Deposition of Particulate from Coal-Derived Syngas on Turbine Blades with Film Cooling

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Overview

- Background
- Objectives
- Experimental Methods
- Results and Discussion
- Future Work
- Conclusion
- Acknowledgments

Background

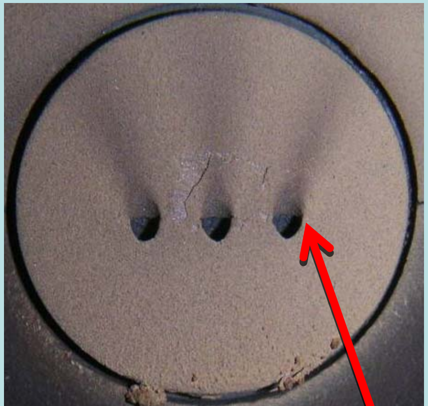
- Alternate fuels (e.g. coal, petcoke, and biomass) are being considered to produce syngas fuels to replace natural gas in power turbines
- Despite gas cleanup, small levels of particulate (e.g. 0.1 ppmw) produce significant quantities (e.g. 2 tons) of ingested material in a large utility power plant during an 8000 hour operating year
- Negative effects of deposition on components and gas turbine performance
- Heavier reliance on innovative cooling strategies: internal cooling and film cooling

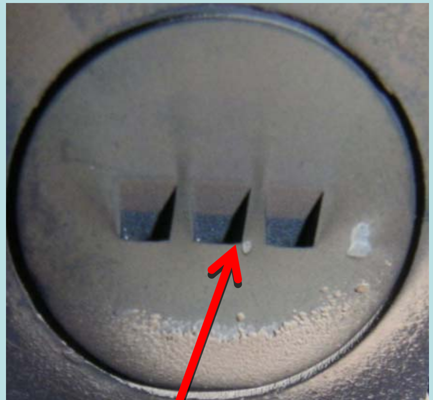
Objective

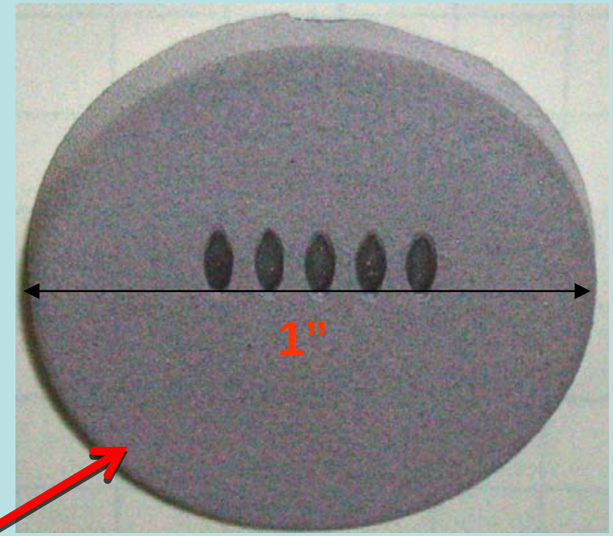
- Develop the capability to generate engine-like synfuel deposits in a laboratory setting with internal and film cooling
- Evaluate the influence of film holes shape, blowing ratio ,TBC and holes spacing on the formation of deposit from coal particulate

Experimental Method

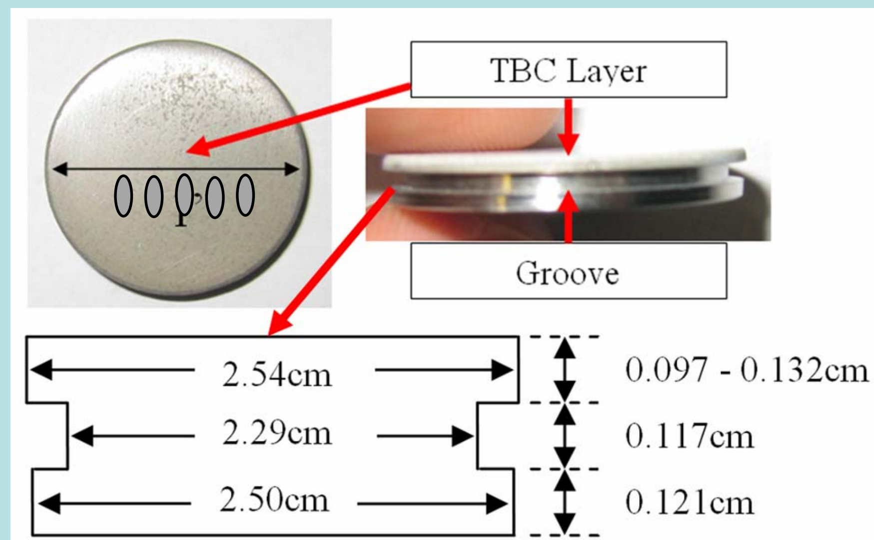
Film Cooling Test Articles







- **Superalloy only**
  - 3 holes, 1.5mm diameter, 3d spacing, cylindrical
  - 3 holes, 1.5mm diameter, 3d spacing, shaped



- **TBC on superalloy**
  - 5 holes, 1mm diameter, 2.25d spacing, cylindrical
  - Block holes 2&4 to obtain 4.5d spacing

Turbine Accelerated Deposition Facility

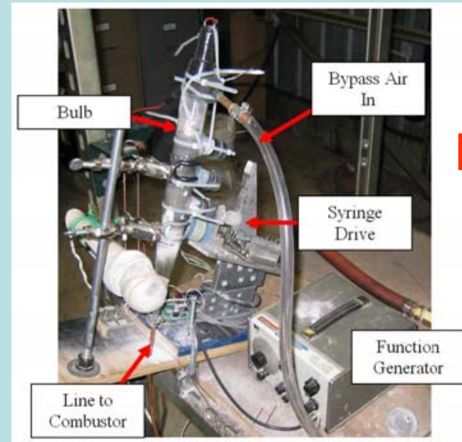
Test coupon held inside exit cup

RGB Camera

Particle acceleration and thermal equilibrium tube.

