Syngas Particulate Deposition and Erosion at the Leading Edge of a Turbine Blade with Film Cooling

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Outline

- Motivation and Objectives
- Overview of Approach
- Computational results
- Experimental results (Uri Vandsburger)
- Conclusions and wrap up

Gas Turbine Needs

- **Use of Syngas fuels derived from coal gasification for IGCC power plants**
- **Minimize Deposition, Erosion and Corrosion (DEC) caused by residual coal ash**
- **Increase durability of turbine components in hot gas path under harsh high temperature and high velocity conditions.**

Objectives

- Investigate deposition in leading edge region of turbine vane with film cooling
- Provide design data on the effect of ash particle size and jet blowing ratio on deposition in leading edge film cooling
- Investigate the effect of deposition on hydrodynamics and heat transfer and cooling effectiveness

Approach-Experiments

- **High temperature experiments at simulated engine conditions**

Above: PIV measurement in an axisymmetric bluff body stabilized premixed combustor

300 kW electric air heaters capable of generating 900F in the test section with up to 1200 SCFM of flow

Below: Apparatus assembled for high pressure operation

Similitude

- **Free stream temperature of 700 K**
- **Temperature similitude**

$$(T_s - T_j)/(T_\infty - T_j)$$

- **Particle hydrothermal similitude**
  - **Momentum and thermal Stokes number**

$T_\infty = 1600K$

$T_s = 1300 - 1500K$

$T_w = 1000K$

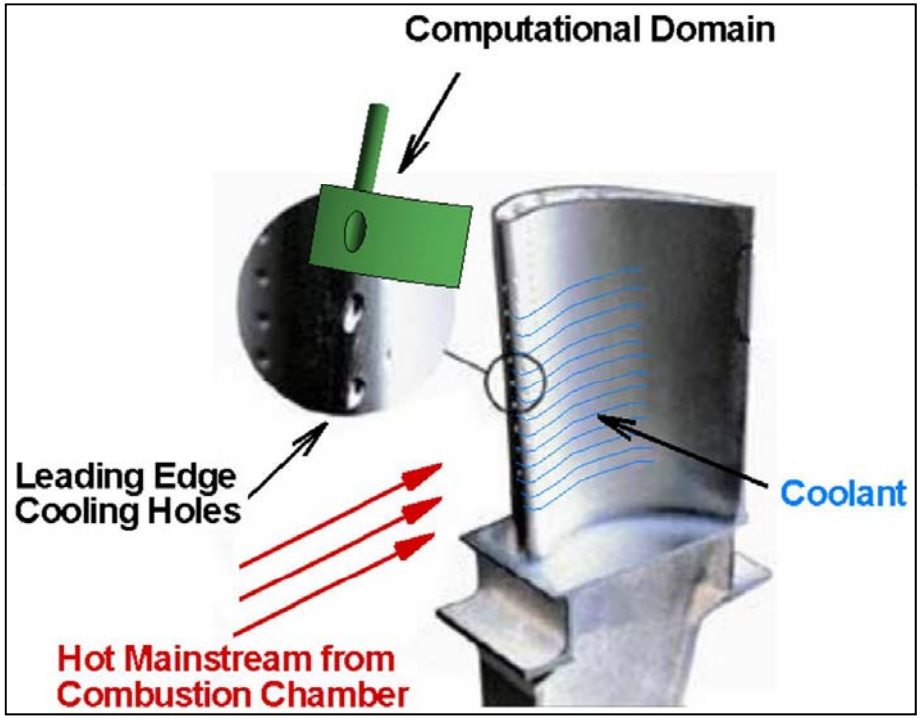
$T_j = 800K$

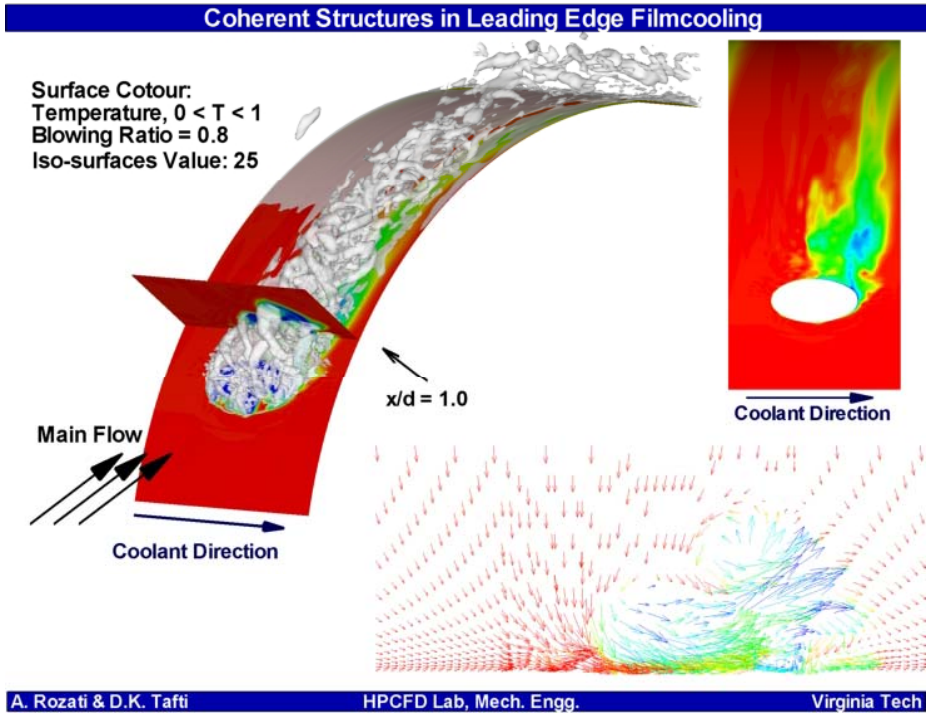
Engine

Particles			
Material	Ash	Teflon	PVC
Diameter (d_p), [μm]	1 to 10	1 to 10	1 to 20
Density (ρ_p), [kg/m^3]	2500	2160	1390
Specific heat (C_p), [J/kgK]	250	1000	900
Softening temperature [K]	1300-1500	400-600	400-550
Momentum Stokes number	5x10^{-2} to 5	5x10^{-2} to 5	3x10^{-2} to 10
Thermal Stokes number	10^{-2} to 1	4x10^{-2} to 4	2x10^{-2} to 8

Approach – Fluid Computations

- **Large- Eddy Simulations (LES) – inhouse code**
- **Reynolds-Averaged Navier-Stokes (RANS) - FLUENT**





Approach-Ash Particle Dynamics

- Particles injected in “real” turbulent field during LES computation (LES+DPM)
- Discrete Random Walk (DRW)
  - Uses mean flow field and computed mean Reynolds stresses (isotropic) from RANS to “construct” instantaneous random turbulent fluctuations to compute particle trajectories and dispersion (DRW-RANS) - FLUENT
  - Uses mean flow field and computed mean Reynolds stresses (anisotropic) from LES to “construct” instantaneous random turbulent fluctuations (DRW-LES) – inhouse code

Approach-Particle dynamics

- **Forces acting on the Particles**

$$\frac{du_i^{*p}}{dt} = \overline{F}^*_{drag} + \overline{F}^*_{buoyancy} - \overline{F}^*_{added_mass} + \overline{F}^*_{basset} + \overline{F}^*_{lift} + \overline{F}^*_{brownian} + \overline{F}^*_{thermophoretic}$$

$$\frac{du_i^p}{dt} = -\frac{1}{St_p}\left(1+0.15Re_p^{0.687}\right)\left(u_i^p - u_i^f\right)$$

$$\frac{dx_i^p}{dt} = u_i^p$$

St_p= particle time scale / fluid time scale

- **Thermal treatment of the particles**

$$\frac{d\theta^p}{dt} = \frac{1}{St_{conv}}\left(\theta^f - \theta^p\right) + \frac{1}{St_{rad}}\left(1 - \theta^p\right)$$

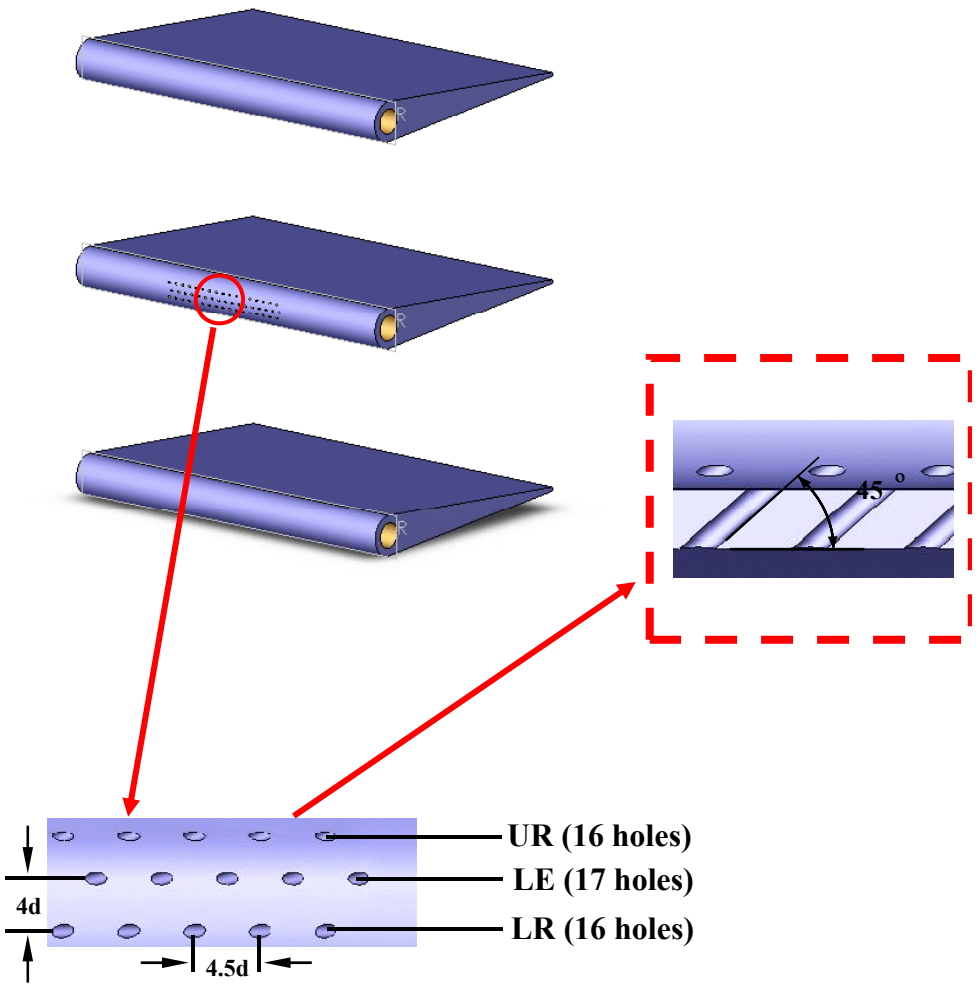
Representative Leading Edge Geometry

3 rows of staggered cooling holes in the leading edge region

49 total cooling holes

1 row of 17 holes
2 rows of 16 holes

The holes are at an angle of 45° to the model surface



D = Diameter of the leading edge
d = Diameter of film cooling hole

D/d = 21.5

Computational Results

Flow Properties and Particle Properties

Leading Edge Geometry	
Blade leading edge diameter (D^*) [m]	0.01
Reynolds number (ReD)	32,000
Coolant jet diameter (d^*), [m]	4.65×10^{-4}
Span-wise pitch (p^*/d^*)	4.5
Flow Properties	
Free stream velocity (U^*_∞), [m/s]	40
Free stream temperature (T^*_∞), [K]	1600
Free stream pressure (P^*_∞), [atm]	20
Free stream density (ρ^*_∞), [kg/m^3]	4.4
Coolant temperature (T^*_j), [K]	775
Coolant-to-mainstream density ratio	2.071
Coolant-to-mainstream blowing ratio (U^*_i/U^*_∞)	0.5, 1.0, 1.5, 2.0

