Impacts of Particulate Ingestion on External and Internal Flow Paths

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The presentation will cover several items related to aero-heat transfer experiments done at Penn State

Introduction to facilities at Penn State

Particle deposition on external surfaces

Particle deposition on internal surfaces

Han et al.
Several flow facilities are available in the PSUExCCL.

- Removable turbine airfoil test section
- Mainstream flow
- Coolant flow
- Wax particulate flow
Several flow facilities are available in the PSUExCCL
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**Flowfield Facility**

**Features:**
- 64x
- Glass/polycarbonate test section
- Optical access in visible light spectrum
- PIV measurements

**Heat Transfer Facility**

**Features:**
- 10x
- MDF test section
- Cutout for Zinc-Selenide window
- Optical access in IR spectrum
- IR thermography measurements
A test facility was developed to investigate rust injection at rotating conditions.
Flowfield measurements are made using time-resolved PIV

PIV orientation in facility

Wake measurements
Constant Z/H = 0 (channel symmetry plane)

Time-resolved:
- 1000 Hz
- 500 Hz Nyquist
- 30x shedding frequency at Re = 2.0e4

Spatially-resolved:
- 1024x1024px
- 125mm x 125mm viewing area
- 7.6 pixels/mm
- y^+ = 5 (between vectors)

Statistical convergence:
- 3000 samples (1000 for convergence)
- Flow crosses domain minimum 60 times
Heat transfer measurements are made with IR thermography.

- IR Camera orientation in facility
- Constant heat flux method
- Top heater
- Bottom heater
- Raw IR Image
- Removable Insulation
- IR Camera
- Line-of-sight
- Air Gap
- Calibration TCs
- Flow
- Heaters
- Pin-fins
- Zinc-Selenide
We need to gain a better understanding of the effects of particle deposition.
Dynamically simulate particle deposition on **external** and **internal** surfaces to determine effects on cooling

High Pressure Turbine – 1\textsuperscript{st} Stage

- Endwall
- Pressure Side (Flat Plate)
- Film-Cooling
- Leading Edge (Showerhead)
- Trailing Edge Cooling
- Double-Walled Liner
- Root of Blade
- Airfoil
- Platform
- Seal Pin Slot

[Hill and Peterson, 1992]
This presentation covers aspects related to dirt, dust, and rust on external and internal flow paths.

External Flow Path
- Scaling issues
- Simulation methods
- Results for three regions

Internal Flow Path
- Scaling issues
- Simulation methods
- Results for two regions
Particle motion and particle phase must be properly scaled from engine to laboratory conditions.

\[ \tau_p = \frac{\rho_p d^2}{18 \mu} \]

\[ \tau_f = \frac{L_c}{U} \]

\[ \text{Stk} = \frac{\tau_p}{\tau_f} \]

\[ \text{Stk} << 1 \text{ particle follows streamlines} \]

\[ \text{Stk} >> 1 \text{ particle trajectory dominated by particle inertia} \]

\[ T_{\text{initial}} = 1320 \]

\[ T_{\text{gas}} = 1220 \]

\[ T_{\text{solid}} = 1260^\circ \text{C} \]

\[ T_{\text{SP}} = 1.2 \]

\[ \text{TSP} = \frac{t_1 + t_2}{L_{\infty}/U_{\infty,i}} \]

\[ t_1 = -\frac{\rho_p C_p V_p}{h A_p} \ln \left[ \frac{T_{p,s} - T_{\infty}}{T_{p,i} - T_{\infty}} \right] \]

\[ t_2 = \frac{\Delta H_{\text{fus}}}{h A_p \left( T_{p,s} - T_{\infty} \right)} \]

\[ L_{\infty} = \text{distance from combustor to turbine surface} \]

\[ U_{\infty,i} = \text{inlet mainstream velocity} \]

[Friedlander, 2000]
Dynamically simulate particle deposition on external surfaces to determine effects on cooling.
Wax was injected in different stages to observe deposition and effectiveness development.

Initially, only large molten particles deposit.

Eventually, small solid particles stick to existing deposits.

