Comparisons of a Coal Ash Deposition Model with Measurements of a Tube in Cross Flow

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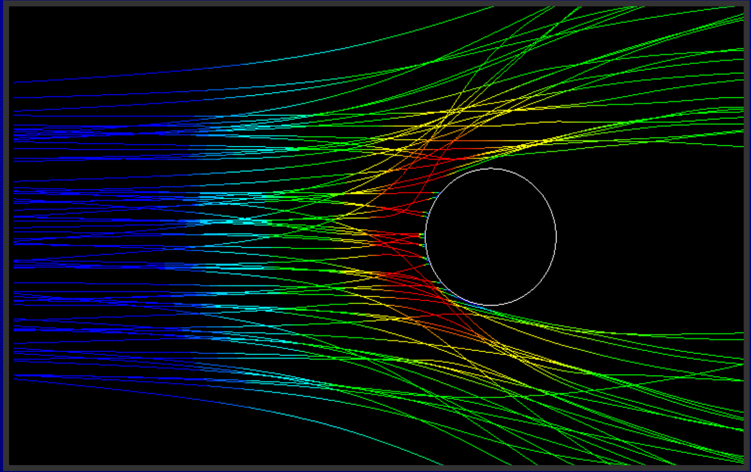
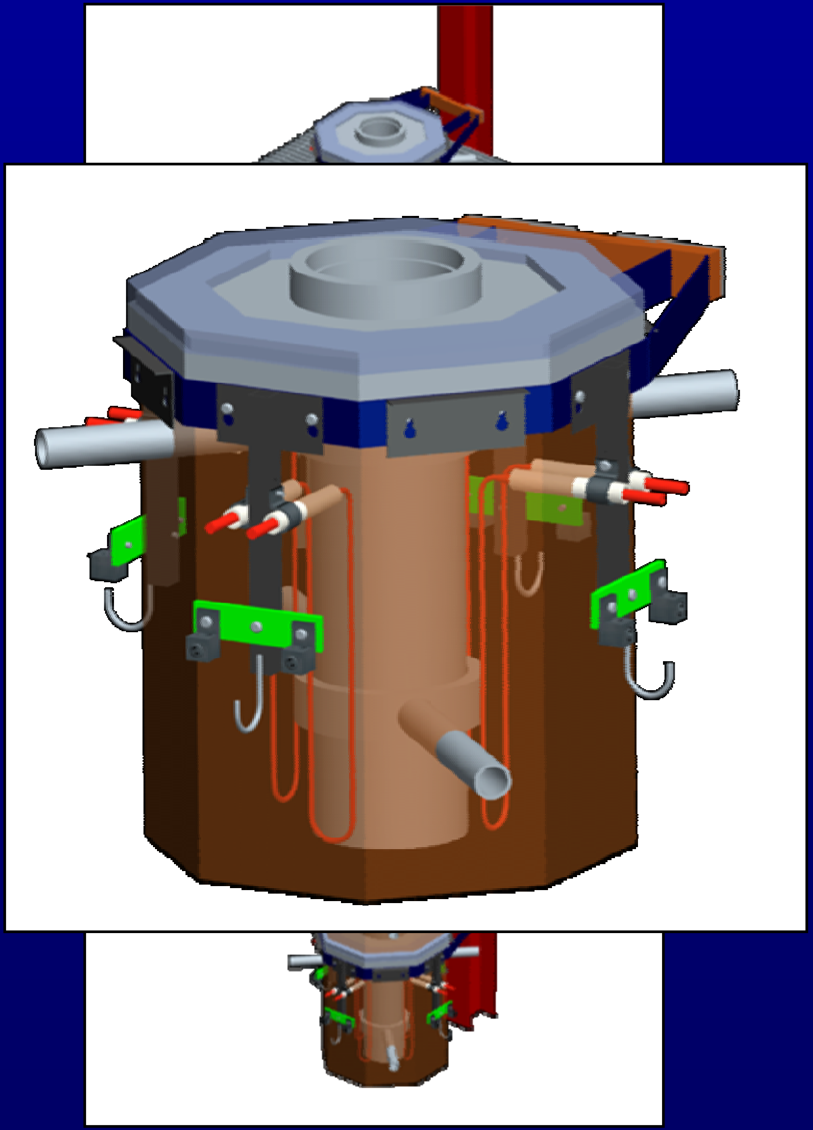
Objective

- Develop an CFD-based model of deposition
  - Fluid Flow
  - Temperature
  - Particle Tracking/Impaction/Sticking
  - Thermal Boundary Condition
  - Quasi-unsteady
- Measure deposition and compare to model



Experimental Facility – Reactor

- 14 ft. Tall x 6 in. Diam. Droptube multi-fuel reactor
- Heated Walls
- Access Ports Spaced 1 ft. Apart Axially
  - Residence Times
  - Measurement Access
- Solid, Gas, or Liquid Fuels
- Natural Gas Air Preheater