Flow properties and leading edge-jet geometry

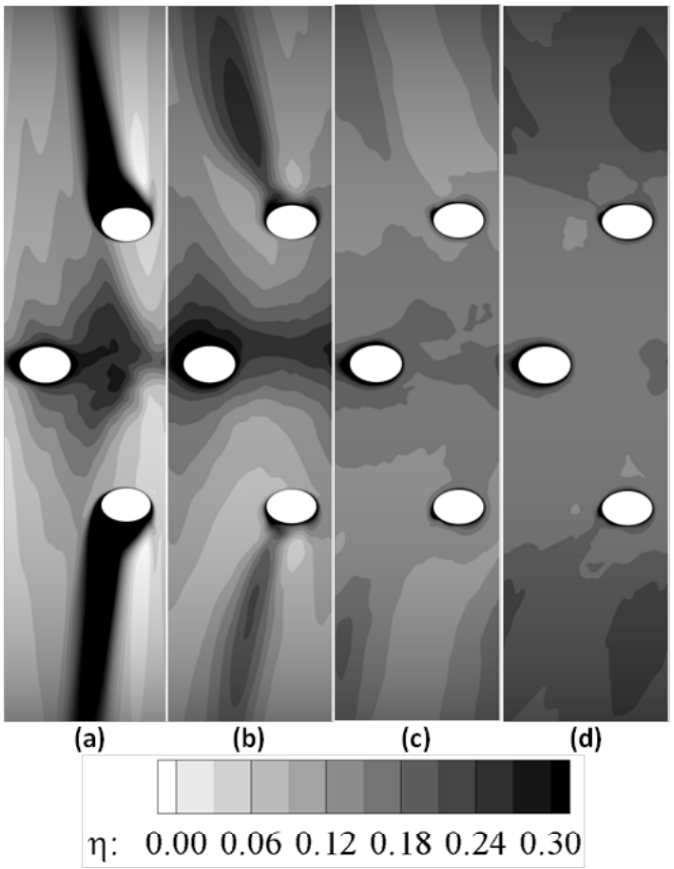
d_p (micron)	St_p	St_{tconv}	St_{rad}
5	0.25	0.0578	2.24
10	1.01	0.215	4.49

Particle diameter and Stokes numbers based on D* and U^*_∞

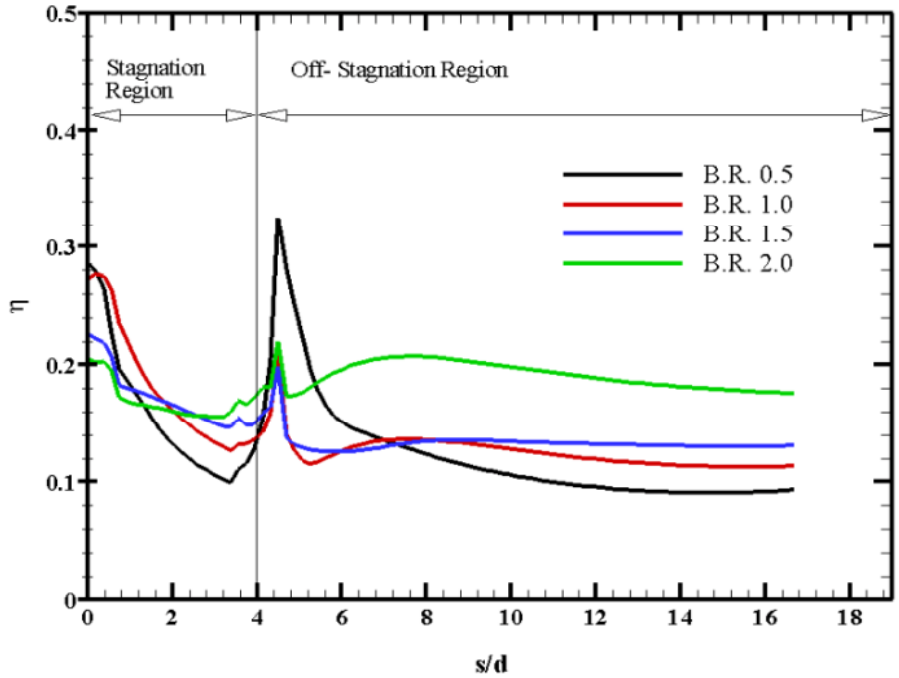
Physics of deposition

- Dependent on aerothermal characteristics in leading edge region and ash particle dynamic response to these conditions
  - Outer flow mean time scales
  - Inner region time scales – lot more difficult to characterize – dependent on jet mainstream interaction and turbulence.
- Dependent on state of ash when it is transported to surface.
- Surface characteristics

Aerothermal Characteristics - Adiabatic effectiveness



(a) BR 0.5 (b) BR 1.0 (c) BR 1.5 (d) BR 2.0



Laterally span averaged effectiveness on the vane surface

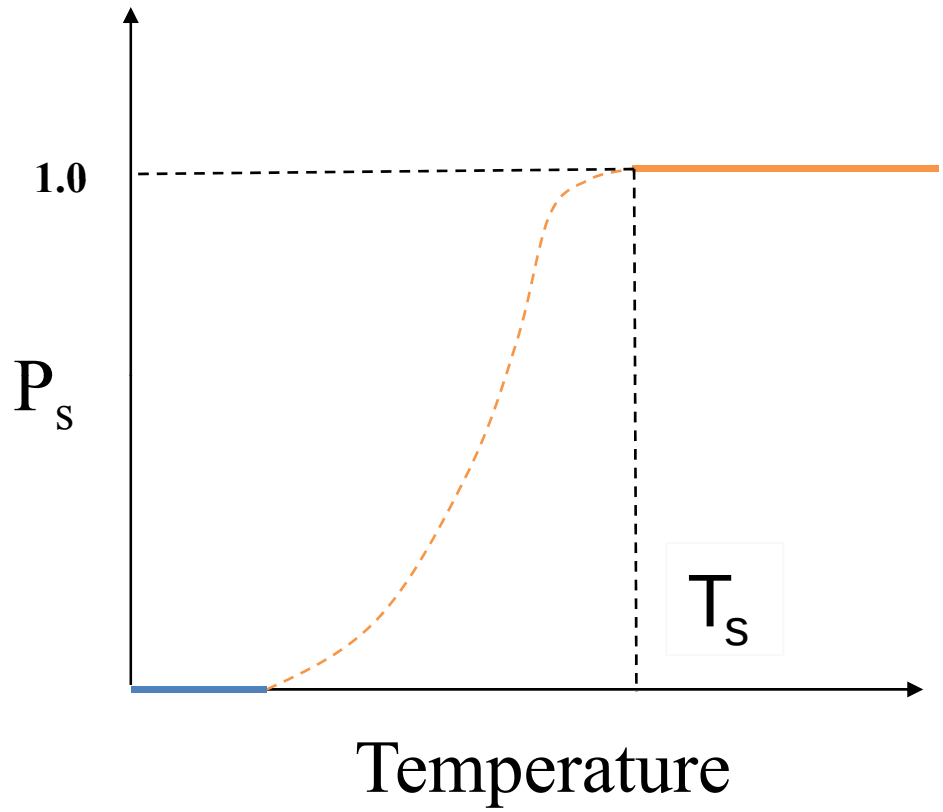
Deposition Model for Coal Ash

- Compute viscosity-temperature dependence of ash based on composition

- Determine softening temperature and set critical viscosity for deposition at $T = T_s$

- Compute sticking probability v/s T

$$P_s(T_p) = \frac{\mu_{crit}}{\mu_{T_p}}$$



Where

Ash Viscosity versus Temperature

- **Model developed based on over 2600 data points and is valid in the viscosity range $10^4 < \mu < 10^9$ Pa.s (Senior & Srinivasachar, 1995)**

- **Viscosity is computed using the following procedure:**

Step 1: Determine mole fractions of all oxides

Step 2: Determine NBO/T

$$\mathrm{NBO/T} = \left\{\frac{\mathrm{CaO} + \mathrm{MgO} + \mathrm{FeO} + \mathrm{Na_2O} + \mathrm{K_2O} - \mathrm{Al_2O_3} - \mathrm{FeO_3}}{((\mathrm{SiO_2} + \mathrm{TiO_2})/2.0) + \mathrm{Al_2O_3} + \mathrm{Fe_2O_3}}\right\}$$

Step 3: Compute the constants A and B

Step 4: Compute viscosity as a function of temperature

$$\log(\mu/T_p) = \mathrm{A} + \frac{10^3 B}{T_p}$$

Step 5: Calculate softening temperature if not known

$$T_{soft} = 92.55 \cdot SiO_2 + 97.83 \cdot Al_2O_3 + 84.52 \cdot Fe_2O_3 + 83.67 \cdot CaO + 81.04 \cdot MgO + 91.92 \cdot a - 7891$$

$$a = (100 - (SiO_2 + Al_2O_3 + Fe_2O_3 + CaO + MgO))$$

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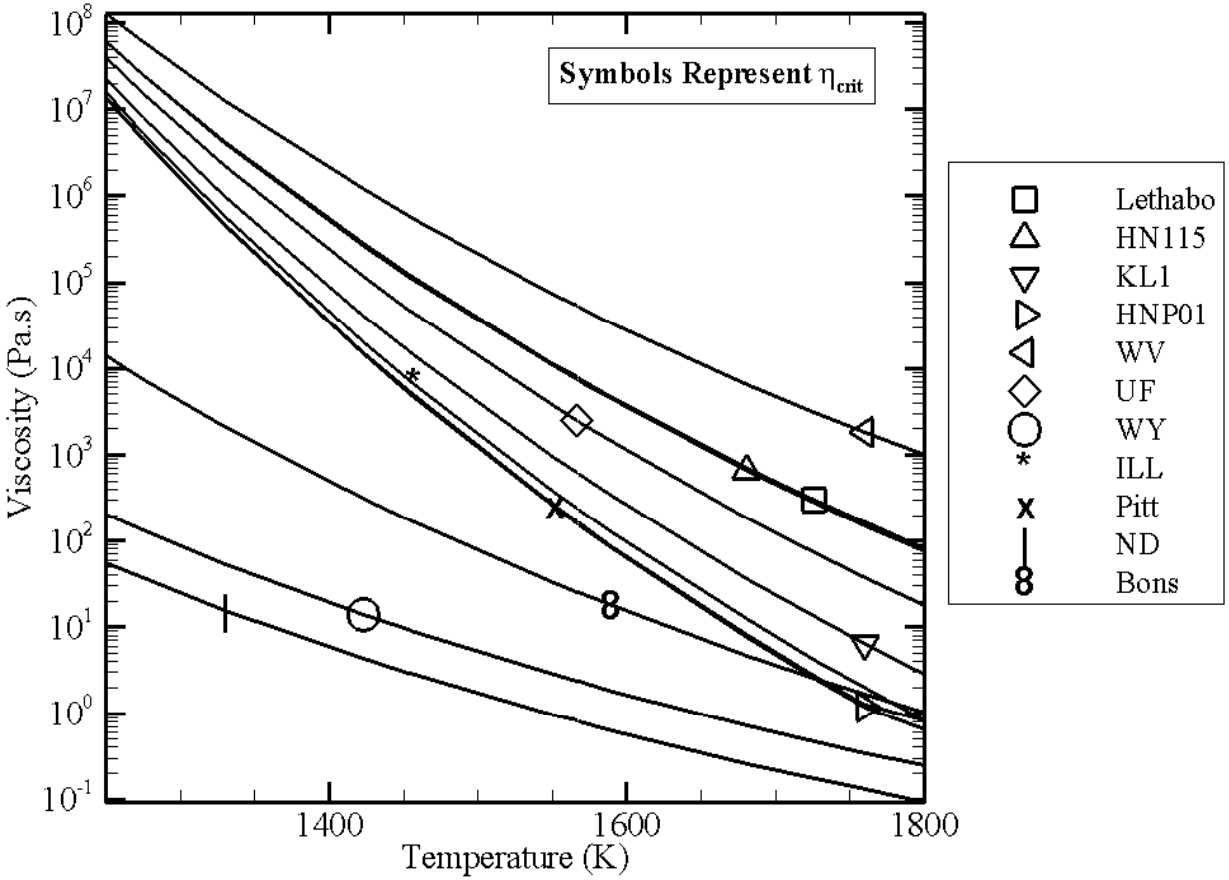
Ash Samples

Table 1 Chemical composition of coal ash samples (%wt.)

