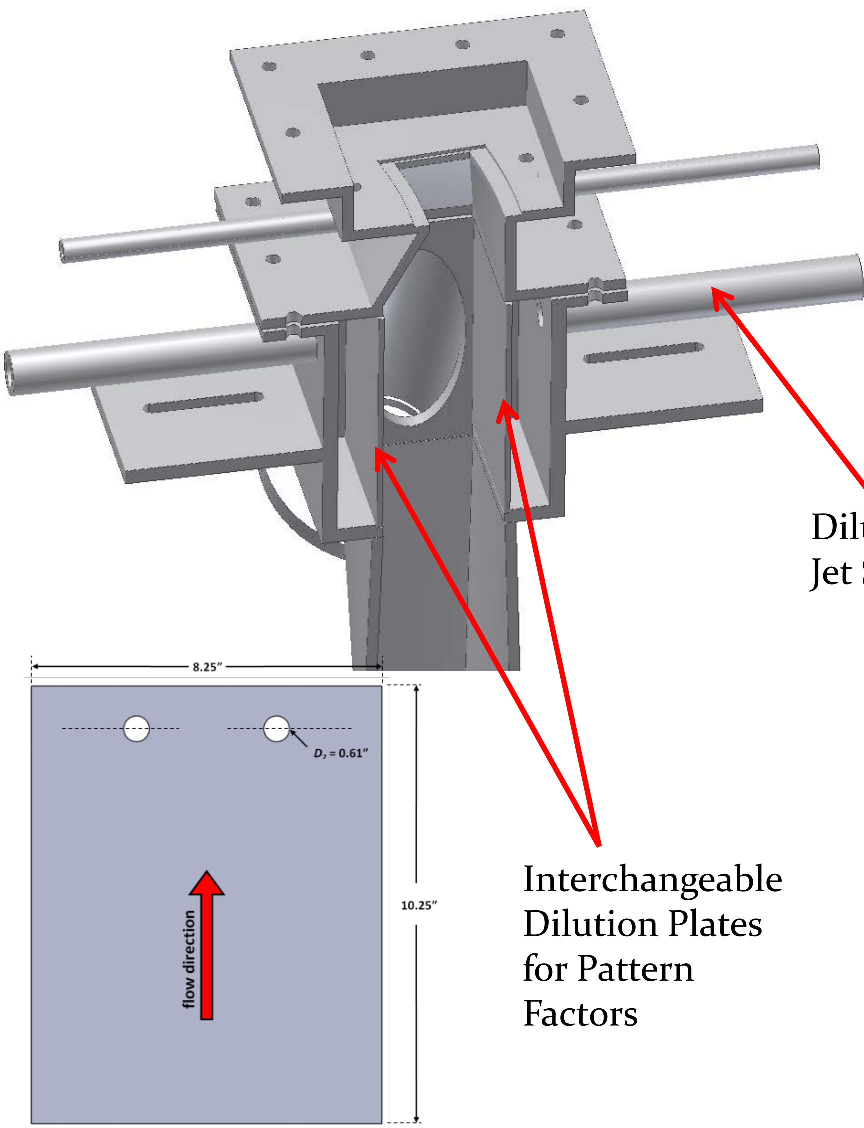
OSU's Turbine Reacting Flow Rig (TuRFR)

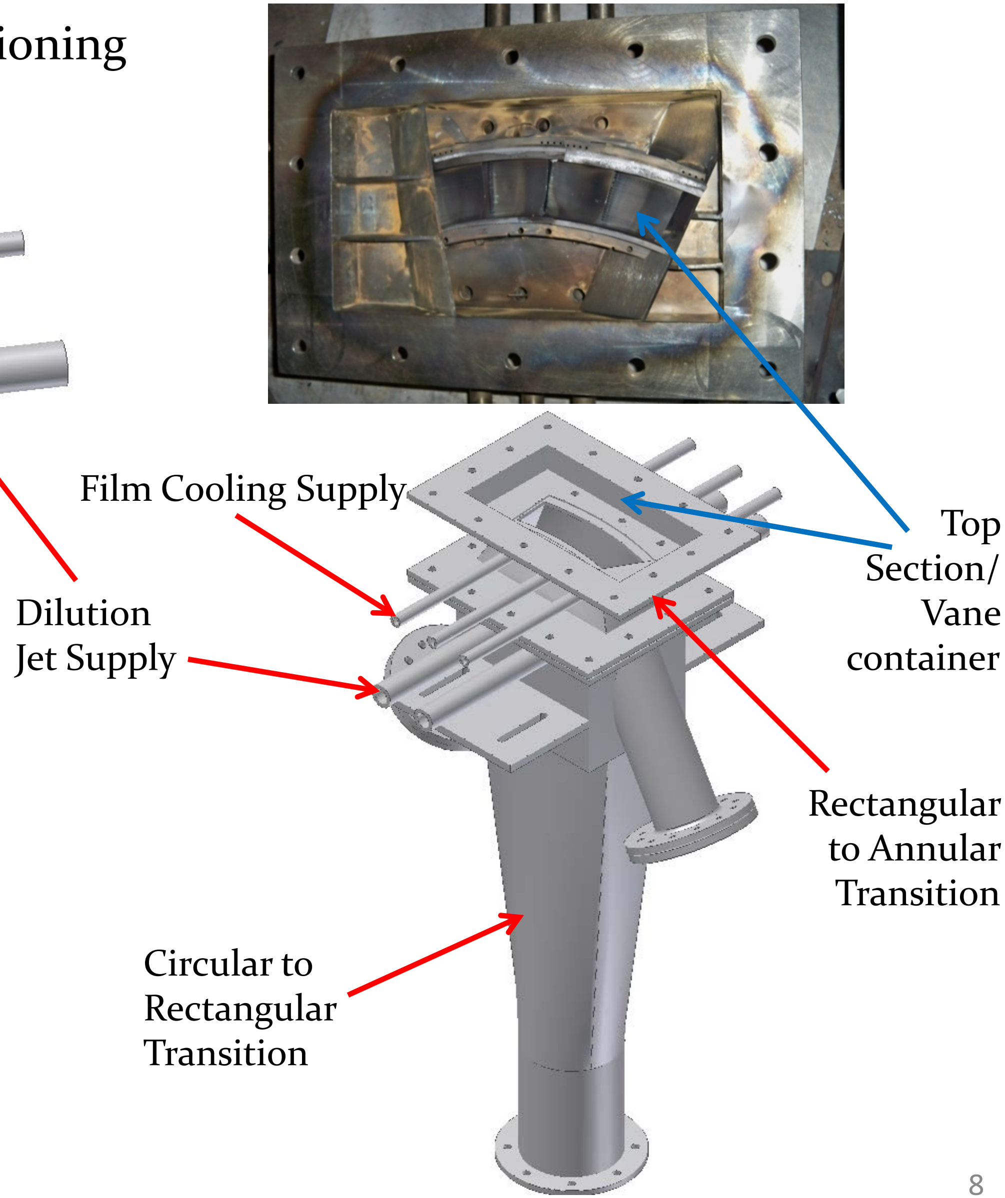
- Natural gas burning combustor rig
- Combustor exit flow accelerated in cone nozzle
- Transition from circular to annular sector
- Real vane hardware (industry supplied) installed in annular cascade sector
- Tt4 up to 1120° C (2050° F)
- Inlet Mach number ~ 0.1
- $300{,}000 < Re_{cex} < 1{,}000{,}000$
- Adjustable inlet temperature profiles
- Adjustable inlet turbulence profiles (through dilution jets)
- Film cooling from vane casing and hub (density ratio 1.6-2.0)
- Ash particulate feed in combustion chamber (10 μm MMD)



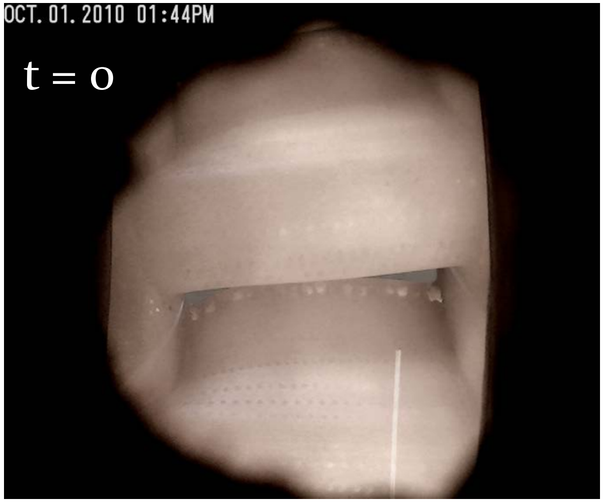
OSU's Turbine Reacting Flow Facility (TuRFR)

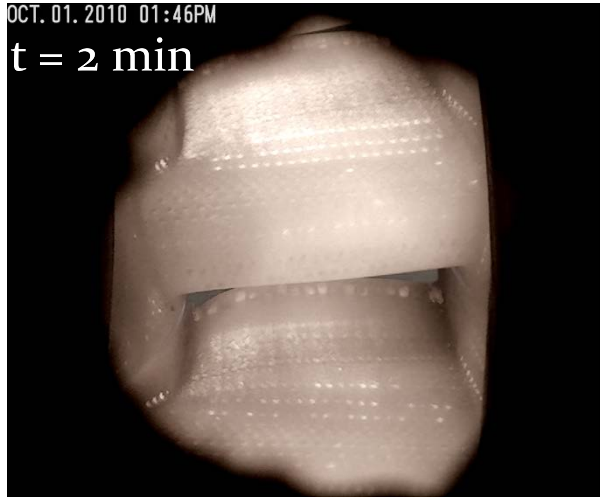
Vane Holder and Upstream Conditioning

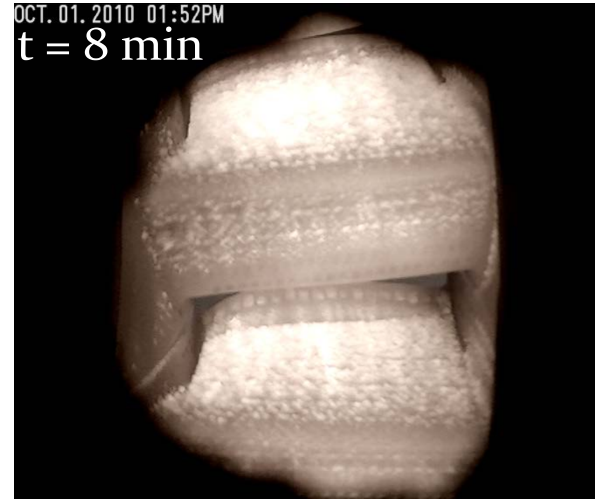


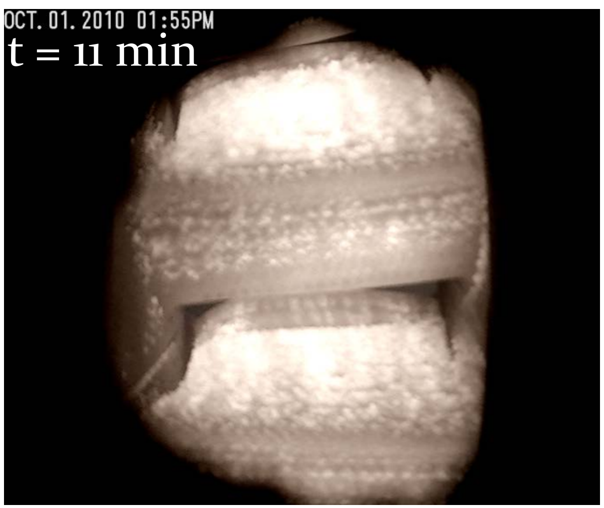


Typical TuRFR Test Sequence

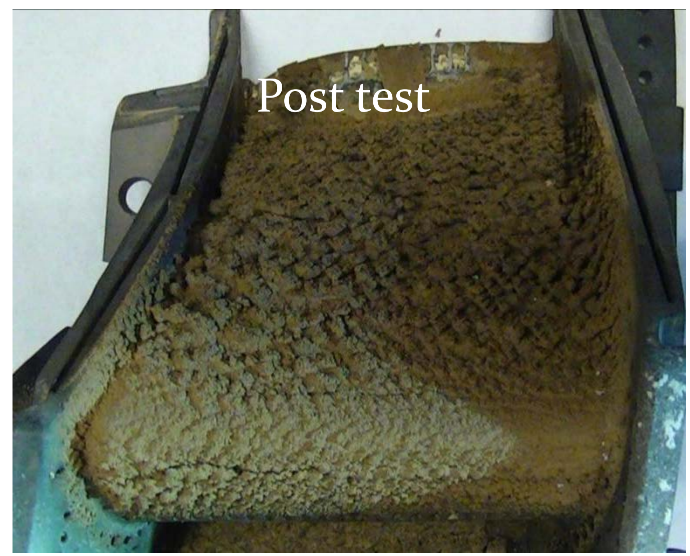








Time Lapse Images
Wyoming
Sub-Bituminous Ash
Test Conditions:
T_{t4}~1900F
M_{in}=0.90



PHASE 1: Uncooled Vane

- Revisit OSU’s current deposition model
- Consult with industry to determine representative hot streak for power turbine.
- Generate hot streak in TuRFR
- Measure hot streak migration and adiabatic wall temperature (uncooled vane)
- Measure deposition patterns and rates with hot streaks
- Compare model predictions with TuRFR hot streak and deposition measurements.
- Modify model as needed.

Accomplishments

- Preliminary CFD Study (AIAA ASM #2012-0474):
  - Modeled hot streak migration and deposition in E^3 vane.
- Characterized hot streak generation in TuRFR with RR vane
- Generated deposits on RR vane in TuRFR with hot streaks
- Developed CFD flow model for RR vane with deposition
- Identified Elastoviscoplasticity Model as candidate deposition model
- Designed, built, and tested model validation test piece

Preliminary Hot Streak CFD Study*

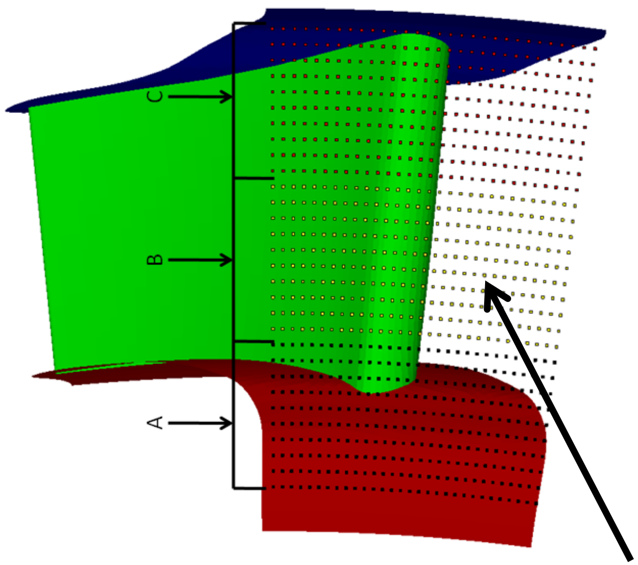
- Particle Trajectories modeled in FLUENT
- Eulerian-Lagrangian Model
- Particles introduced after flow model converges
  - Account for drag, heat transfer on particles
  - Account for turbulent dispersion
- Critical Viscosity deposition model (Tafti et al.)
- Sub-bituminous ash properties
- Gaussian hot streaks (1:2 ratio with vanes)
- 5% inlet turbulence

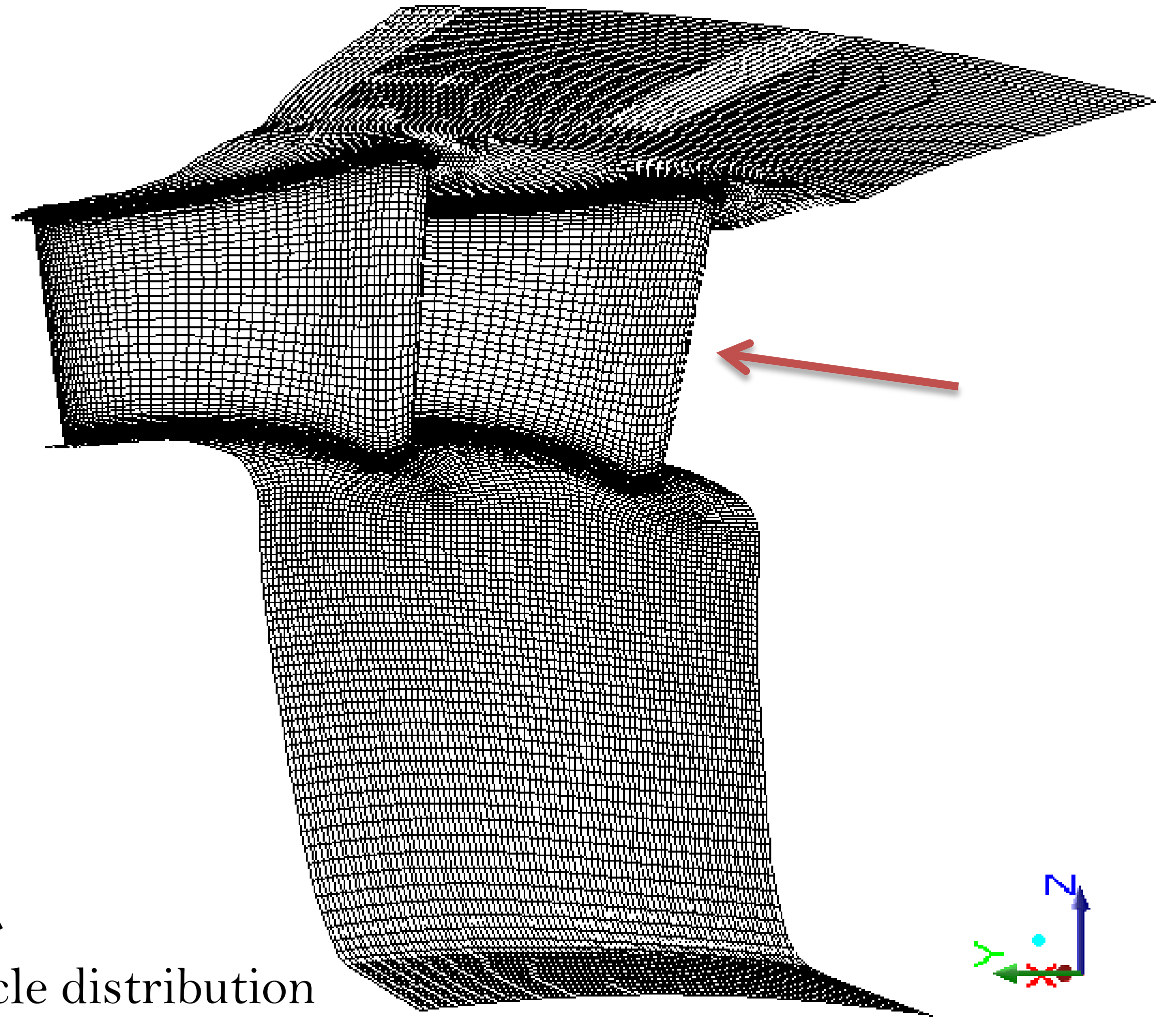
*Casaday, B.P., Ameri, A., Bons, J.P., 2012, "Effect of Hot Streaks on Ash Deposition in Turbine Vane Passage", presented at AIAA Aerospace Sciences Meeting in Nashville, TN, Jan 9-12, 2012. Paper #AIAA-2012-0474

Geometry and Grid

GE- E^3 HP-Vane

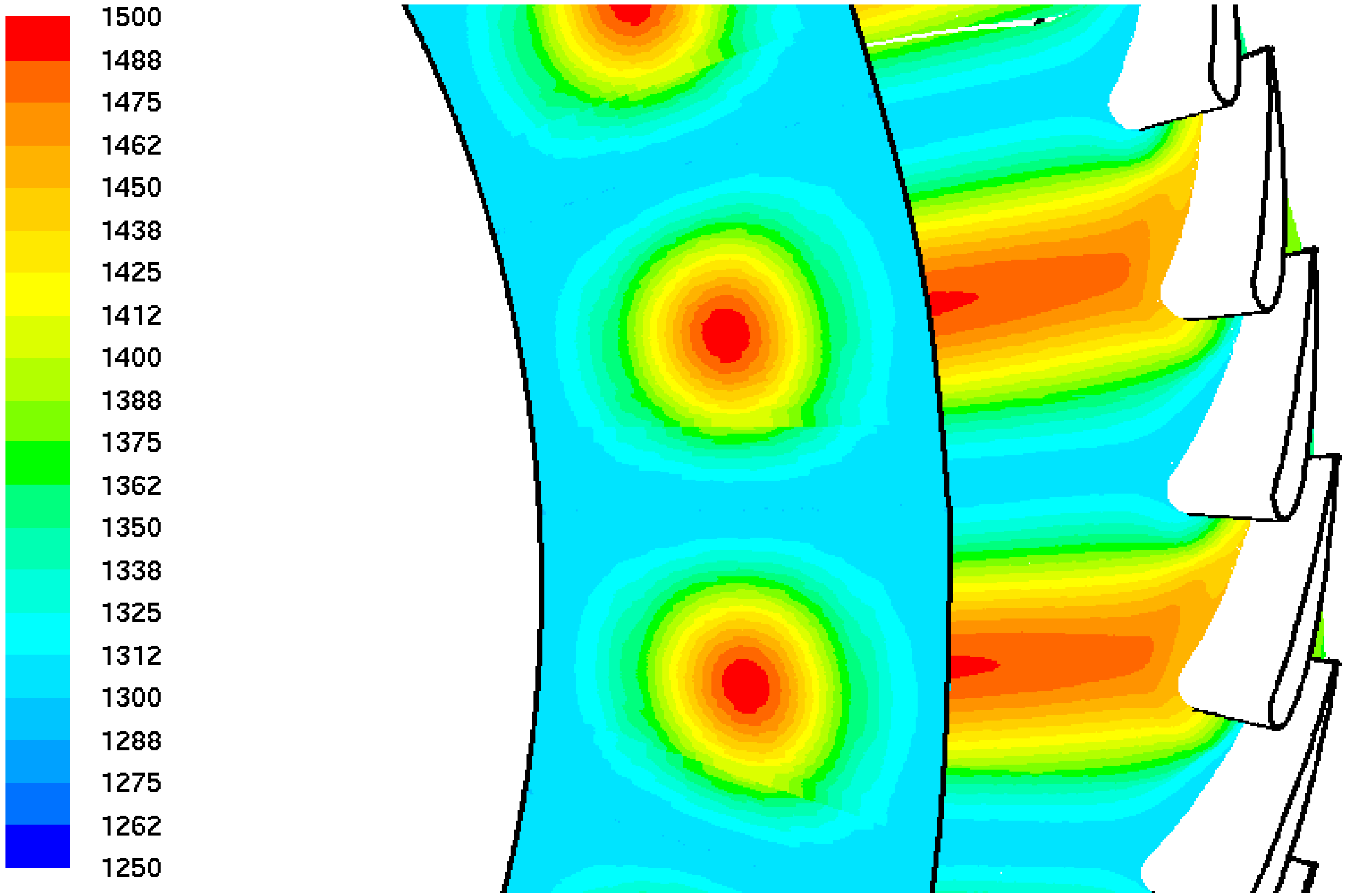
Extended inlet





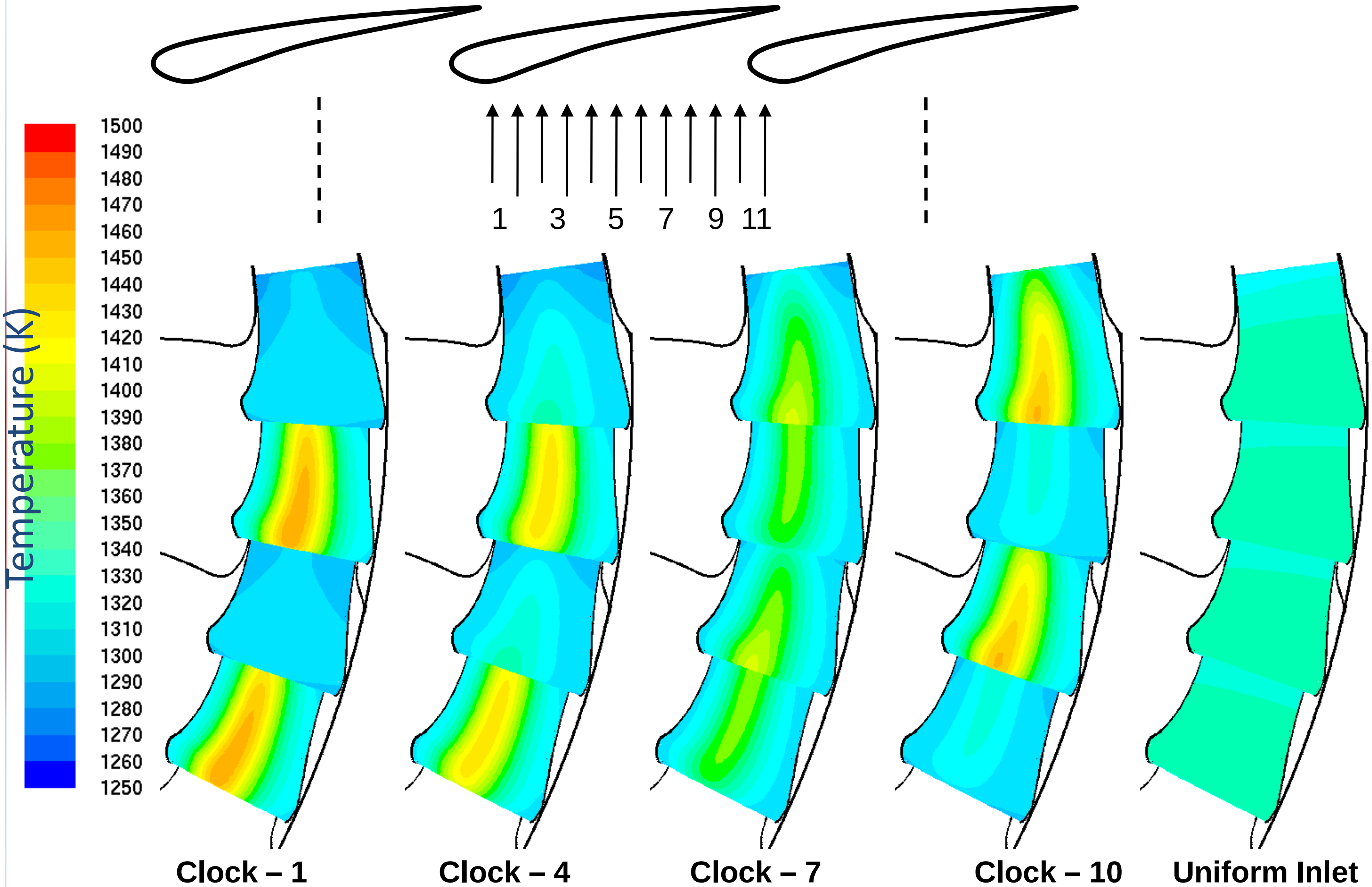
Uniform particle distribution at inlet plane.