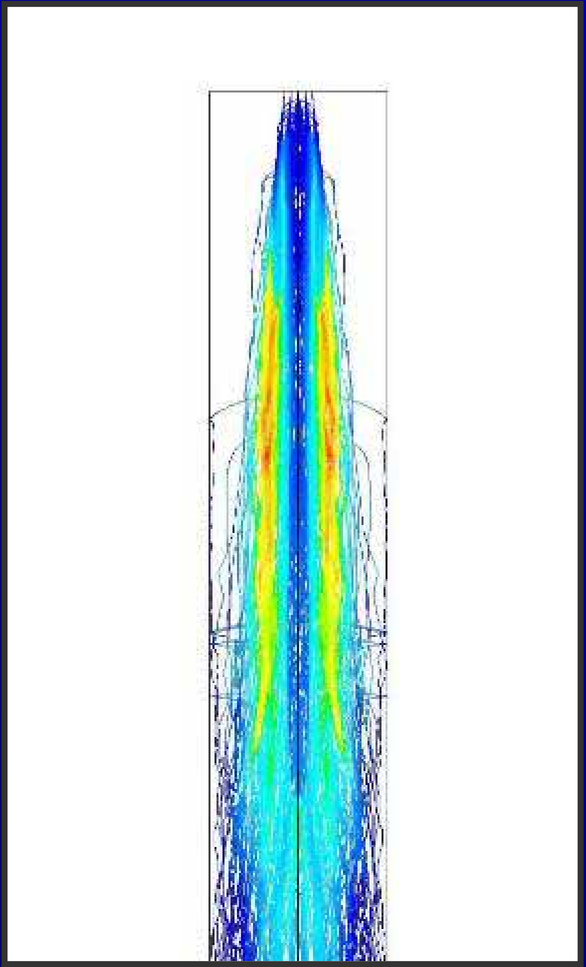


Experimental Facility – Probe

- Air-cooled Probe
- Surface-mounted Thermocouple
- Removable Deposition Collection Section
  - 10.1 cm long x 1.27 cm Diameter

CFD Simulation

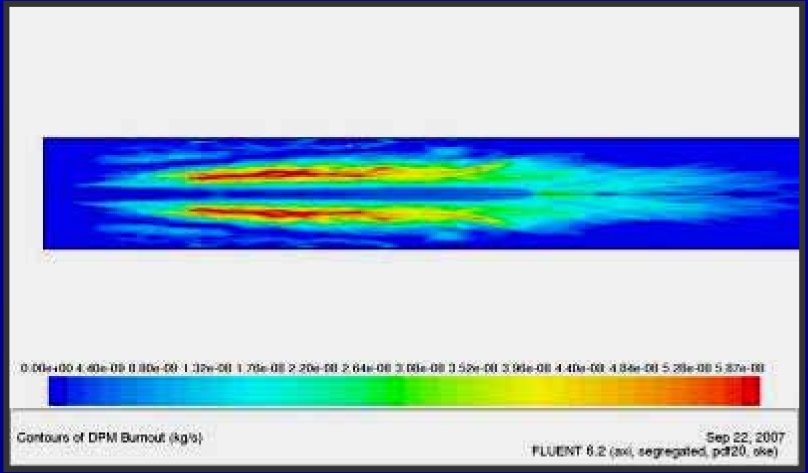
- Solid Particle Combustion
- Particle Tracking
  - Impaction
  - Capture
- Thermal Boundary Conditions
  - Heat Flux
  - Emittance
- Quasi-Steady-State
- Coordination

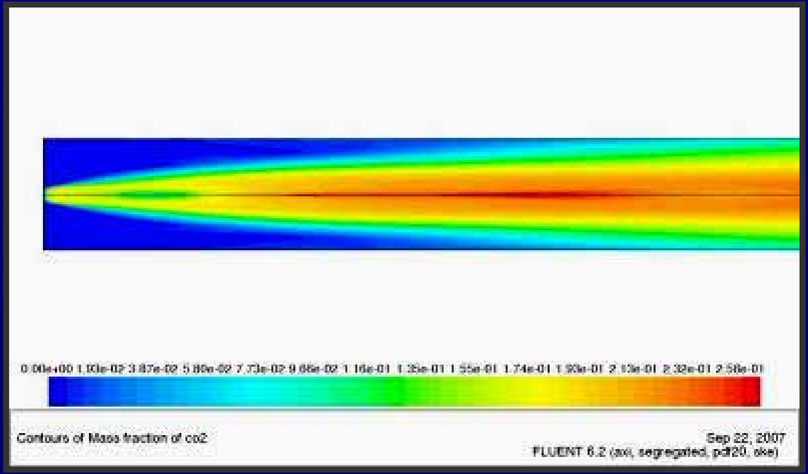


Particle Trajectories
Colored by Burnout Rate

Combustion – Chemistry

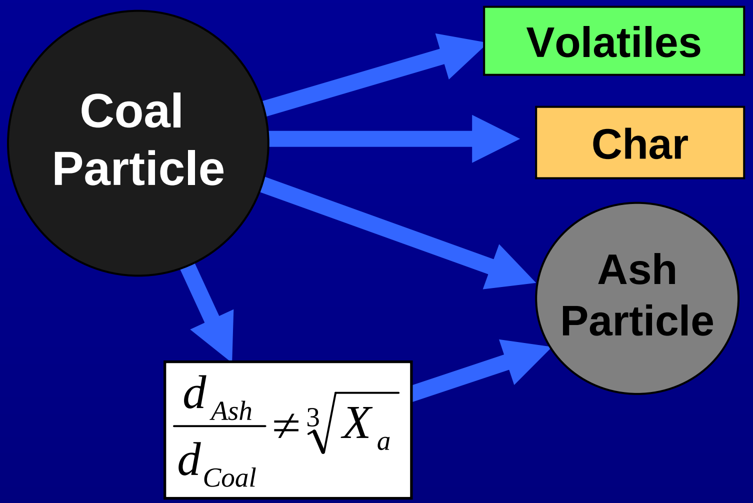
- Devolatilization
  - CPD Model
- Char Burnout
  - Kinetics / Diffusion Limited
- Equilibrium
  - Preprocessed PDF Lookup Tables