	Lethabo	HN115	KL1	HNP01	WV	UF	WY	ILL	Pitt	ND	Crosby
SiO_2	60.33	42.3	47.1	50.1	60.43	46.86	35.59	46.62	50.37	23.68	55.44
Al_2O_3	29.73	34.5	35.3	32.9	30.69	23.24	15.15	14.41	21.04	7.94	18.39
Fe_2O_3	2.68	6.17	4.72	8.42	3.03	21.02	7.53	26.80	21.23	9.82	5.00
TiO_2	1.37	2.24	1.96	1.51	2.02	1.00	1.40	0.73	1.14	0.47	1.46
P_2O_5	0.41	0.55	0.19	0.34	0.69	0.69	3.02	1.00	0.90	3.85	2.00
CaO	3.58	8.55	5.67	1.37	0.42	1.68	18.92	2.74	1.37	18.43	6.66
MgO	1.19	1.00	0.75	0.62	0.67	1.00	4.76	0.72	0.65	7.44	3.26
Na_2O	0.14	0.21	0.26	0.45	0.27	0.27	2.10	0.88	0.53	10.20	5.09
K_2O	0.45	0.76	1.33	2.17	0.97	2.65	1.01	3.15	2.00	1.35	1.71
S	0.10	0.04	0.03	0.01	0.81	1.60	10.53	2.94	0.78	16.82	0.98
MnO	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T_{soft} K	1726	1633	1773	1768	1760	1566	1423	1457	1551	1330	1590

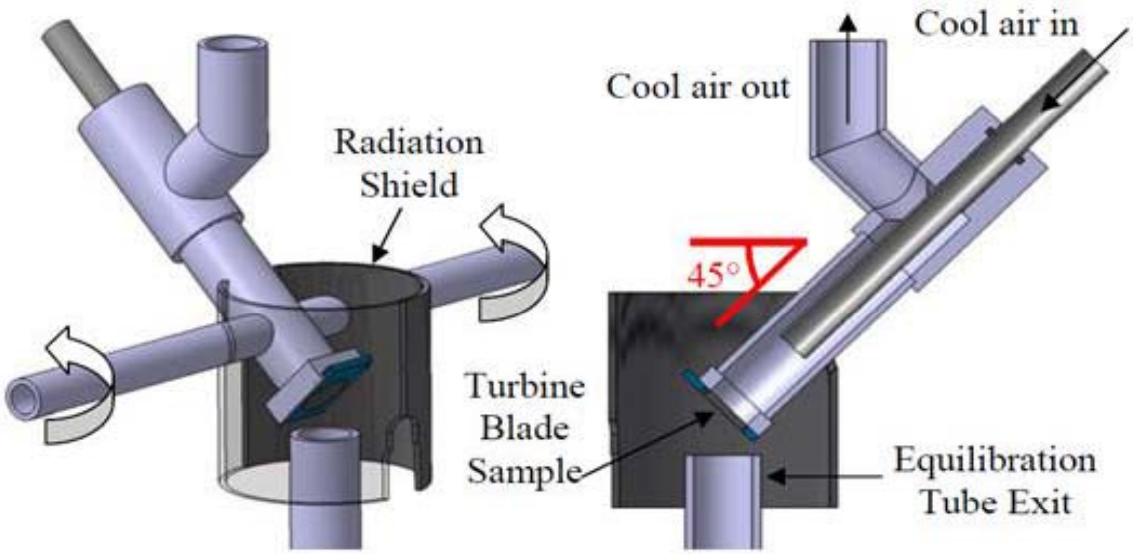
Coal Ash Temperature-Viscosity Curves



Implementation

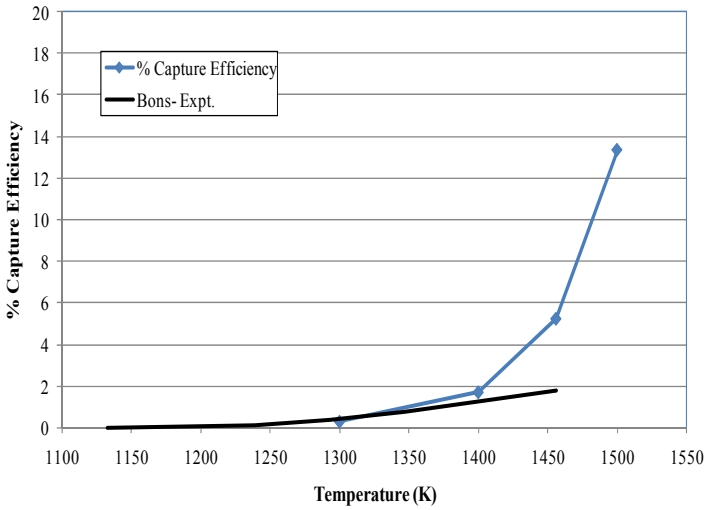
- Record particle wall collision statistics
  - Particle temperature, particle velocity, particle impact angle
- Compute particle viscosity and probability of sticking
- Generate uniform random number for each particle collision
- If random number is smaller than the calculated sticking probability the particle is assumed to deposit otherwise elastically rebounded.

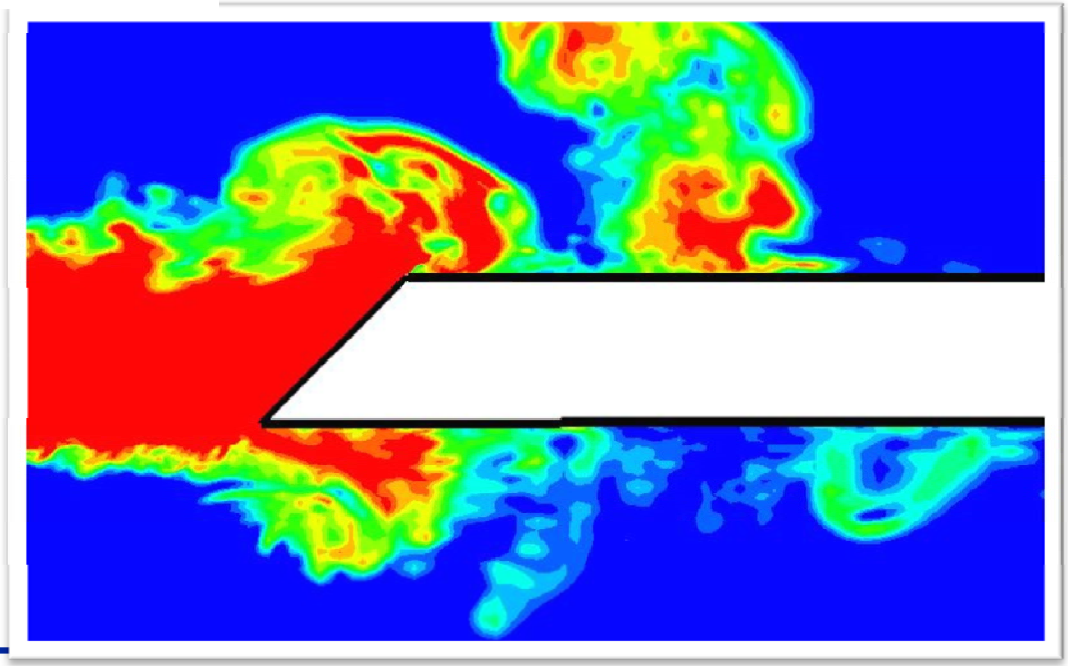
Model Validated with experiments



Computational

Experiment of Crosby et al.





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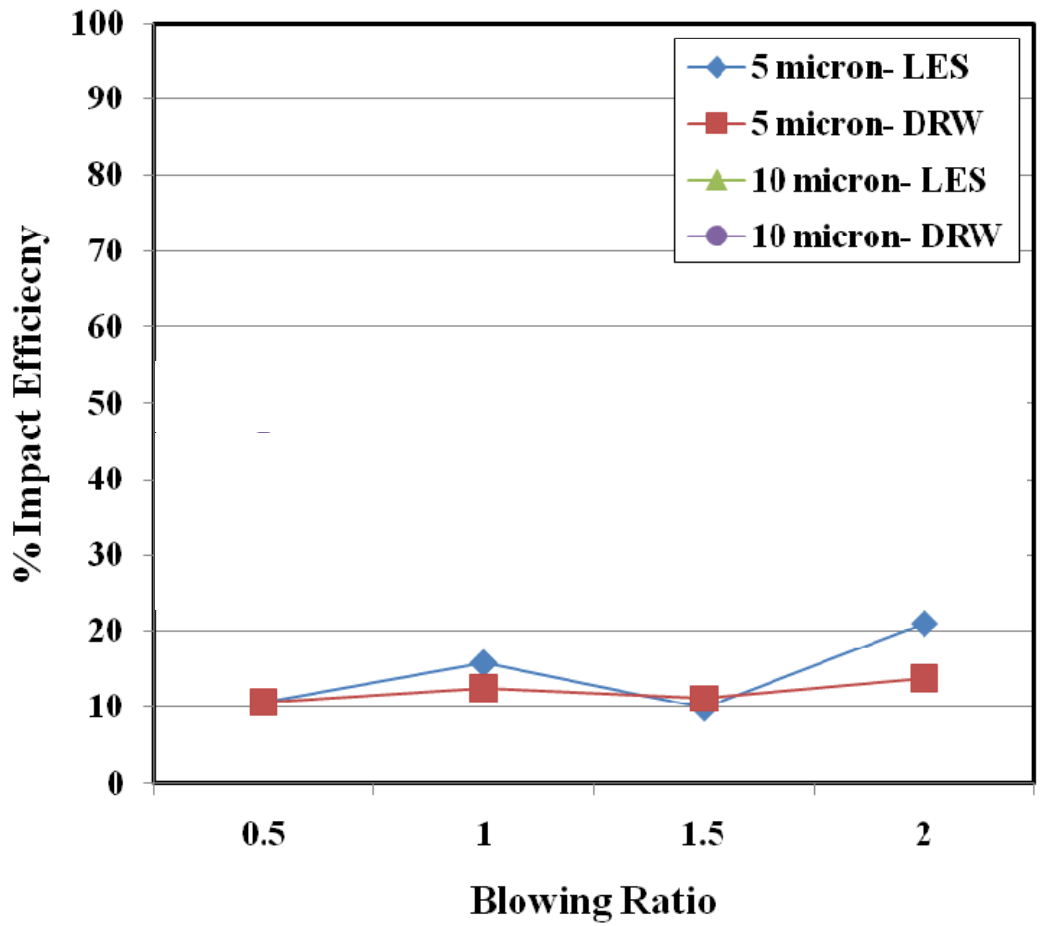
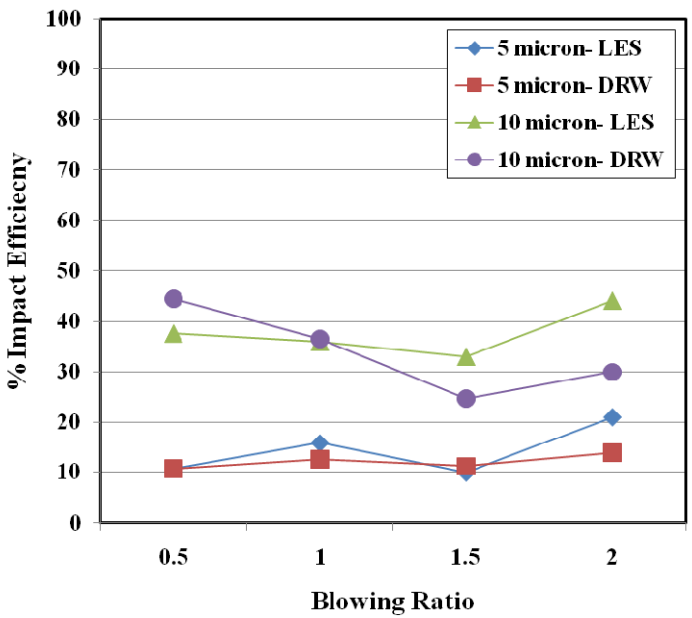
Leading Edge Results – Impact Efficiency