Particulate injection

Natural gas combustor

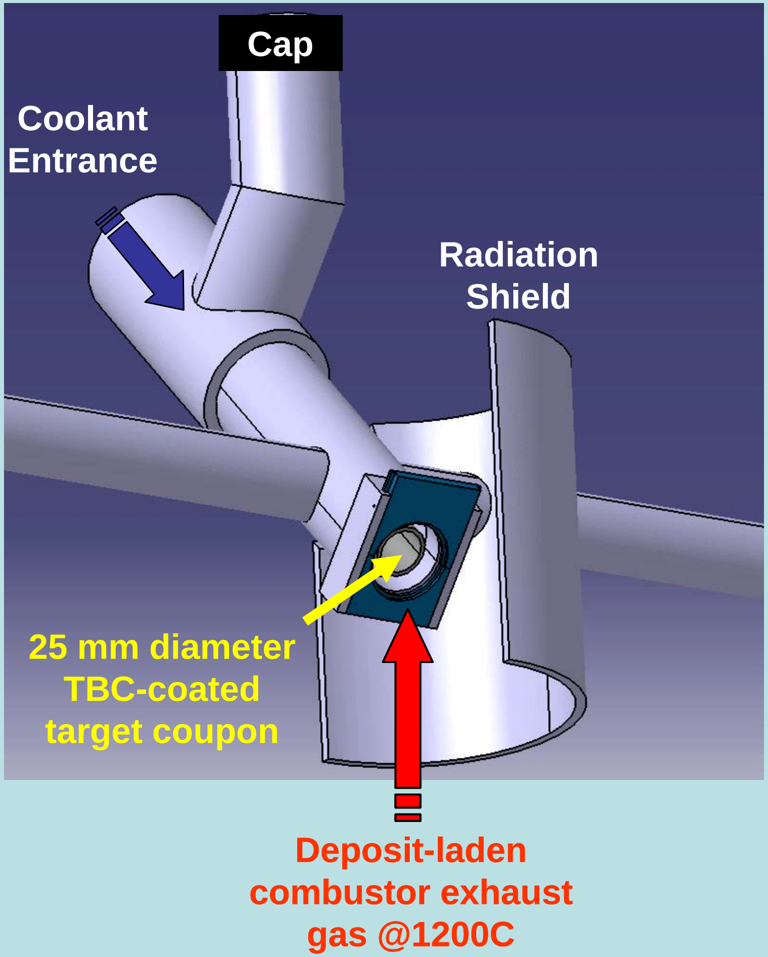


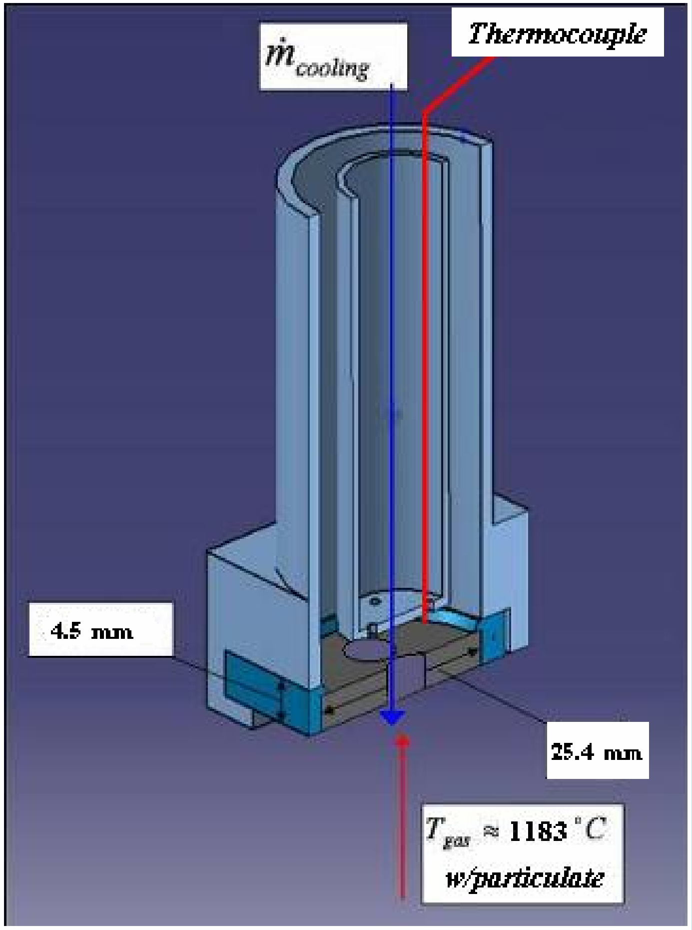
Particle Feeder

- Design Parameters to match: temp, velocity, angle, materials, particle size, chemistry, and concentration.
- Inconel construction allows max jet temperature of @1200 C degree.
- Exit velocities up to 300m/s – deposition by inertial impaction.
- Match net particle throughput:

8000hrs x 0.1ppmw ≈ 4hrs x 200ppmw

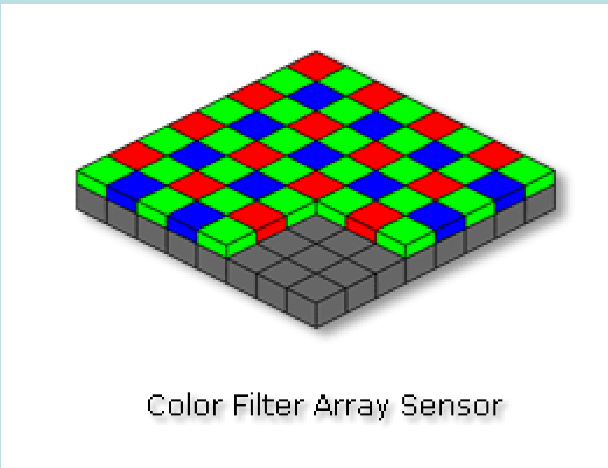
Redesign for Coolant Path

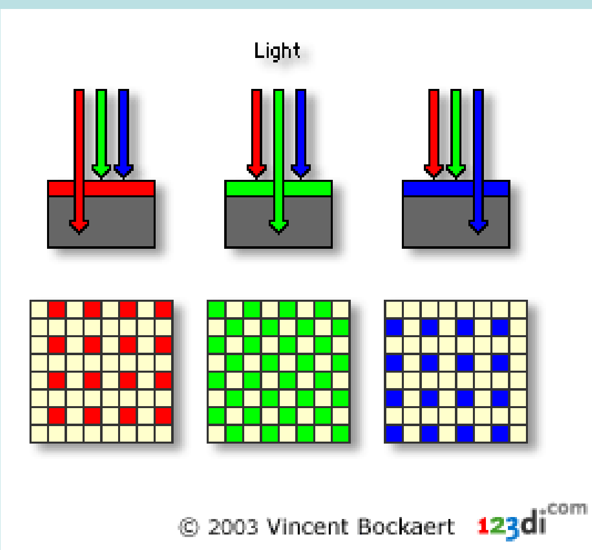




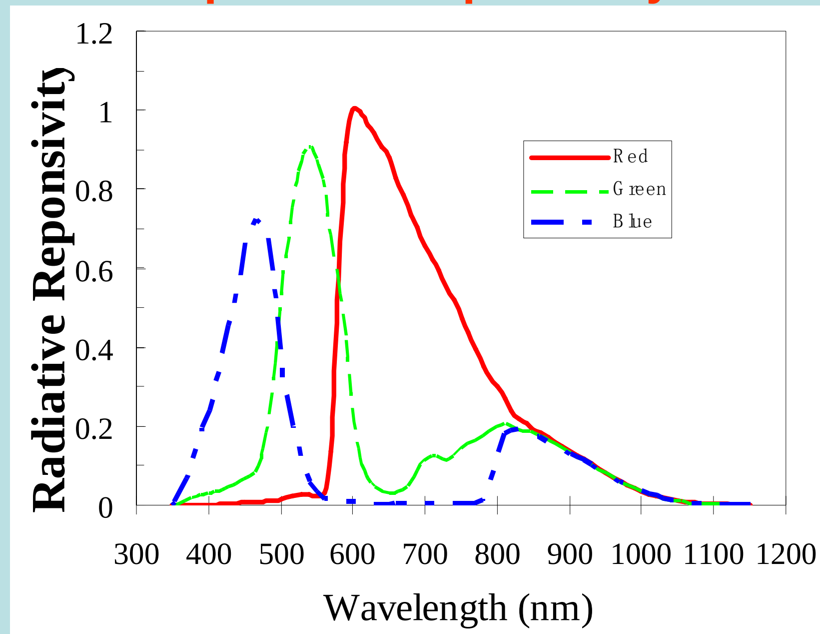
Temperature Measurement

Color image reconstruction
from **a Bayer filter** (Bockaert, 2003)