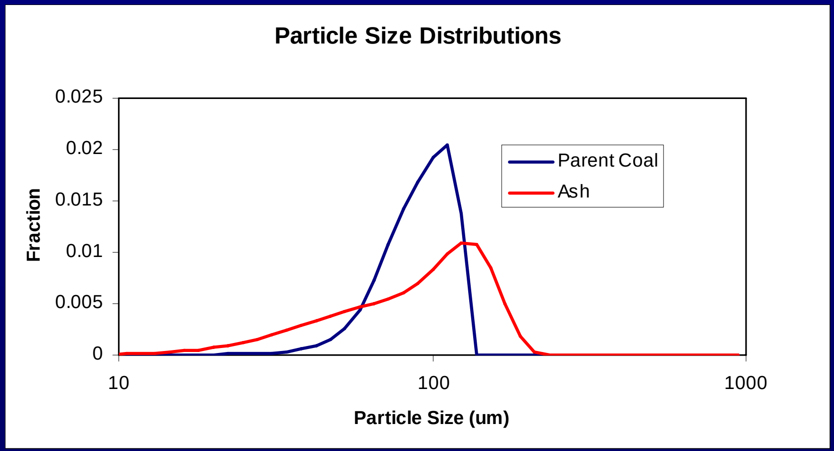


Particle Size Distributions

- Shrinking Particle Model is Not Accurate
  - Fragmentation
  - Agglomeration
- Two Simulations
  - Combustion (Reactor)
  - Depositon (Probe)
  - In Series

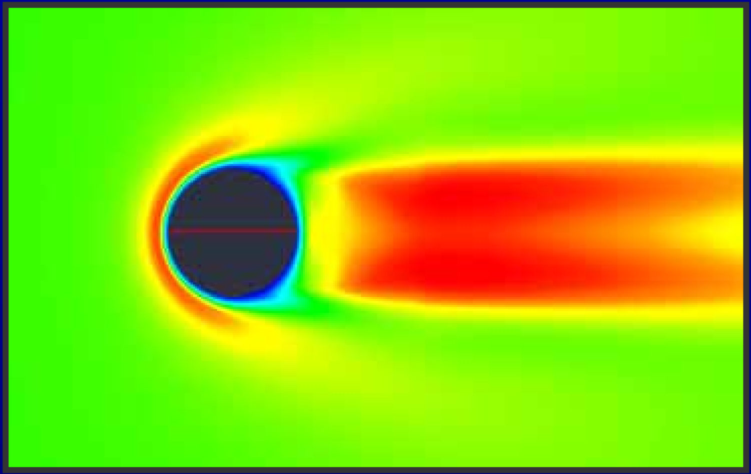


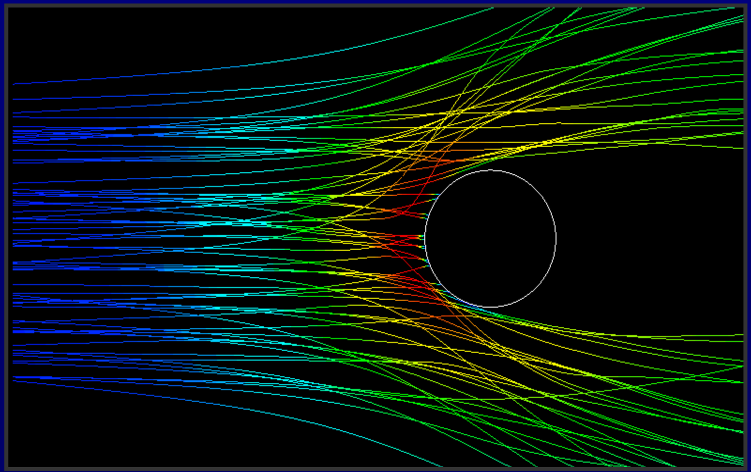
$$\frac{d_{Ash}}{d_{Coal}} \neq \sqrt[3]{X_a}$$



Random Walk Particle Tracking

- 4^{th} Order Runge-Kutta Trajectory Integration
- Stochastic Random Walk
  - Normally Distributed Velocity
  - Random Eddy Lifetime