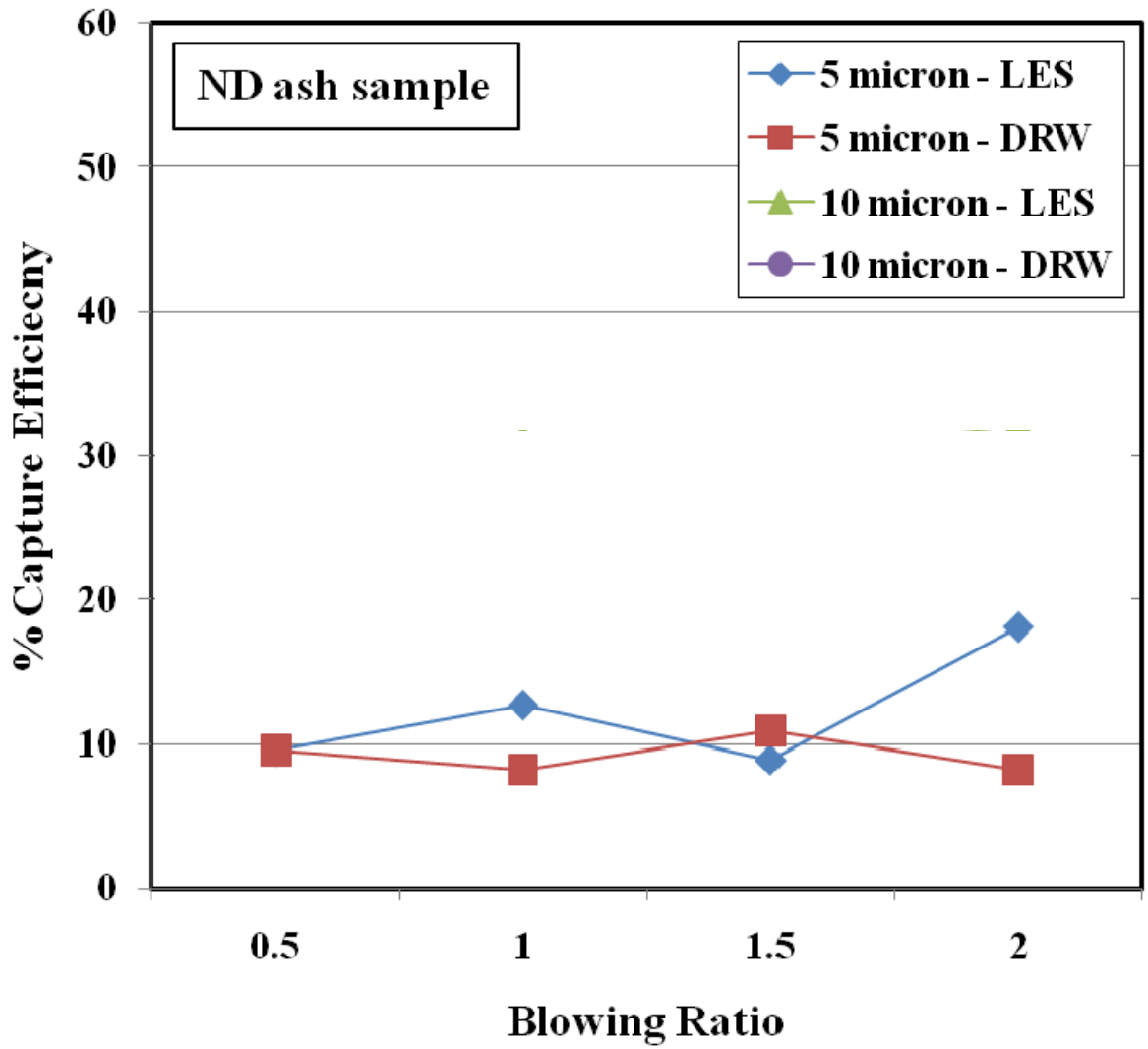
DRW-LES



Results – Capture Efficiency – ND Ash Sample

DRW-LES





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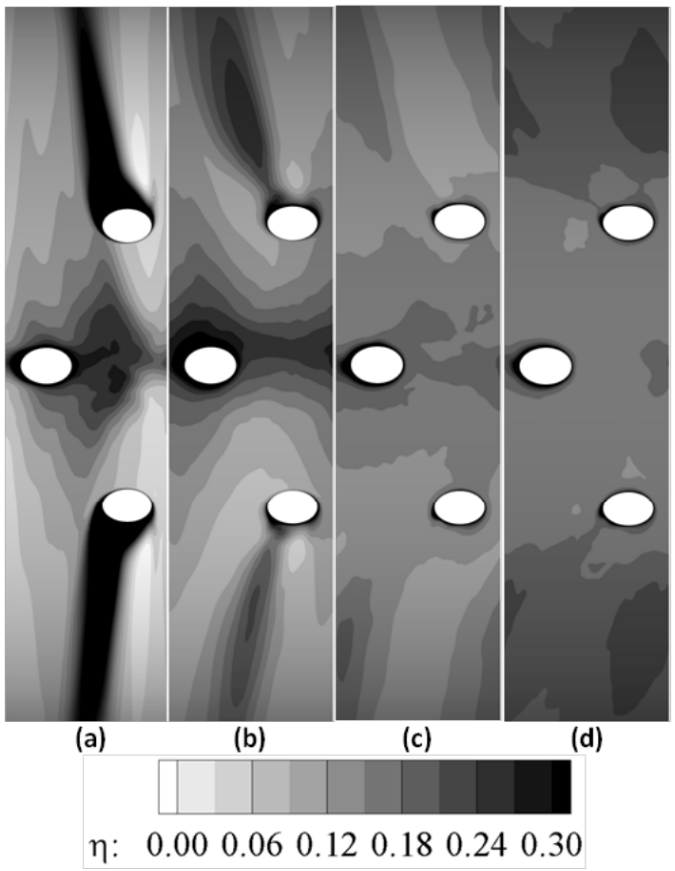
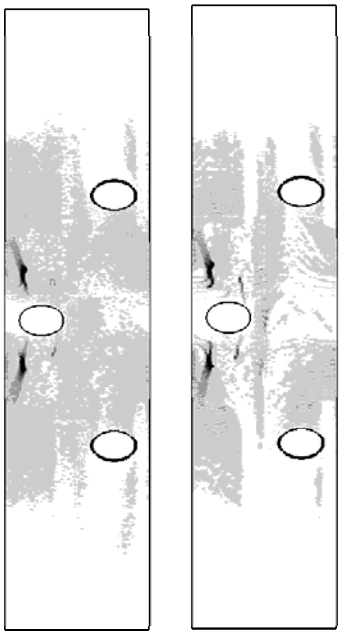
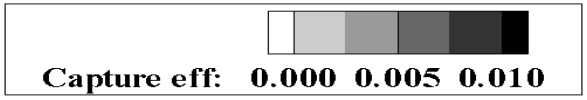
Results – % Capture Efficiency– 5 μm – ND Ash Sample

DRW-LES



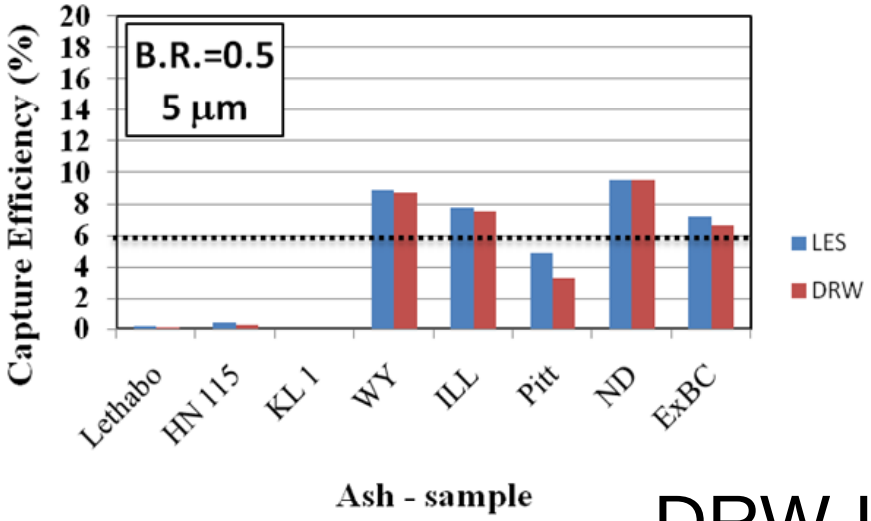


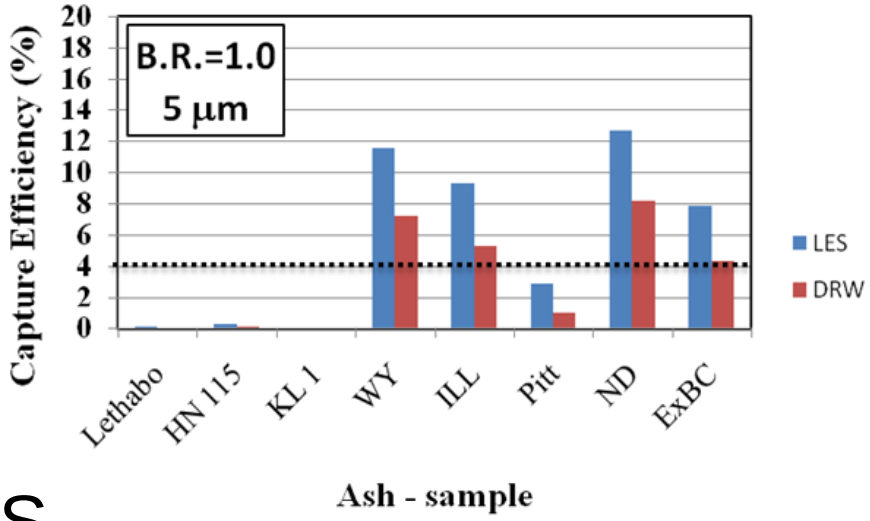
(a) B.R. = 0.5



Direction of the coolant flow is from right to left

Results – % Capture Efficiency – 5 μm – All Ash Samples





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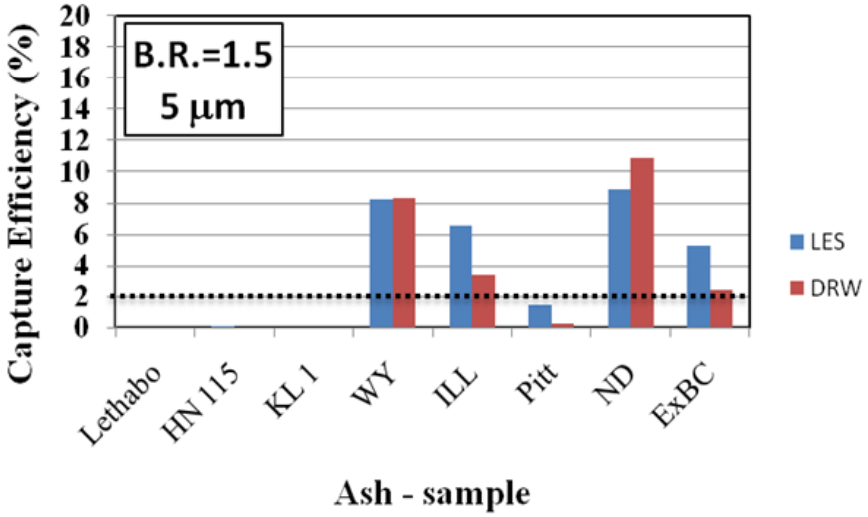
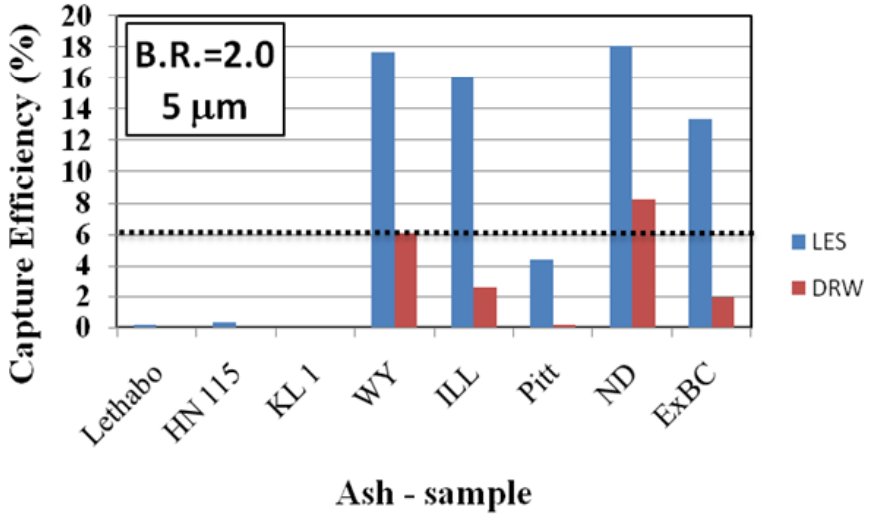
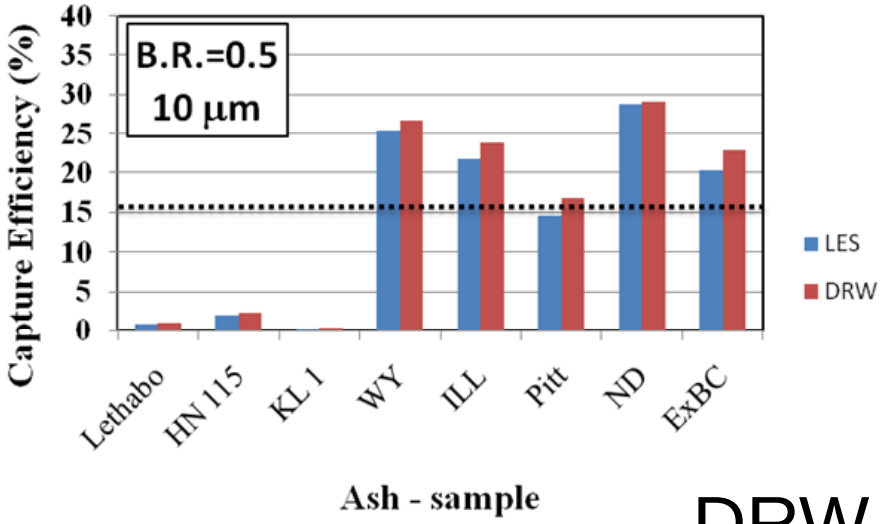
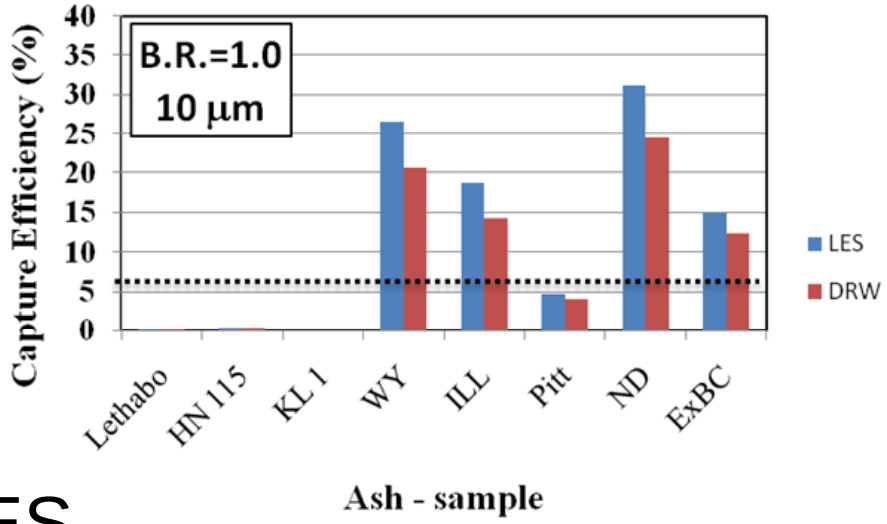