Spectral Responsivity

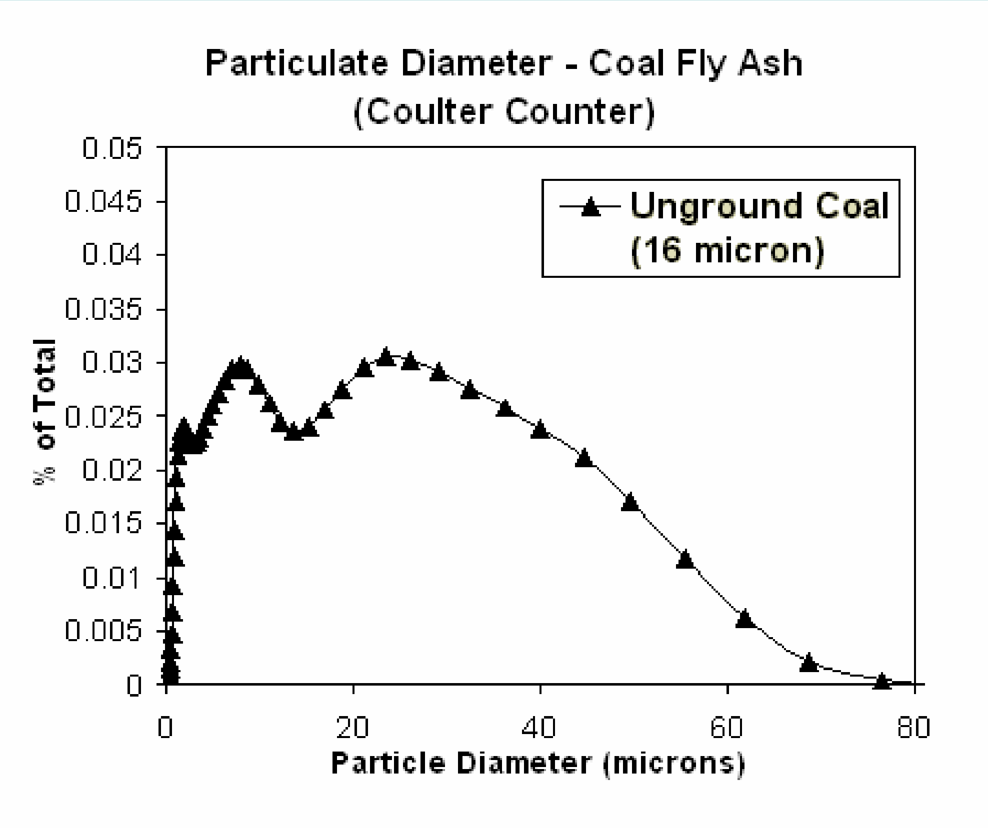


$$P_i = \int_{t_1}^{t_2} s_i \int_{\lambda_1}^{\lambda_2} \varepsilon_b I_{b,\lambda} \beta_\lambda \tau_\gamma \, d\lambda dt$$

- **Each color (RGB) has different spectral response (S_λ)**
- **Intensity measured on each color**
- **BG (or RB) ratio used to determine temperature**
  - assume surface emissivities are constant and equal

Particulate Sample Preparation

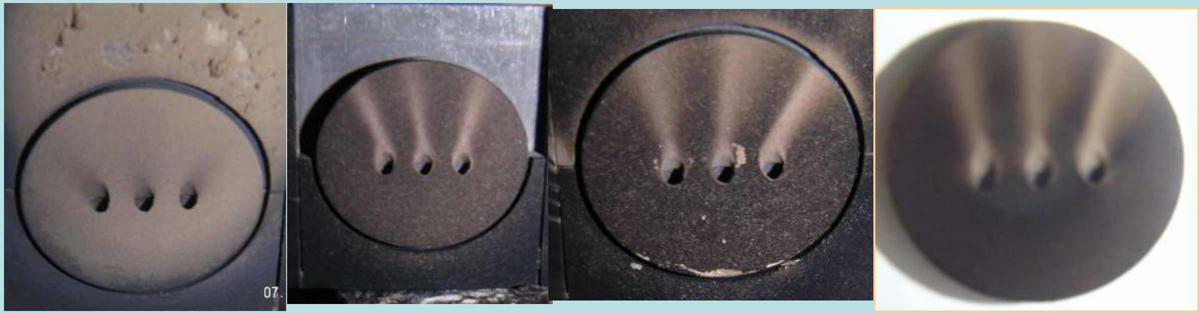
Coal
(power plant fly ash)



Mass mean diameter:16 μ m
Bulk density: 0.99 g/cc
Apparent density:1.98 g/cc

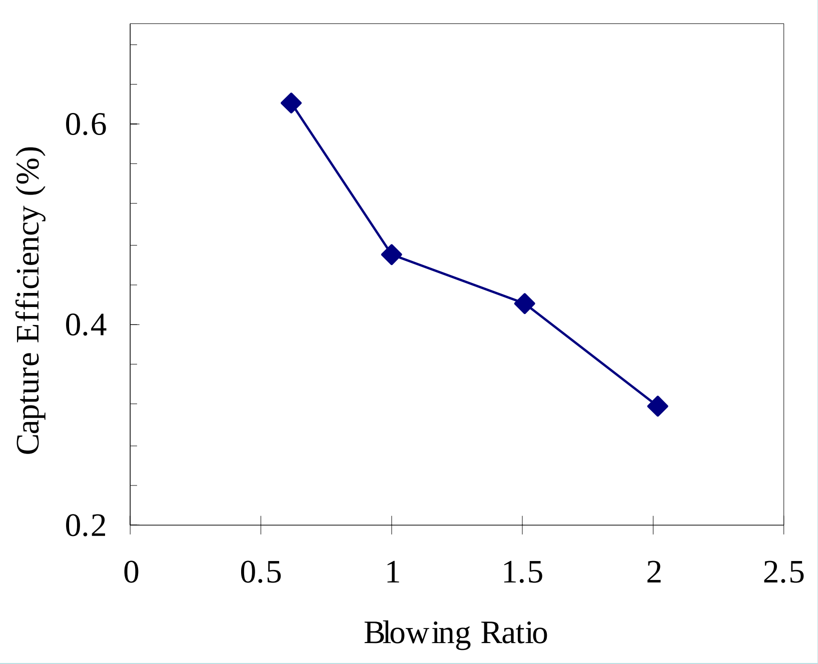
Results and Discussion

Cylindrical Holes, Metal Coupon



Flow Direction

a) M=0.6 b) M=1.0 c) M=1.5 d) M=2.0



Testing Conditions: Inconel alloy,3-cylindrical holes, d=1.5 mm, 3d spacing, M=0.6, 1.0, 1.5, 2.0; 4 hr tests, Density ratio=1.8-2.3