Particle Deposition

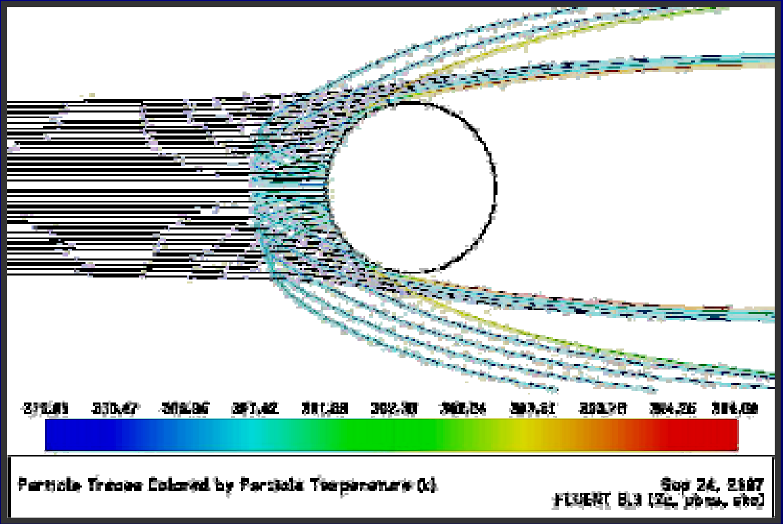
- Mechanisms
  - Inertial Impaction
    - Large Particles
  - Eddy Impaction
    - Small Particles
  - Thermophoresis
  - Condensation
  - Chemical Reaction

$$\dot{m}_{deposit} = \dot{m}_{fuel} X_{ash} \frac{A_{probe}}{A_{reactor}} \eta G$$

$$Impaction\ Efficiency = \eta$$

$$Capture\ Efficiency = G$$

$$Collection\ Efficiency = \eta G$$



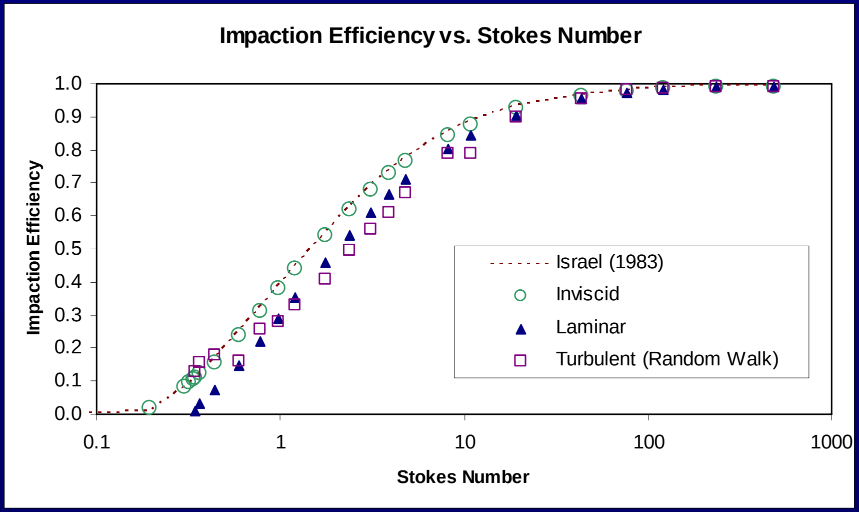
Particle Impaction

- Strong Function of Stokes Number
  - Particle Diameter
  - Flow Velocity
- Slight sensitivity to Reynolds Number, Turbulence

$$Stk = \frac{\rho_p d_p^2 V_g}{9 \mu_g d_{Probe}}$$

$$Re = \frac{\rho_g V_g d_{Probe}}{\mu}$$

$$\eta = \frac{1}{\frac{b}{(Stk - a)} + \frac{c}{(Stk - a)^2} + \frac{d}{(Stk - a)^3}}$$

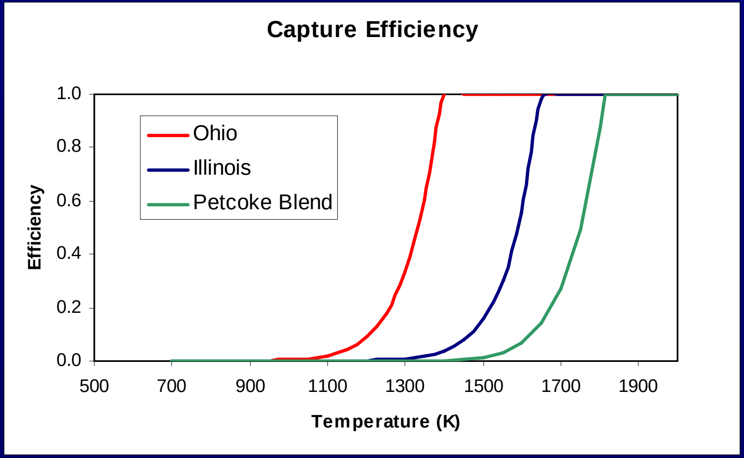


Particle Capture Efficiency

- Viscosity Model by Browning (2003)
- T_S is a function of ash composition
- Capture Model by Walsh (1990)
- Critical viscosity is not well known ($1\text{-}10^4$ Pa·s)

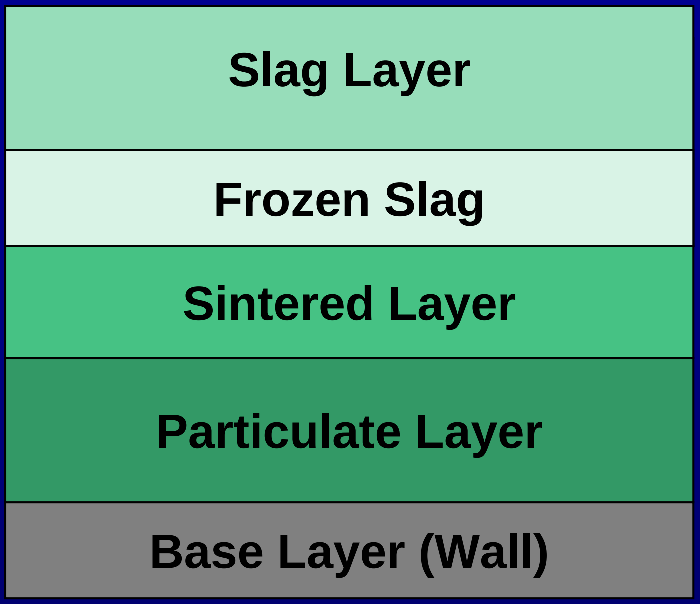
$$\log\left(\frac{\mu}{T-T_S}\right)=\frac{14788}{T-T_S}-10.391$$