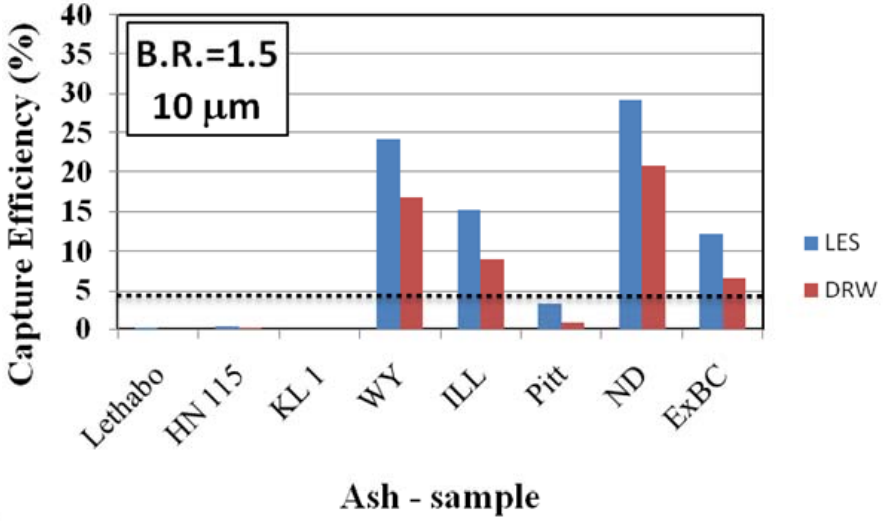


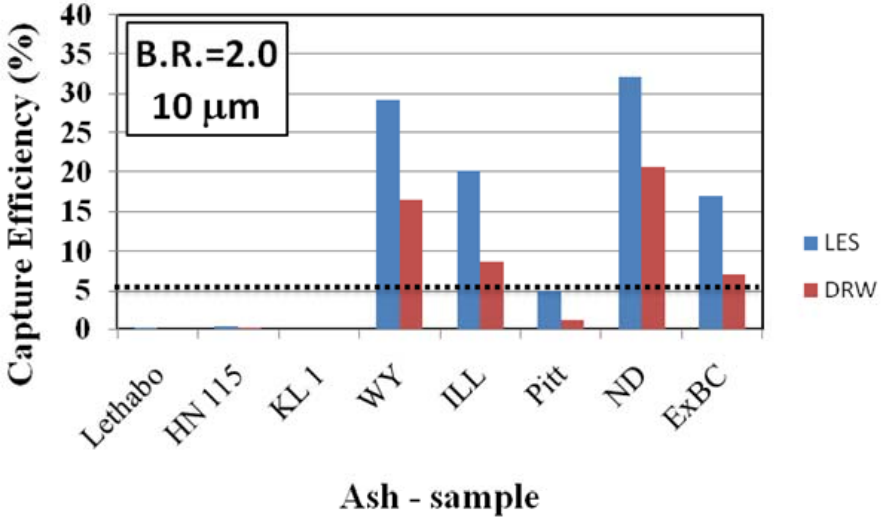
Results – % Capture Efficiency – 10 μm – All Ash Samples