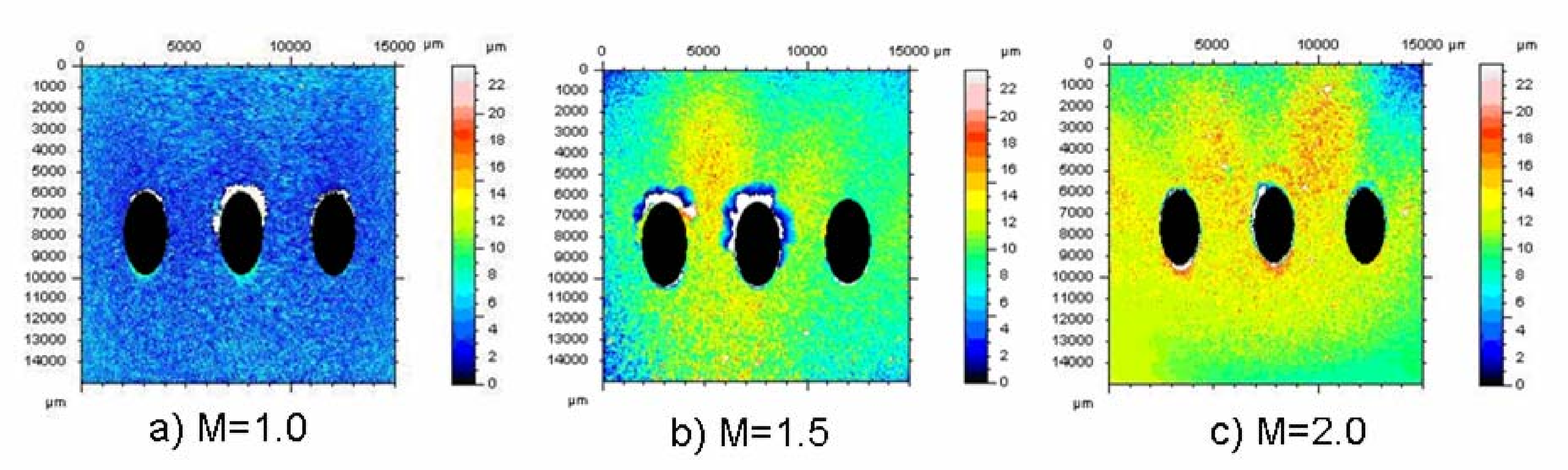
Deposit Pattern: The flow channels seen downstream of the left and right side holes deviate somewhat from the expected stream-wise direction

Capture efficiency: Blowing ratio increased from 0.6 to 2, the capture efficiency decreased by 50%.

$$\text{Net Capture Efficiency} = \frac{\text{Deposit Mass}}{\text{Total Particulate Ingested}}$$

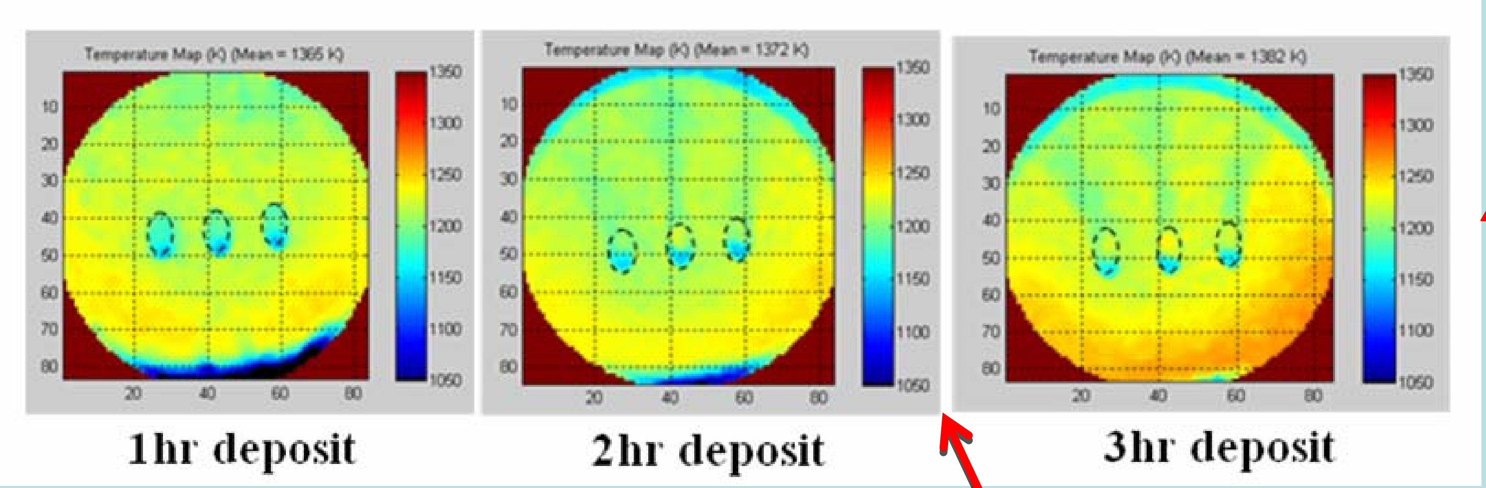
Cylindrical Holes, Metal Coupon

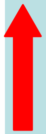
Deposit Thickness Map



- T8000 contact profilometer was used for a statistical evaluation of the roughness of the deposits
- 15 mm by 15 mm square area at a data spacing of 20 um
- The ridges between film cooling holes are apparent at a blowing ratio of 2 but not apparent at M = 1