$$G=\frac{m_{deposited}}{m_{particle}}=\min\left[\frac{\mu_{critical}}{\mu},1\right]$$



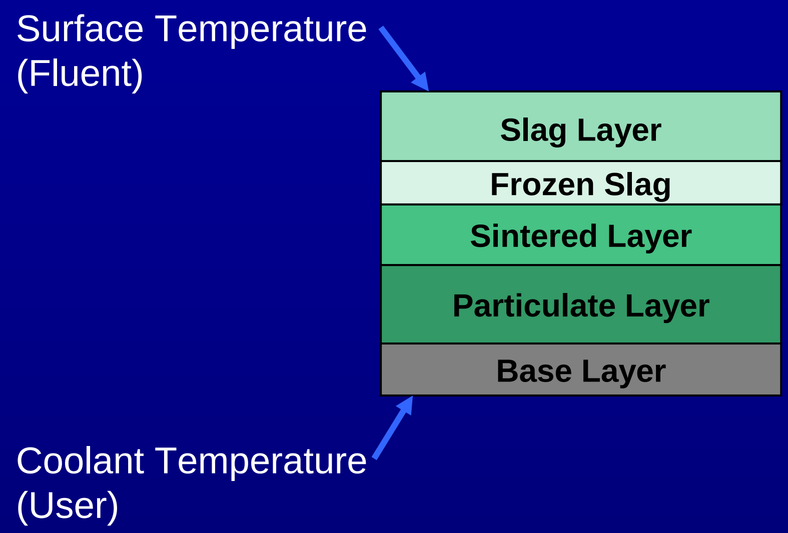
Ash Layer Accumulation

- Ash Particle's Mass is Deposited Into An Ash Layer Based on Local Surface Conditions
- Deposit Thickness and Thermal Resistance Accumulation



Ash Layer Properties + BC

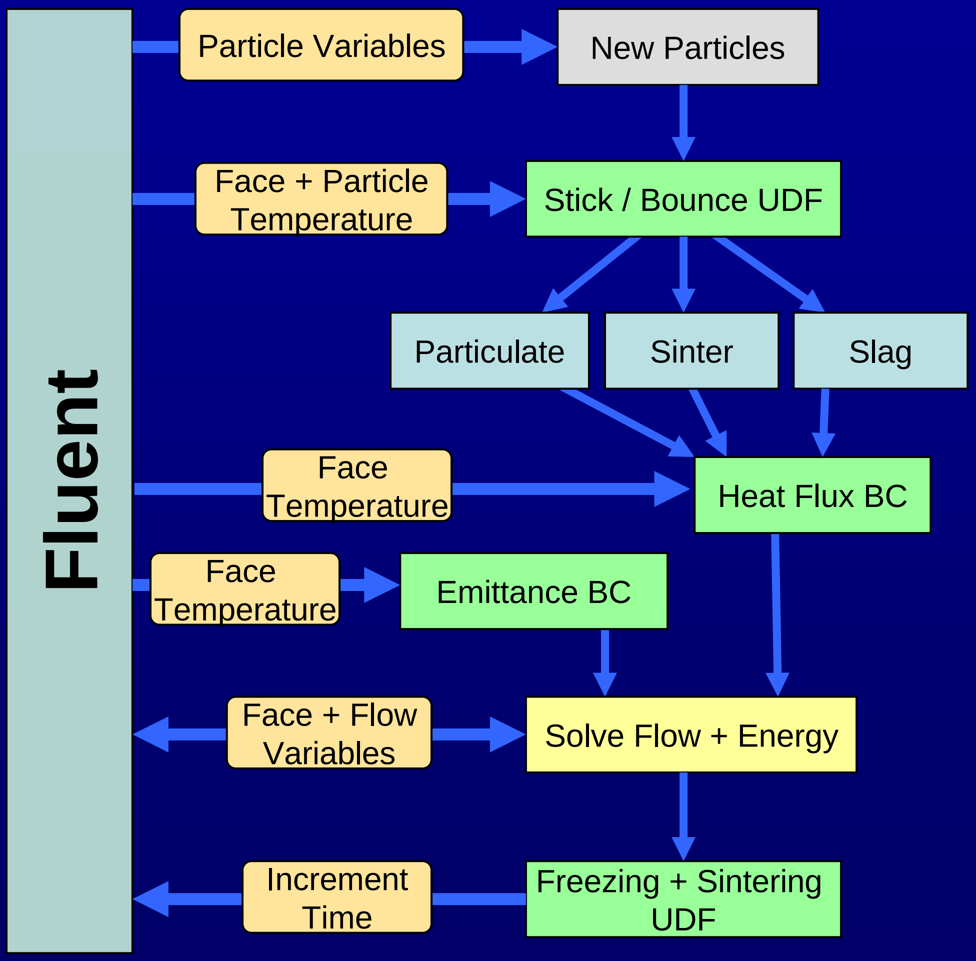
- Surface Temperature
  - From Fluent (all Fluent-internal Heat Flux)
- Coolant Temperature
  - From User
- Effective Thermal Resistance
  - Sum of Individual Thermal Resistances
- 1-D Heat Flux Calculated from Temperatures and Effective Resistance
  - Back to Fluent as BC



$$q'' = \frac{T_{Surface} - T_{Cool}}{R_{Sinter} + R_{Particulate} + R_{Frozen} + R_{Slag}}$$