Hot Streak Inlet Temperature Profiles

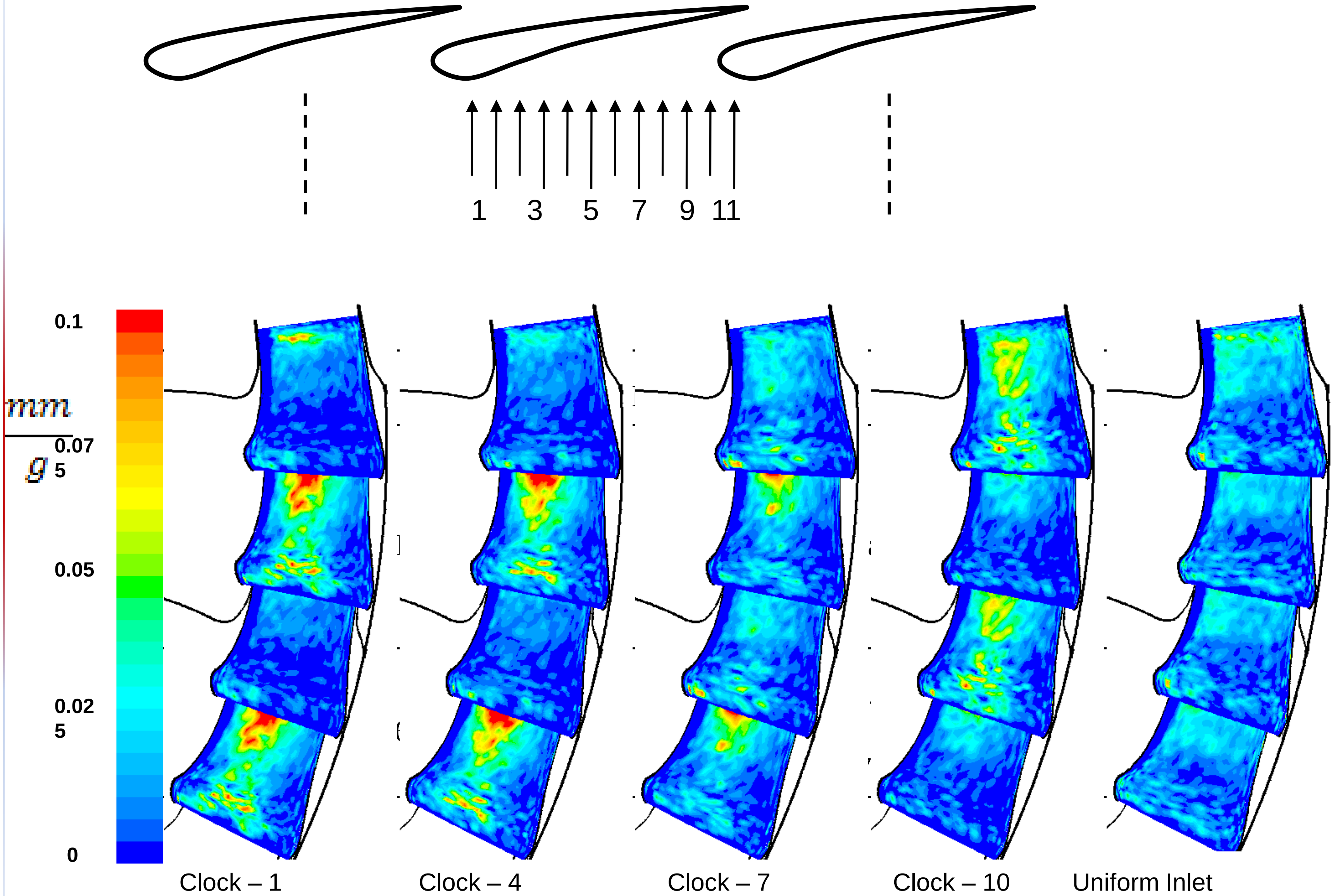


- One Streak per vane doublet.

Surface Temperature Profiles



Deposition Locations



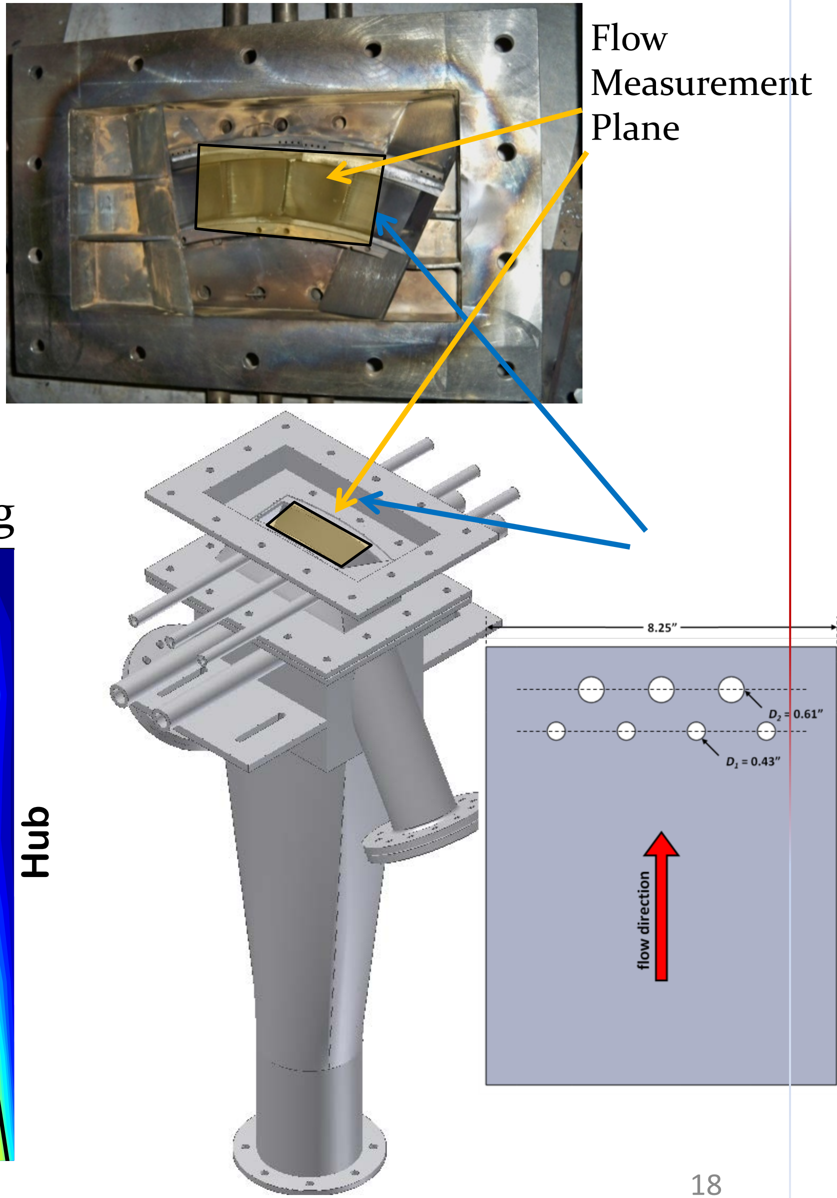
Conclusions of Preliminary Study

- For the turbulence level attempted, hot streaks survive the vane passages.
- The relative position (and count ratio) of H.S. w.r.t. to the vanes affect the deposition patterns.
- The relative position of H.S. w.r.t. to the vanes affect particulate content of the flow downstream of the vanes.
- The effect of H.S. on deposition is strongly related to the Stokes number.

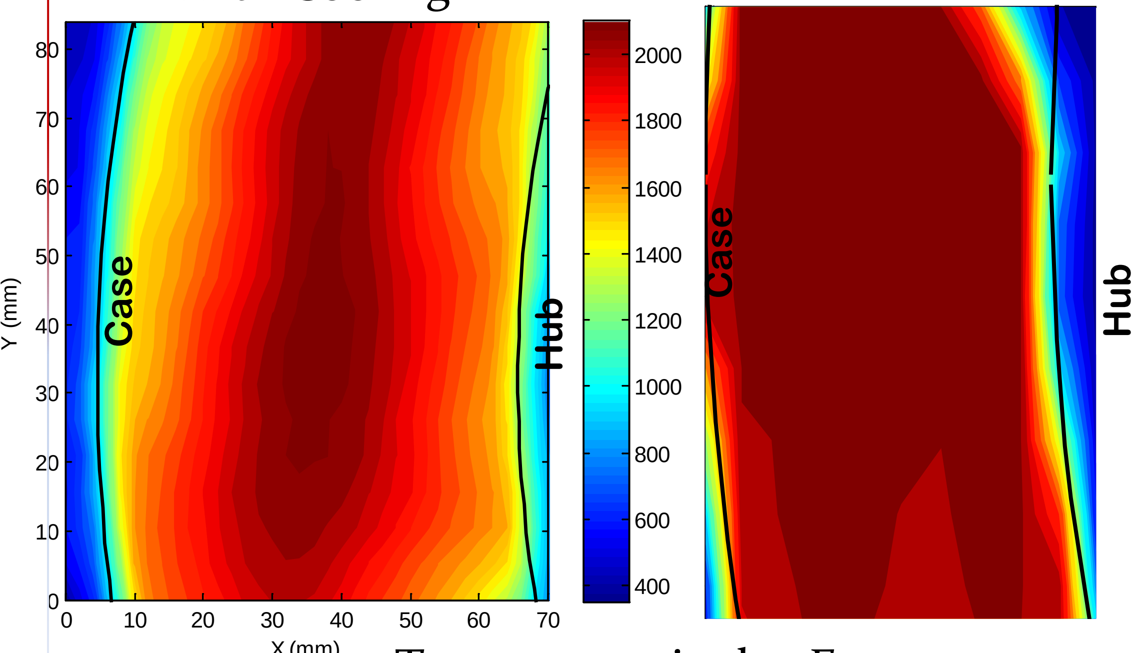
Initial Hot Streak Generation Attempt in TuRFR

Inlet Plane Temperature Profiles (without vanes installed)

- Dilution cooling causes radial temp. distribution
- Little change in tangential direction
- Uniform temp. distribution without cooling
- Peak to edge temp. - adjustable



With Cooling | Without Cooling

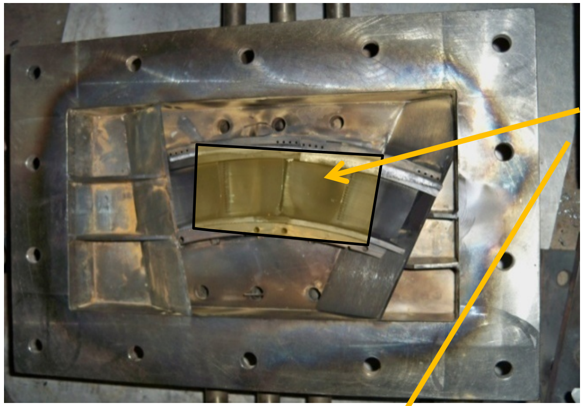


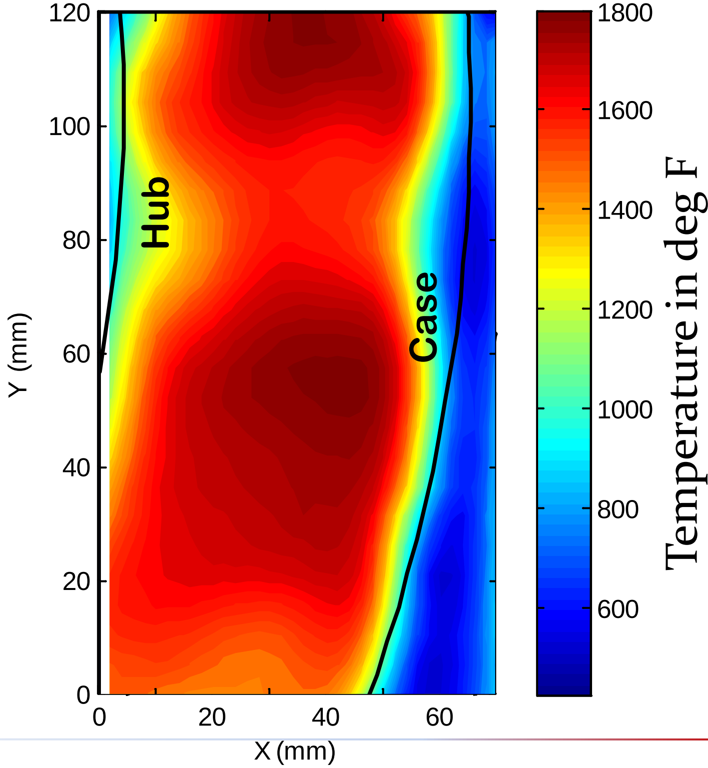
Temperature in deg F

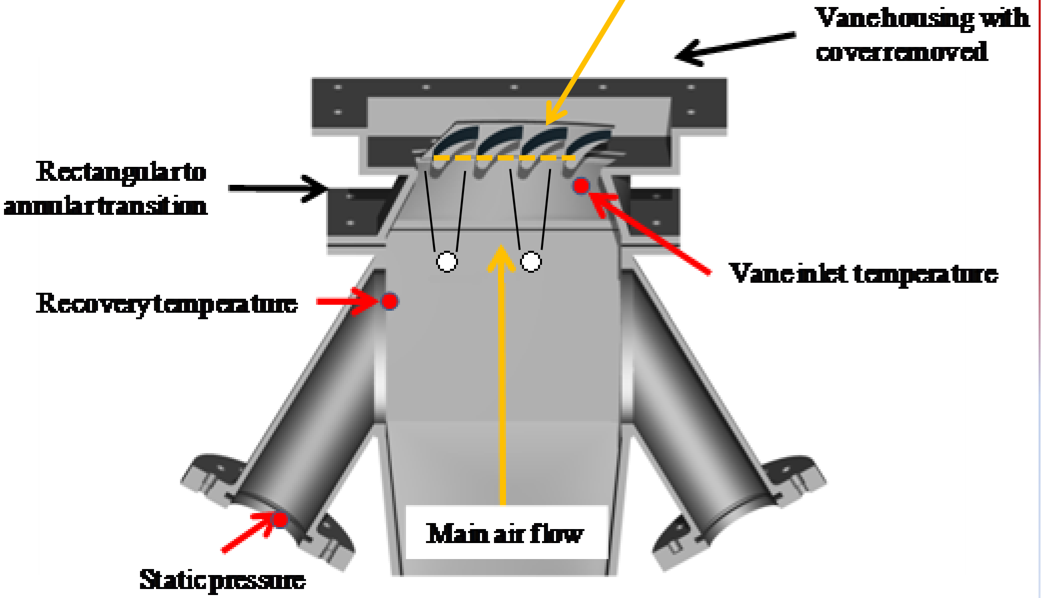
Hot Streak Generation – Iteration #2

New Plate Design

- Two ½” holes on each plate
- Spaced two vane pitches apart (to alternate hot vane, cold vane)
- Used empirical relation to ensure coolant penetration
- Offset hole locations to allow two clocking positions when plates are reversed



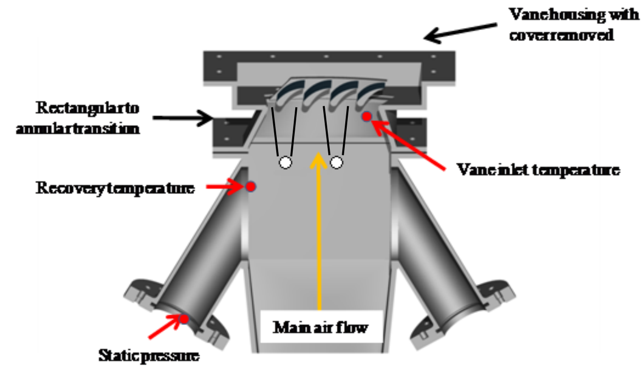




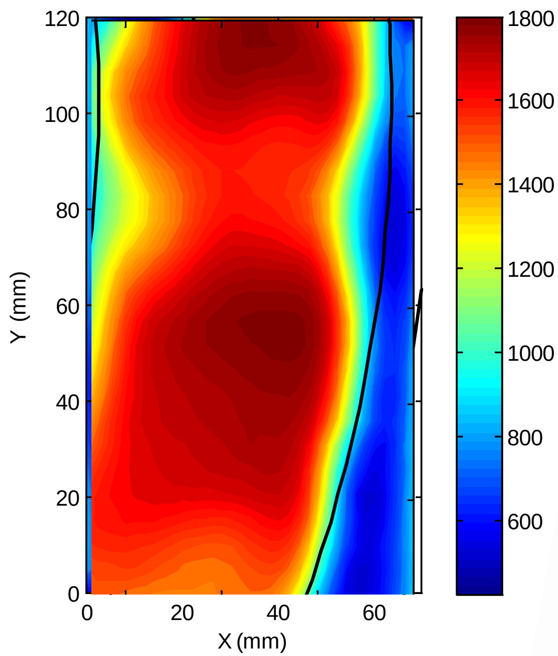
Hot Streak Deposition Test #1

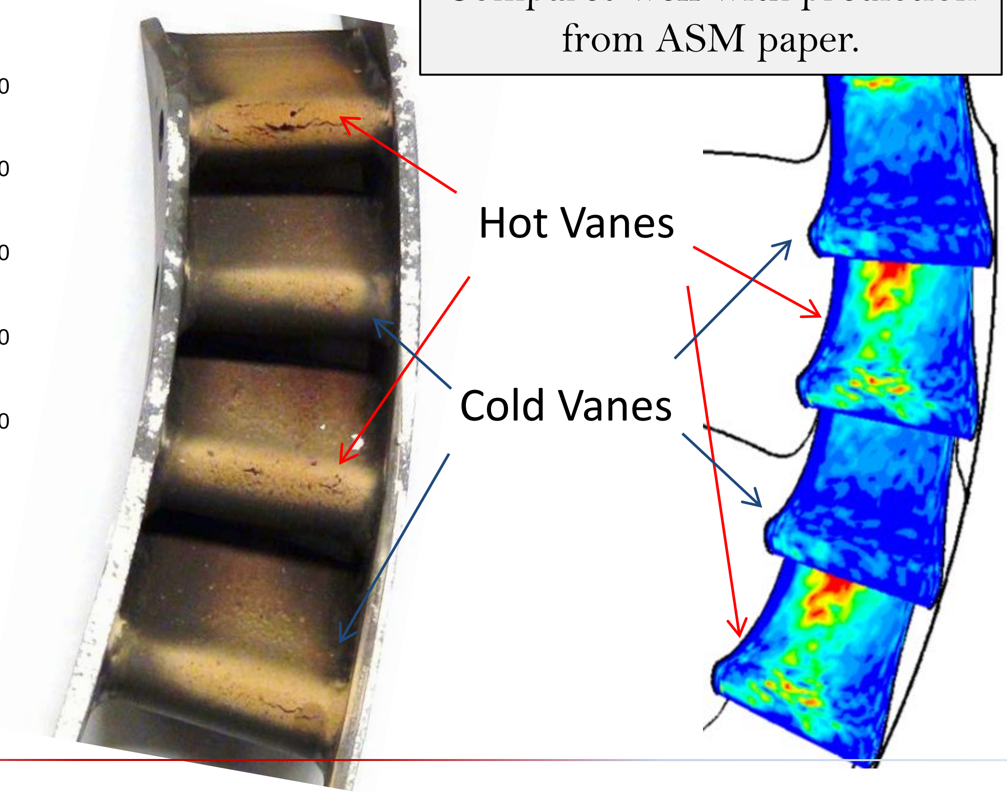
Deposition Test Using Hot Streak Temperature Profile

- Rolls Royce vane segment (no FC holes)
- JBPS ash, MMD=6.4 μm
- RESULTS: "Hot" vanes capture more particulate than "cold" vanes.



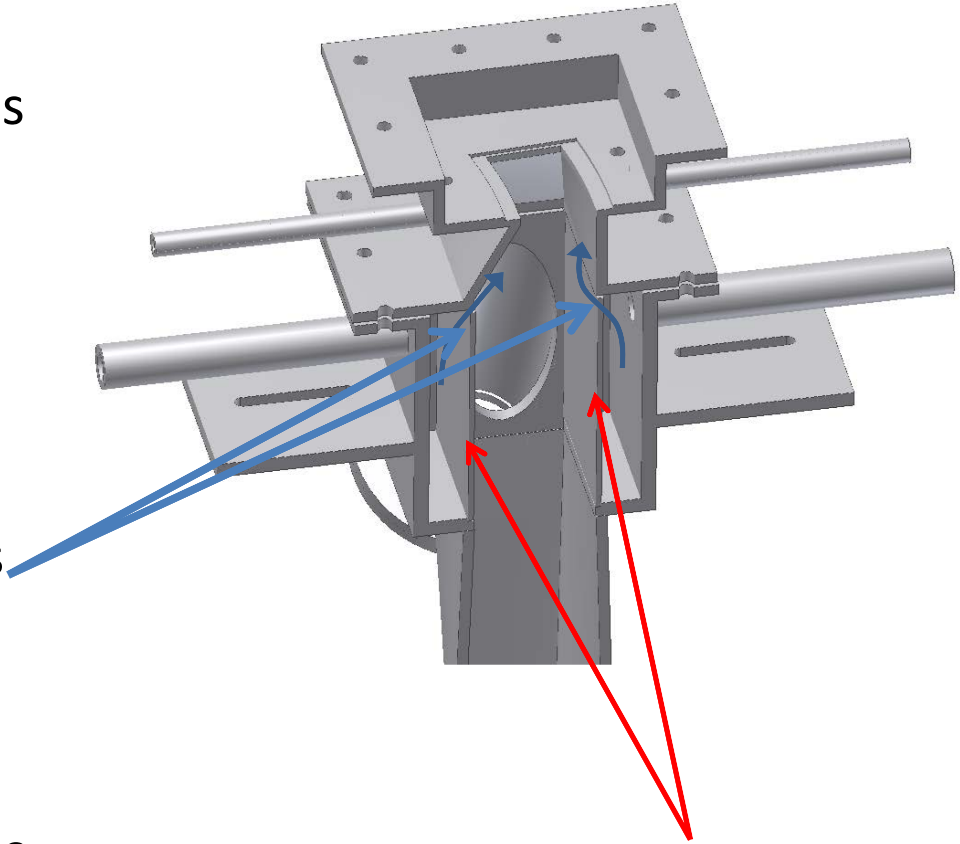
Compares well with prediction from ASM paper.





Post Test Assessment

- Qualitative match to predictions from ASM paper (GE E^3 vane)
- Rerun CFD calculation with matched TuRFR operating conditions and RR vanes – TOO MUCH DILUTION FLOW!
- Upon further inspection: plates were bowing and leaking dilution air into the flow
- Welded ribs to add more contact area and reduce leakage
- Repeat hot streak test

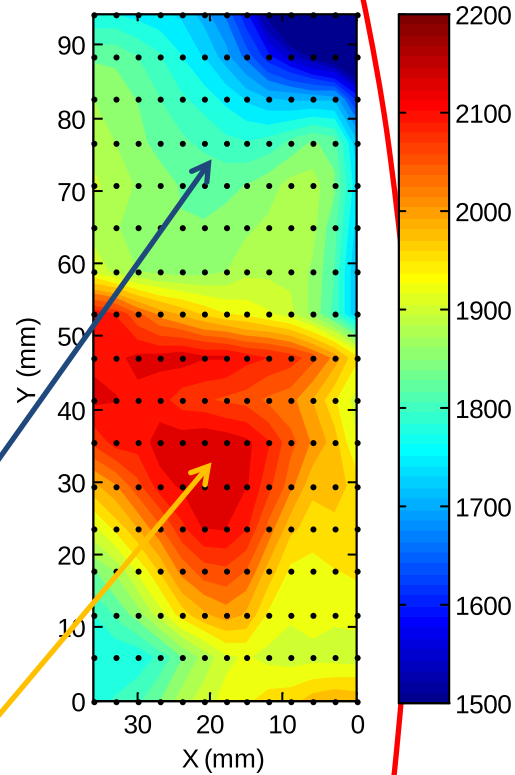


Interchangeable Dilution Plates for Pattern Factors

Hot Streak Deposition Test #2

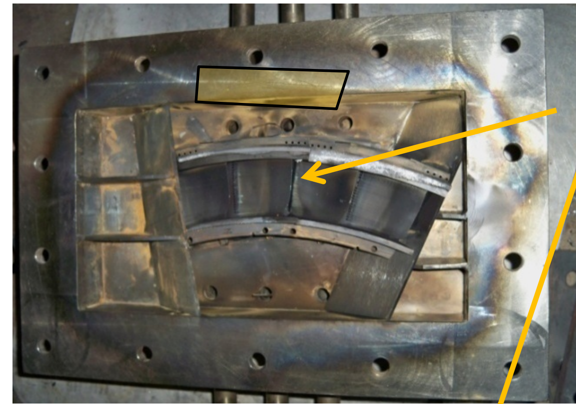
Exit survey with vanes installed

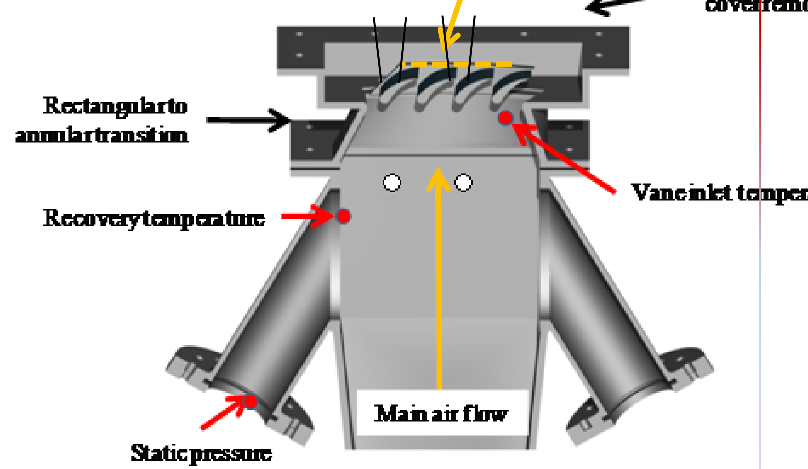
- RR vanes
- 15% dilution each side (same as test #1)
- Same ash size, type
- Limited accessibility for exit survey



Exit Flow from “Cold” Passage

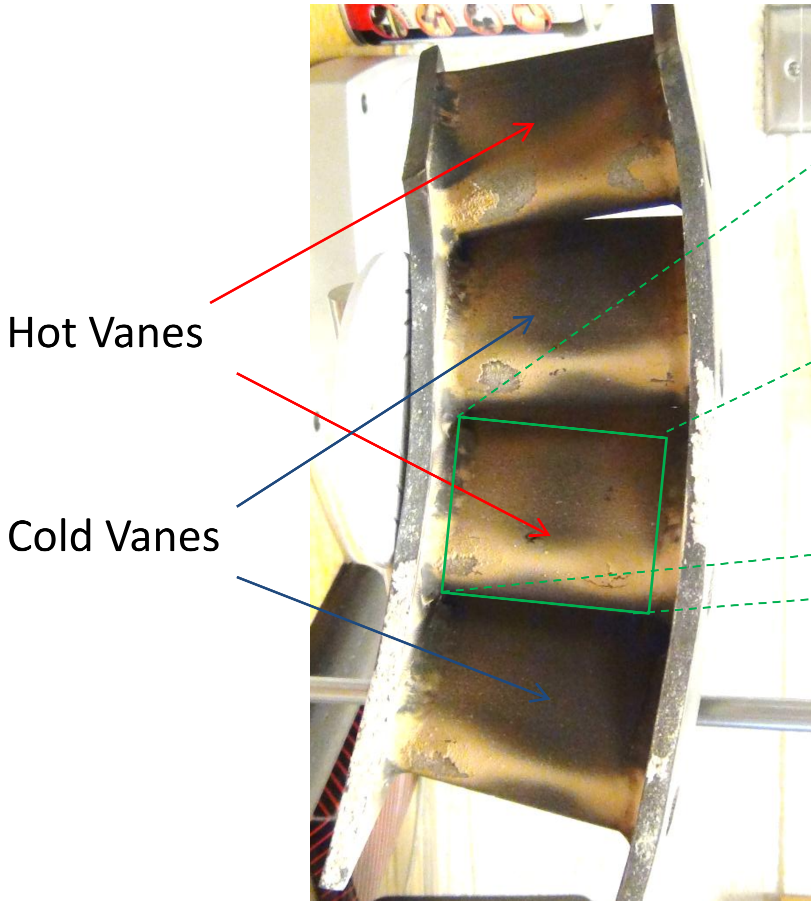
Exit Flow from “Hot” Passage

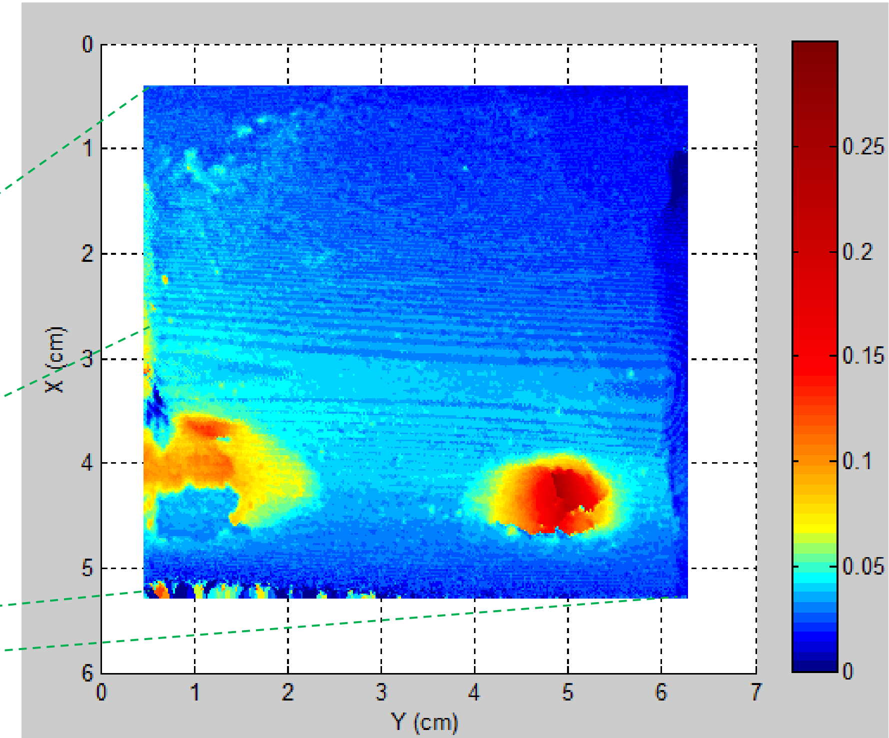




Hot Streak Deposition Test #2

- Deposits most prominent away from midspan.
- Hot vane only slightly higher accumulation than cold vane.
- CFD provides some answers.