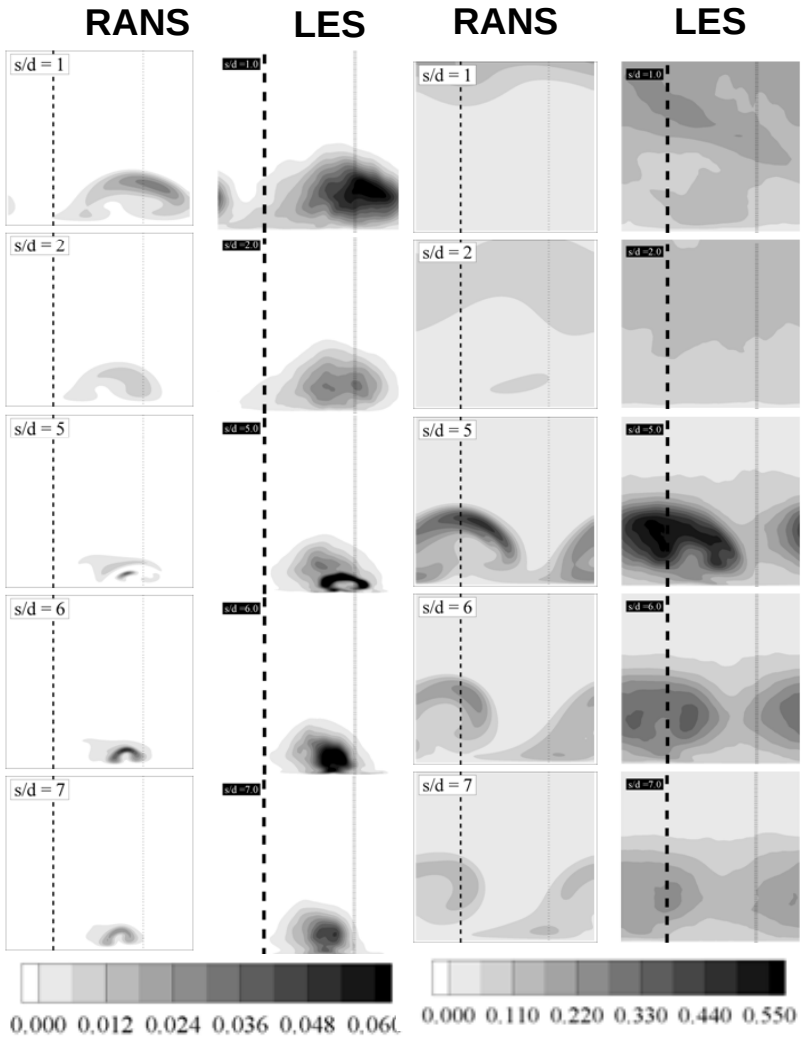
DRW-LES



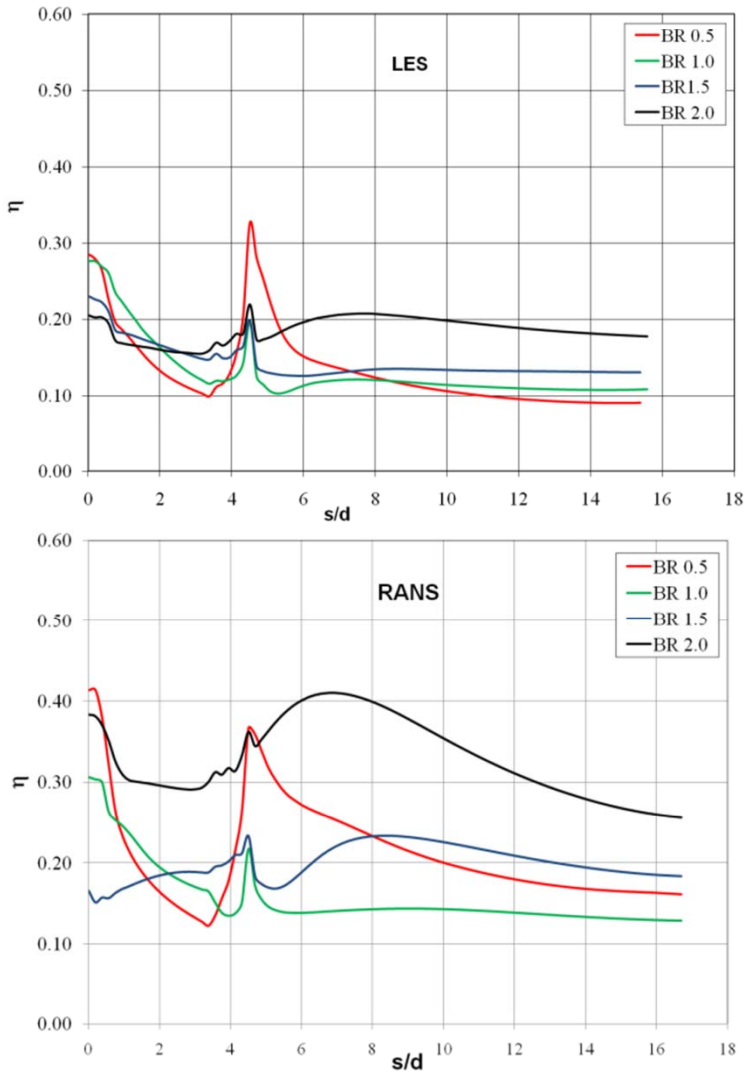


RANS versus LES

- **RANS grid and conditions exactly the same as LES**



Turbulent kinetic energy

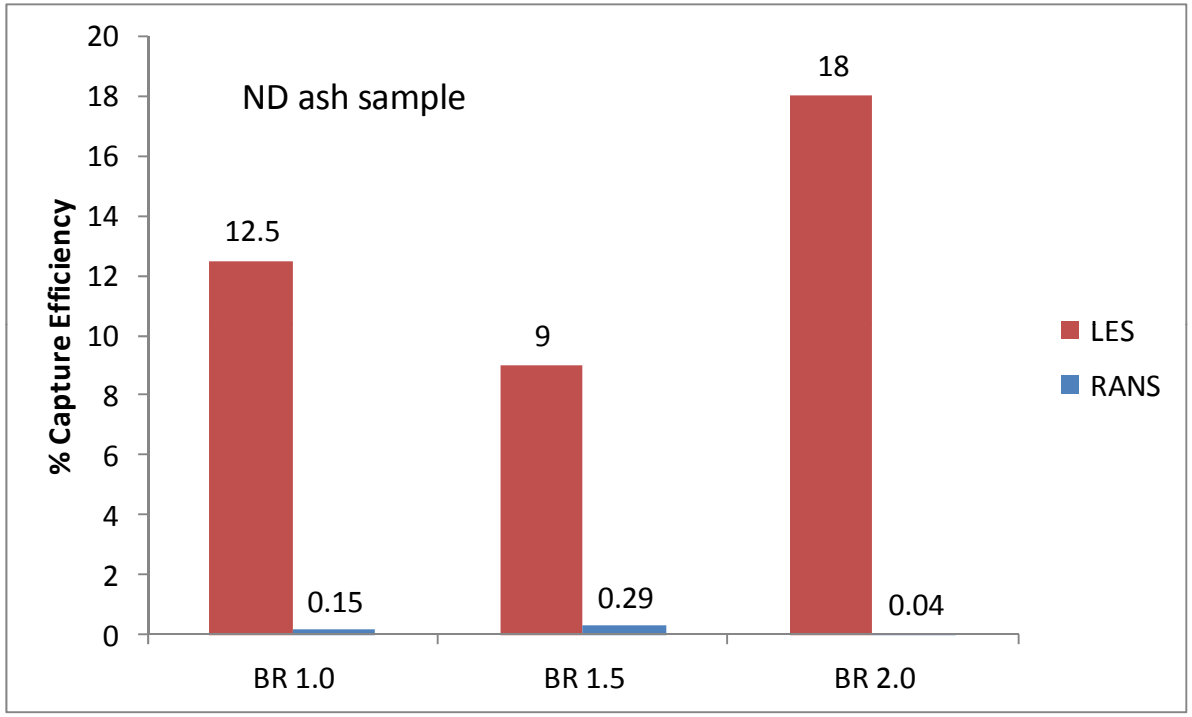


Spanwise averaged effectiveness

BR=0.5

BR=2.0

Deposition Comparison



Conclusions

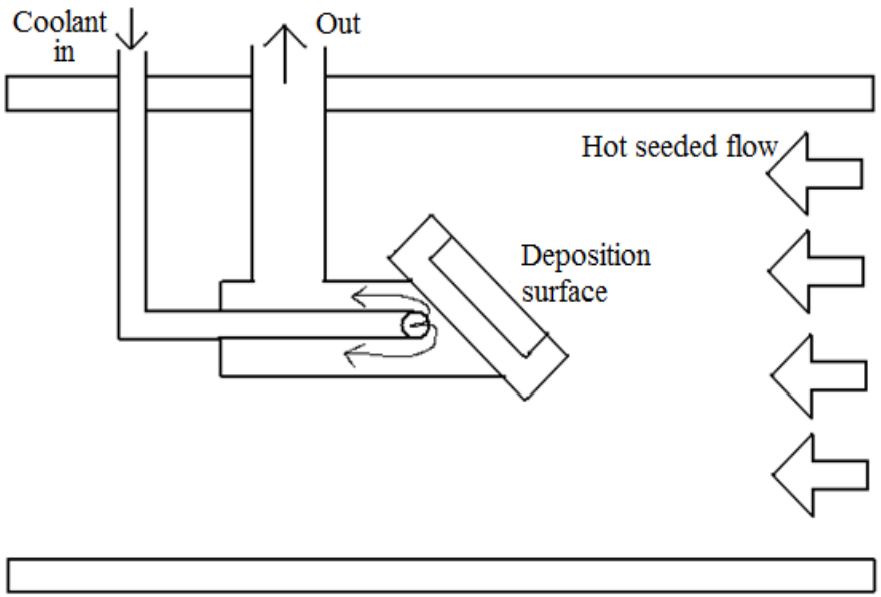
- **Ash deposition and capture efficiency is a strong function of particle Stokes number and ash composition and viscosity. Blowing ratio has a second-order effect.**
  - **For St_p (based on approach velocity and leading edge diameter) less than 0.1, few ash particles get to the vane surface but instead flow around it. Blowing ratio has some effect.**
  - **For St_p greater than 2 to 3, all particles in the direct line of sight of the leading edge will impact the leading edge. The amount of deposition will depend on the sticking characteristics of the ash.**

- $\left(T_{soft} - T_c\right)/(T_\infty - T_c) > 0.90$ **reduces deposition substantially in the geometry studied.**

Experimental Highlights

Validation Methodology

- **Validate particle substitution effort to predict deposition on leading edge**
- **Vary Particle Loading Factor to simulate extended operational time**
- **Characterize effect of temperature, velocity, and blowing ratio on deposition rate**
- **Lower particulate melting point allows for reduced experimental temperatures and time**



$$PLF = \left[\frac{Mass\ flux\ of\ particles}{Mass\ flux\ of\ air}\right] * time$$

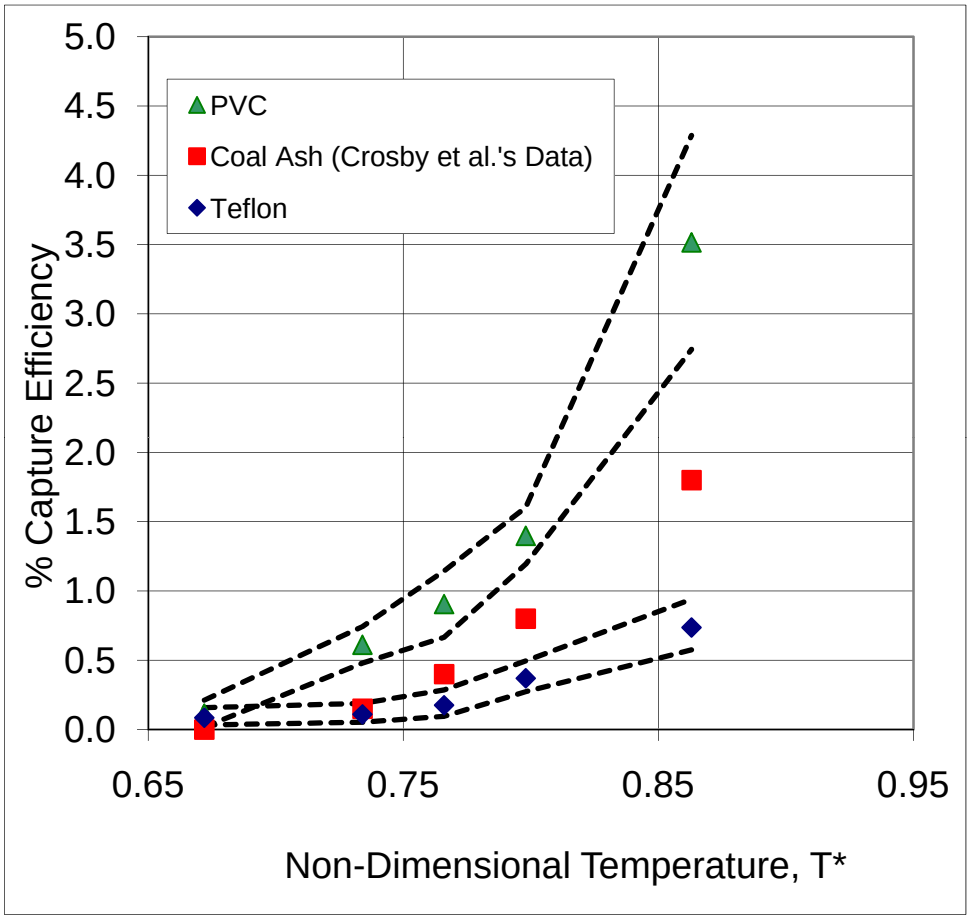
$$Stk_p = \frac{\tau_v^*}{D^* / u_\infty^*} = \frac{\rho_p^* d_p^{*2} / 18\mu^*}{D^* / u_\infty^*}$$

$$T_1^* = \frac{T_\infty}{T_{melt}}$$

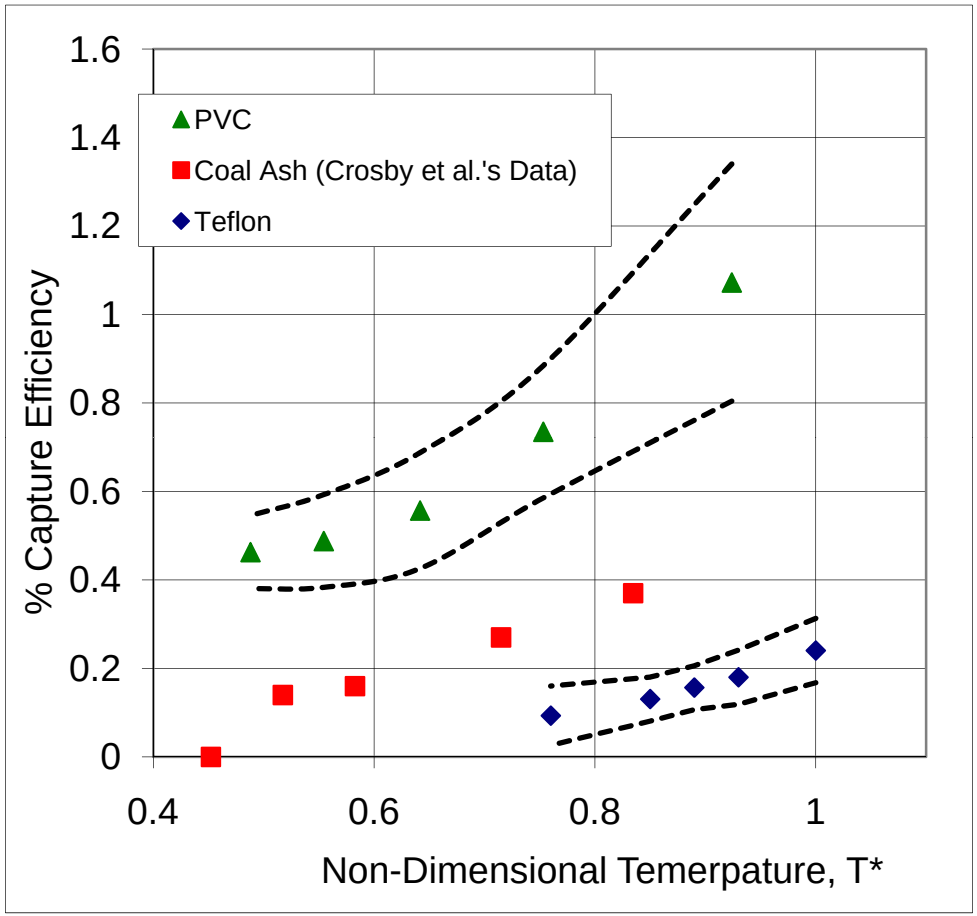
$$T_2^* = \frac{T_{melt} - T_\infty}{T_{melt} - T_{surf}}$$

Experimental Proof of Concept Results

Without cooling series



With backside cooling series



Capture efficiency vs temperature results compared to coal ash
Dashed lines are experimental uncertainty, +/- 1 standard deviation

Experimental Setup - Facility

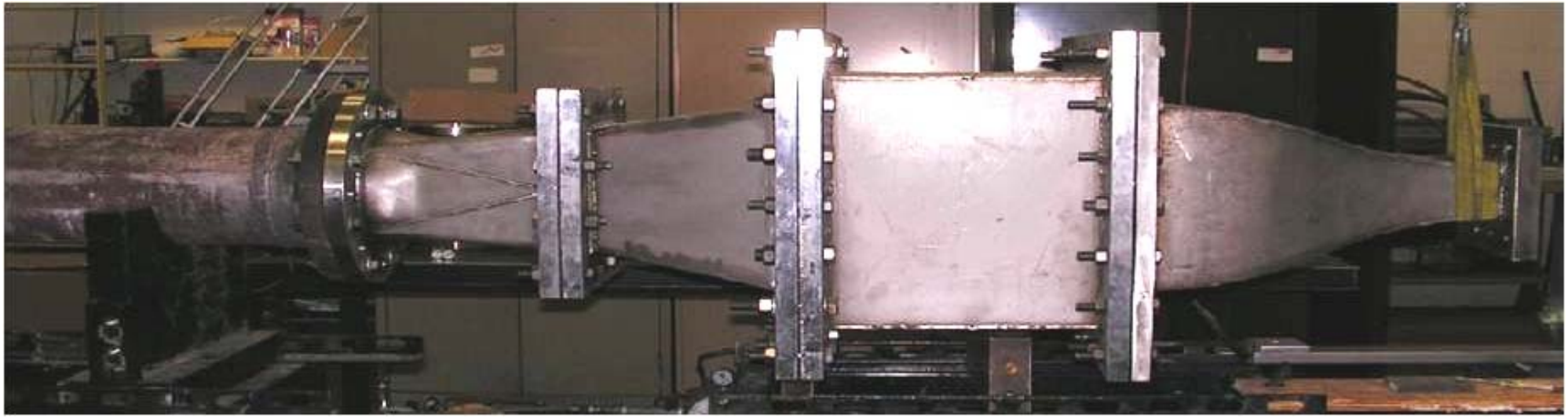
Combustion System Dynamics Lab

- **Air flow rates up to 1250 SCFM and pressures up to 10 atm**
- **Air heater to achieve T_∞ = 1000 °F**