I = 0.23
M = 0.50

Before Deposition After 1200g After 2400g After 3200g
Effectiveness reduction approached an equilibrium state as deposition area coverage increased.
Deposition within leading edge cooling holes decreased with an increase in blowing ratio.
All three trench depths reduced the negative impact of deposition on endwall cooling effectiveness.

\[ \eta_{total} = \frac{A_{passage} \eta_{passage} + A_{LE} \eta_{LE}}{A_{passage} + A_{LE}} \]

- No Trench - Effectiveness
- 0.4d Trench - Effectiveness
- 0.8d Trench - Effectiveness
- 1.2d Trench - Effectiveness

Total Area-Averaged Effectiveness, \( \bar{\eta}_{total} \)

Total Effectiveness Reduction, \( \frac{\bar{\eta}_o - \bar{\eta}}{\bar{\eta}_o} \)
Contouring can alter cooling patterns and lead to deposition regions.

TSP = 0.3

Flat

TSP = 1.1

Molten

Flat

Contour

Contour

M = 1.0

Area-Averaged Effectiveness, $\eta$

0.0
0.05
0.1
0.15

0 0.2 0.4 0.6 0.8 1

TSP

0.3

1.1

Solid

Molten

Flat Before Deposition

Flat After Deposition

Contour Before Deposition

Contour After Deposition
Experimental deposition patterns were similar to computationally predicted accretion rates.
Effects of deposition on cooling varied with location

- Flat Plate
- Leading Edge
- Vane Endwall - No Trench
- Vane Endwall - 0.8d Trench
- Blade Endwall - Flat
- Blade Endwall - Contoured

Effectiveness Reduction (%) vs. M (Mach number)
Dynamically simulate particle deposition on **internal** surfaces to determine blockage effects and heat transfer implications.

High Pressure Turbine – 1\textsuperscript{st} Stage

Double-Walled Liner

[Trailing Edge Cooling]

Airfoil

Seal Pin Slot

Platform

Root of Blade

[Hill and Peterson, 1992]
Injection sand amounts were determined based on field hardware.

\[
\%RFF = \frac{FF_0 - FF}{FF_0}
\]

\[
FF = \frac{\dot{m} \sqrt{T_0C}}{P_\infty}
\]

\[
PR = \frac{P_{0C}}{P_\infty}
\]
Sand diameter causes the melting point to be lower than is reported for this chemical substance.

Room Temperature

Reported Melting Temperature

2930°F [Incropera & DeWitt]
3130°F [Handbook of Chem. & Phys. 1981]
The impingement jets and film-cooling jets were tested both staggered and aligned.

+ = impingement holes
o = film-cooling holes
The S/D = 3.1 had less blockage due to decreased crossflow and decreased jet spreading.
A similar trend for spacer thickness was seen with both staggered and aligned holes. 

PR = 1.3, 150 < $D_s$ < 3800 $\mu$m Sand, Sand = 0.35 g
Rust can form in components along the flow path for secondary air used to cool the turbine blades.

[Diagram of a turbine system with labels for Compressor, Combustor, Heat Exchanger, Filter, and Turbine.]

Rust on Rotor Hardware

Rust in Secondary Air Piping

http://powerccl.co.uk/turbine-corrosion.html
Rust particles entrained in the secondary flow can deposit in the axial seal pin region between blades.

**Purpose of seal pin is to:**
- Prevent ingress of mainstream gas flow
- Damping mechanism

**Particle deposition in seal pin leads to:**
- Flow blockage and particle conglomeration
- Prevents free movement of pin

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**Diagram:**
- Secondary Flow at Axial Seal Pin
  - Axial Seal Pin
  - Rotation
  - Mainstream Gas Flow
  - Air Leakage Flow
  - Platform Gap
  - $p_1$, $T_1$
  - $P_{02}$, $T_{02}$

- Gap Between Platforms
  - Rear Blade Clearance
  - Front Blade Clearance
  - Front Blade Platform (Flat)
  - Air Leakage Flow
  - Seal Pin

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**Equations:**
- $p_1$, $T_1$
- $P_{02}$, $T_{02}$
Effects of temperature and compaction due to rotation were evaluated for an axial seal pin.