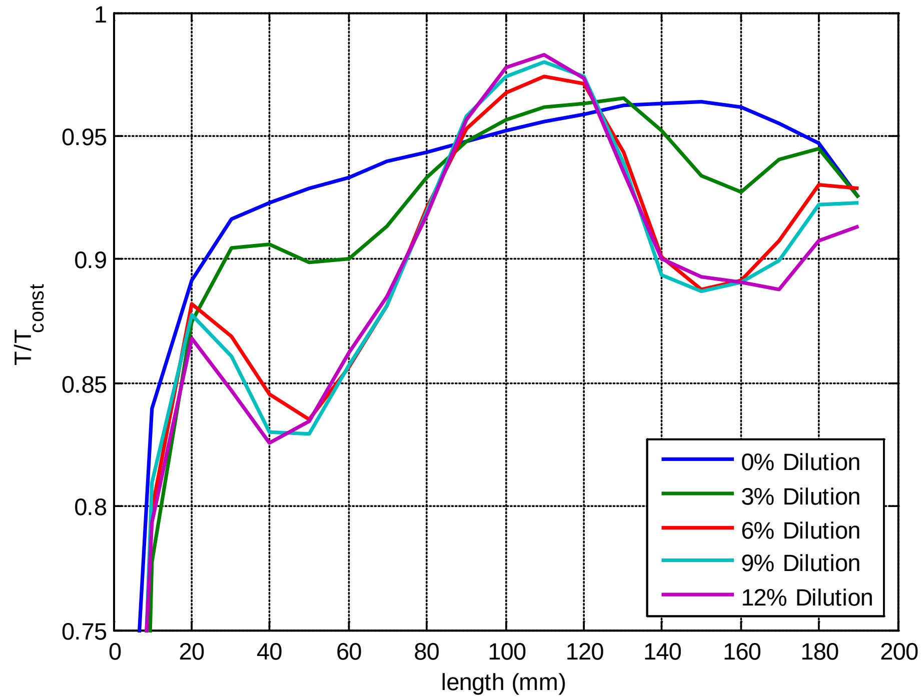


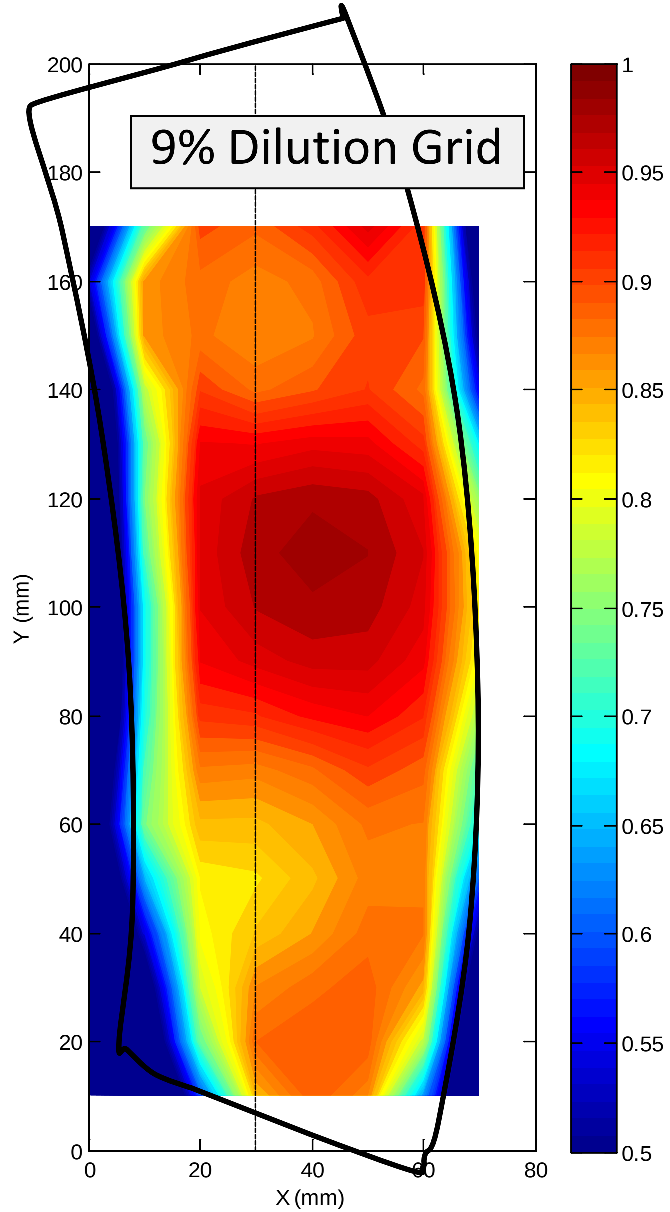


Deposit thickness on vane surface in cm

Hot Streak Deposition Test #3

- Pitchwise traces with varied dilution levels
- 2000 deg F base temp
- Percentage represents fraction of total flow from each side
- Dilution above 6% shows hot streak pattern at center of passage



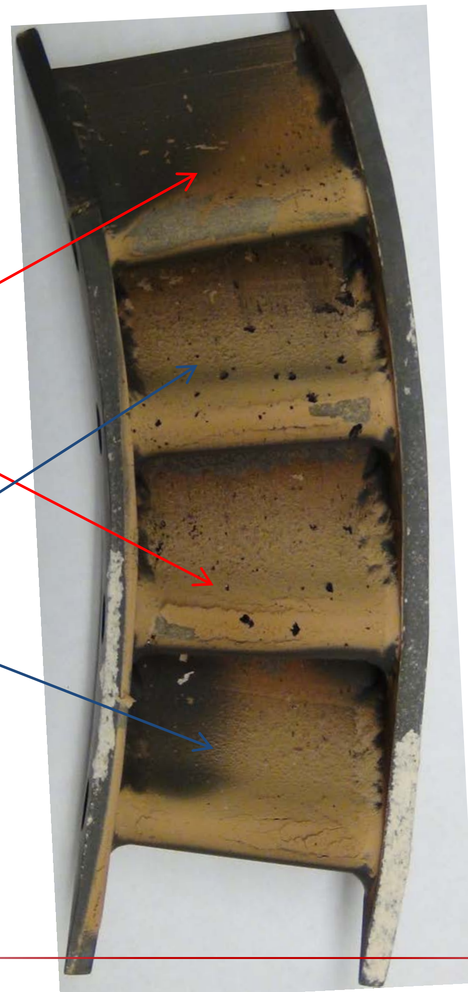


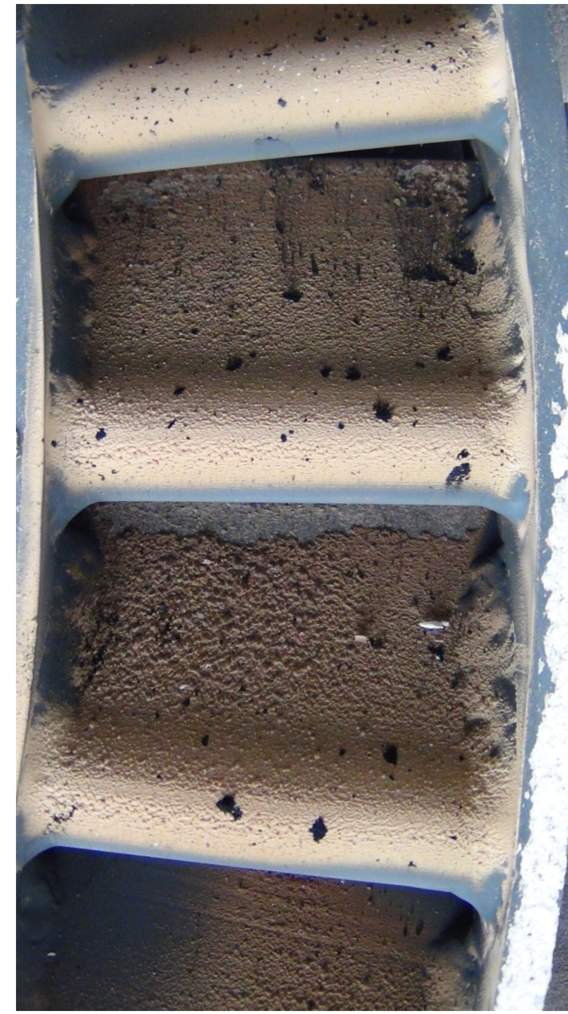
Hot Streak Deposition Test #3

- RR Vane set
- 9% Dilution each side
- Main temperature of (2000) deg F
- 91.1 g JBPS ash MMD=6.4 μm
- Weak evidence of hot streaks on deposition patterns
- 40% Higher capture efficiency on “Hot” vanes compared to “Cold” vanes

Hot Vanes

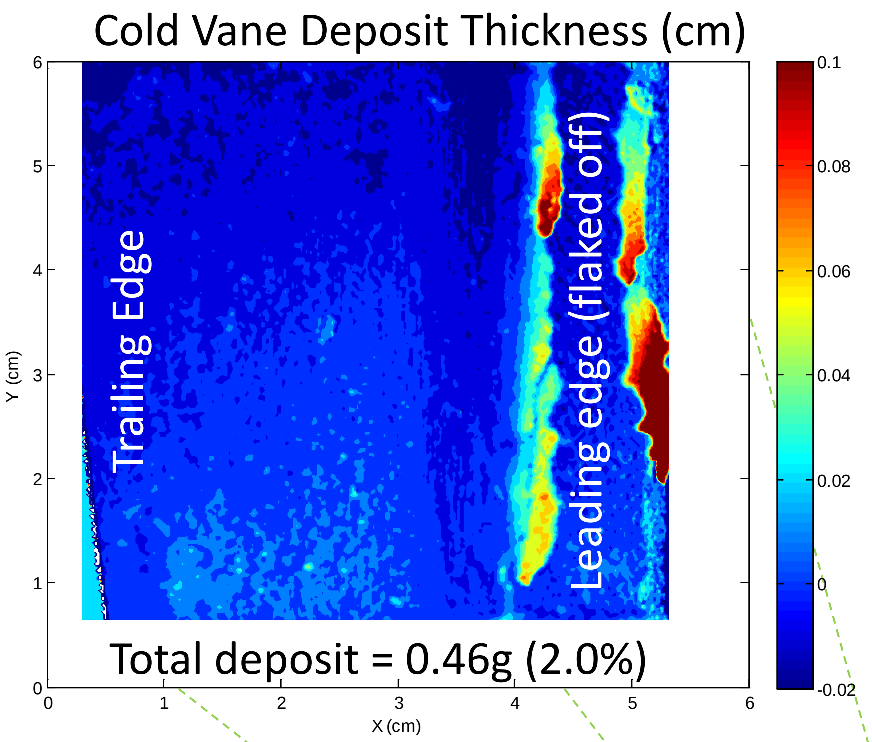
Cold Vanes

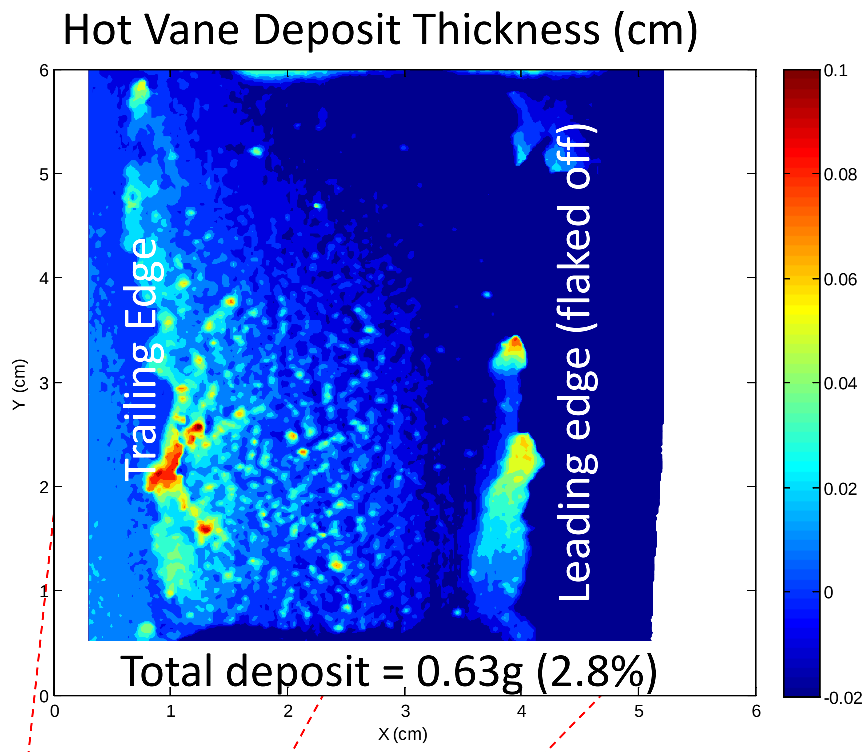




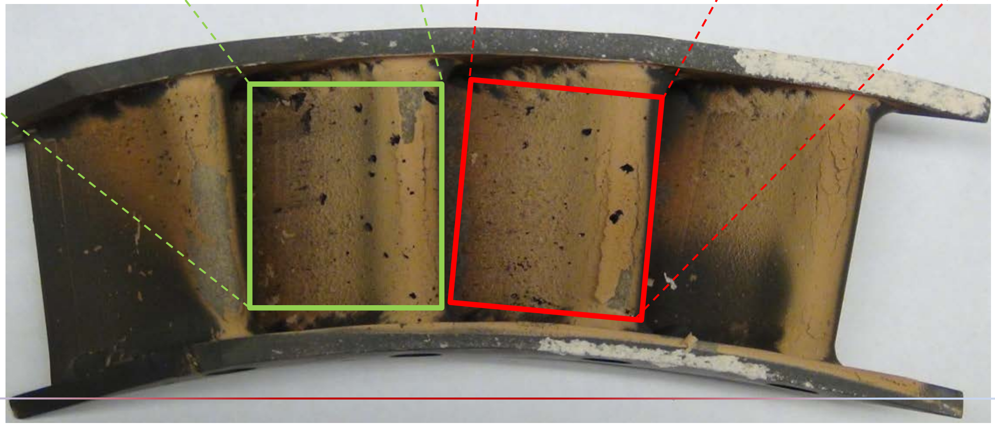
Laser Scan Results forthcoming

Hot Streak Deposition Test #3



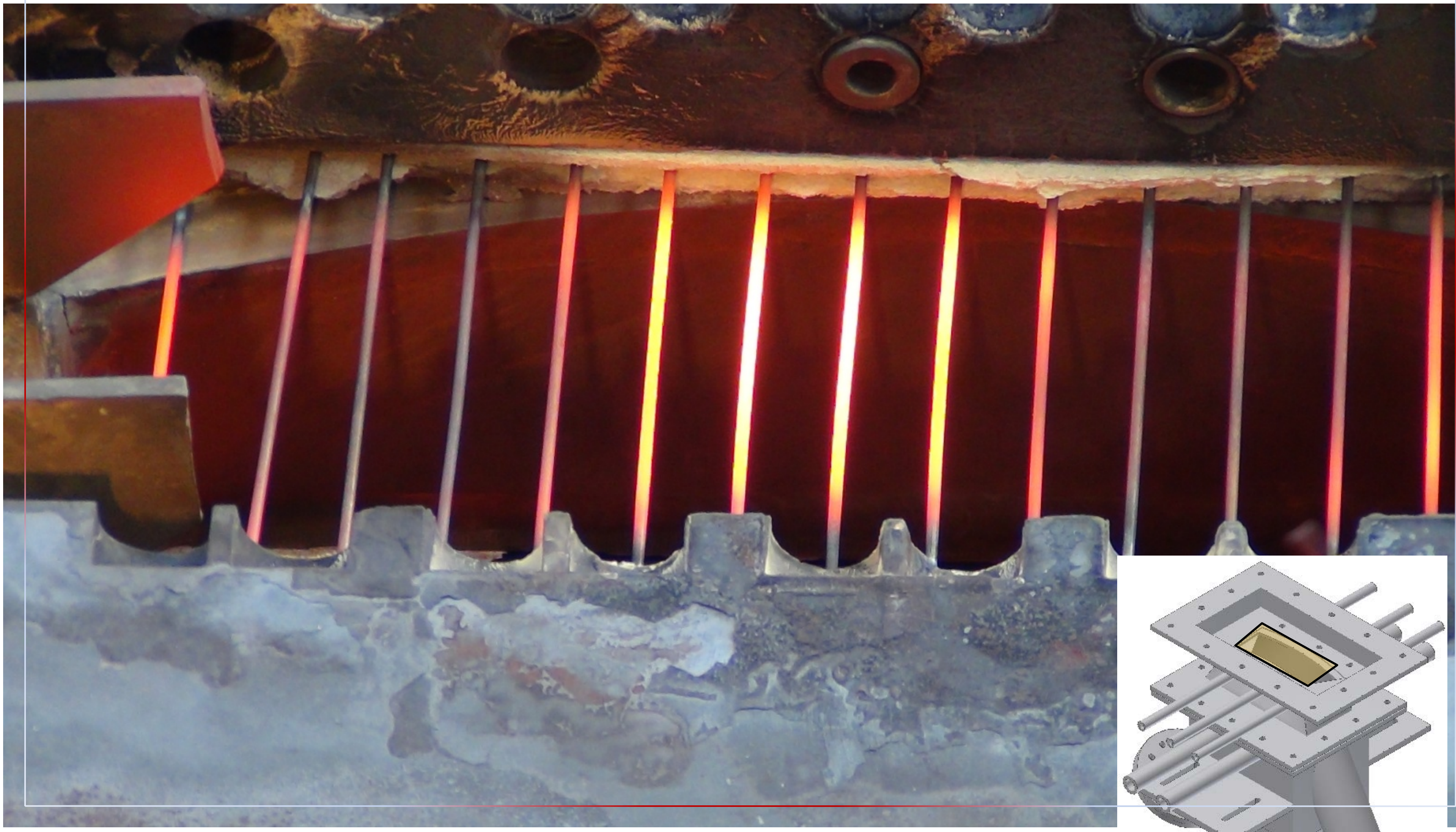


Scans show hot vane has thicker deposits over most of pressure surface

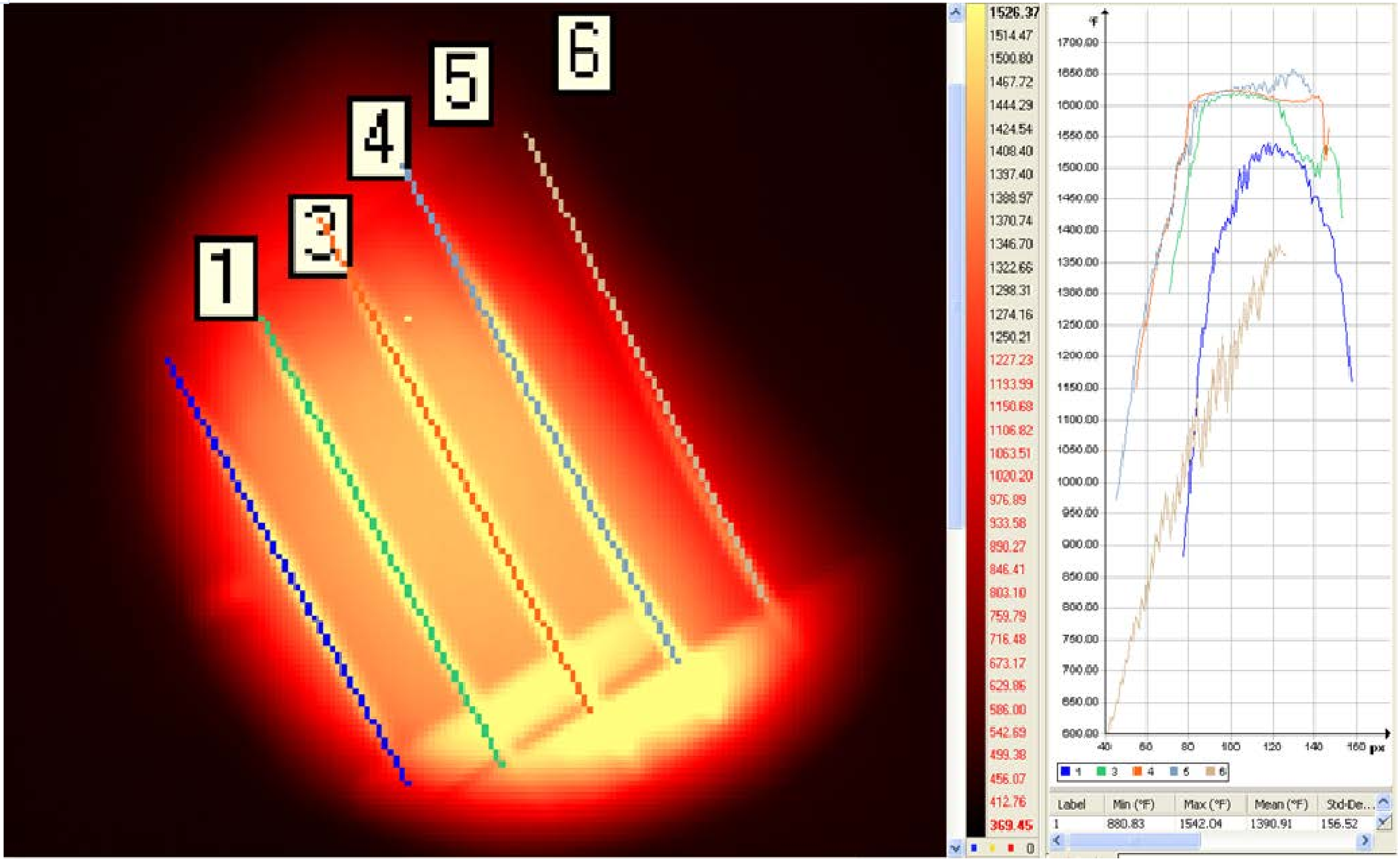


Inlet Plane Measurements with Vanes Installed

- Inconel Rods show hot streak location (without vanes)



Survey with Vanes - IR Image of Rods



- Use inverse method to infer flow temperature.
- Steady state energy equation
- Balance between axial conduction and local convection.
- Results pending…

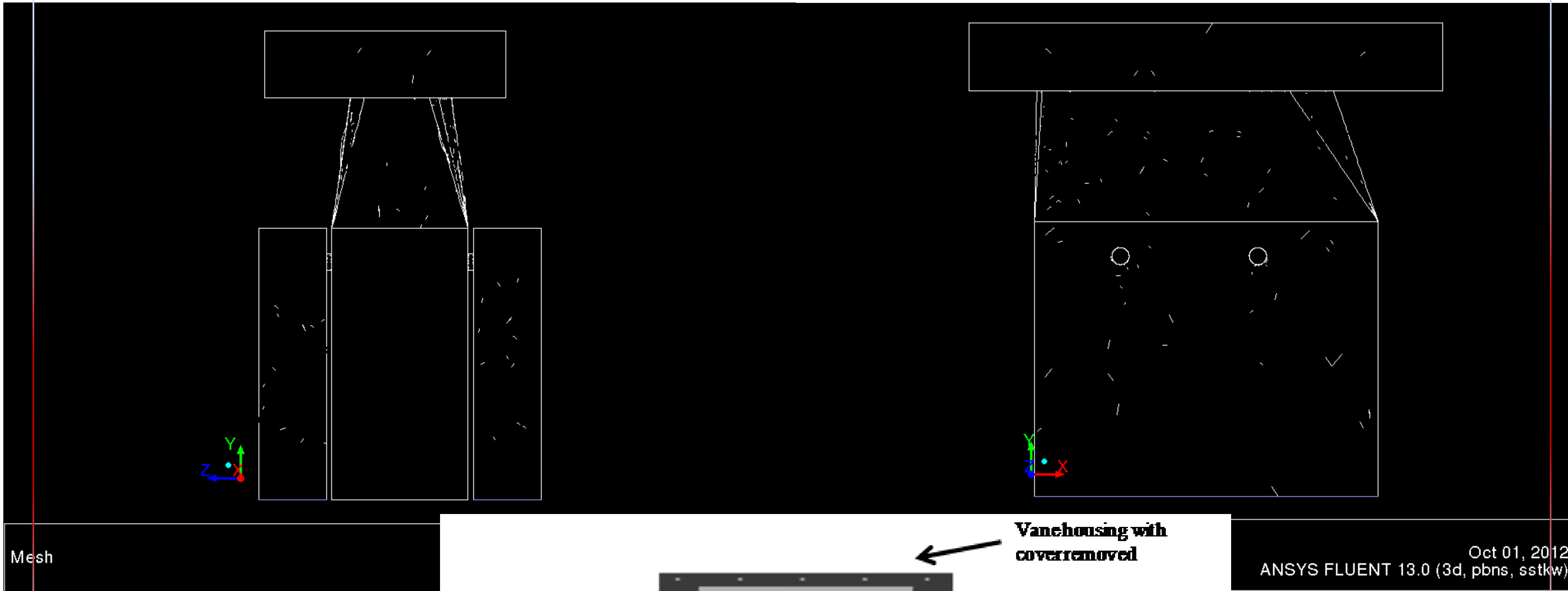
Modeling of hot streak and deposition in the TuRFR

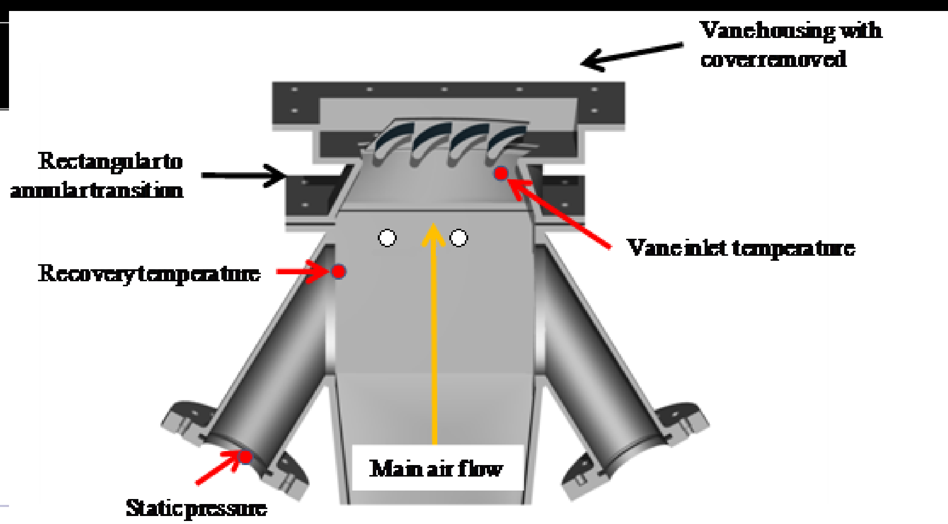
- Measurements of inlet boundary conditions including the hot streaks were made without the vane at a location upstream of where the leading edge of the vane would be.
- Matching the measured inlet b.c. (including the hot streaks) by modeling the flow passage upstream including the dilution flows.
- Initially simulation exclude the vanes to match the vane inlet boundary condition.
- Upon matching the vane inlet condition, vanes are included.
  - Run deposition and compare with experimental tests.

Vane Inlet Conditions

- Match to experimental conditions as closely as possible.
- Determine if boundary conditions lead to inlet profile that matches measurements.
- Domain consists of section of TuRFR upstream of inlet.
  - Excludes vanes
  - Includes dilution jets
- Use measured information for boundary conditions where possible.