- **Turbulent, swirl and bluff body stabilized research combustors**
- **PDA – Phase Doppler Anemometer**
- **Experiments were conducted on the modular combustor configured for the deposition study**

Experimental Setup – Particle Deposition Rig

- **Rectangular Cross sectional area, 3.5” x 5.4” (w x h)**
- **Contraction section reduces area by 15:1 ratio**
- **Setting section has series of screens and a honey comb to reduce turbulence**

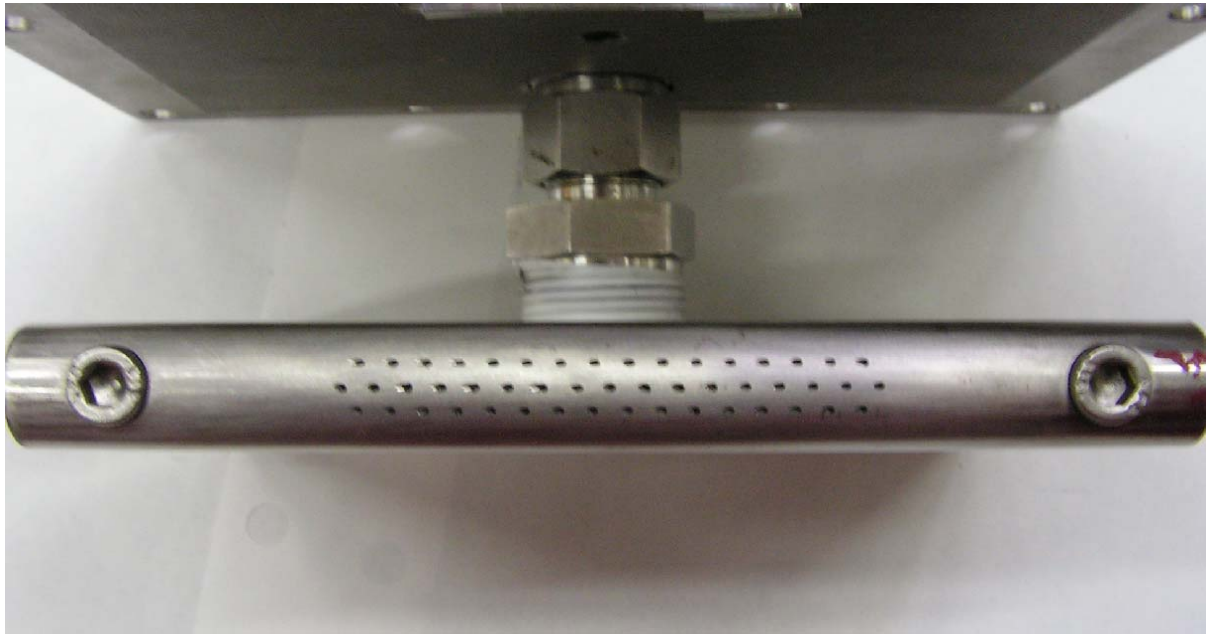


Flow →

Test Section ↑

Experimental Setup - Blade Geometry

- Blade diameter = 5/8”
- Cooling hole diameter = 1/32”
- 3 rows, 49 total cooling holes
- Top and bottom rows are angled 23° off horizontal
- All holes are angled 45° along spanwise direction



Experimental Setup – Model Chamber

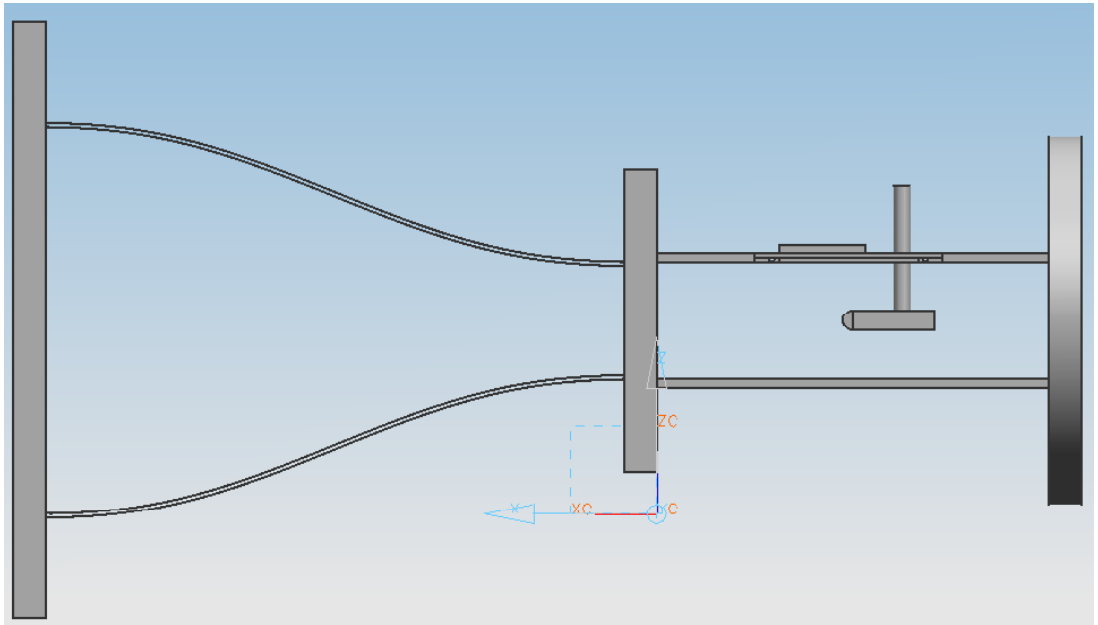
- **Blowing ratio between 0 and 4**

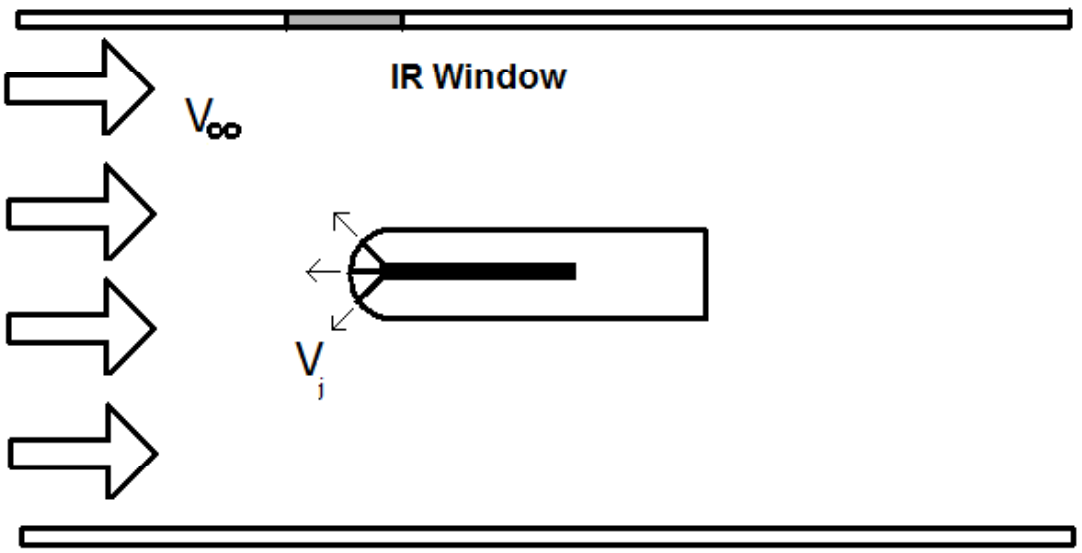
$$BR = \frac{\rho_{cool}\, U_{cool}}{\rho_{\infty} U_{\infty}}$$

- **Turbulence level of 1.6%**

$$Tu = \frac{u'}{U_{\infty}}$$

- **Infrared window for measurements**
- **FLIR #SC630 IR camera**



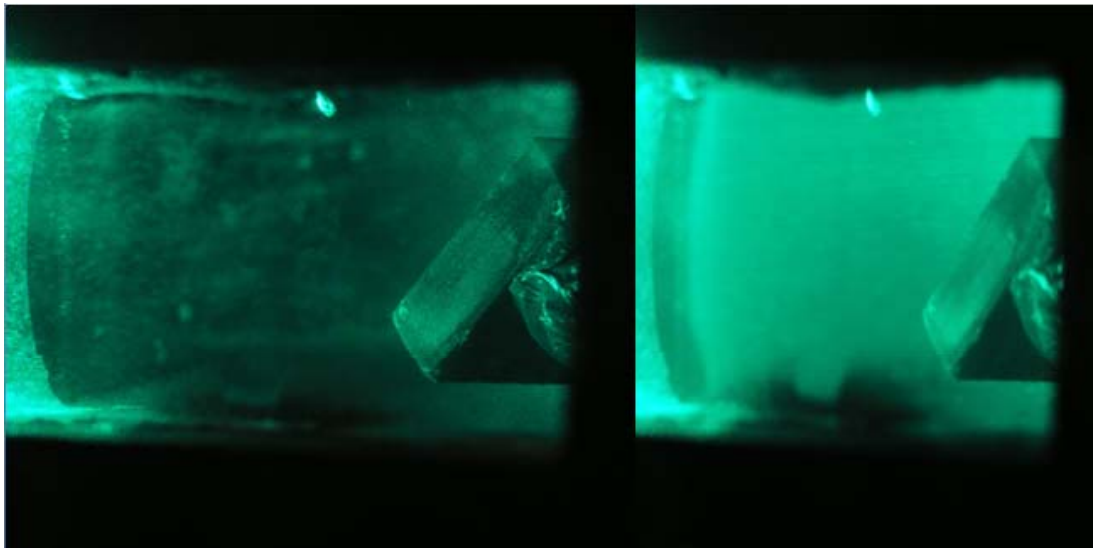


Experimental Setup – Particulate Injection

- **Delavan spray injection nozzle**
- **1% by volume mixture of PVC and alcohol**
- **4.0 liters/hr, 4.5e-5 kg/s particle flow rate**
- **90° cone angle**

- **Planar laser verification of uniform distribution**

No particles W/ Particles

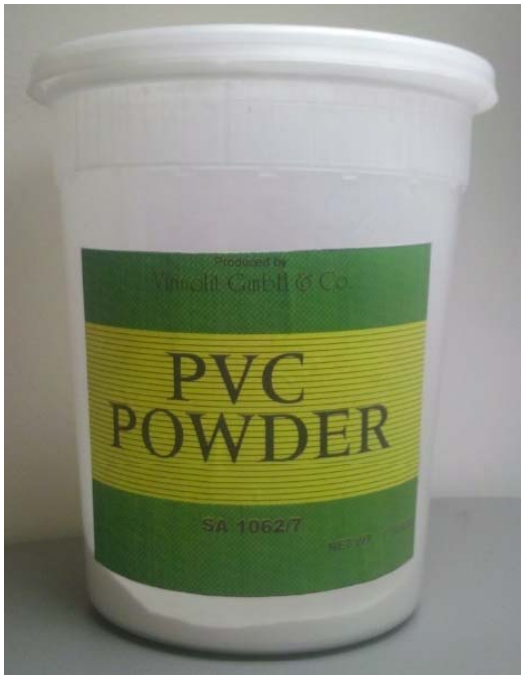


Experimental Conditions

- **Testing specifications:**

Re_d = 17,000-21,000	Stokes # = 3	PLF = 100 ppm-hr
U_∞ = 30 m/s	T_∞ = 505 K	Duration = 12-15 min

- **Coolant temperatures vary between 315K and 331K**
- **Exposure time represents 500 hours of turbine operation**