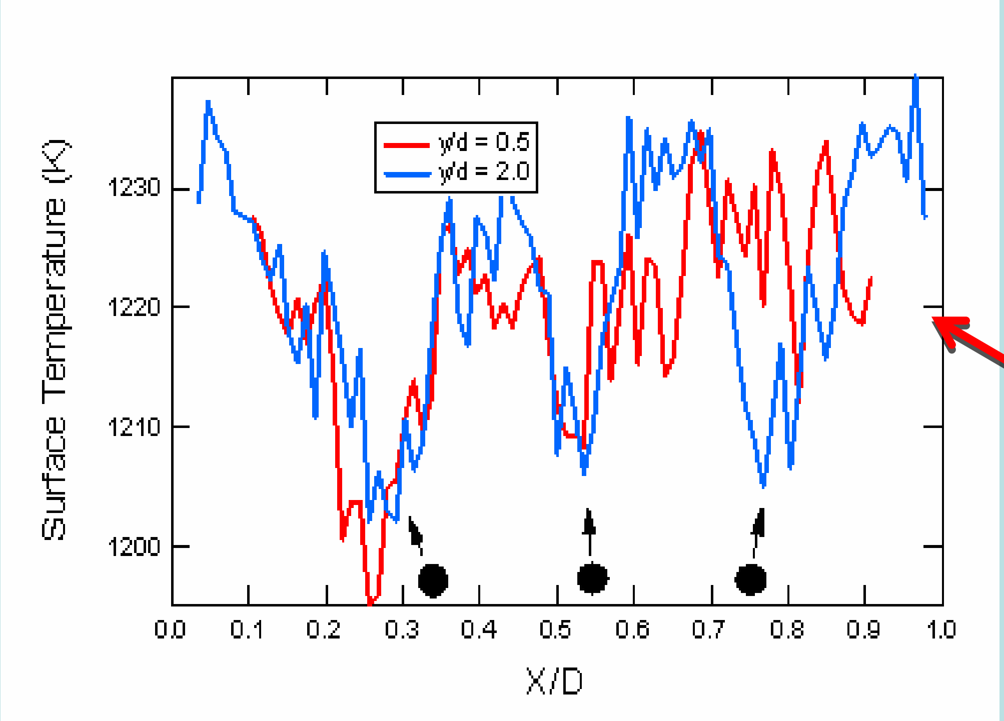
Cylindrical Holes, Metal Coupon





Flow Direction

Coupon front-side temperature map at M= 2.0

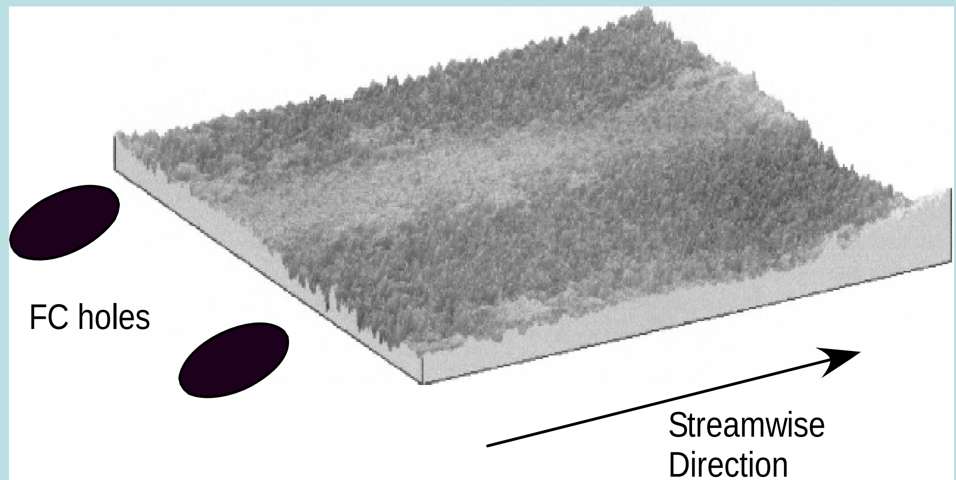


Span-wise distribution of temperature at Y/d = 0.5 and 2, M = 1.5.

Cylindrical Holes, Metal Coupon

(**4 hrs test, coal particulate, coupon with deposit residue, 3d spacing**)

Flow Direction

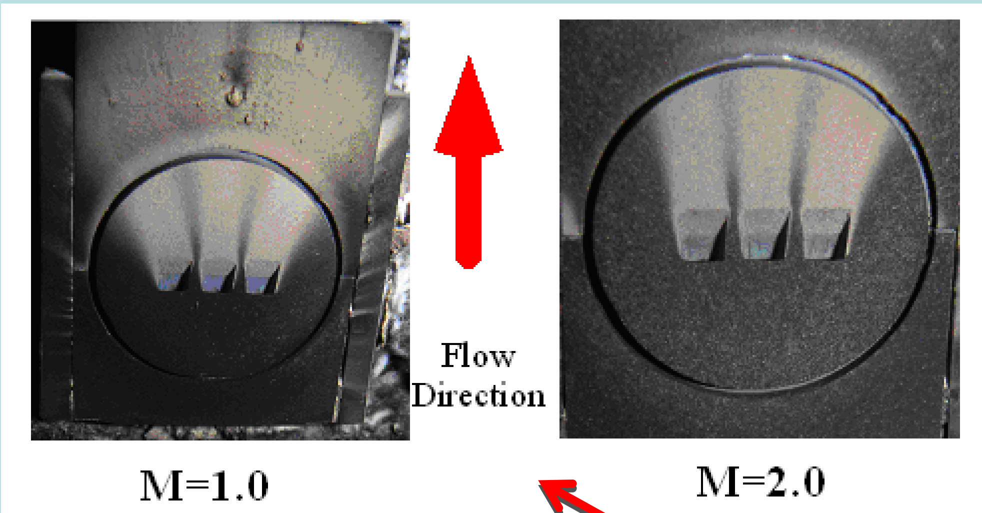


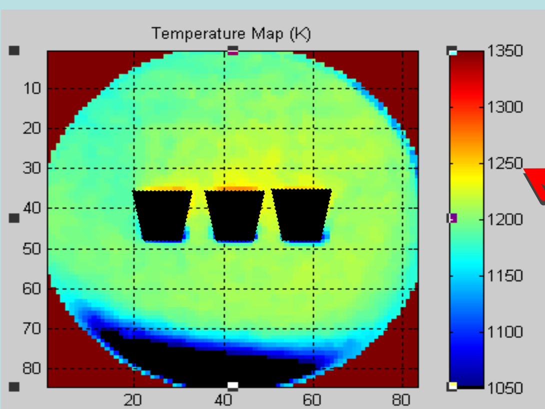
TADF deposits

Serviced turbine blade deposits

Shaped Holes, Metal Coupon

(4 hr test, coal particulate, shaped holes, 3d spacing, D.R. ≈2.2, 70ppmw)