Vane Inlet Conditions - Domain

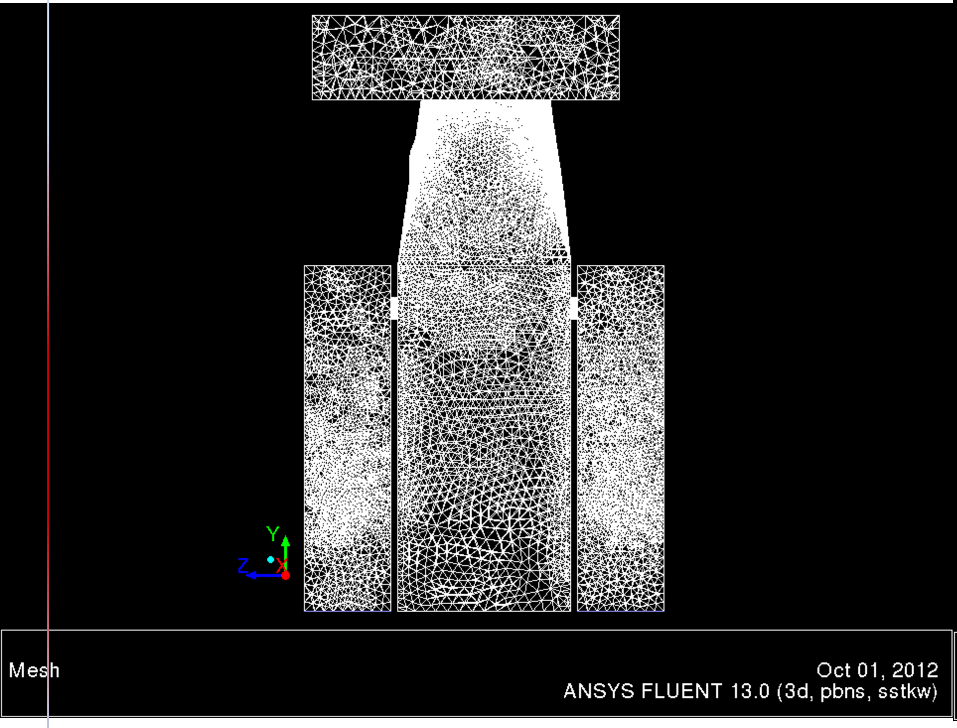


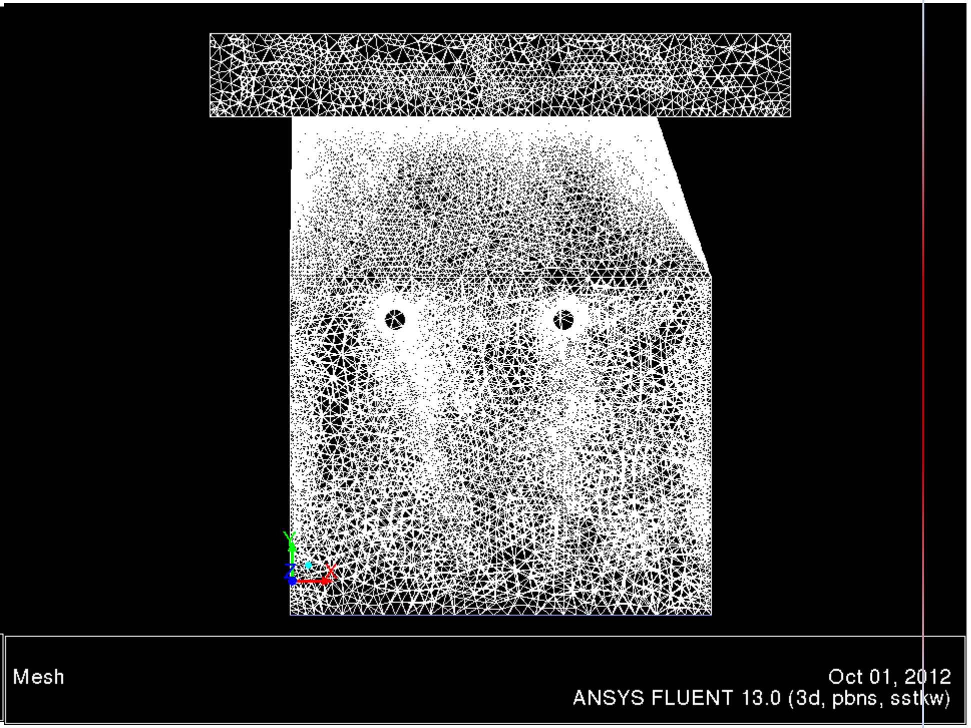


Grid

- Unstructured mesh.
- About 2.5 million cells.
- Began with a relatively coarse grid and refined using FLUENT's adaption based on gradients:
  - Assumption that error occurs in regions with large gradients
  - Adapted based on large temperature gradients
  - Region where cold jets interact with hot crossflow refined

Vane Inlet Conditions - Grid





Vane Inlet Conditions – B.C.'s

- Main inlet and dilution inlets set as mass flow inlet boundary conditions:
  - Constant mass flow rate
    - For each dilution jet, inlet set as a percentage of total mass flow
  - Constant temperature
    - Main inlet temp.:1366K, Dilution inlet temp:: 310K
  - Turbulence intensity
    - Main inlet: 5-10%
    - Dilution inlets: 5%
- Outlet set as a pressure outlet:
  - Target mass flow rate set: 0.3636 kg/s (total mass flow rate)

Vane Inlet Conditions

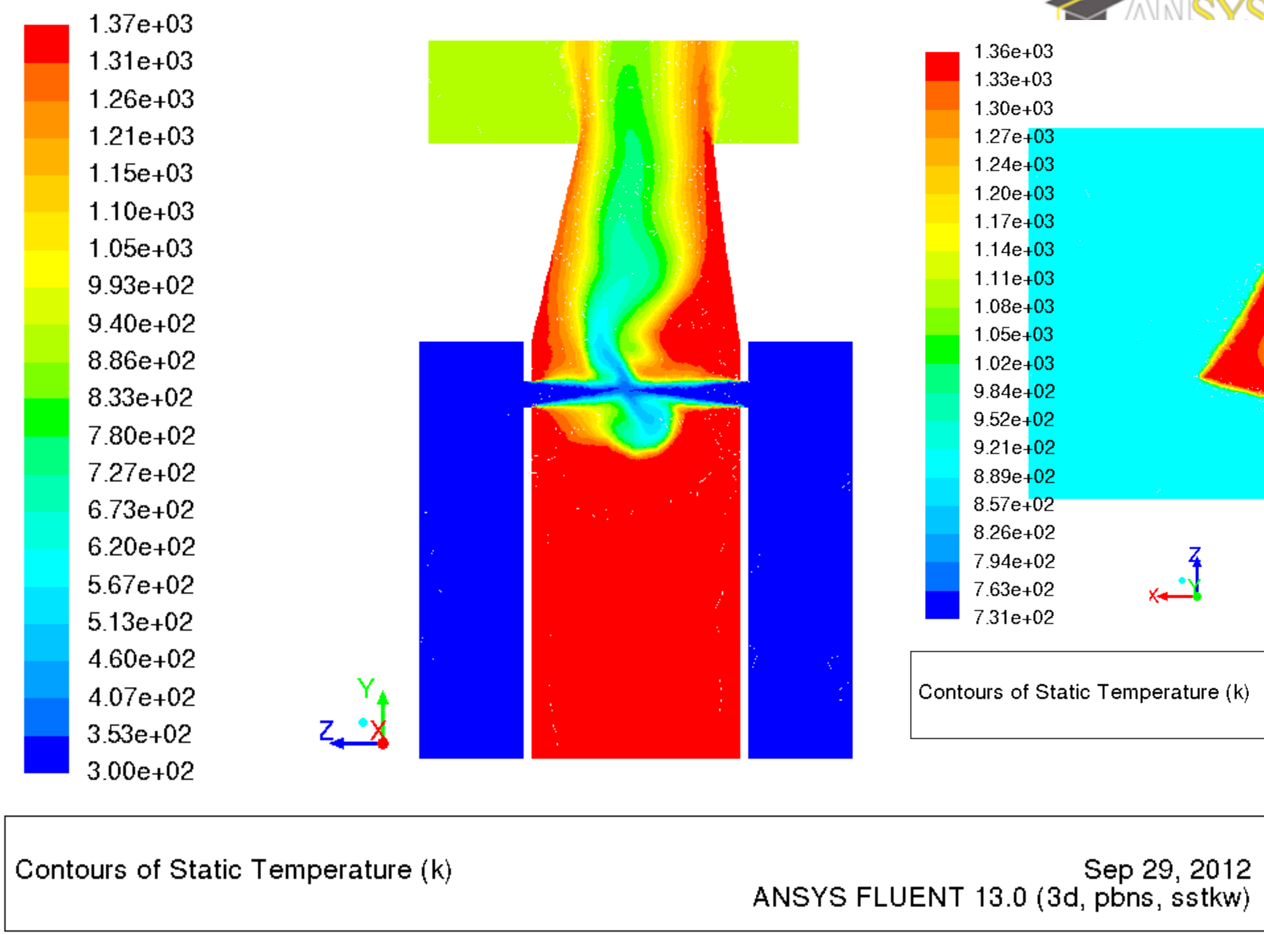
Turbulence Model

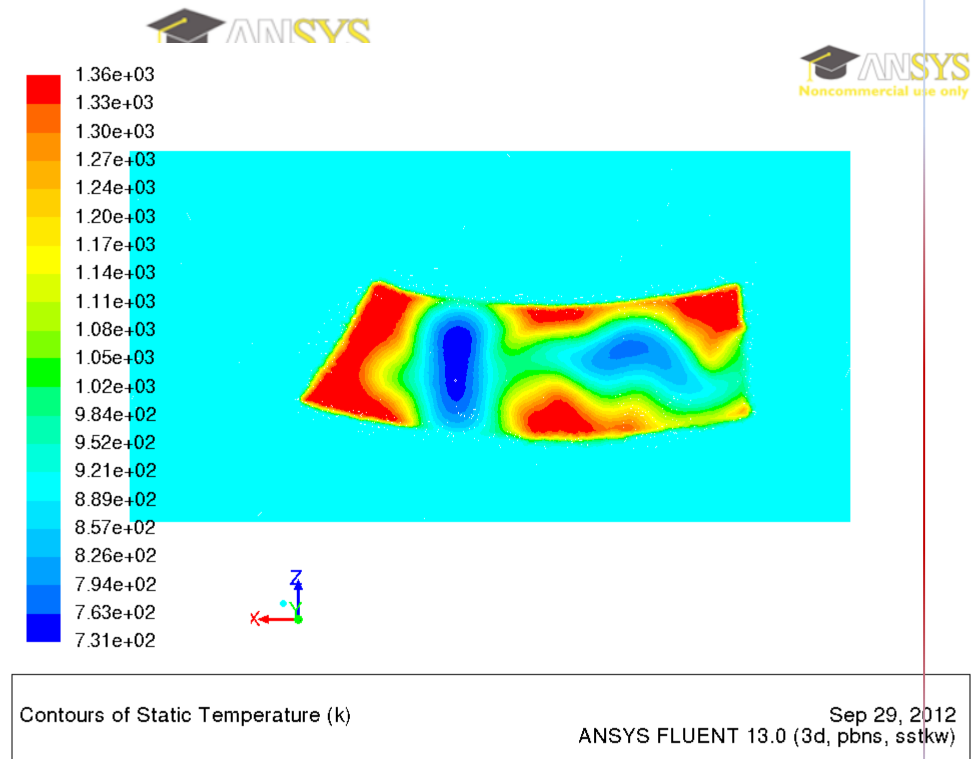
- k-ω SST model
- Low-Re Corrections enabled

Look at Effect of…

- Dilution rate
  - 3%, 15%
- Turbulence levels at main inlet
  - 5%, 10%

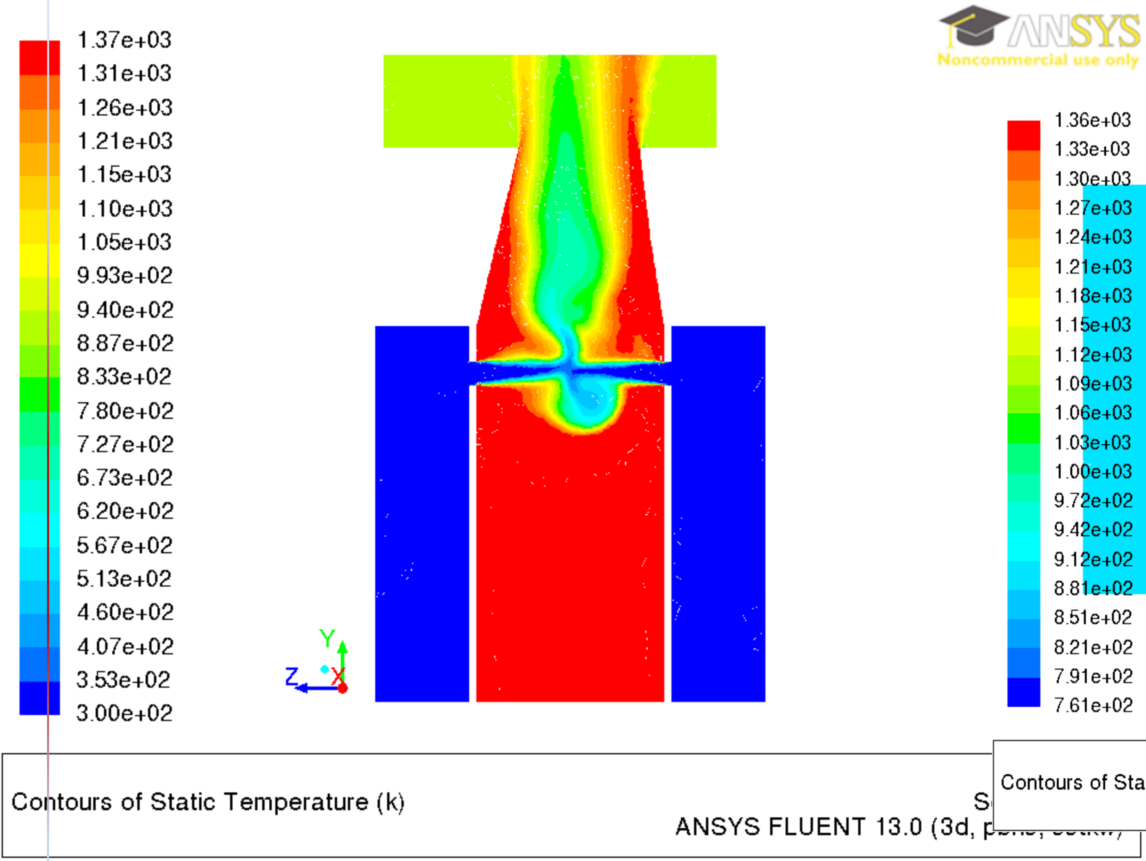
Vane Inlet Conditions

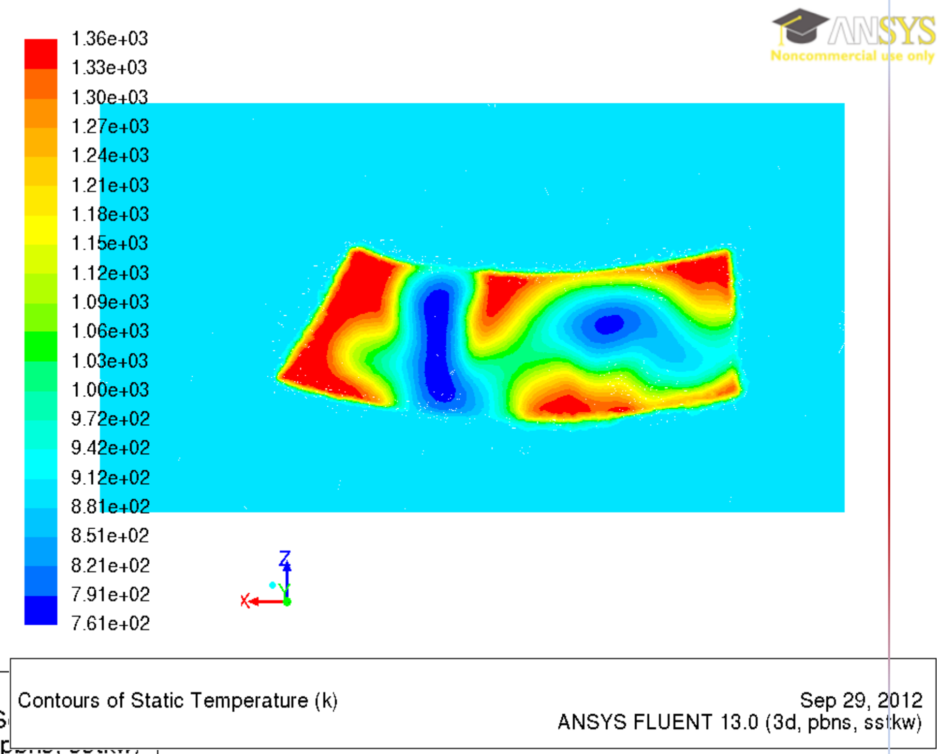




- Dilution – 15%
- Turbulence Intensity – 5%

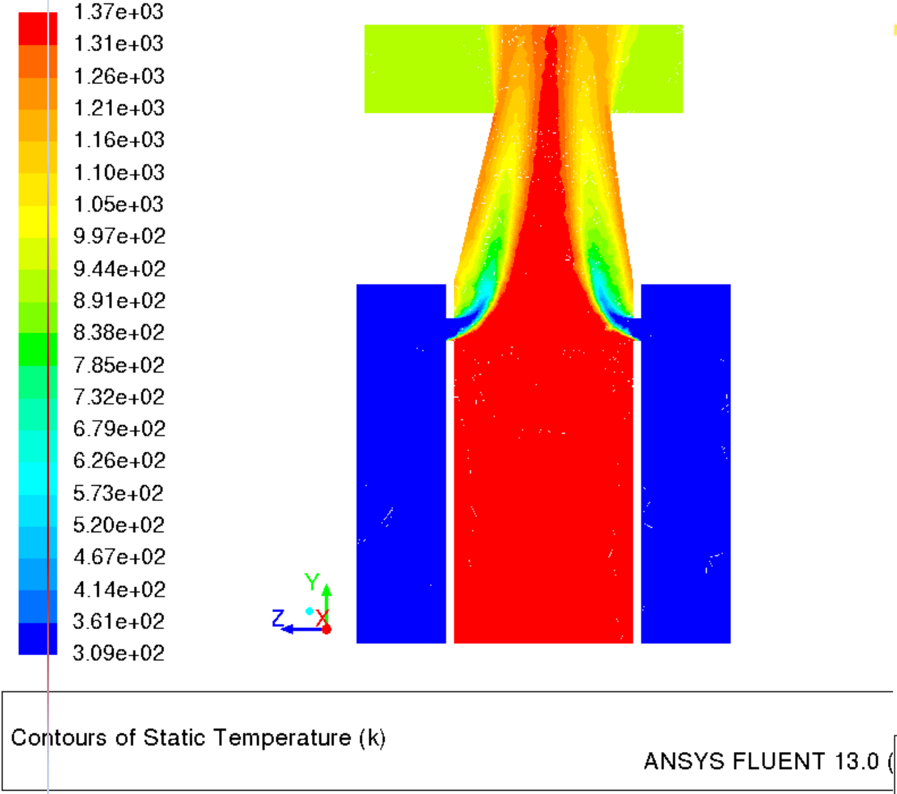
Vane Inlet Conditions

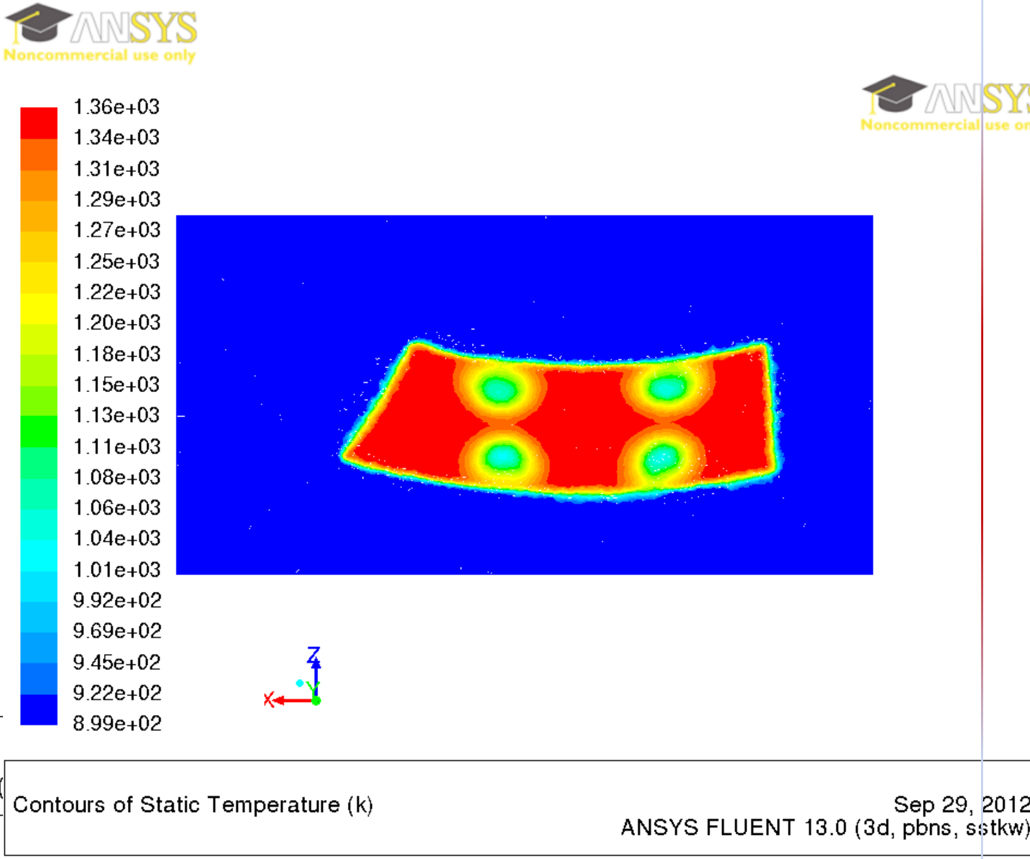




- Dilution – 15%
- Turbulence Intensity – 10%

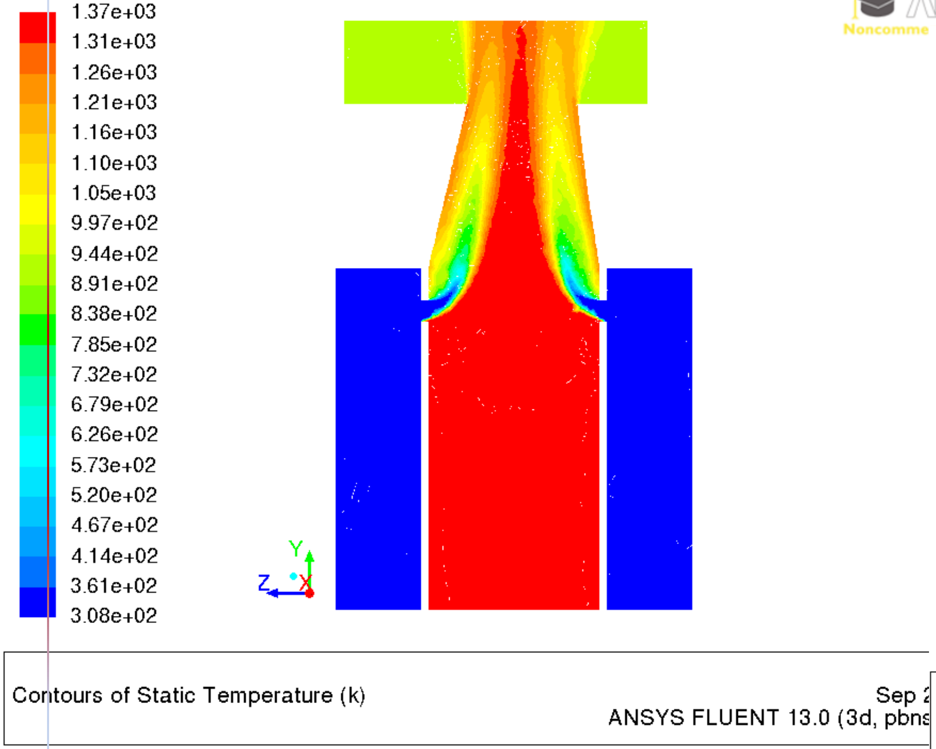
Vane Inlet Conditions

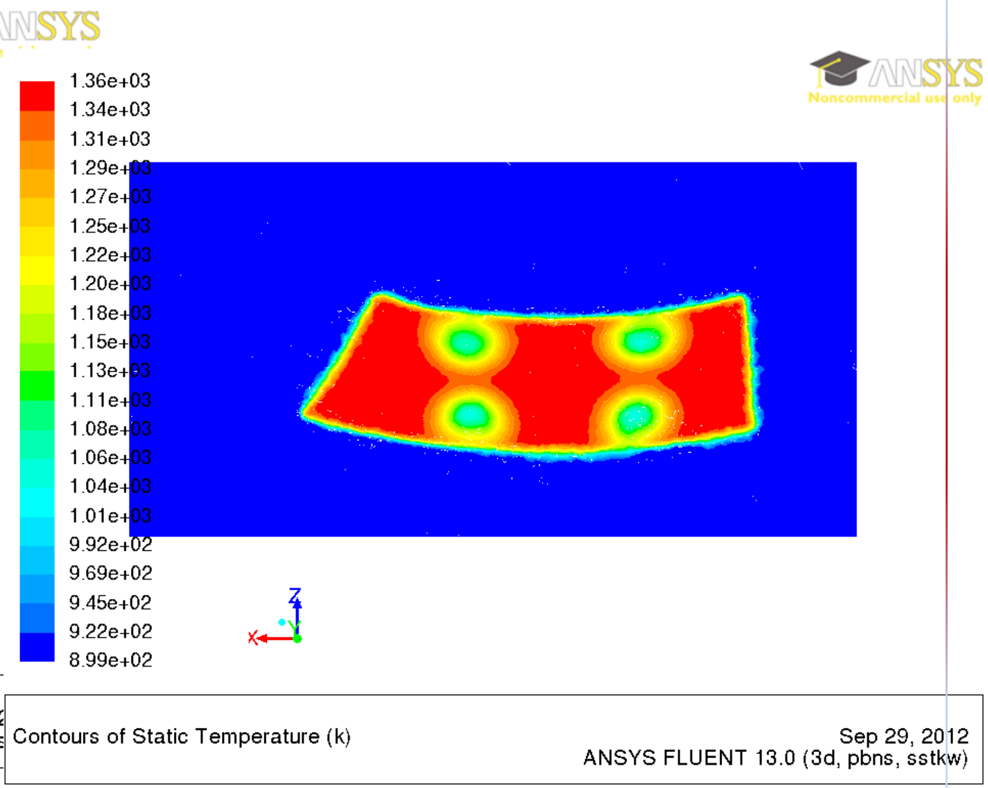




- Dilution – 3%
- Turbulence Intensity – 5%

Vane Inlet Conditions





- Dilution – 3%
- Turbulence Intensity – 10%

Vane Inlet Conditions - Dilution

- Varying dilution rate results in dramatic changes in the behavior of the dilution jets
- High dilution
  - Jets impinge
  - Cold flow ‘fans’ across the duct
  - Undesirable inlet temperature profile (no hot streak)
- Lower dilution
  - Jets do not interact much
  - Inlet temperature profile closer to measured profile

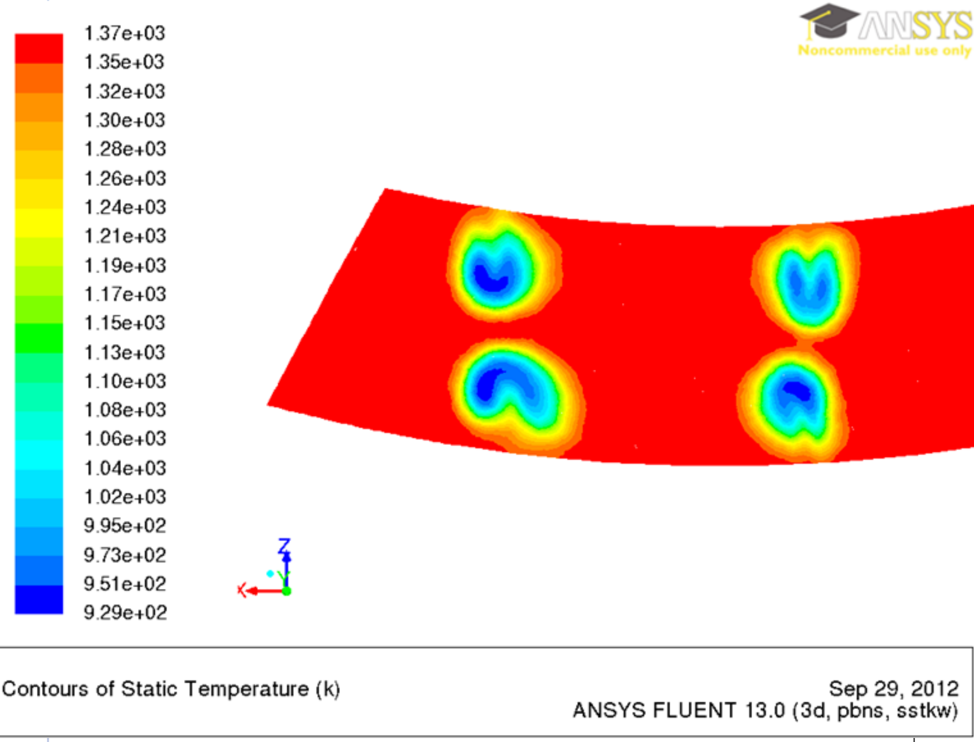
Vane Inlet Conditions - Turbulence

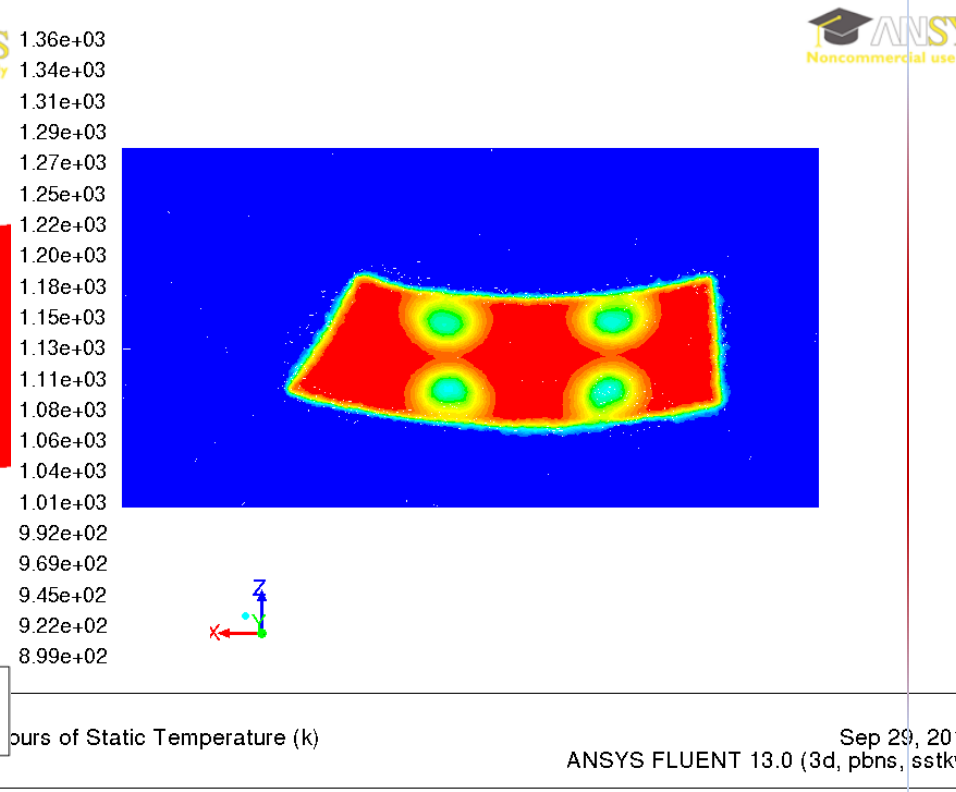
- The effect of increasing the turbulence intensity is hypothesized to be similar to reducing the dilution rate by increasing the mixing and reducing interaction of the jets.
- Early computations showed that to be the case; further computations showed minor effects due to change in Tu. That may be due to the turbulence model deficiencies.
- The effect of turbulence intensity on the shape of the inlet boundary condition is still undetermined.