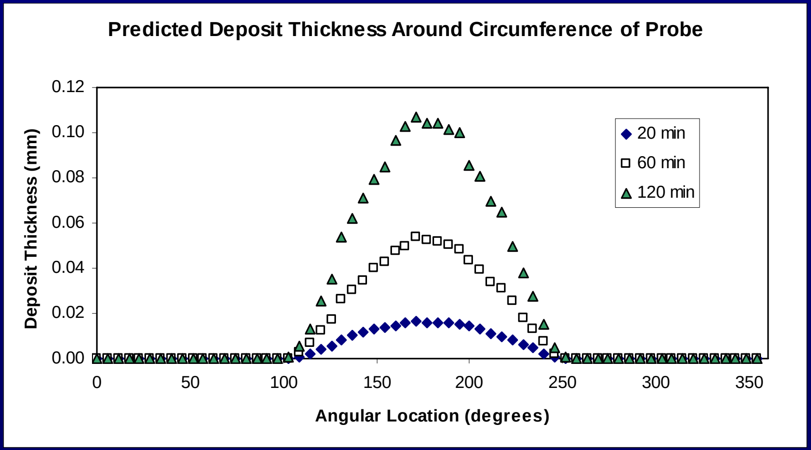
Coordination Algorithm

- Start With Converged, Clean-Wall Solution
- Outer Loop
  - Inject Particles
    - Accumulate Ash Layer
  - Inner Loop
    - Solve Flow + Energy Equations
  - Check For Freezing / Sintering of Sub Layers
  - Increment Time
- Minimally Invasive
  - Interpreted (Not Compiled) UDFs



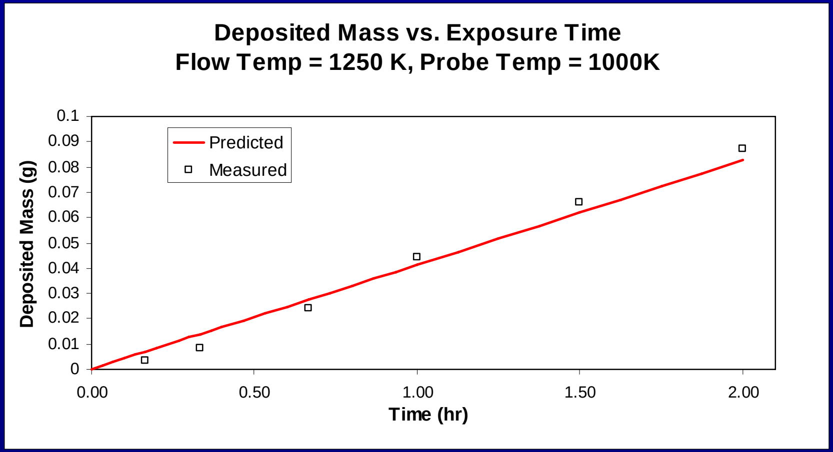
Results

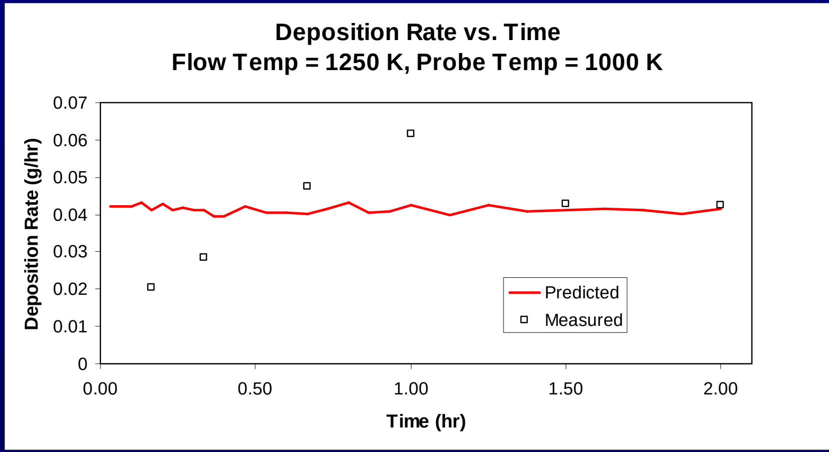
- Deposited Mass Measured
  - Function of Time
- Critical Viscosity Parameter Tuned to Match Single Case