Deposit Patterning

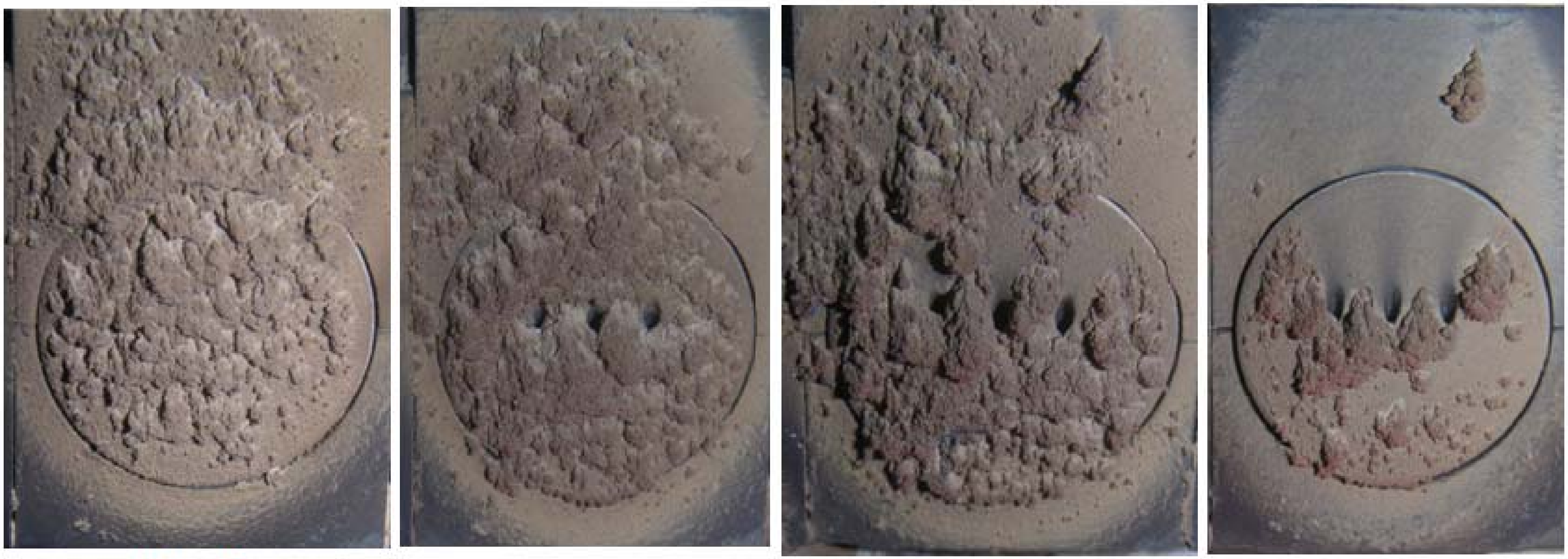
Temperature Profile

- The area affected by the shaped hole coolant is larger than that of the cylindrical holes
- Cooling areas from individual hole almost overlap
- Shaped holes reduce the surface deposit more efficiently than cylindrical holes
- Uniform temperature in the entire lateral region downstream

Cylindrical Holes, TBC Coupon

(1 hr test, coal particulate, cylindrical holes, 2,4 holes plugged, 4.5d spacing, D.R. ≈2.2, 310 ppmw)

Deposit Pattern



M=0
(No impingement cooling)