Effects of rust on static engine hardware

Development of a rotating facility and method

Effects of temperature and rotation on rust particles

Effects of rotation on rust deposition
Flow blockage was found to increase with pressure ratio due to particle lodging at high velocities.
Some key physical observations resulted from tests of the metal oxide compounds at high temperatures

Most changes take place above 1500°F

Prolonged exposure to high-temperatures yielded similar results with shorter exposure

Particles conglomerate into large chunks at temperatures between 1700-2000°F (955-1093°C)

Red iron-oxide Fe₂O₃ turns black at elevated temperatures
Turbine-representative rotational forces resulted in significant compaction of rust particles.

The effects of the centrifuge were similar on previously heated and unheated samples and for rotating speeds corresponding to $\Omega = 1$ and $\Omega = 6$. 

**Table: Centrifugal Acceleration**

<table>
<thead>
<tr>
<th>Sample</th>
<th>$r$ (mm)</th>
<th>$\omega$ (rpm)</th>
<th>$a_c$ (x g)</th>
<th>$\Omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>turbine first row</td>
<td>856</td>
<td>3,600</td>
<td>12,400</td>
<td>1</td>
</tr>
<tr>
<td>centrifuge</td>
<td>108</td>
<td>10,000</td>
<td>12,100</td>
<td>1</td>
</tr>
</tbody>
</table>

Before centrifuging: $\rho = 0.9$ g/cm$^3$

After centrifuging: $\rho = 2$ g/cm$^3$
A modified centrifuge simulated effects of rotation; surface roughness was matched on specimens.
The flow function was similar for each of the three test coupons and scaled with the flow area.

\[ \Omega = 0.002 \]

![Graph showing flow function and test configurations](image)

**Test Configurations**
(Top View of Chamber)

- **Single Coupon**
  - Sealed
  - Flow

- **Three Coupons**
  - Flow

Legend:
- coupon 1-1
- coupon 1-2
- coupon 1-3
- single coupon curve fit
- three coupons, scaled by one-third
After injection, particles sizes were analyzed showing deposits near seal pin to be smaller.
Flow blockages were nominally independent of rotational forces for this particular geometry.

Each data point represents an average of at least three tests, each test with flow through three identical test coupons.

RFF measurement uncertainty: ±9% of measured value

RFF repeatability for 3-test average: ±7% (95% confidence interval)
In conclusion, the effects of deposition can have profound impacts on heat transfer. Trenches and endwall contouring can help to mitigate the negative effects of deposition on cooling effectiveness. Double-walled liners can be designed to reduce blockages. Centrifugal effects can be important in some designs. Testing is needed to determine what the effects might be!
Those who really do all the work.....

And...Seth Lawson, Nick Cardwell, Cam Land, Scott Walsh, Steve Lynch, Duane Breneman
In conclusion, the effects of deposition can have profound impacts on heat transfer.

Trenches and endwall contouring can help to mitigate the negative effects of deposition on cooling effectiveness.

Double-walled liners can be designed to reduce blockages.

Centrifugal effects can be important in some designs.

Testing is needed to determine what the effects might be!
Back-Up Slides
Wax droplets were tracked in the Lagrangian frame as discrete particles with simulated dispersion

\[
\frac{du_{p,i}}{dt} = \frac{\sum F_i}{m_p} \\
= F_{D}(u_i - u_{p,i}) + \frac{g_i (\rho_p - \rho)}{\rho_p} + \frac{\rho}{\rho_p} u_{p,i} \frac{\partial u}{\partial x_i}
\]

Particle Accel. = Drag force + Gravity + Pressure gradient (Stokes’ Law)

\[
F_D = \frac{18}{\rho_p d_p^2} \frac{C_D Re_d}{24}
\]

\[
C_D = a_1 + \frac{a_2}{Re_d} + \frac{a_3}{Re_d^2} \quad [\text{Morsi & Alexander, 1972}]
\]

Simulated turbulent dispersion: Discrete Random Walk (DRW)
Random gas phase fluctuating velocity

\[
u_i = \bar{u}_i + u_i'
\]

\[
u_i' \approx \text{rand} \times \sqrt{2k/3}
\]

Heat transfer: Lumped capacitance

\[
m_p C_p \frac{dT_p}{dt} = hA_p (T - T_p)
\]

Solidification process model

\[
\int hA_p (T_{p,s} - T) dt = m_p h_{\text{fusion}}
\]
Flow visualization was performed with a high speed camera and Nd:YLF pulsed laser.