Results

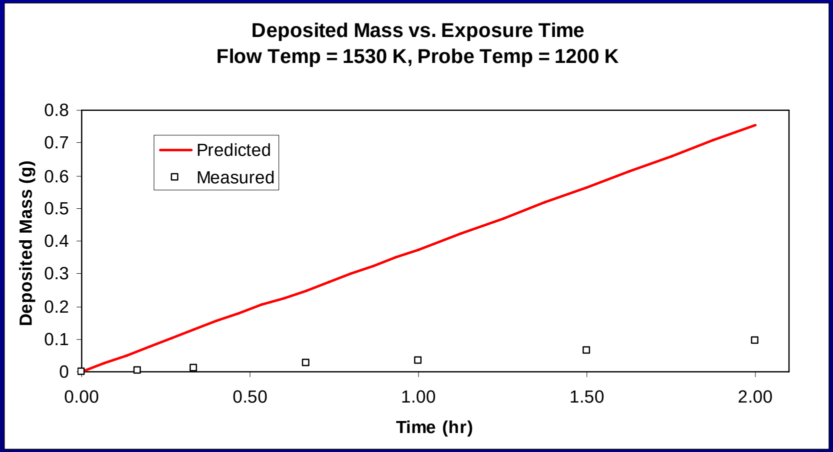
- Flow Temperature
  - 1250 K
- Probe Temperature
  - 1000 K
- Tuned Critical Viscosity
  - 350 Pa·s
- Deposition Rate Increases then Falls and Flattens

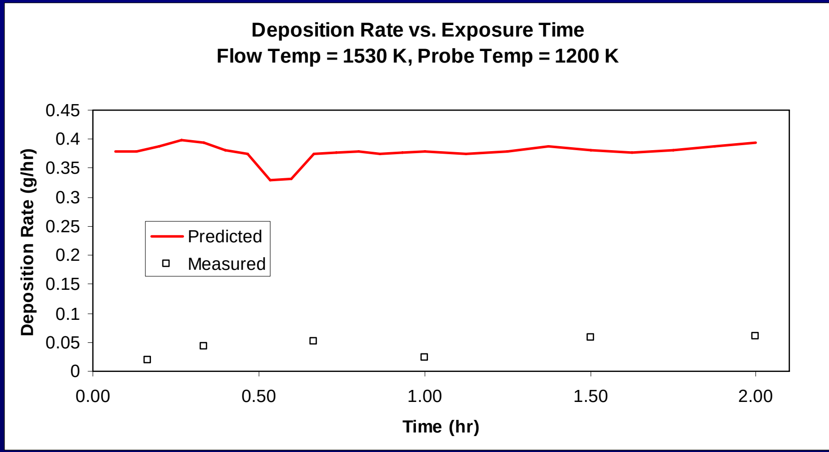




Results

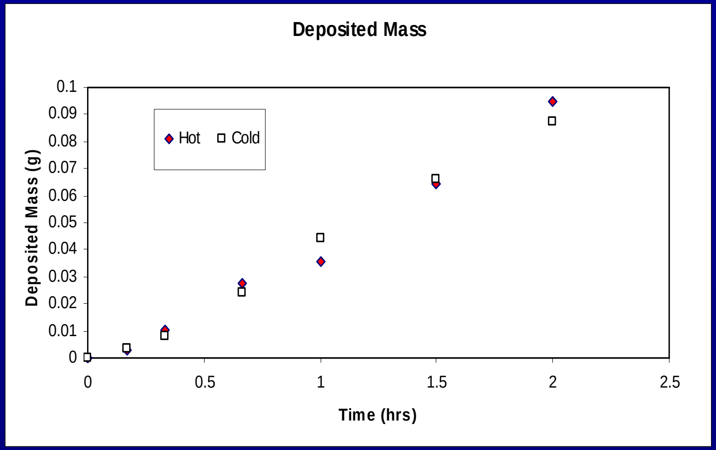
- Increased Flow Temp.
  - 1530 K
- Increased Probe Temp.
  - 1200 K
- Model Significantly Overpredicts Deposition Rate
- Higher Temperatures Cause Higher Flow Velocity
  - May Erode Particulate Ash Layer

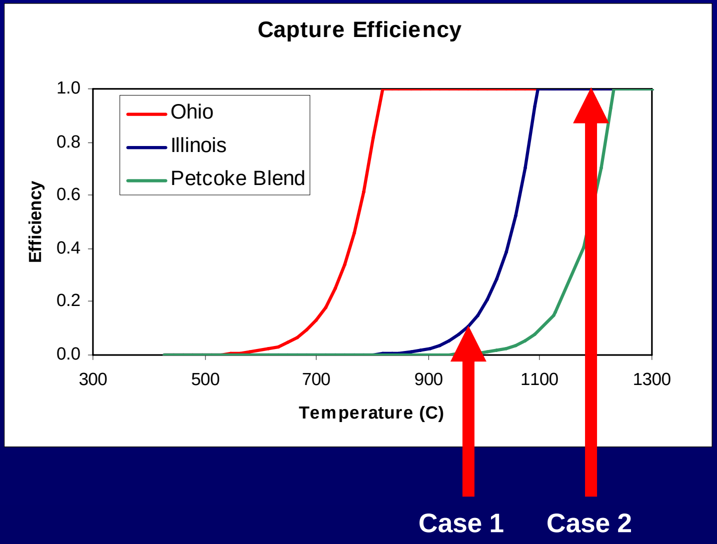




Conclusions

- Model predicts 8x increase in deposition rate
  - 2nd case flow temperature higher than “critical" temperature
- Measured rate shows no increase