Including Vanes

- Boundary conditions that produce a desirable inlet profile **as** determined …
- Run same conditions, with vanes included in the domain.
- Once each solution has converged, run deposition using FLUENT’s discrete phase modeling.

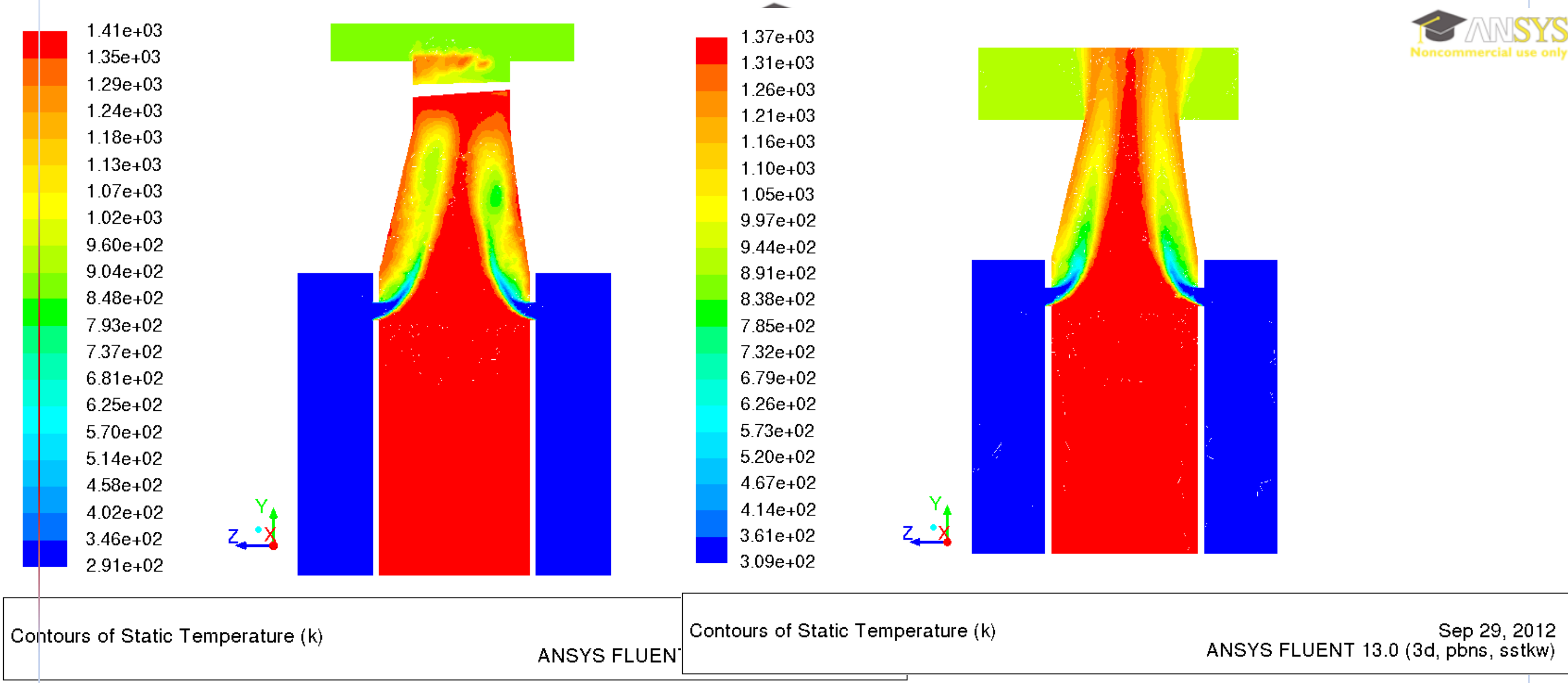
Vane   No Vane





- Dilution – 3%
- Turbulence Intensity – 5%

Vane No Vane

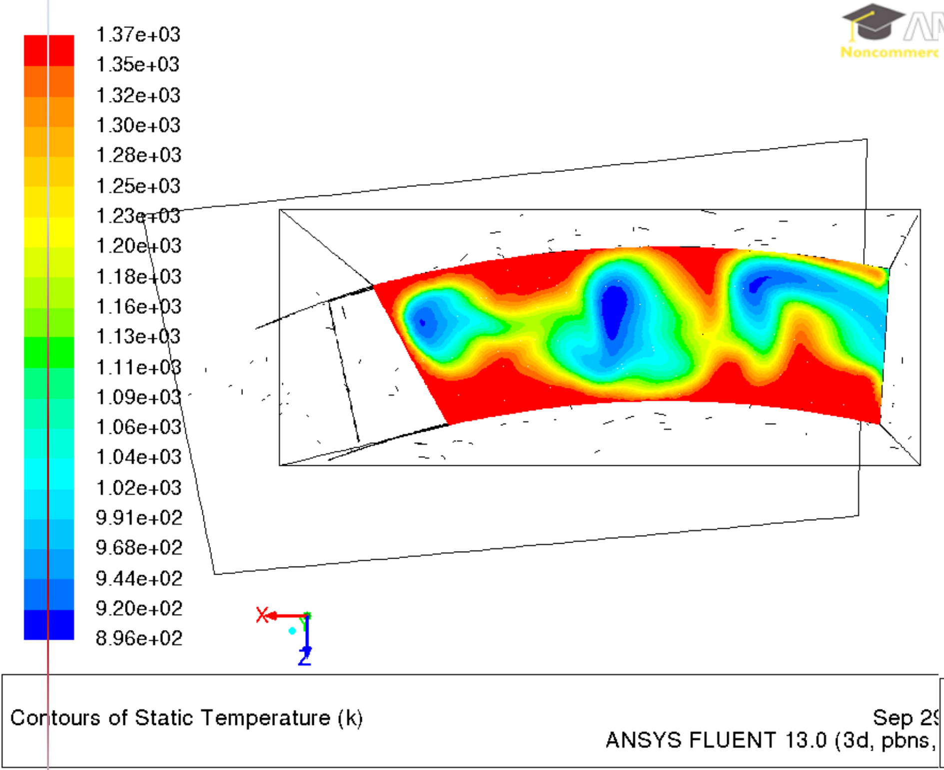


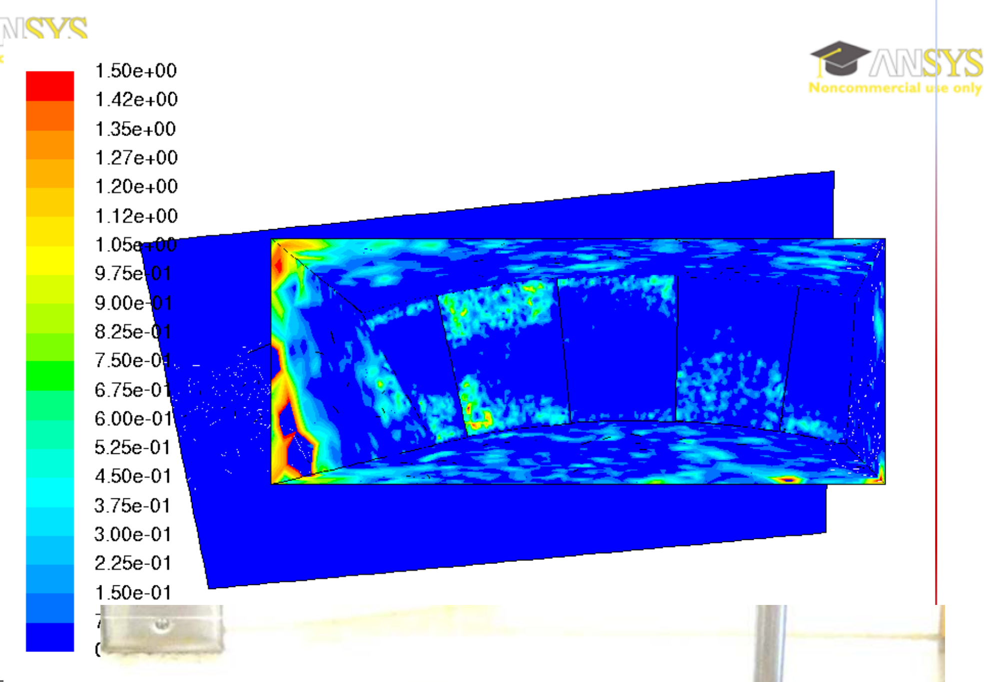
- Dilution – 3%
- Turbulence Intensity – 5%

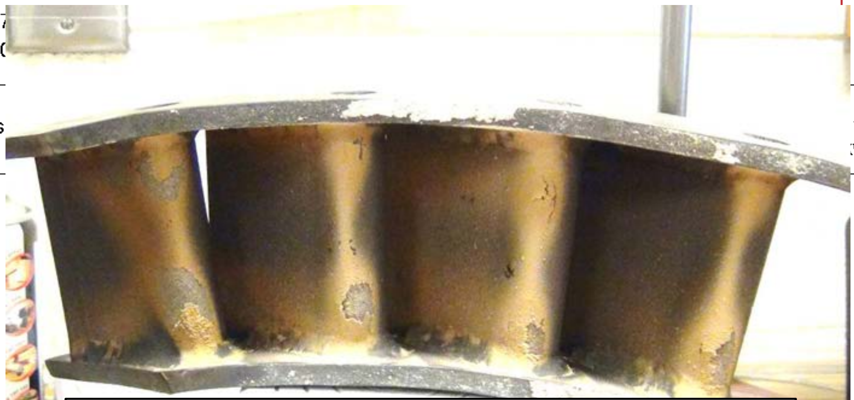
Deposition

- FLUENT discrete phase model used to track particles through the flow.
- User defined function implements the critical viscosity model on particle impacts on walls.
- Following results show:
  - Temperature profile of inlet
  - Contour plot that gives a measure of particle deposition on vanes.

Deposition



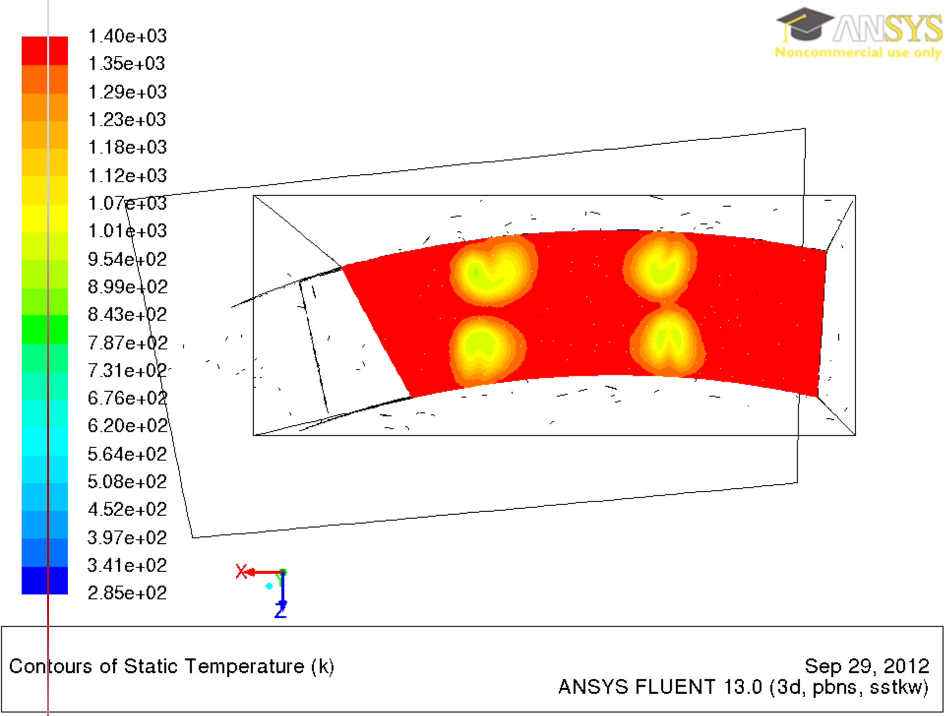


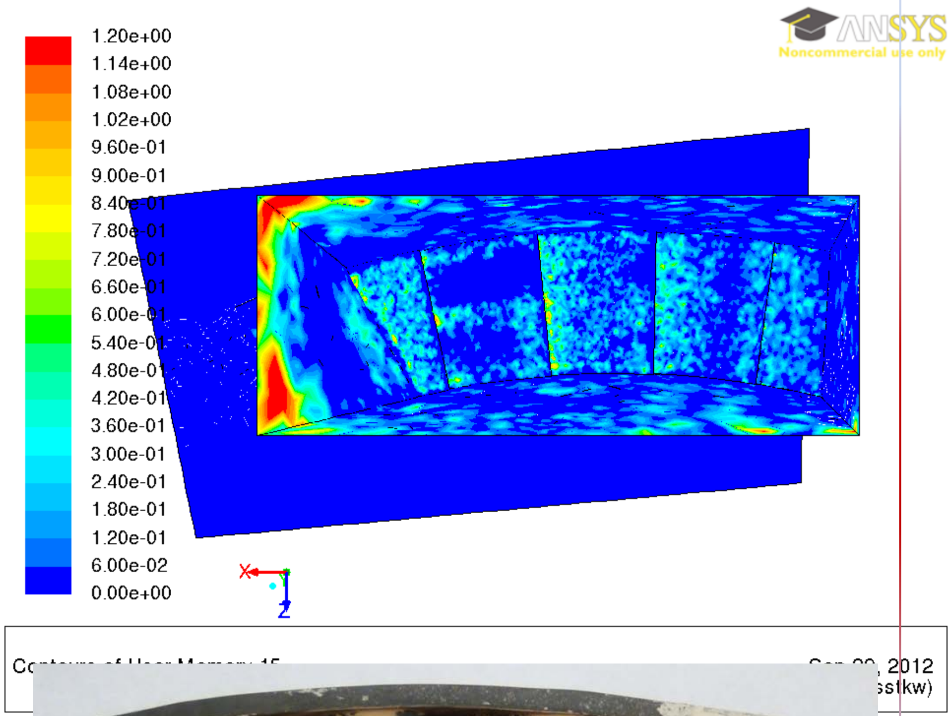


TuRFR Test #2, 15% Dilution

- Dilution – 9%
- Turbulence Intensity – 10%

Deposition





- Dilution – 3%
- Turbulence Intensity – 10%

TuRFR Test #3, 9% Dilution

Deposition

- Inlet temperature profile does not match the experimental measurements well enough as of yet and more work is required.
- Not enough mixing is occurring:
    - Hot and cold areas too ‘uniform’ and ‘distinct’
    - Will investigate different turbulence models and inlet conditions.
- Deposition correlates with temperature as necessitated by the deposition model and physics.

Deposition Modeling

- Critical Viscosity Model (PLASTIC DEFORMATION ONLY)
    - Tafti and Sreedharan (IGTI 2010)
    - probability of sticking exclusive function of particle viscosity and thus f(Temp) ONLY.
    - NO sensitivity to particle size, impact velocity or angle of impingement
    - Does NOT model elastic deformation or adhesion energy

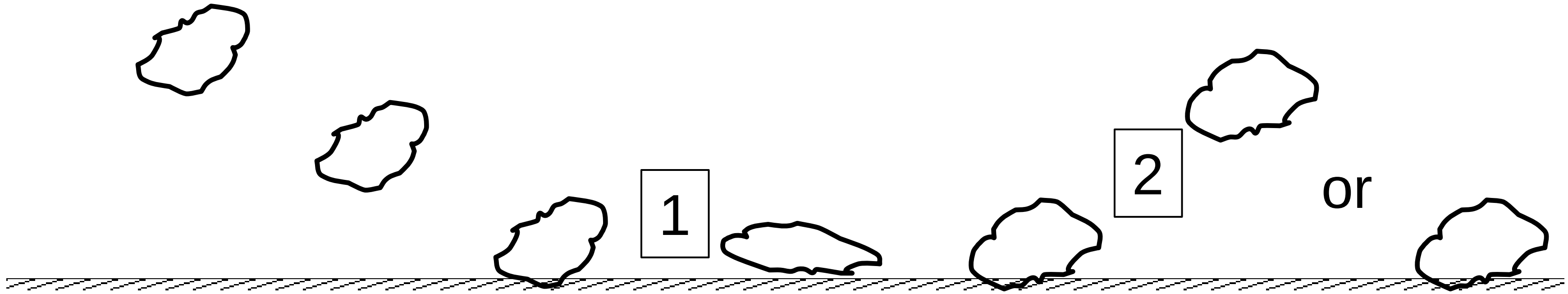
-

- Critical Velocity Model (ELASTIC DEFORMATION ONLY)
    - Brach and Dunn (UND, 1992) & El-Batsh and Haselbacher (2000,2002)
    - particle sticks IF normal velocity < critical velocity
    - critical velocity is f(size, Youngs Modulus, Poissons ratio)
    - Youngs Modulus is f(Temp)
    - Does NOT model plastic deformation!!!

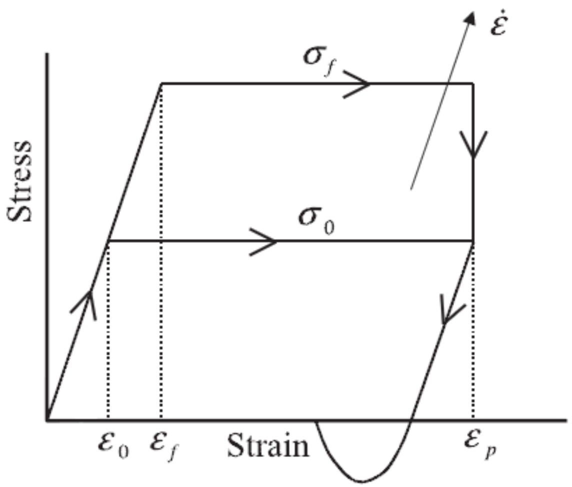
Combination of the Models

- Critical Viscosity is dependent upon the effect of plastic deformation occurring at high temperatures
- Critical Velocity is dependent upon the effect of the adhesion force occurring at lower velocities
- An impact model that incorporates both adhesion and plastic deformation would be optimal

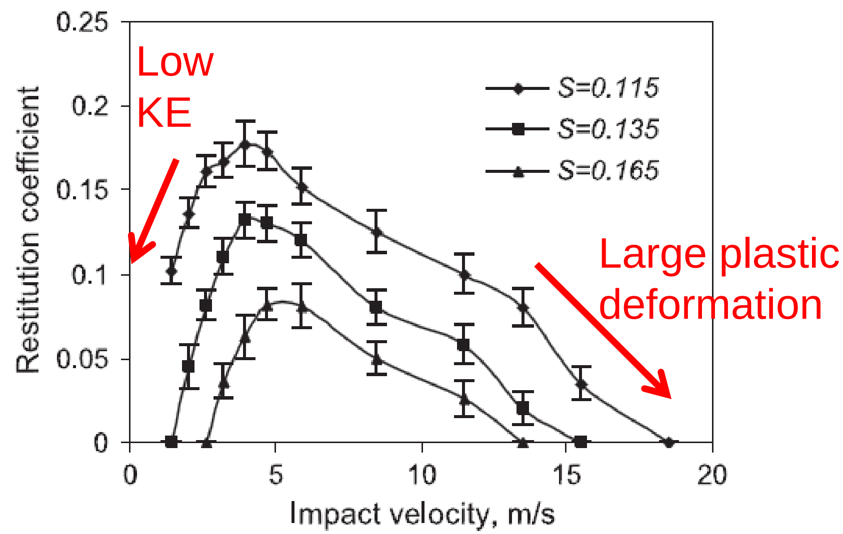
Elastoviscoplasticity



1. Inbound kinetic energy used to elastically and plastically deform particle.
2. If residual kinetic energy exceeds work required to overcome surface adhesion – particle detaches.



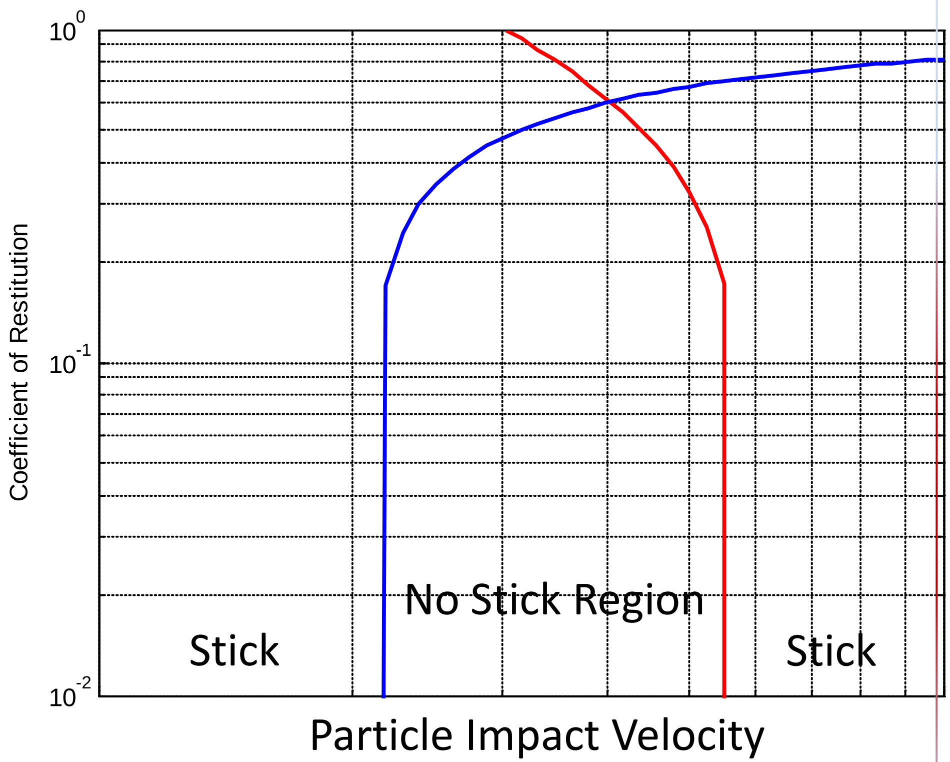
Yield stress is dependent on rate of strain.



Calcium carbonate powder - 10-50μm.
S is liquid to solid ratio.

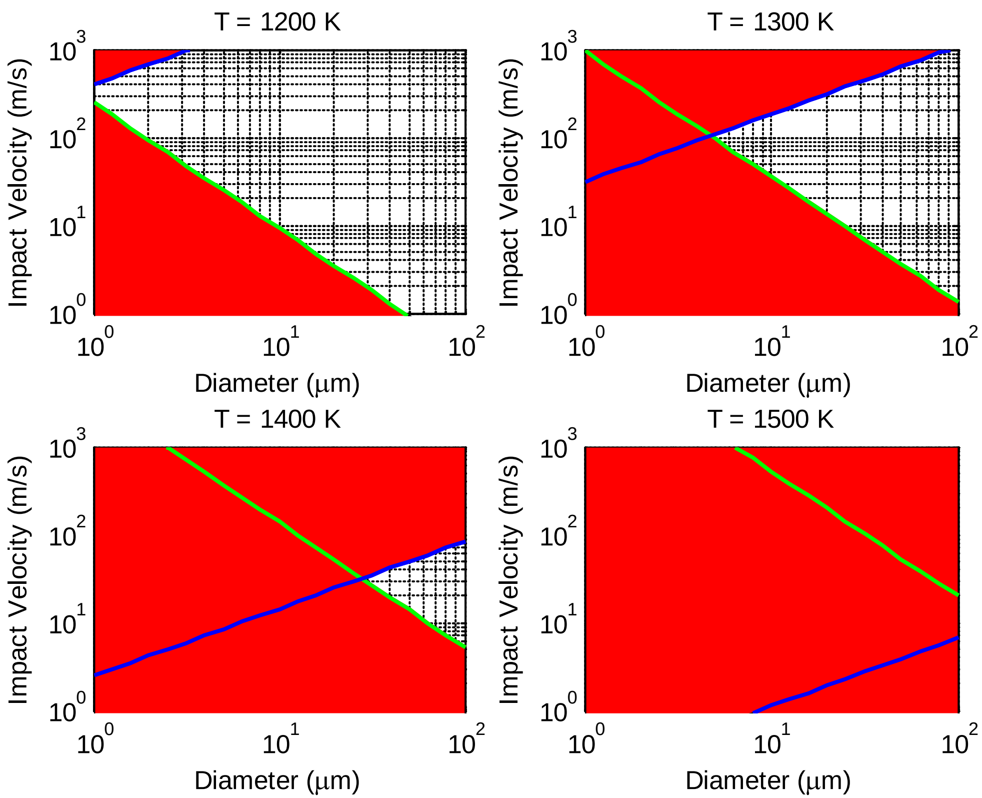
Elastoviscoplasticity

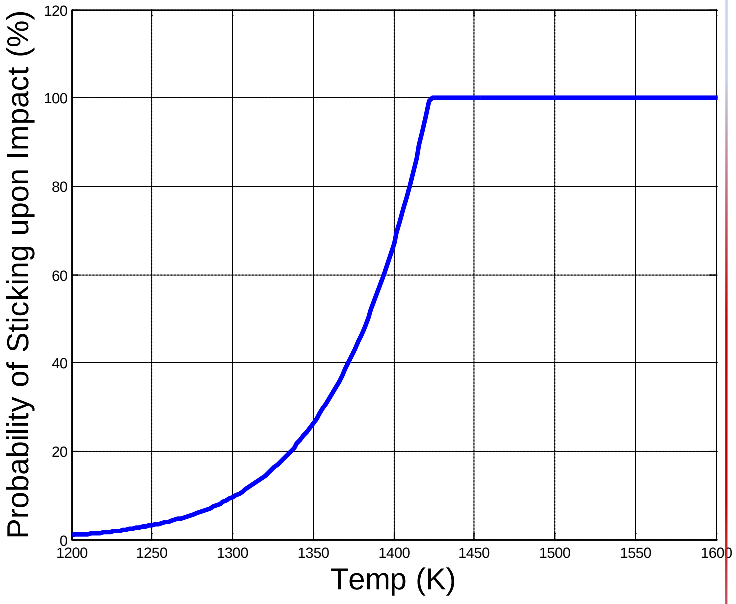
- Technique is sensitive to the parameters desired for the deposition model
  - Temperature
  - Size
  - Mass
  - Velocity
  - Properties of the particle and surface
- Some variations include adhesion
- Calculations can be made for each impacting particle
  - Requires the data for yield stress
  - This data may be acquired through experimentation or empirical modeling



Model predicts coefficient of restitution based on particle impact velocity and material properties. Blue line represents critical velocity relation (elastic deformation only) and red line represents EVP (plastic deformation).