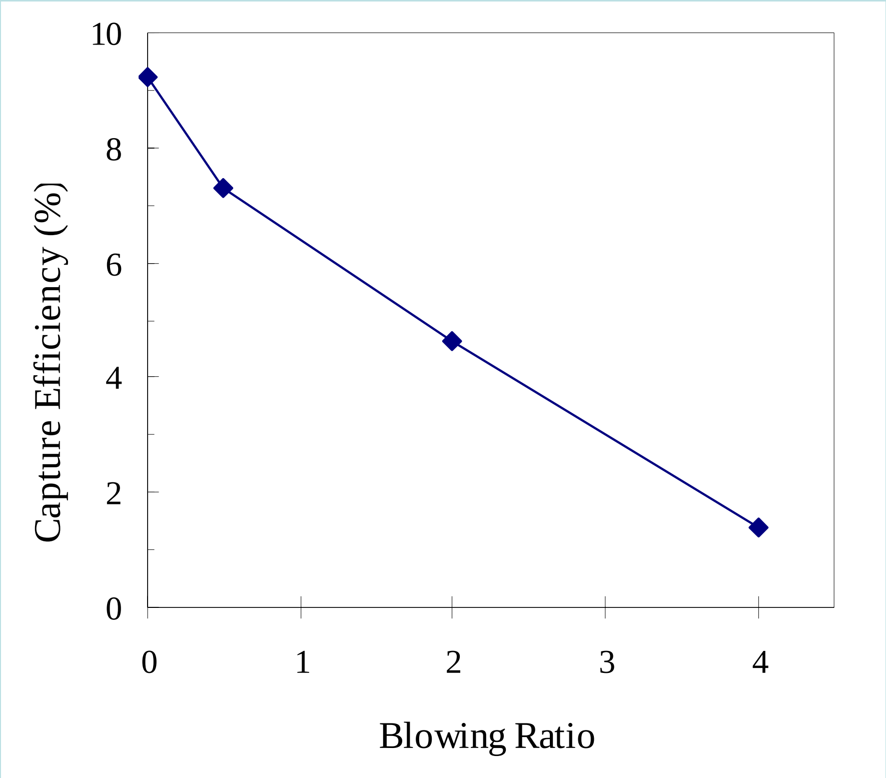
M=0.5

M=2

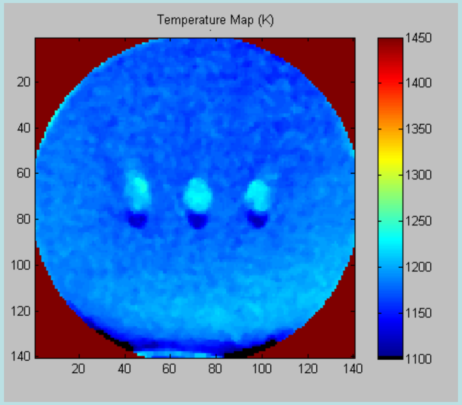
M=4

Cylindrical Holes, TBC Coupon

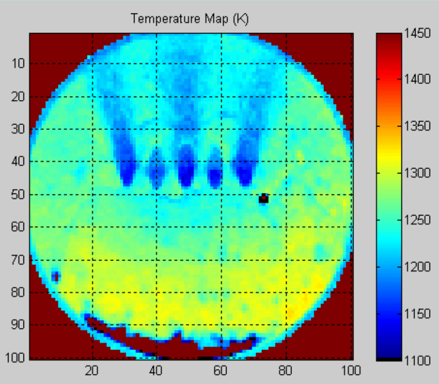
Capture efficiency



Temperature Map at M=2.0



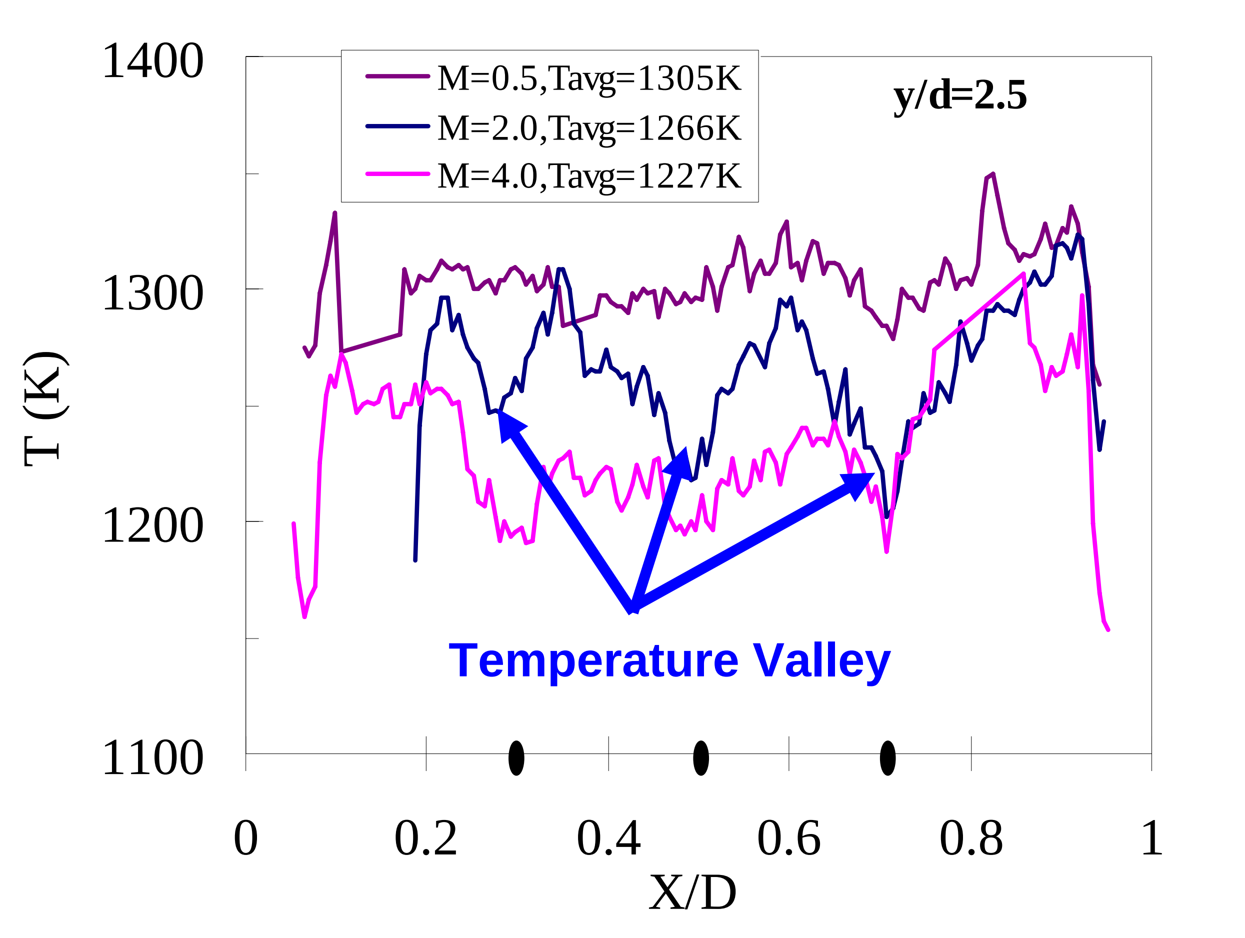
Bare metal coupon



TBC coupon

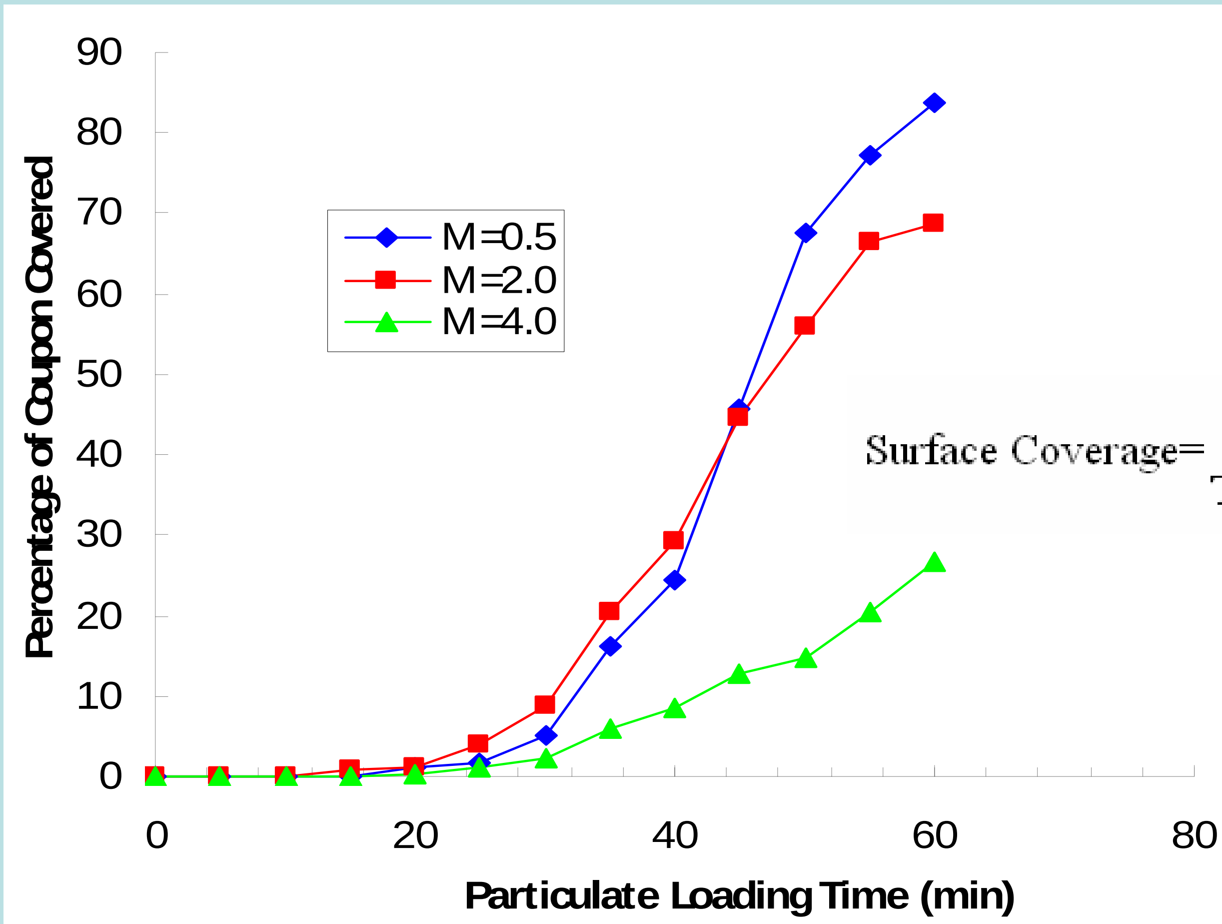
Cylindrical Holes, TBC Coupon

Span-wise Distribution of Temperature Downstream



Cylindrical Holes, TBC Coupon

Deposit Surface Coverage



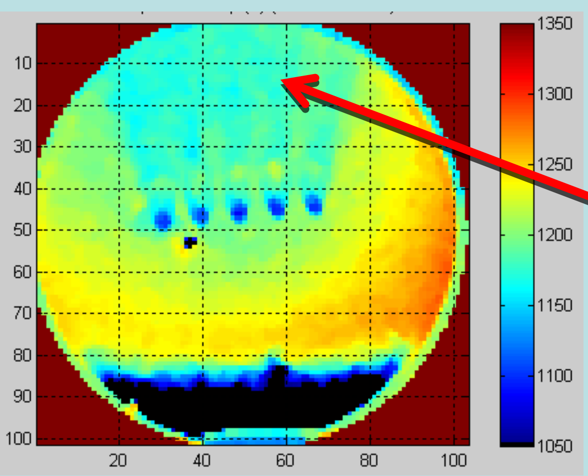
$$\text{Surface Coverage} = \frac{\text{Deposit Area}}{\text{Total Surface Area}}$$