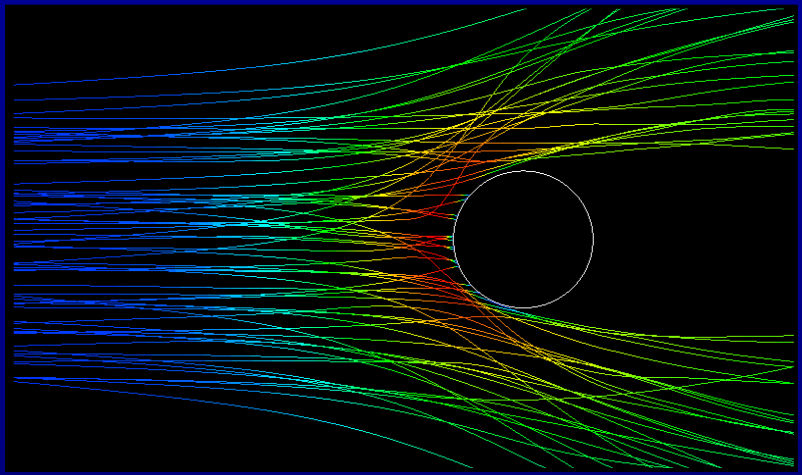


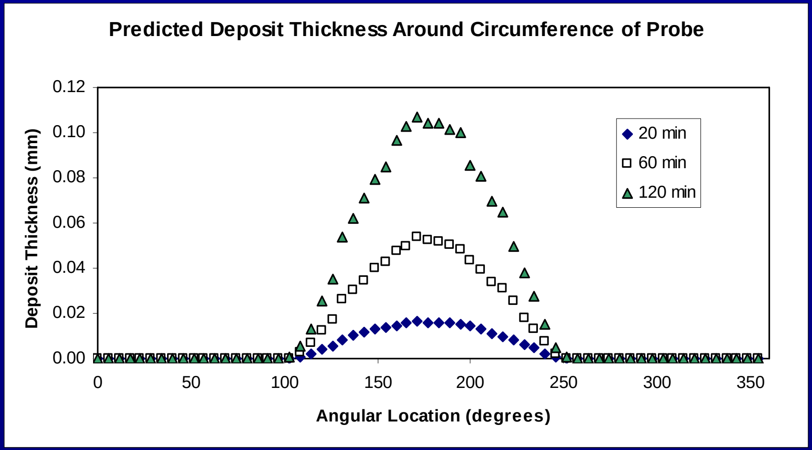


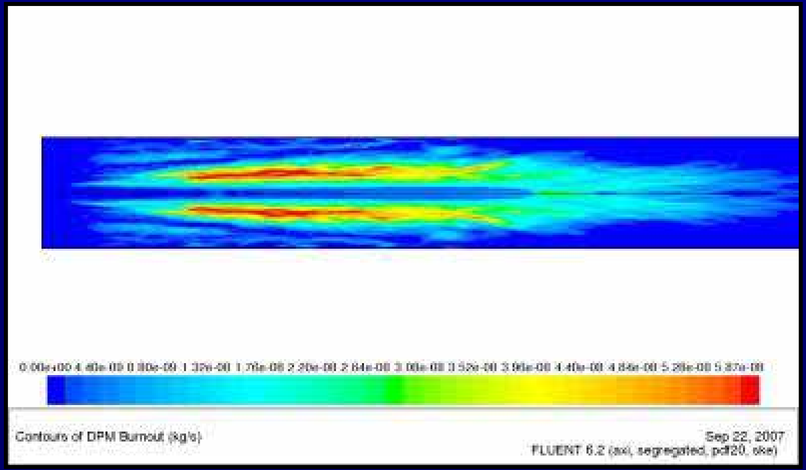
Conclusions

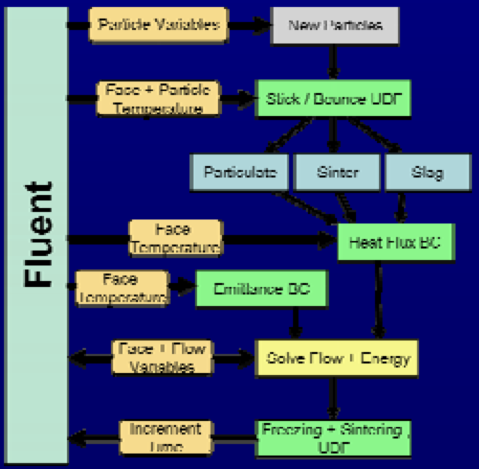
- Submodels successfully implemented and combined
- Model predicts increase in deposition rate with temperature when none is measured
- Particle Fragmentation / Agglomeration Model Needed
- Particulate Layer Removal Model Needed

Questions?




Predicted Deposit Thickness Around Circumference of Probe
Deposit Thickness (mm)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
50
100
150
200
250
300
350
Angular Location (degrees)
20 min
60 min
120 min


Contours of DPM Burnout (kg/s)
Sep 22, 2007
FLUENT 6.2 (axi, segregated, pdf20, ske)


Fluent
Particle Variables
New Particles
Face + Particle Temperature
Stick / Bounce UDF
Particulate
Sinter
Slag
Face Temperature
Heat Flux BC
Face Temperature
Emittance BC
Face + Flow Variables
Solve Flow + Energy
Increment Time
Freezing + Sintering UDF