Elastoviscoplasticity vs. Critical Viscosity





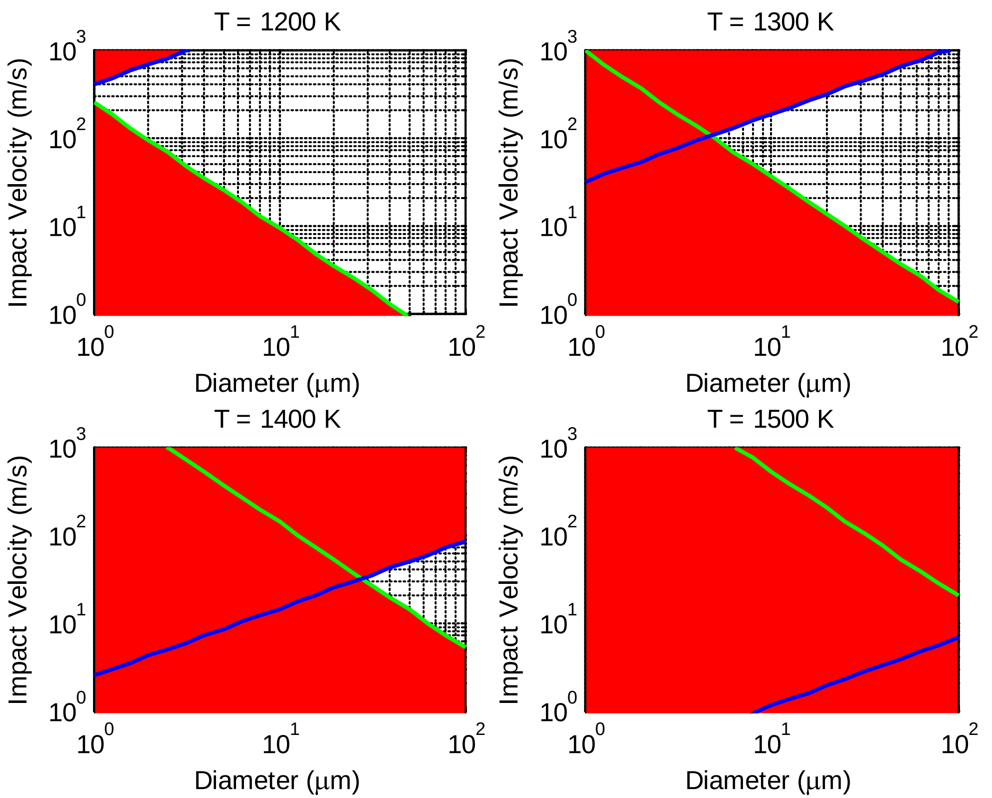
Sticking Sensitivity

- Particle sticks if impact velocity is:
  - Lower than critical velocity threshold (Green line; elastic deformation)
  - Larger than plastic deformation threshold (Blue line)
  - Red region = stick
- Otherwise, particle rebounds with a coefficient of restitution governed by available kinetic energy

Critical Viscosity Model

- Sticking probability only dependent on temperature
  - No dependence on impact velocity, particle diameter

Elastoviscoplasticity



Sticking Sensitivity

- Particle sticks if impact velocity is:
  - Lower than critical velocity threshold (Green line; elastic deformation)
  - Larger than plastic deformation threshold (Blue line)
  - Red region = stick
- Otherwise, particle rebounds with a coefficient of restitution governed by available kinetic energy

Model contains multiple "tunable" parameters

- Most sensitive are Young's Modulus (stiffness) of particle and surface (E_p & E_s) and particle yield stress (σ_p)
- All change with temperature, and may require empirical relations or experiments to calibrate
- Changes to these parameters alters line locations in associated plots, but trends remain consistent.

Model Validation Data

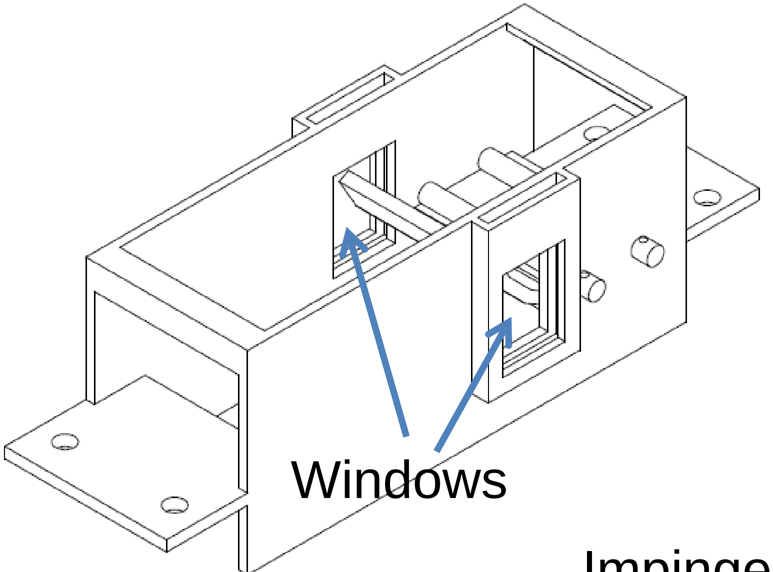
Objective:

- Validate particle sticking models, determine appropriate model parameters
- Determine particle Modulus of Elasticity and Yield Stress as functions of temperature
  - Use validation experiments to determine the coefficient of restitution (COR) for particles of various sizes, initial velocities, temperatures
  - Set E(T) and σ_0(T) to match observed deposition trends

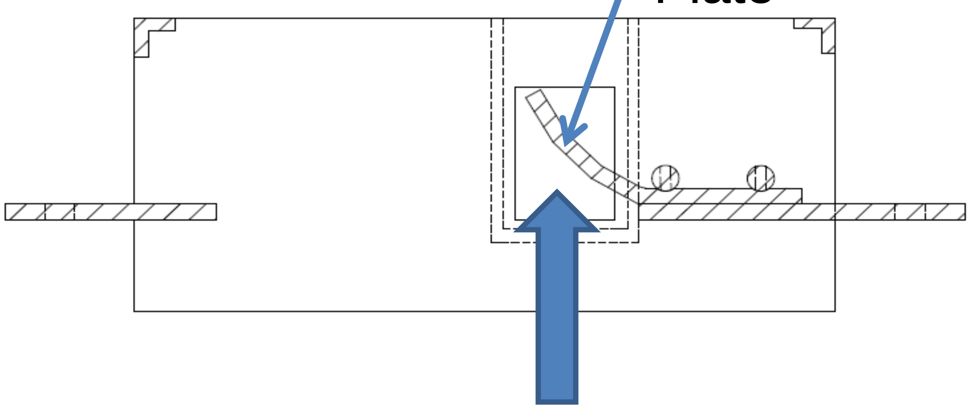
2 Possible Sources:

- Dynamic particle impact measurements in TuRFR
- Static stress-strain testing at Oak Ridge National Lab (Dr. Edgar Lara-Curzio)

Model Validation Test Piece

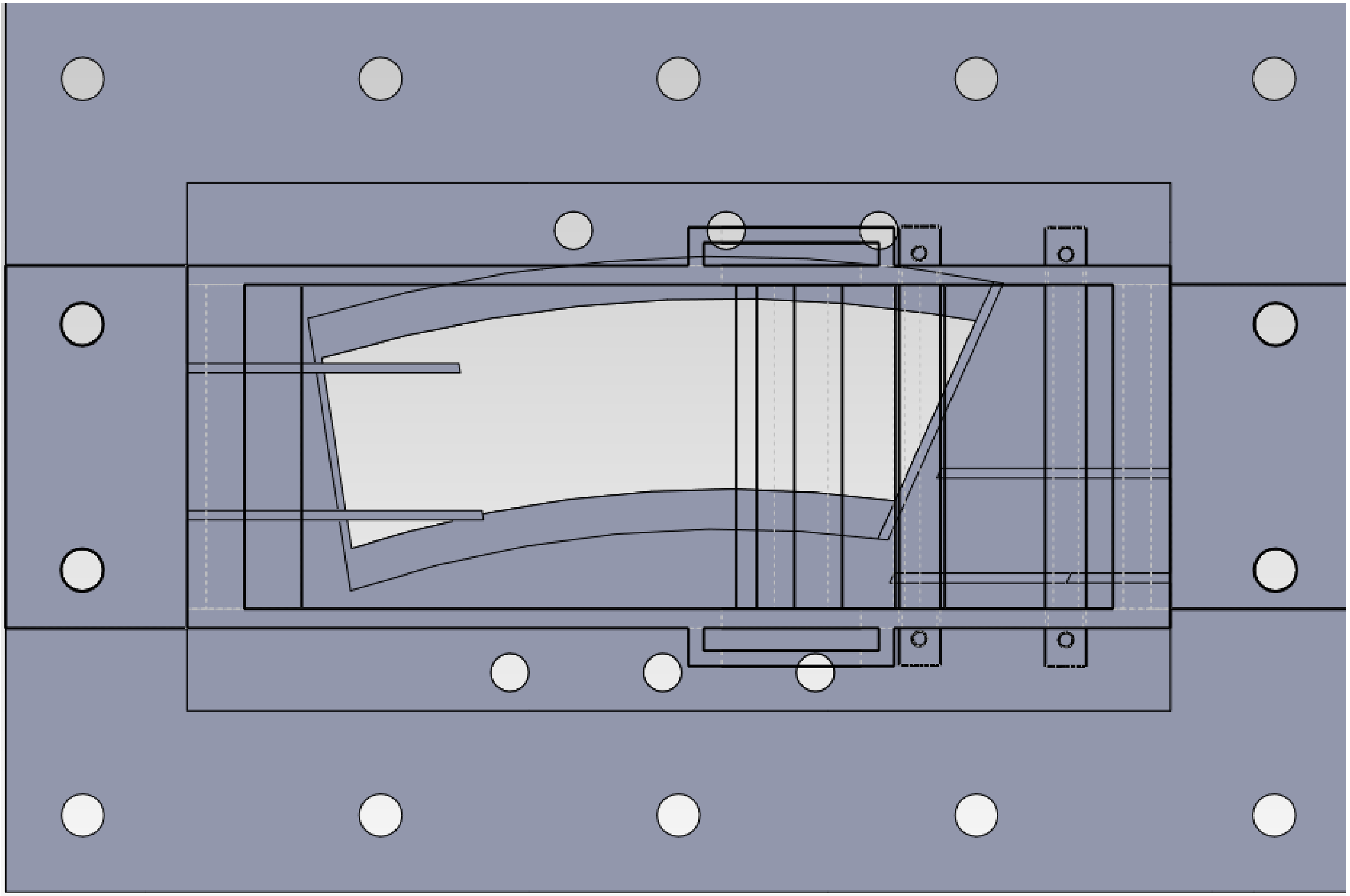


- Bolts to existing TuRFR top-piece
- Optical access for camera, LED
- Particulate laden flow impinges on interchangeable impingement plate, shown with 30°, 45°, and 60° impingement angles



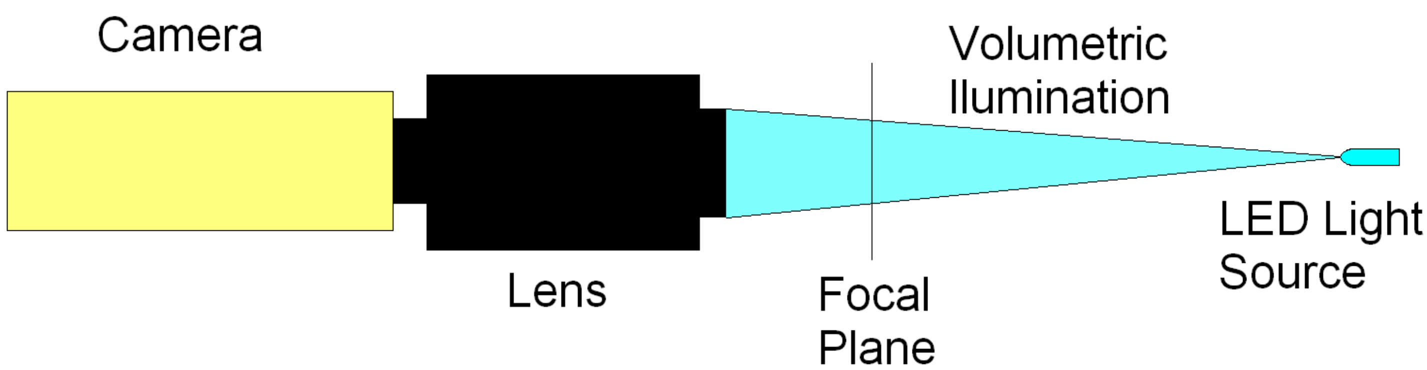
- Backside and internal cooling possible
- Surface temperature measured with attached thermocouple and/or IR camera possible

Model Validation Test Piece



PSV Imaging

- Particle Shadow Velocimetry* is used to measure:
  - Pre and post-impact velocity (COR)
  - Impact and rebound angle
  - Sticking probability
  - Size

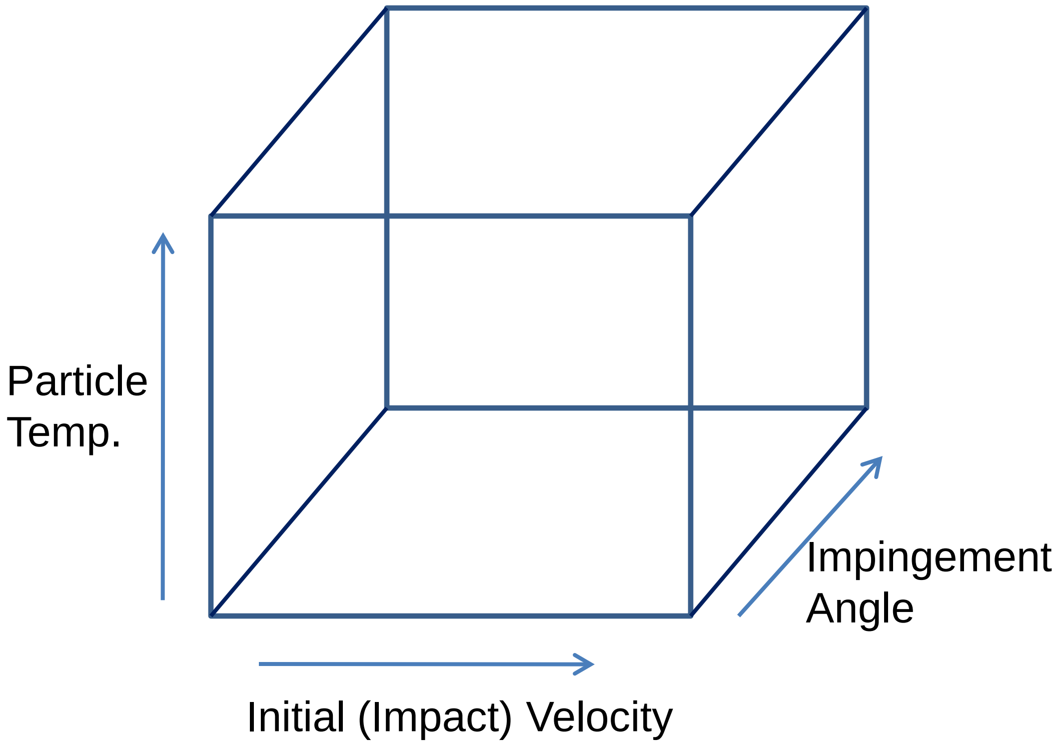


*Pioneered by Dr. Jim Crafton at ISSI.

PSV Imaging Variants

- Two configurations:
  - High frame rate (~25+ KHz) camera (current setup)
    - Generally high signal to noise ratio
    - Straightforward setup, 1 image yields one “instantaneous” point in time
    - Expensive, relatively low resolution
  - Low (~1Hz) frame rate, color camera
    - Pulse 3 LEDs (RGB) independently, with a period ~μs
    - Each pulse represents “instantaneous” point in time
    - Use camera to record several pulses in single exposure
    - Split RGB pixels to obtain time history of particle movement
    - Lower signal to noise ratio, but less expensive and higher resolution

Design of Experiments



- Particle size will be varied by virtue of the various particle sizes injected
- Impingement angle will vary naturally to an extent, so 1-2 nominal plate angles should yield data between 10° and 80°

*In these tests, plate temperature would be dictated by flow temperature. Backside cooling would be possible, but this would enlarge the test matrix.

Testing Progress

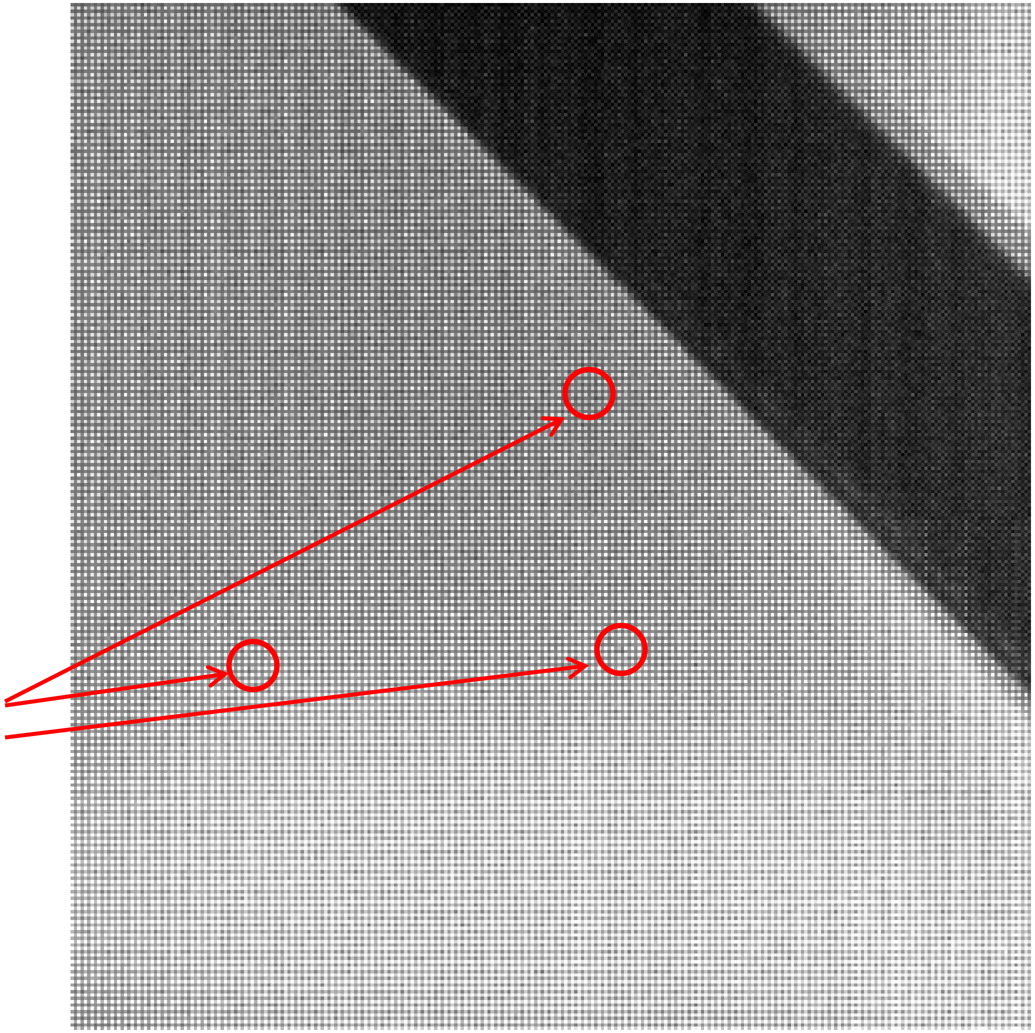
- Three hot runs have been performed
  - 2 with Bituminous ash (MMD ~20 μm)
  - 1 alternating between Lignite ash and Arizona road dust
- All tests performed at temperatures ranging from 1000-2000° F
- Nominal mass flow varied between 0.4 lbm/s-0.8 lbm/s
  - Velocity of particles at mass flow greater than 0.8 lbm/s may be too fast for current high speed camera to capture

Challenges faced at High Temperature

- Thermal turbulence created due to mixing of hot and cold gas at TuRFR exit
  - Degrades image quality
  - Complicates particle identification
- Deposition of test material on windows
  - Obscures camera view of rebounds
  - Tests can be safely run without windows, but this exacerbates heat wave issue due to increased mixing

Cold Flow, No Windows

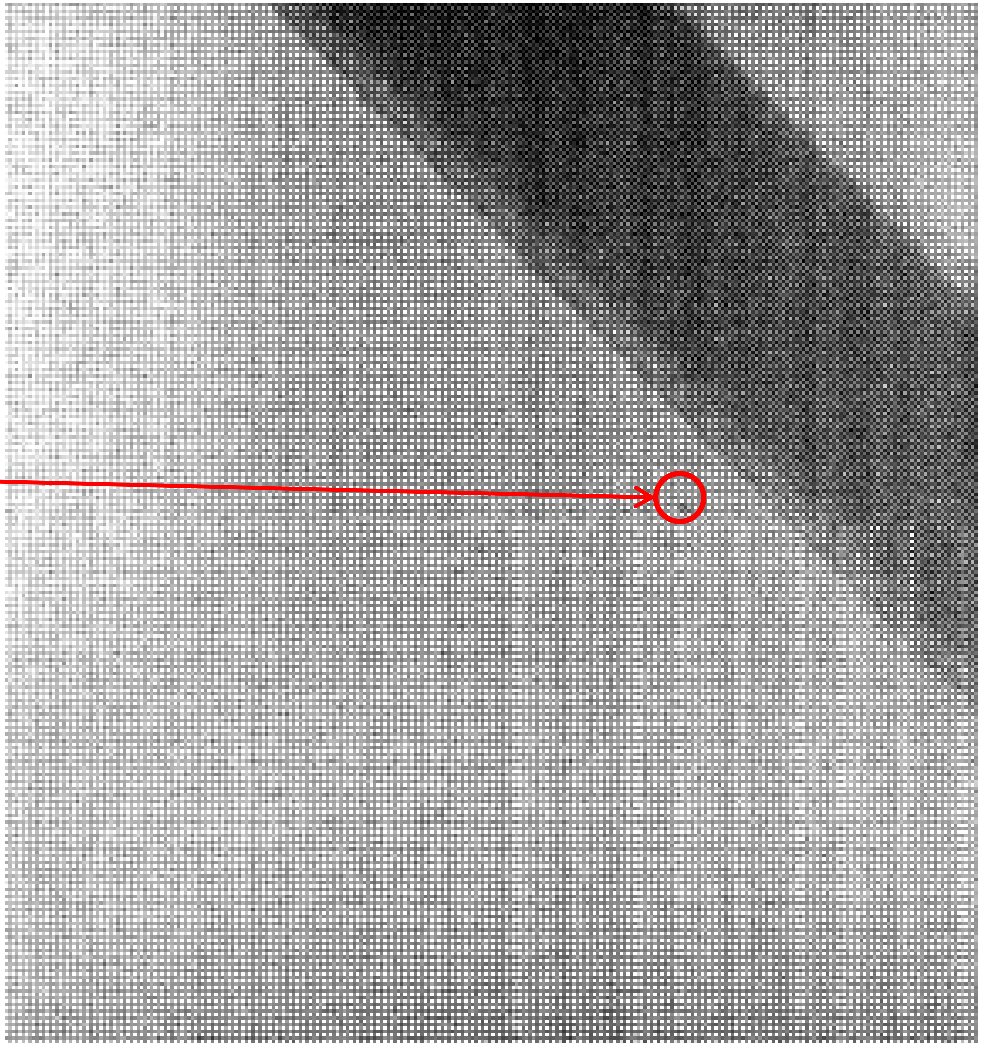
- Raw, unprocessed image
- Near optimal background lighting
- Minimal shadowing near plate
- Particles present, but difficult to see due to small size



Mass Flow: 0.4 lbm/s, Cold Flow, Unground Lignite ash

Cold Flow, With Clean Windows

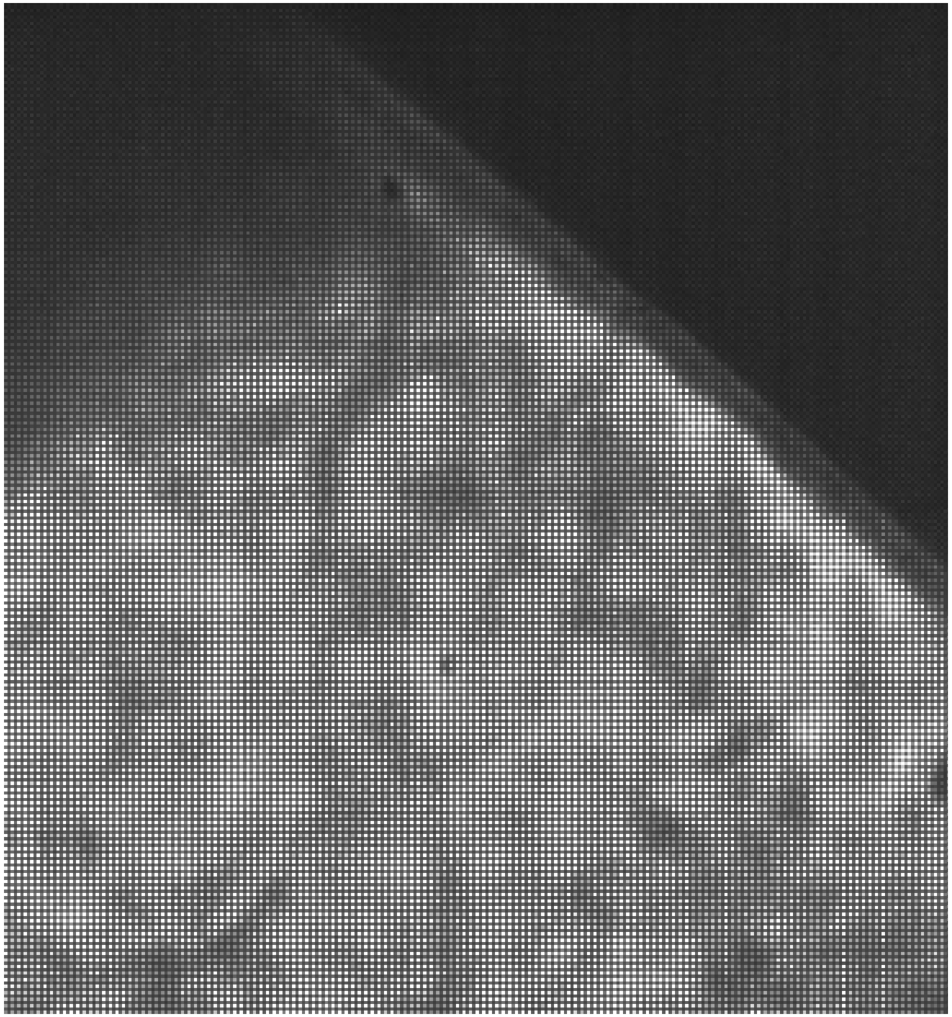
- Raw, unprocessed image
- Image blurred due to windows
- Particles somewhat obscured by windows