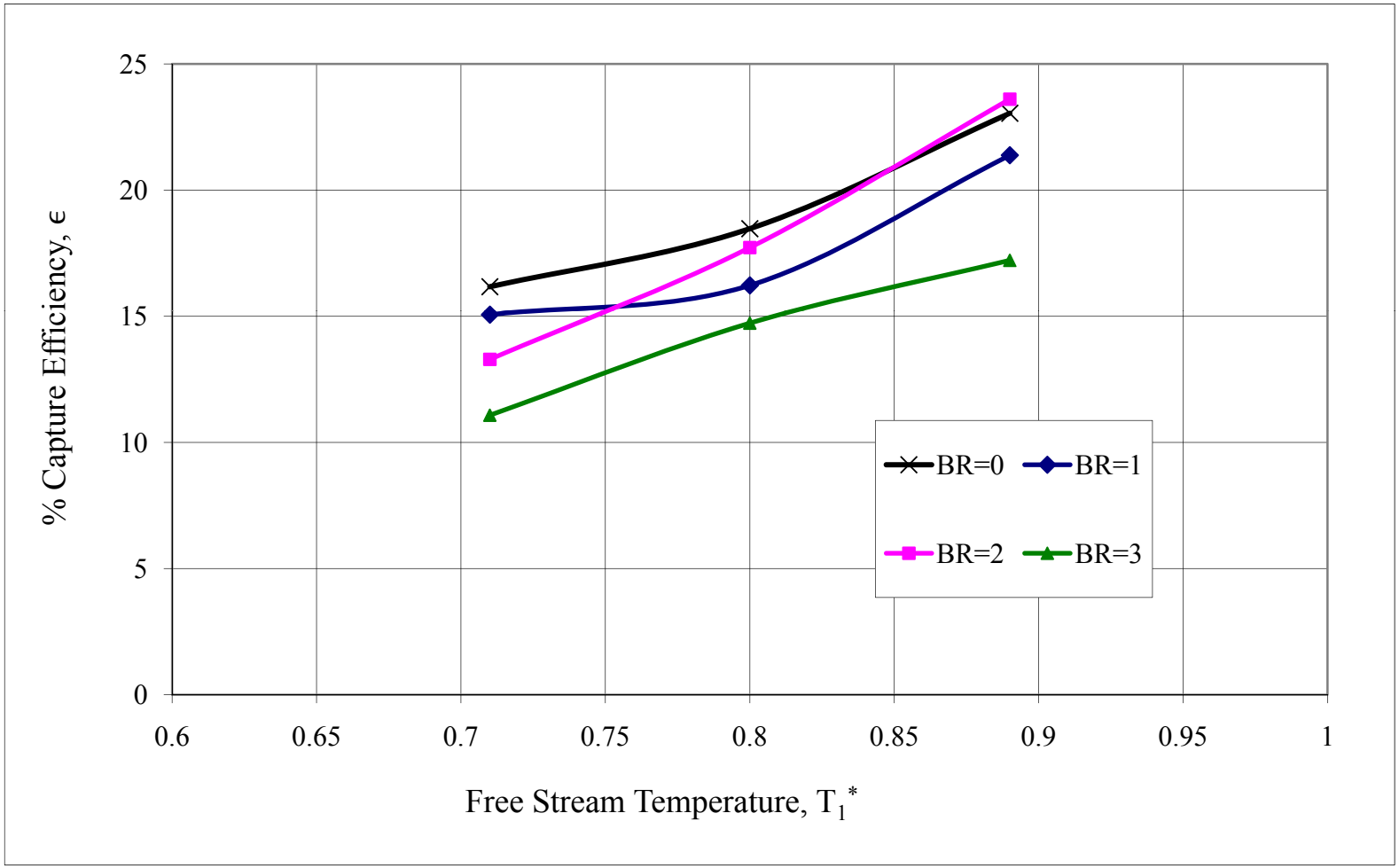
Experimental Analysis

- **Curved surface does not allow profile scanning**
- **Particulate collected from model and weighed**
- **To yield the capture efficiency:**

$$\epsilon = \frac{m_{deposit}}{m_{approach}}$$

Experimental Results

Experiments on Leading Edge Film Cooling



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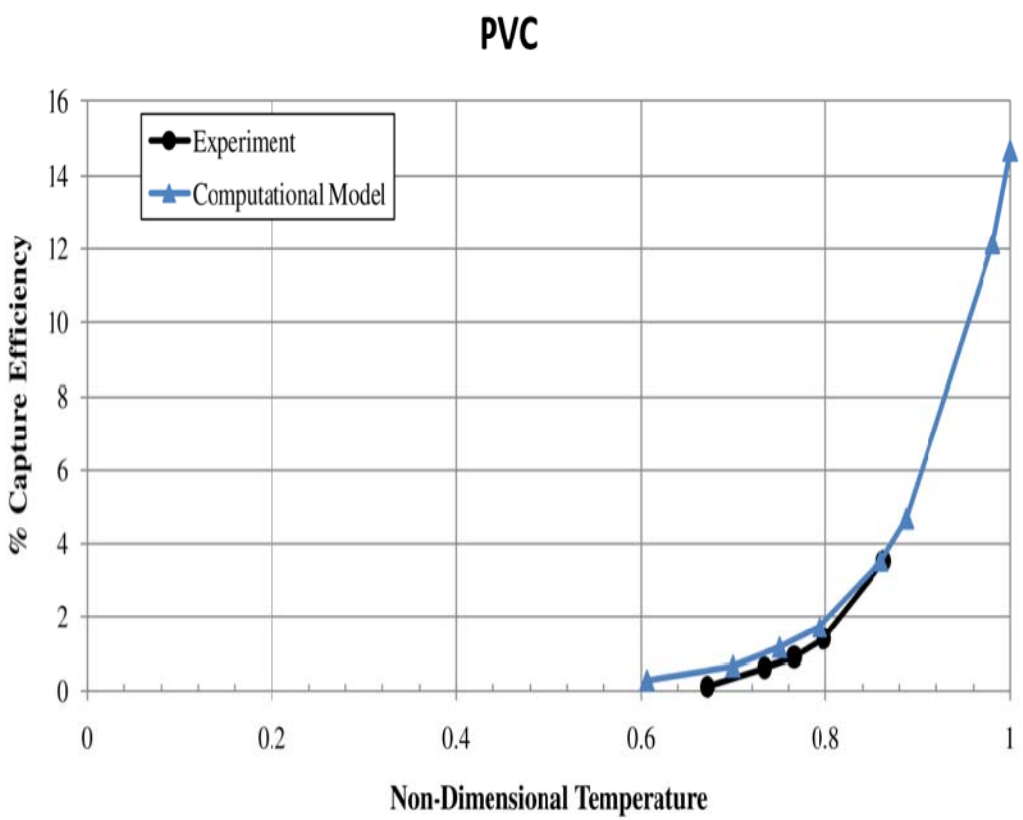
Deposition Model for PVC

- **Calibrated from coupon experiments**
  - **-Assume exponential probability function**

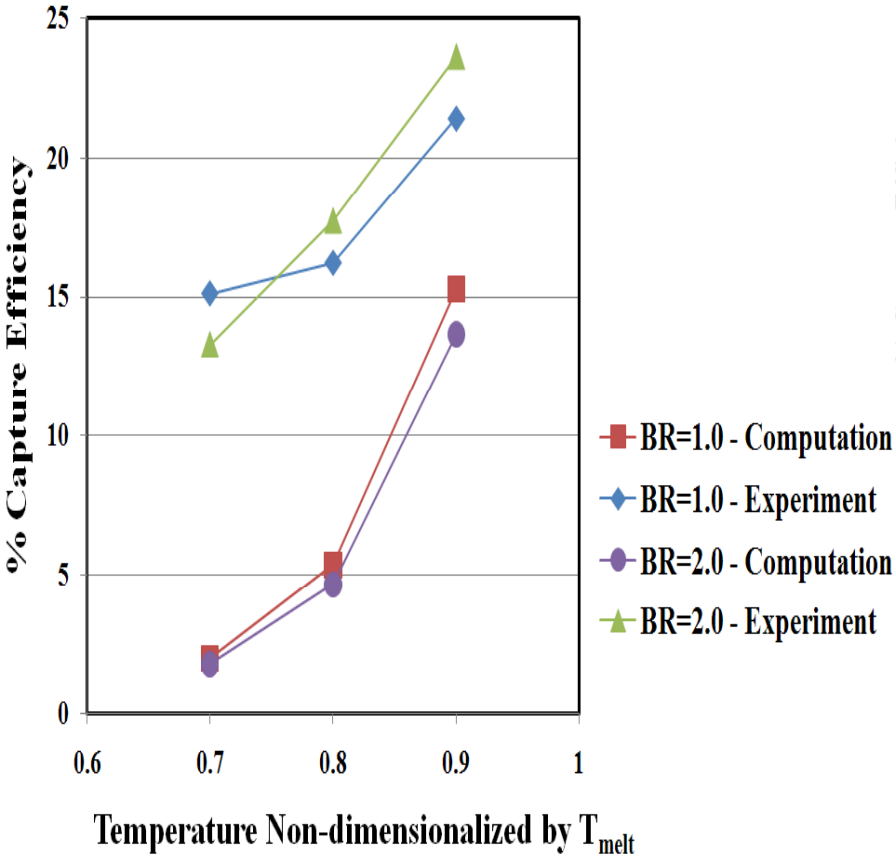
$$P_s(T_p) = P_0 \cdot e^{k \cdot T_p}$$

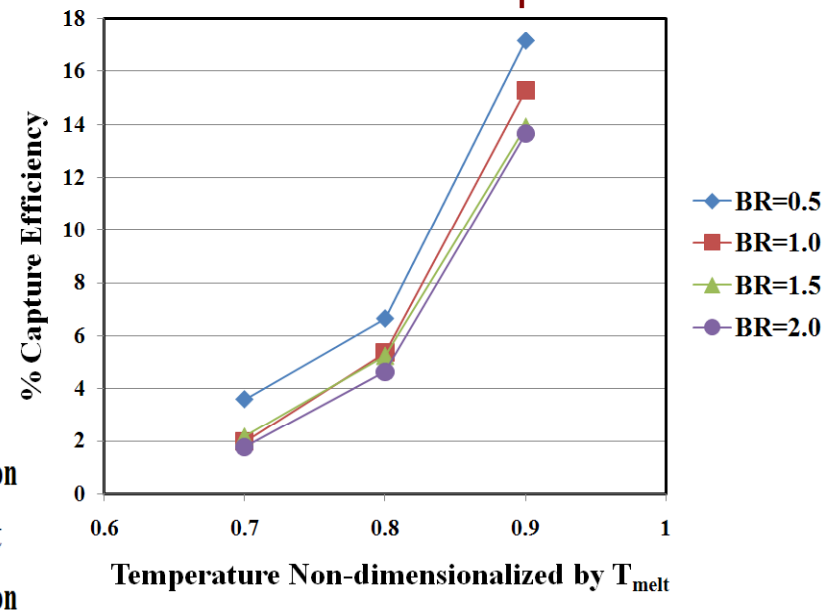
  - **-P_s - Sticking probability at T_p**
  - **-T_p- non-dimensional particle temperature $T_p = T_p^*/T^*_{melt}$ (T^*_{melt}=533K)**
  - **- model calibrated at $P_s(1)=1$ and experimental data to obtain**
  - **- P_0 = 1.06E-05**
  - **- k = 11.4**

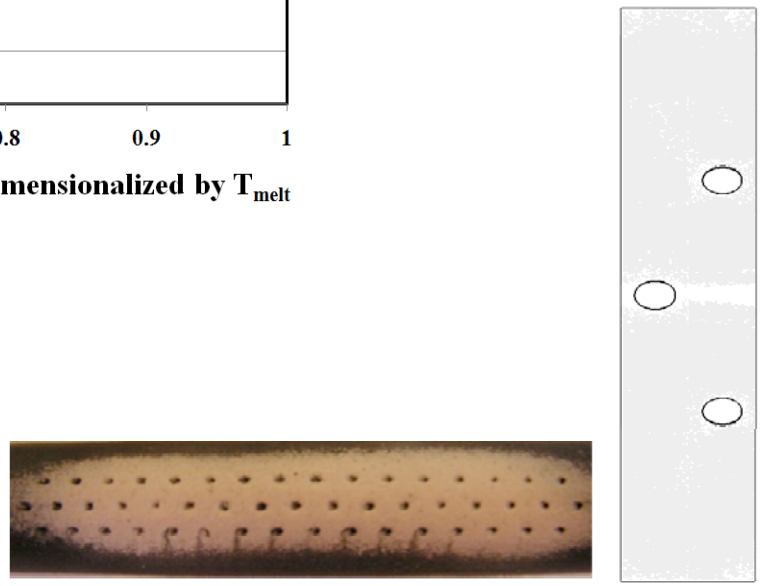


Predictions of PVC deposition at leading edge

DRW(LES)+PVC deposition model (St_p=3, St_{conv}=2.4)







BR=2.0

Remaining Tasks

- **Install new heaters in experimental facility**
- **Will allow higher temperatures (up to 800 K) with higher flow rates (up to 0.7 kg/s) and particle Stokes numbers more in line with actual ash.**

Thank You
Questions?