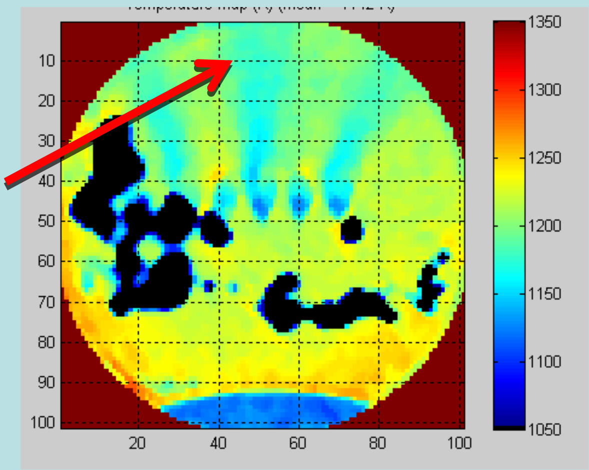
Effect of Hole Spacing

1 hr test on TBC, M=2.0
2.25d spacing

1 hr test on TBC, M=2.0 ,2,4
holes plugged, 4.5d spacing

Deposit
Patterning





Temperature
Map

Conclusions

- For bare metal coupon with cylindrical holes,
  - deposits formed ridges between the cooling holes downstream of coolant injection
  - coincided with the temperature map
- Capture efficiency decreased with the increase of blowing ratio for the sample with differing hole configuration
- Shaped holes have more span-wise coverage than the cylindrical holes and reduce amount of deposition

Conclusion (cont.)

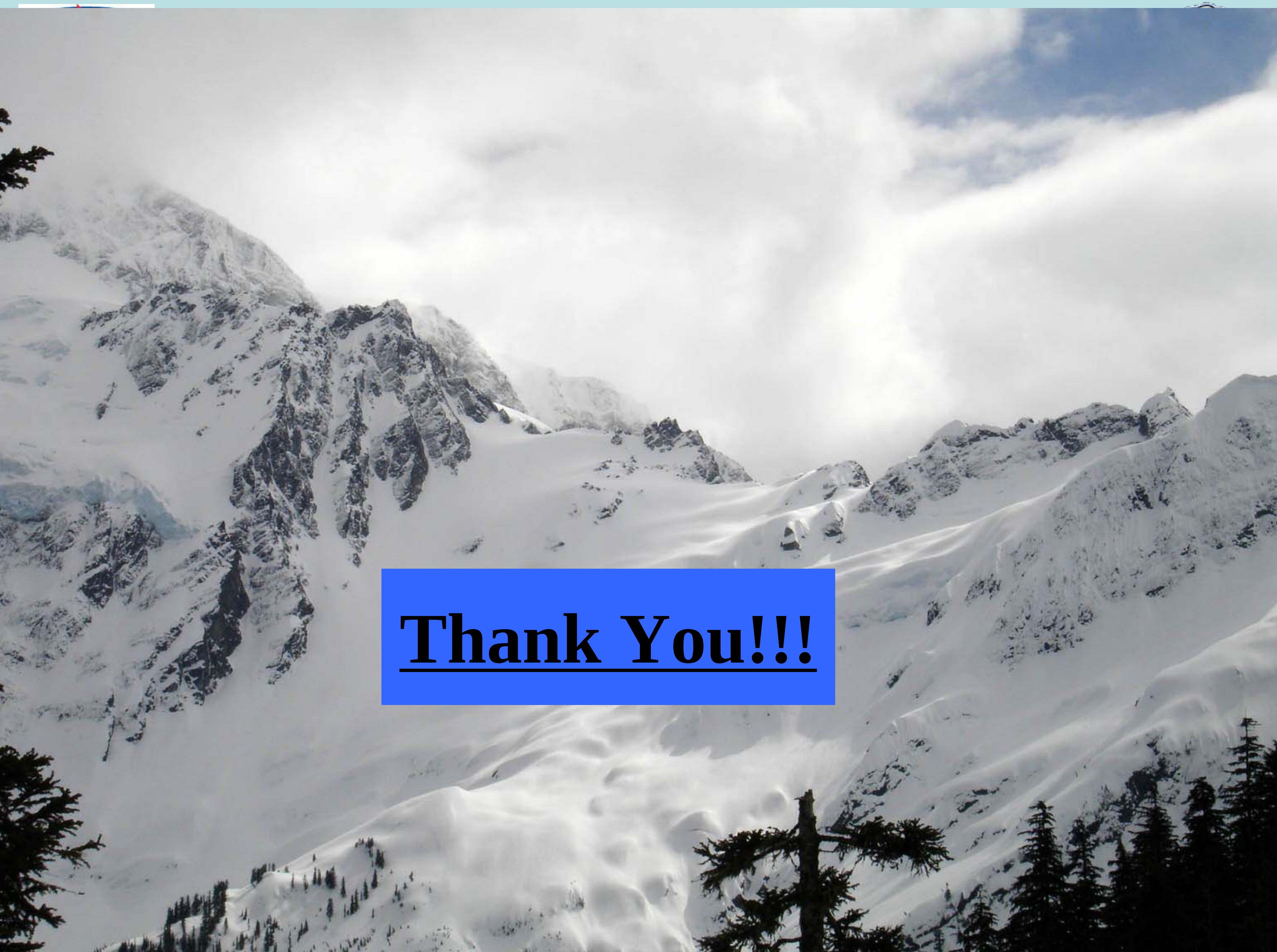
- Particulate capture efficiencies for the TBC coupon were higher than for the bare metal coupon
- Non-uniformity in surface temperature on TBC sample increased with blowing ratio
- Close hole spacing increased coolant coverage to reduce deposition in the coolant path

Future Work

- Examine how deposition is affected by hole spacing and trench configuration
- Develop a simple deposition model coupled with a film cooling scheme to simulate experimental conditions
- Use CFD model to
  - quantify film cooling effectiveness and heat transfer coefficient
  - predict deposition at the varying conditions

Acknowledgments

- Sponsored by DOE/SCIES
- Arun Mehta from Pacificorp
- Ken Forster and Kevin Cole


Thank You!!!