Mass Flow: 0.4 lbm/s, Cold Flow, Unground Bituminous ash

Hot Flow, No Windows

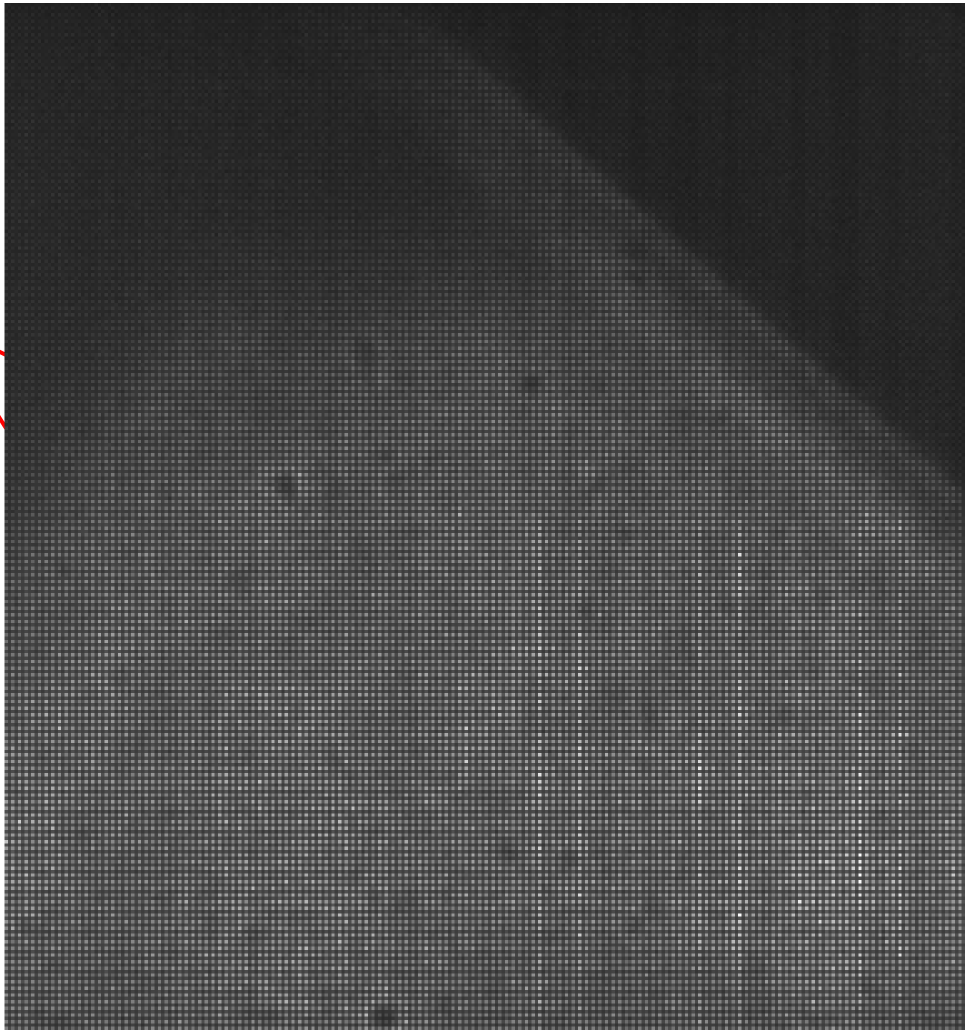
- Raw, unprocessed image
- Large particles visible, smaller particles obscured by heat waves
- Inconsistent, fluctuating background makes processing difficult



Mass Flow: 0.4 lbm/s, Hot Flow ~1000° F, Unground Bituminous ash

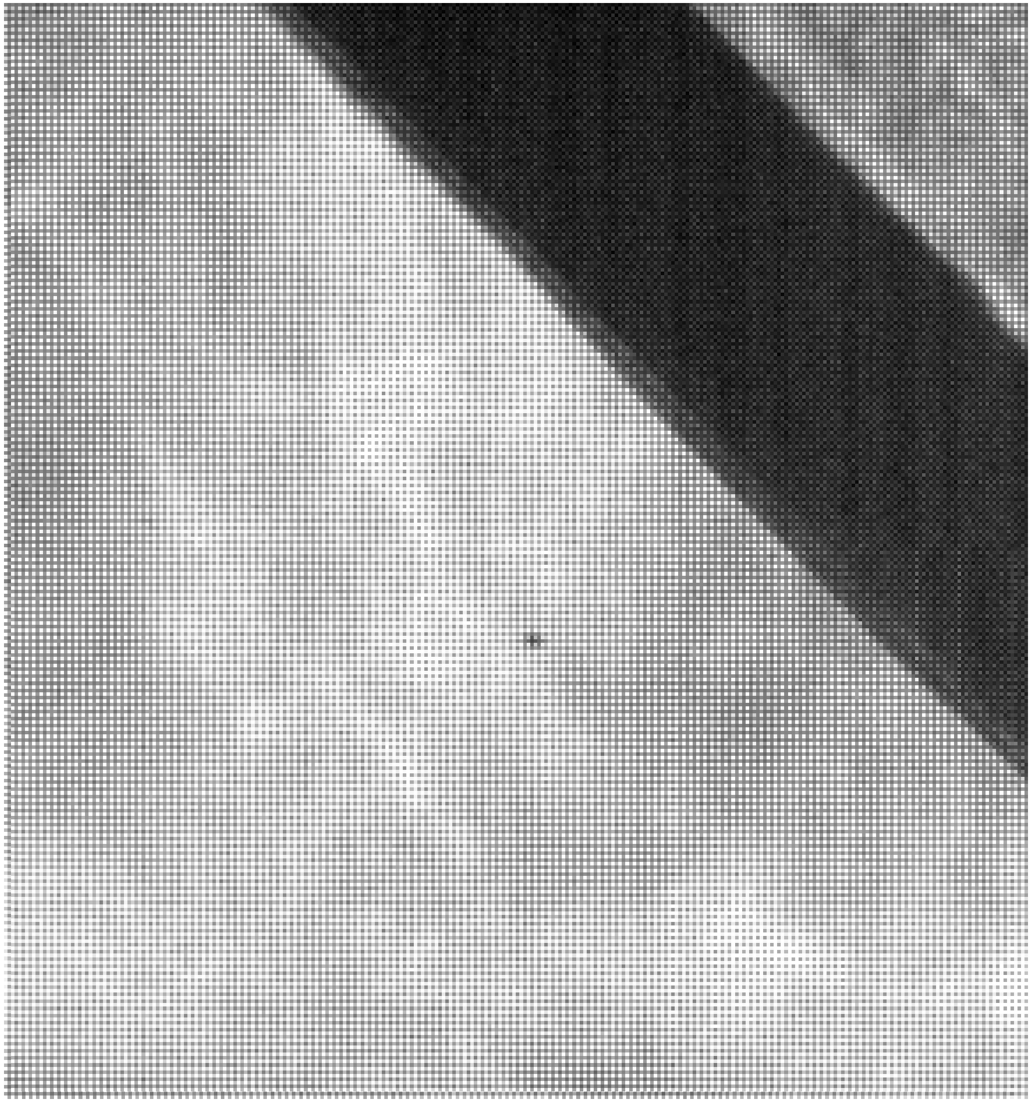
Hot Flow, With Dirty Windows

- Raw, unprocessed image
- Image blurred due to windows, deposit on window visible
- Heat waves still present, reduced and dimmed by windows
- Overall image dimmed, making particle detection difficult



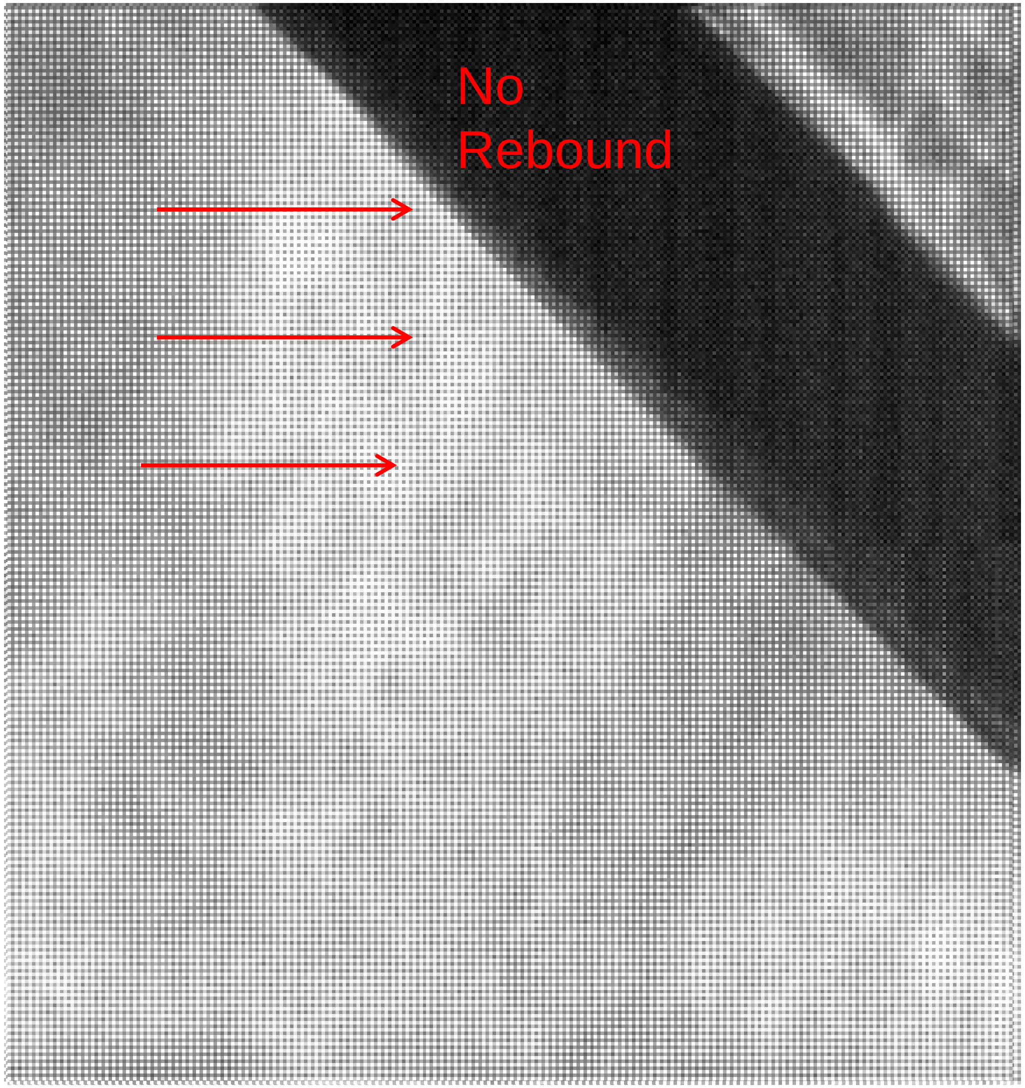
Mass Flow: 0.4 lbm/s, Hot Flow ~1500° F, Unground Bituminous ash

High Temperature Rebound, No Windows



Mass Flow: 0.4 lbm/s, Hot Flow ~2000° F, Unground Bituminous ash

High Temperature Deposit, No Windows



Mass Flow: 0.4 lbm/s, Hot Flow ~2000° F, Unground Bituminous ash

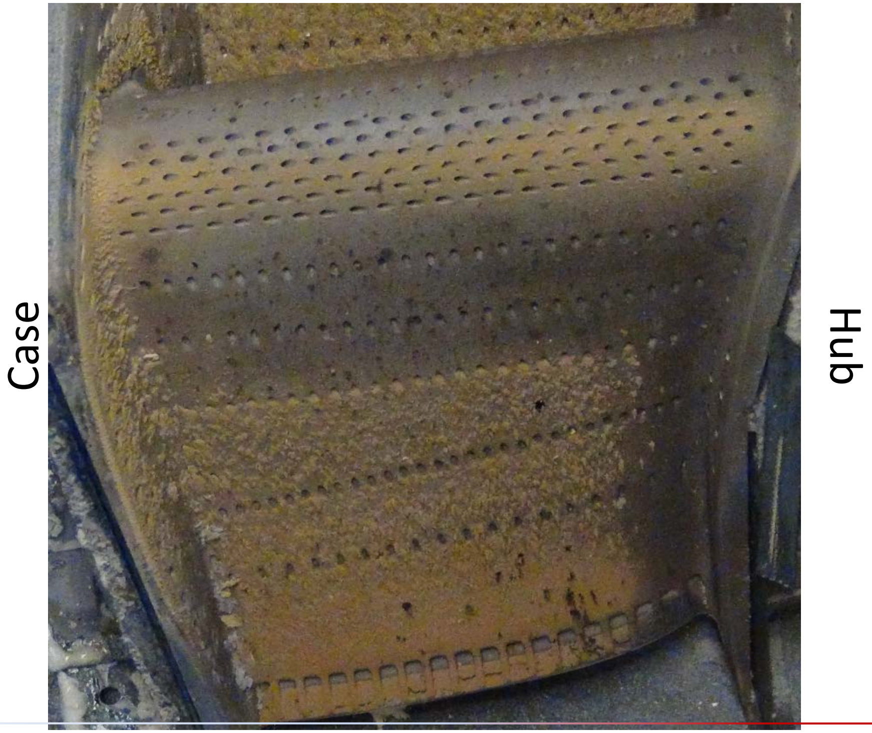
PHASE 2: Cooled Vane

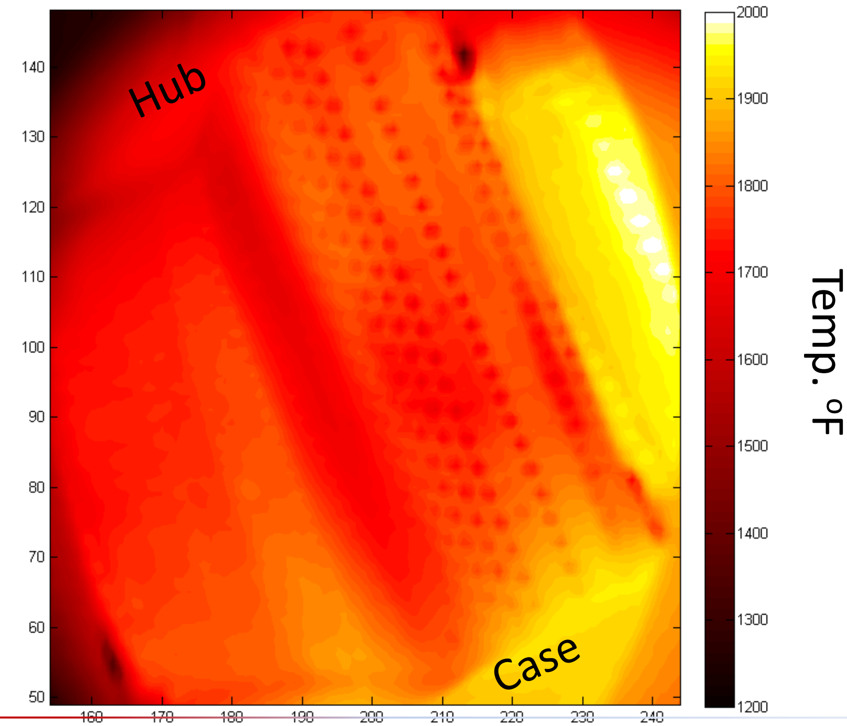
- Measure hot streak migration and wall temperature for cooled vane
- Measure deposition patterns and rates with hot streaks for cooled vane
- Compare model predictions with TuRFR hot streak and deposition measurements.
- Modify model as needed.
- Propose and explore design modifications that will mitigate particulate deposition on turbine vanes.

Infrared Measurements

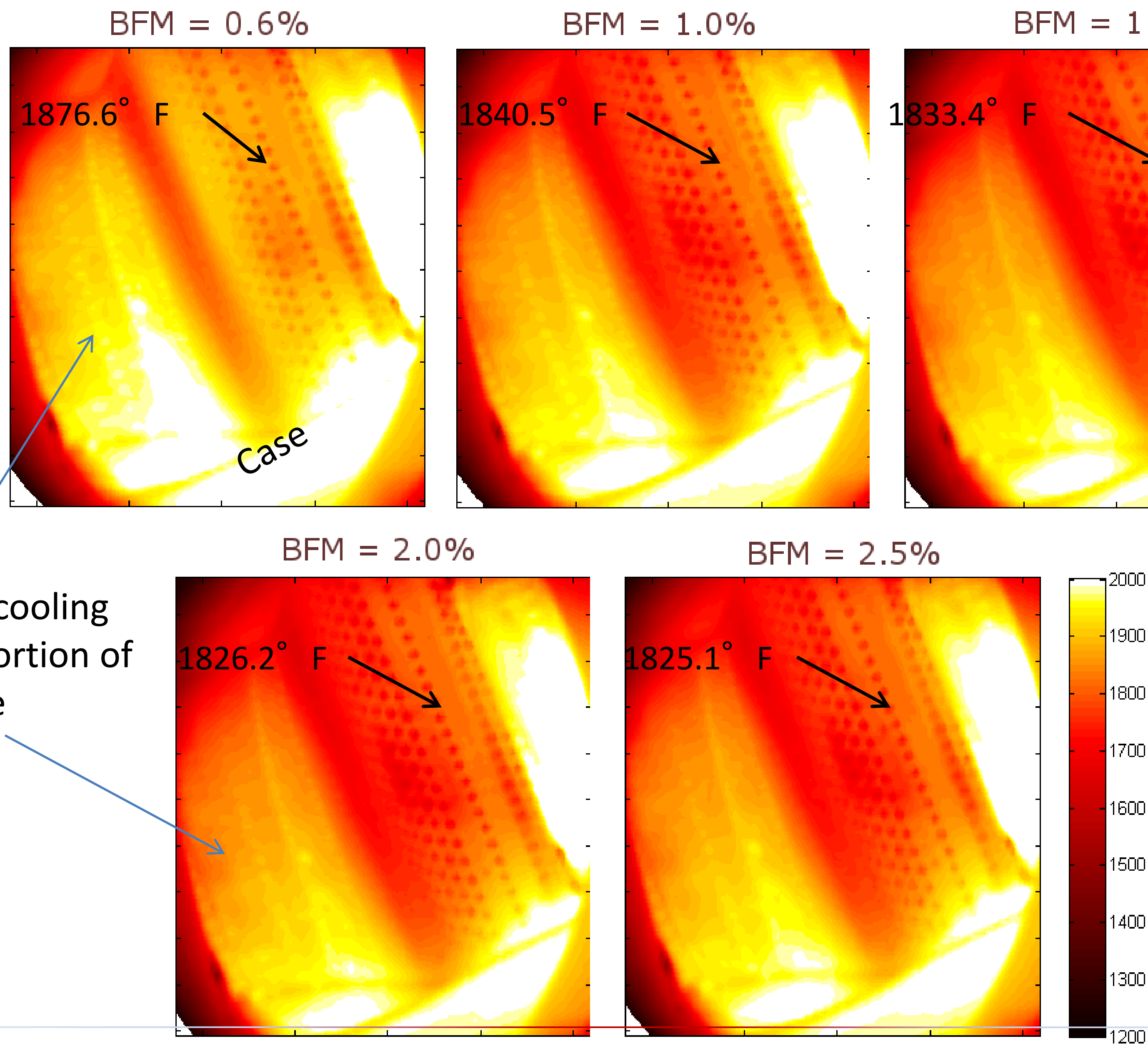
- Camera calibrations from 1200 °F to 2000 °F are conducted for each test article of different material
- Band pass filter removes flame noise
- Custom cooling box to maintain constant camera temperature
- Zoom lens for enhanced spatial resolution

Higher metal temperature enhances sticking probability leading to higher deposition rates. (Trailing edge was not cooled adequately for this test.)





Effect of Varying Backflow Margin (BFM)



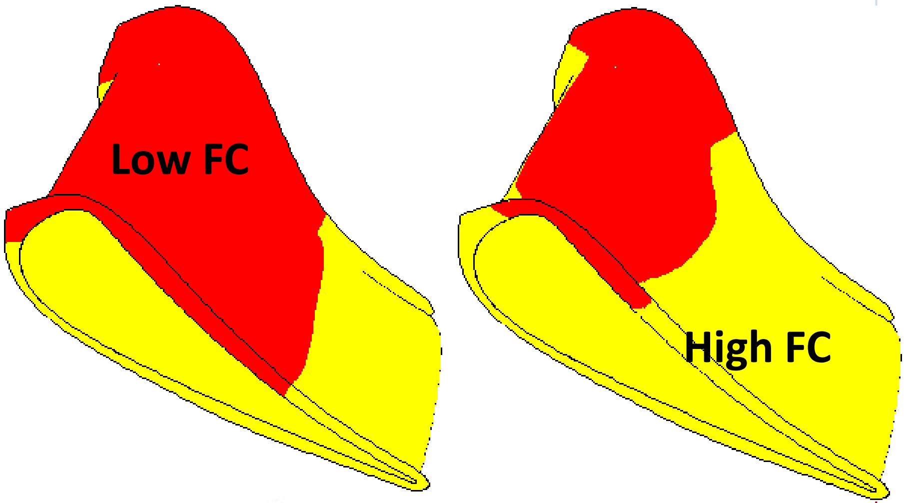
No film cooling on aft portion of the vane

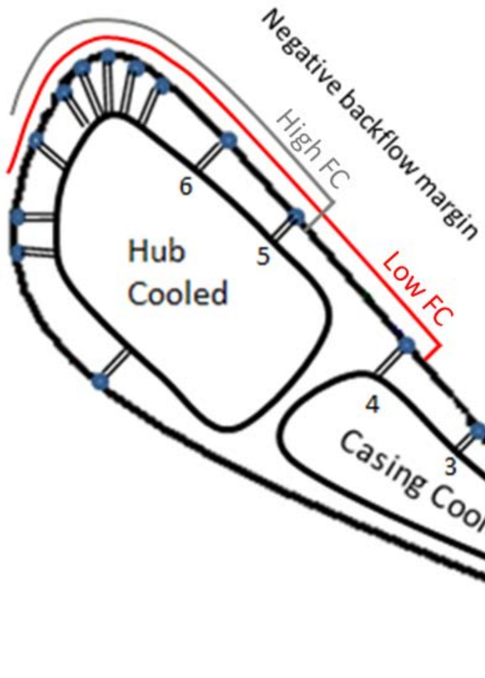
Film Cooling Description

<u>Three Cooling Setting:</u>

- **No Cooling**
- **Low FC**
  - Unknown mass flow. Meant to be 9% FC
  - Coolant temp = **416 ºC**
  - Only film cooling on rows 1, 2, and 3 of the pressure surface
- **High FC**
  - **33%** higher coolant mass flow. Meant to be 12% FC
  - Coolant temp = **160 ºC**. Lower coolant temperature due to increase in mass flow.
  - Film cooling extended to row 4
  - Higher mass flow increased the pressure in the cooling cavity reducing the negative backflow margin region

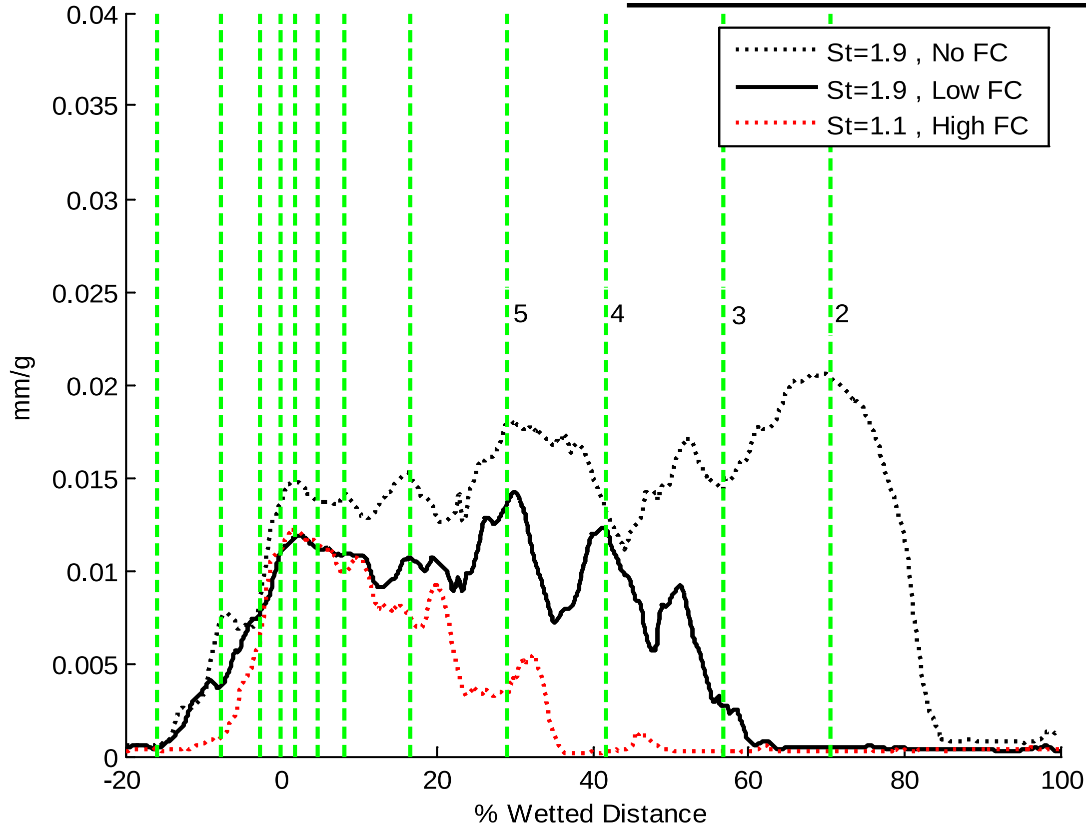
Facility now upgraded to allow full film cooling and hotter/constant film cooling temperatures

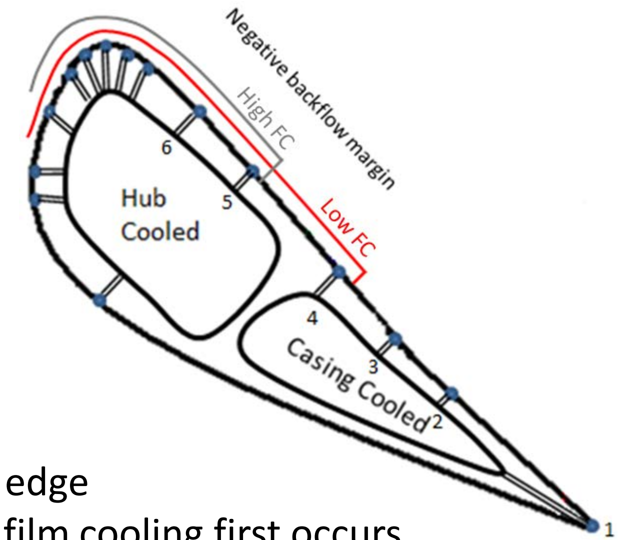




Post Test Results

Laser Scans Traces





- High FC enhances deposit retreat towards the leading edge
  - Low FC deposits stop on film cooling row 3 where film cooling first occurs
  - High FC deposits stop on row 4
- Peaks and valleys of the deposit show some correlation with the film cooling rows
  - Peaks occur at or near cooling rows

PHASE 3: Rotor

- Incorporate deposition model into unsteady rotor-stator code
- Extract hot streak data from OSU GTL rotating uncooled turbine test data
- Extract hot streak data from OSU GTL rotating cooled turbine test data
- Geometry modeling and gridding
- Compare model predictions with rotating data.
- Modify model as needed.
- Propose and explore design modifications that will mitigate particulate deposition on turbine rotors.