Laser Frequency $\sim$ 6kHz
Camera Speed = 2 kHz

Composite images $\sim$ 20 Frames (0.01s)

$\lambda$ = 0.23
Vane Stagnation

$\lambda$ = 3.6
Vane Stagnation

No Trench

0.8d Trench

Saddle Pt.

EAR Export Classification: ECCN 9E991
Digital pictures showed effects upstream of the film-cooling plate of the varying spacer thicknesses.

- S/D = 1.6
- S/D = 2.3
- S/D = 3.1
- S/D = 4.7
- S/D = 6.3
Deposition varied with blowing ratio and was thickest near stagnation at $M = 1.0$.
Wax droplets were tracked in the Lagrangian frame as discrete particles with simulated dispersion.

Discrete Phase Model - DPM
Volume Fraction = 7 x 10^{-7}
One-way coupling
Turbulent Dispersion – DRW

Outlet: Escape
Walls: Trap Particles
Inlet: Injection Plane
(Rosin-Rammler distribution)

Median = 35 µm

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\[ \text{Mass Fraction} > d_p, Y \]

Experiments
CFD - Rosin-Rammler Model
The sand diameter and densities dictate how the sand travels through the flow

Sample | Density (g/cm³) | Mean Diameter (µm)
Test Dust ISO 12103-1, A2 Fine | 2.71 | 18.5
Test Dust ISO 12103-1, A4 Coarse | 2.68 | 37.3
Sieved Test Dust | 2.68 | 50.0
Sand ingested can deposit on internal surfaces blocking channels and roughening surfaces.

For a given PR, the amount of air through a channel drops due to sand blockage.

At the actual Re number, the Nusselt number also drops due to sand blockage.

Overall heat transfer effect is between 5-10%.
Leading edge cooling effectiveness increased with blowing ratio while coolant jets were attached.

\[ M_L = \rho_c C_D \sqrt{2 (p_c - p_{\infty,l}) / \rho_c} / \rho_\infty U_\infty \]

\[ C_D = 0.6 \ [\text{Byerly, 1989}] \]
Deposition patterns were sensitive to trench depth having a strong correlation with coolant patterns.

\[ TSP_{\text{max}} = 1.2 \text{ (m)} \]
Impingement holes aligned with film-cooling holes caused increased blockage.

$S/D = 3.1, 150 < D_s < 3800 \, \mu m$ Sand, $\text{Sand} = 0.35 \, g$

![Graph showing %RFP vs PR for staggered and aligned plate spacing]
On an endwall effectiveness reduction was as high as 30% for passage cooling holes.
To simulate engine Stokes numbers, wax particles need to be 13x larger than fly ash particles.

<table>
<thead>
<tr>
<th>Engine (Fly Ash)</th>
<th>Laboratory (Spa Wax)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Density, ( \rho_p ) (kg/m(^3))</td>
<td>1980</td>
</tr>
<tr>
<td>Inlet Gas Velocity, ( U_w = U_p ) (m/s)</td>
<td>501</td>
</tr>
<tr>
<td>Gas Viscosity, ( \mu ) (kg/m-s)</td>
<td>5.549x10(^{-5})</td>
</tr>
<tr>
<td>Hole Diameter, ( d=L_c ) (cm)</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Bons et al. [2001], Albert [2008]

Bons et al. [2007]
The methods used to dynamically simulate effects of deposition were applied in a wind tunnel facility.
Typical experiments made use of gravity fed sand into the test coupons.