URETI /GTL's Stage

- Experiments on single stage HP turbines were conducted at OSU GTL under URETI program.
- Experiments involved temperature inlet b.c.'s of **uniform, radial and hot streak**.
- Both **uncooled** vane and **cooled** vane were used.
- Hot Streak **targeted** at mid-pitch or vane leading edge
- Hot Streak intensity varied
- Cooling rate varied
- Q_{wall} measured

GTL's Relevant Cases

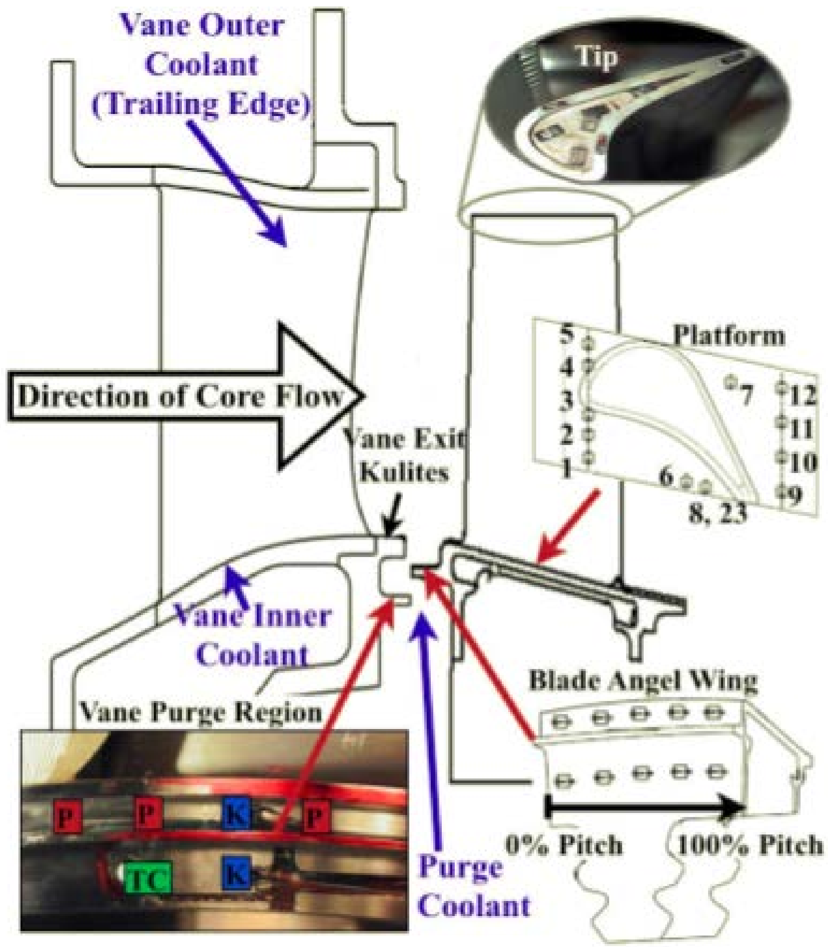


Figure 1. Schematic of instrument locations (not to scale)

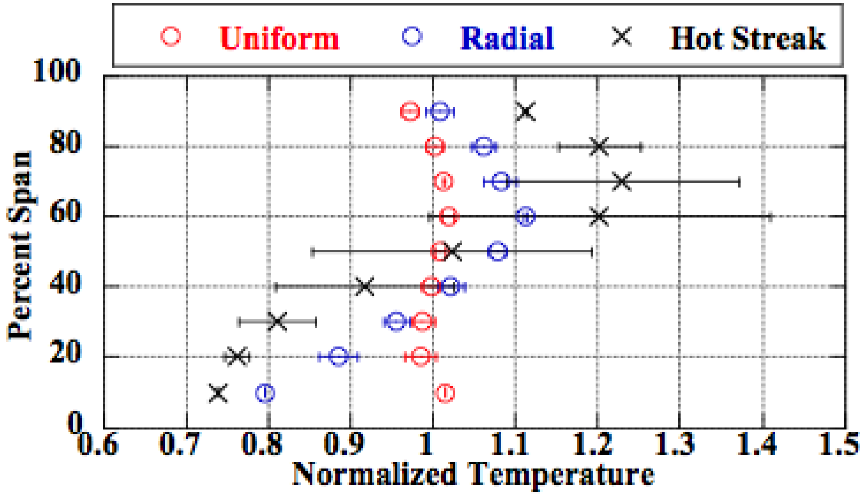


Figure 2. Comparison of inlet temperature profile shapes for runs without cooling

GTL's Relevant Cases

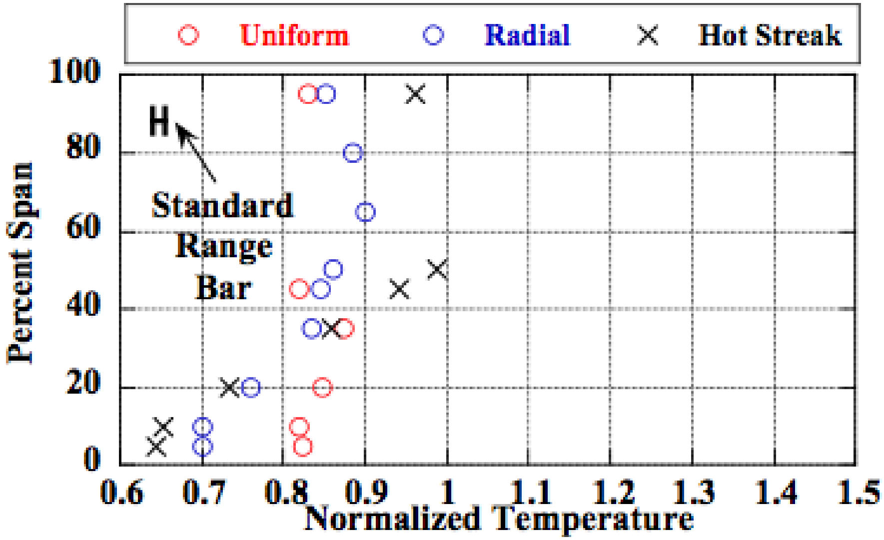


Figure 3. Comparison of rotor inlet temperature profiles measured by blade leading edge thermocouples for runs without cooling

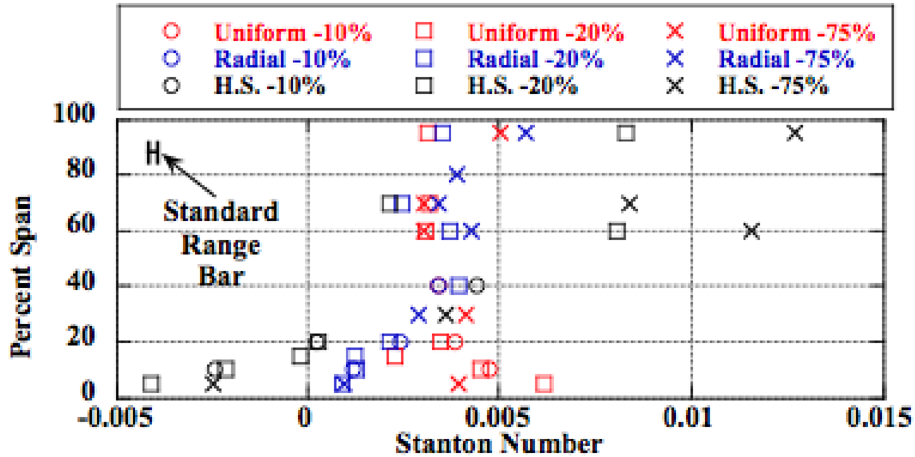
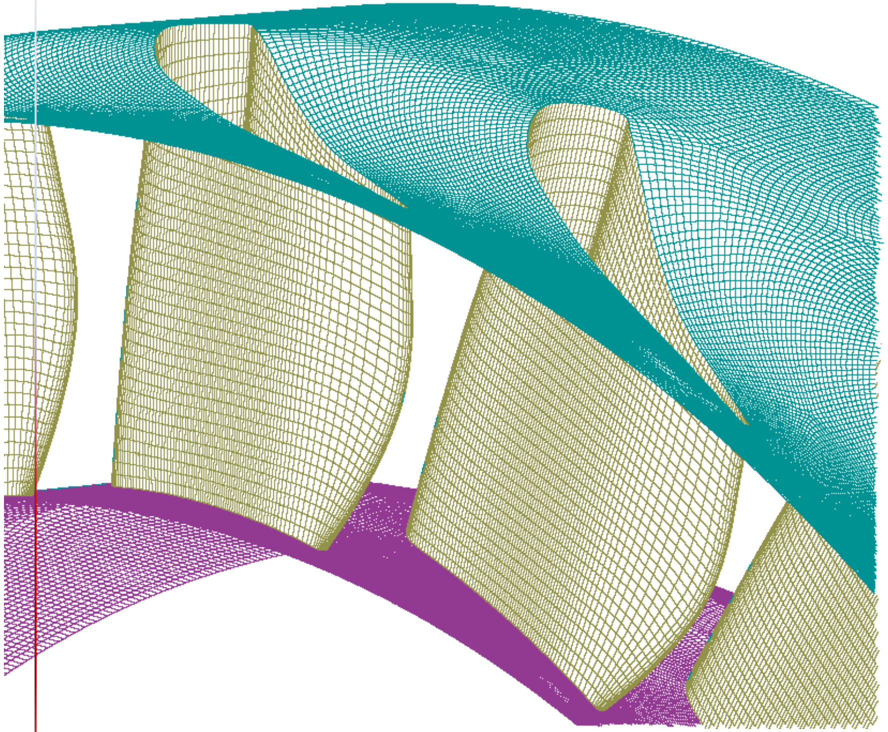
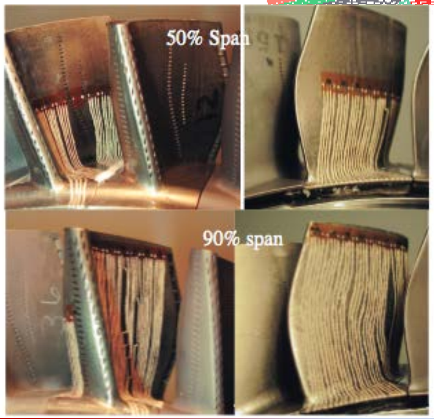


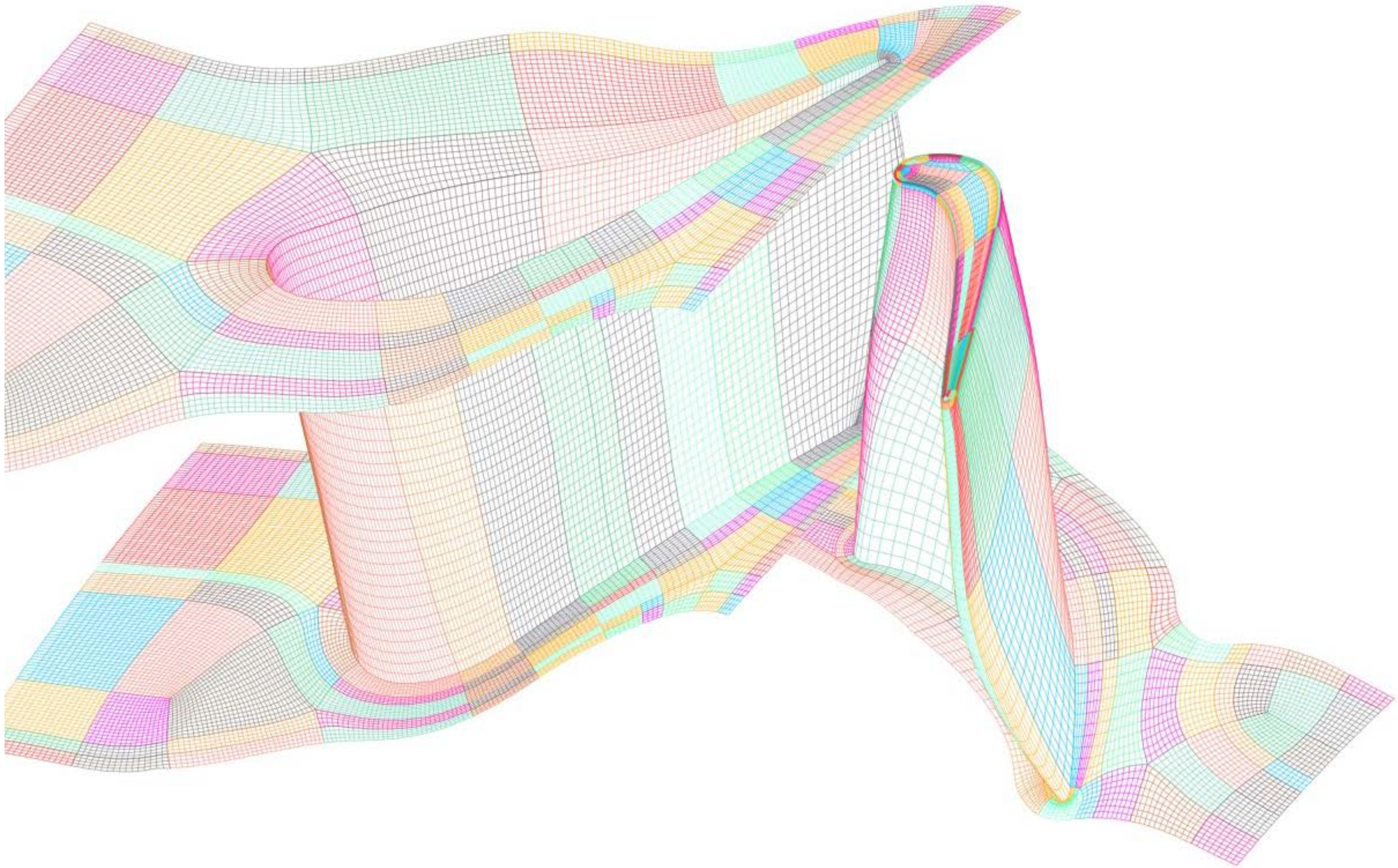
Figure 4. Stanton Number distributions for pressure surface with different inlet temperature profile shapes

URETI Experiments (Hot Streak)

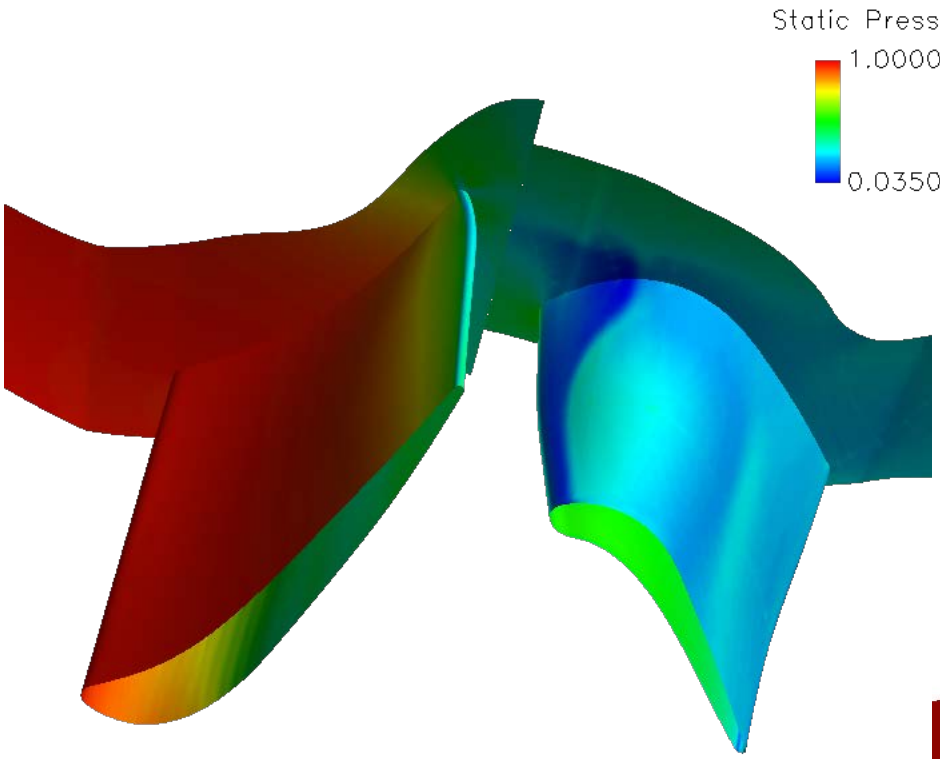


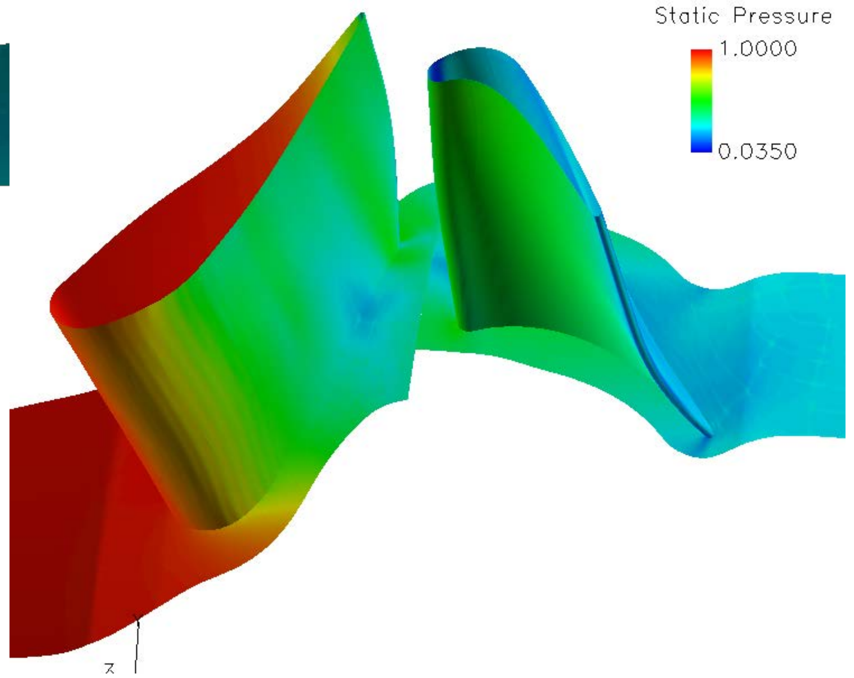


Stator and Rotor grid (Coupled)

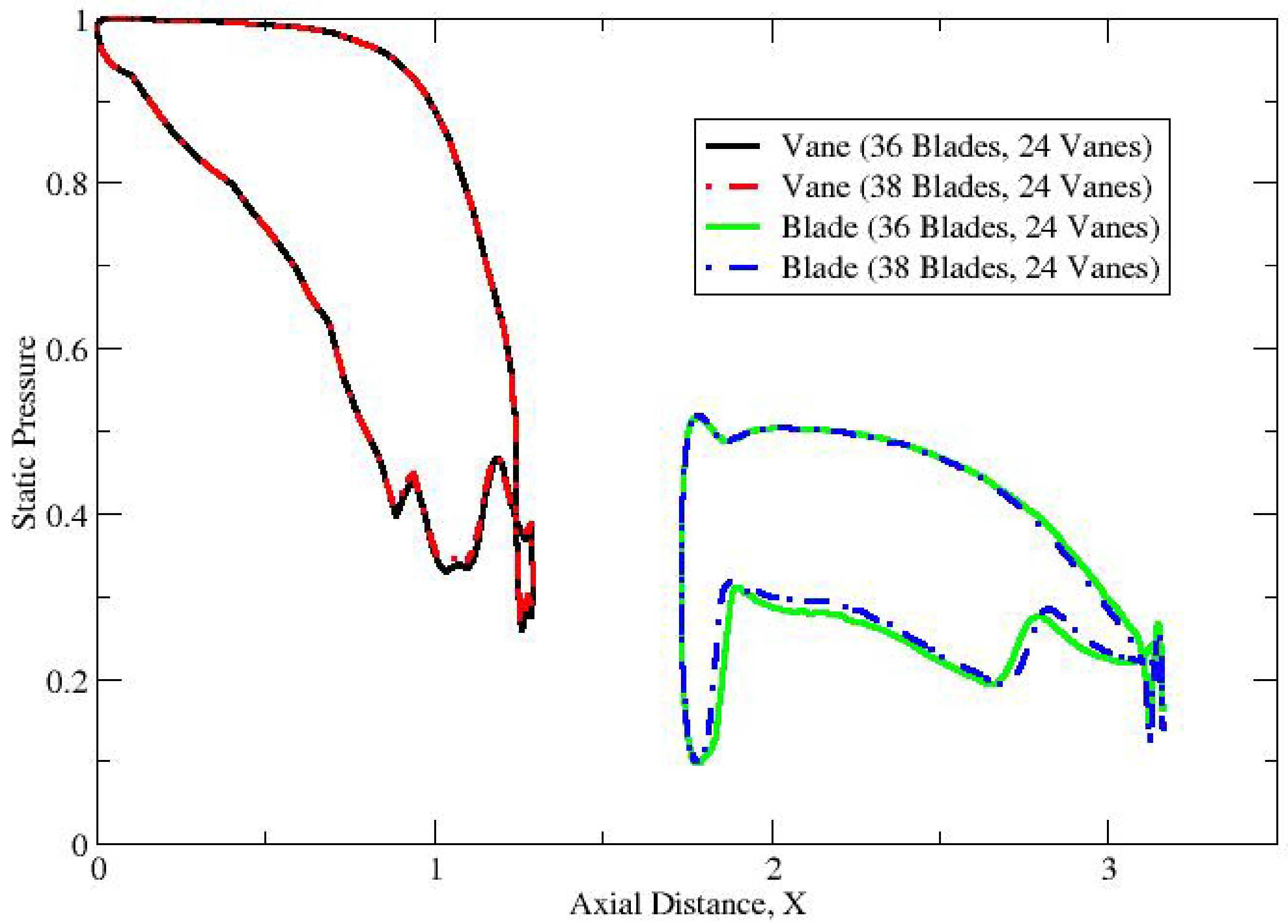


URETI EXPERIMENT, Pressure (mixing plane)





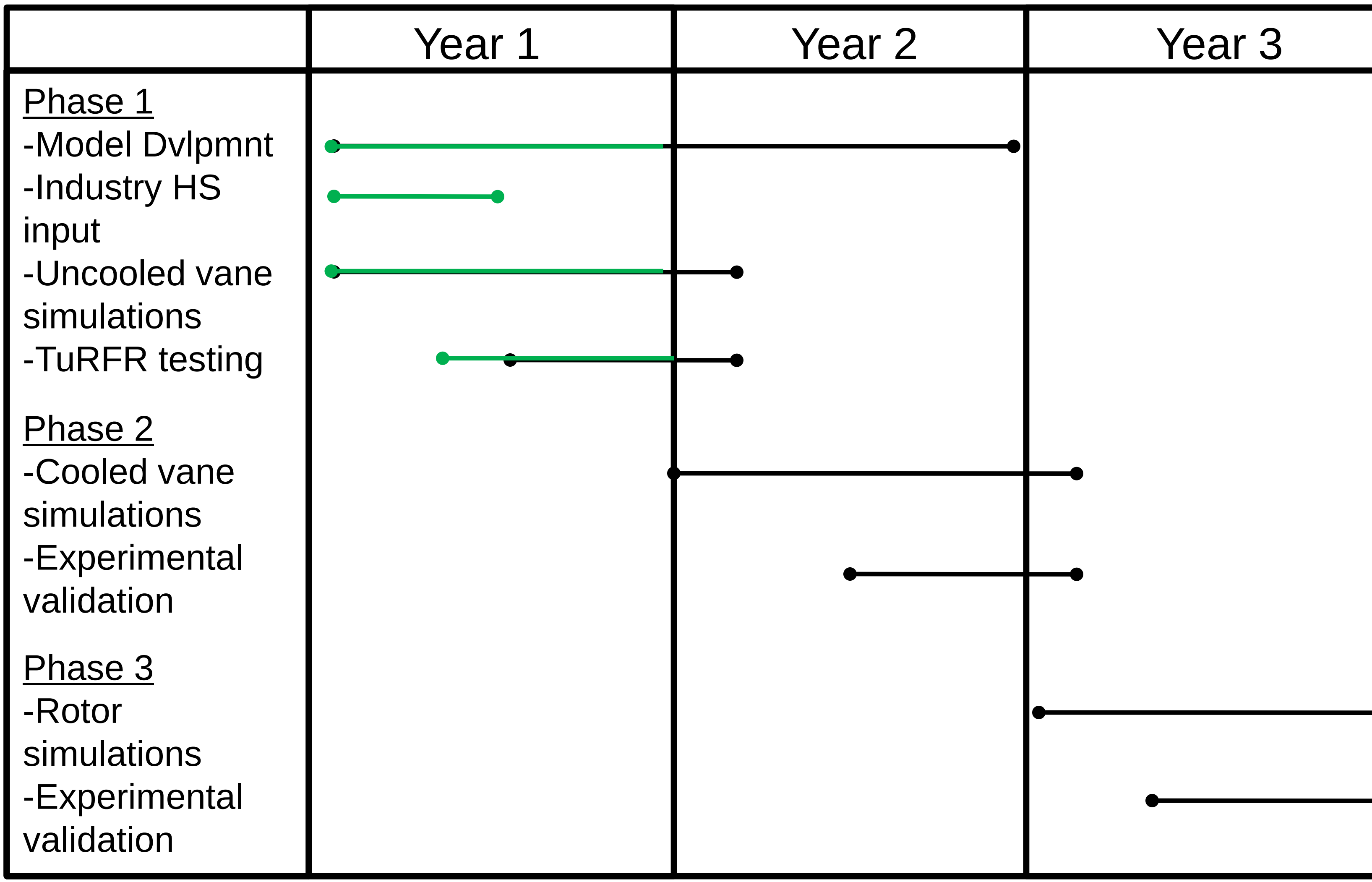
Pressure Distribution Midspan Mixing Plane



URETI Stage Plan

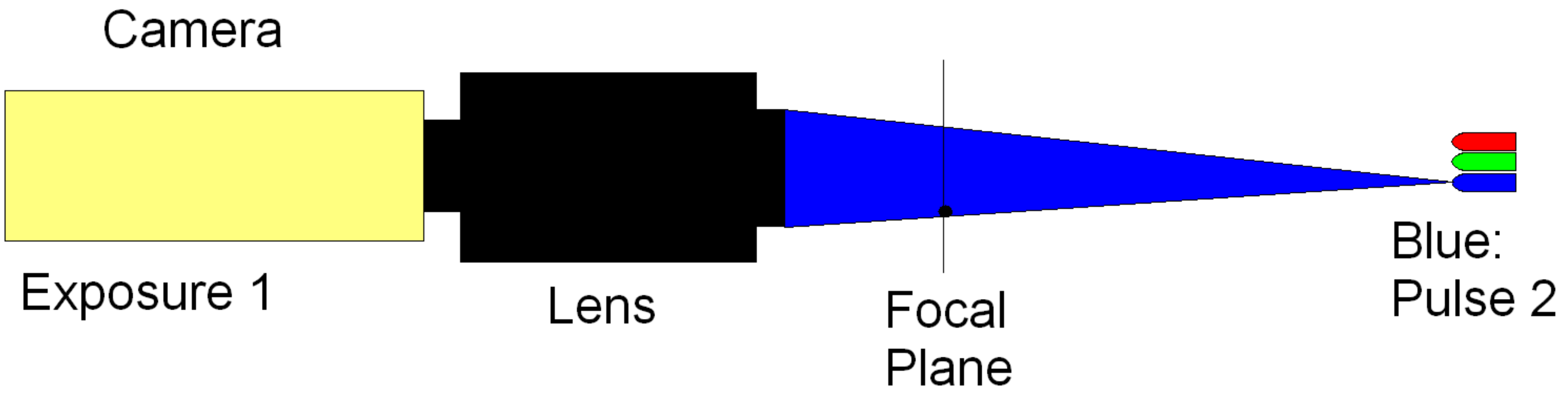
- Will Commence running stage in unsteady mode with uniform inlet condition without cooling.
- Will use a 2 to 3 ratio of the vanes to blades for convenience and based on the computations presented.
- Temperature distribution and wall heat trasnfer will be compared for the two cases by computing the heat transfer coefficient.

Gantt Chart


Year 1
Year 2
Year 3
Phase 1
-Model Dvlpmnt
-Industry HS input
-Uncooled vane simulations
-TuRFR testing
Phase 2
-Cooled vane simulations
-Experimental validation
Phase 3
-Rotor simulations
-Experimental validation


QUESTIONS?

PSV Imaging: Color Camera



Future Work

- Revise existing particle tracking algorithm being used on cold rig
  - Detect particles in poor quality images
  - Detect particles that deposit on plate
- Record better quality images
  - Reduce deposition on window (skinnier plate)
  - Reduce heat waves by running with windows installed
- Continue testing with various particle compositions