Thermal Transport to a Reactor Wall with a Time Varying Ash Layer

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Objective

Characterization of the time dependent surface temperature and heat flux through an ash deposit at a reactor wall

Outline

- Introduction and Background
- Thermal and Mass Transport Methodology
- Model Scenario
- Model Results
- Work in Progress

Introduction and Background

Inorganic constituents are a principle factor
- -boiler size
- -heat transfer characteristics
- -boiler-side corrosion rates.

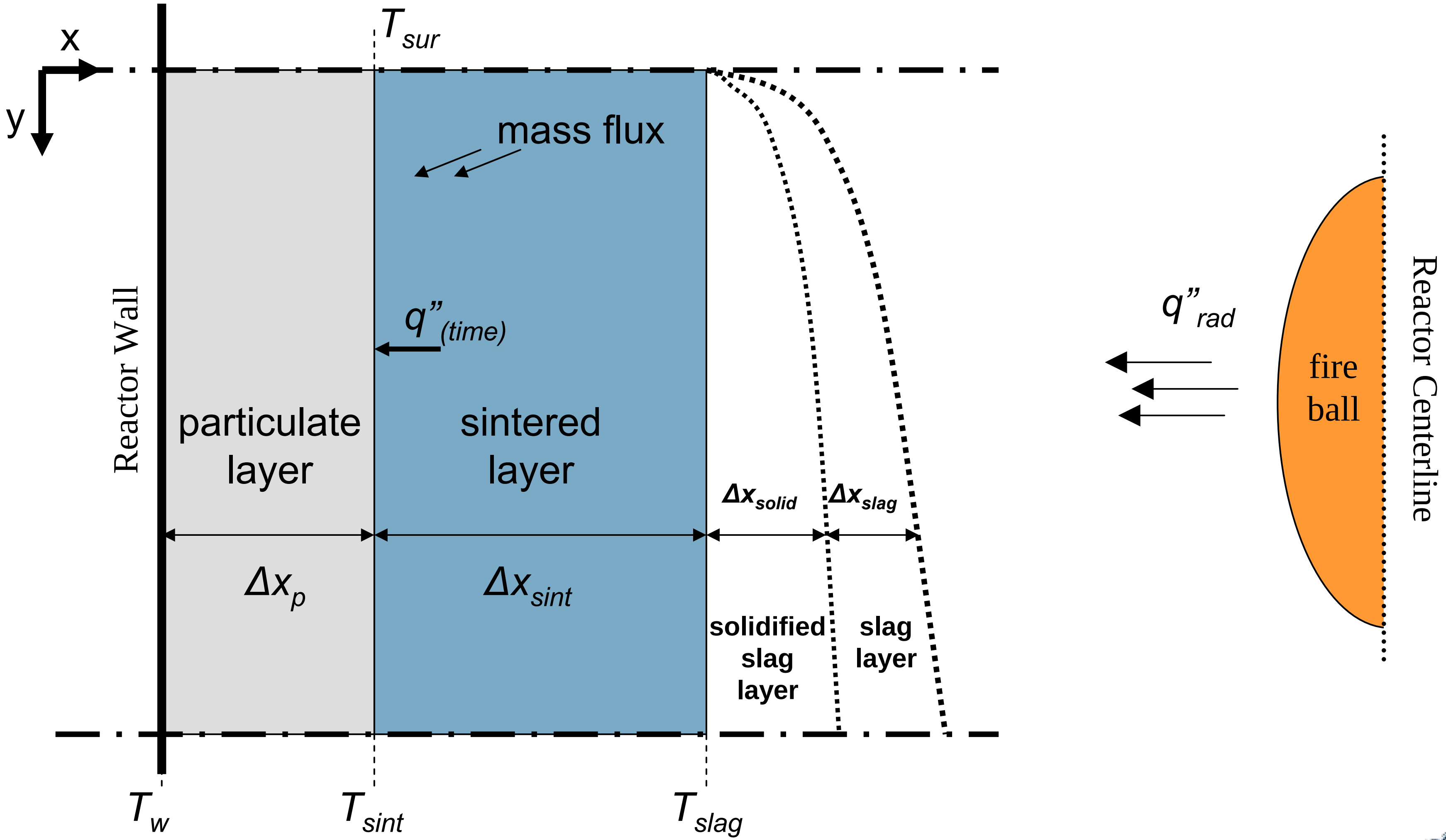
Ash deposits develop on boiler tubes and walls
- -reduced heat transfer
- -increased corrosion

Dynamic deposit morphology
- -heavily dependant upon temperature – deposit thickness

Characterization of ash deposit
- -deposition rate
- -deposit thickness
- -surface temperature
- -heat flux

An effective model will improve boiler reliability, efficiency, and flexibility

Ash Deposit Model



Model Assumptions

Quasi-steady thermal transport

- Deposit thickness grows very slowly compared to the transient thermal transport
- FLUENT solves for steady state transport at each time step

1-D heat transfer (neglecting conjugate heat transfer)

- constant ash properties throughout each layer:
  - coefficient of thermal conductivity, k
  - density, ρ, and emittance, ε
  - specified mass flux, $\dot{m}''$, and mass fraction captured, G
- Ash deposit negligibly thin compared to reactor width

Deposit is on a vertical wall

Specified wall temperature

Specified effective slagging and effective sintering temperatures

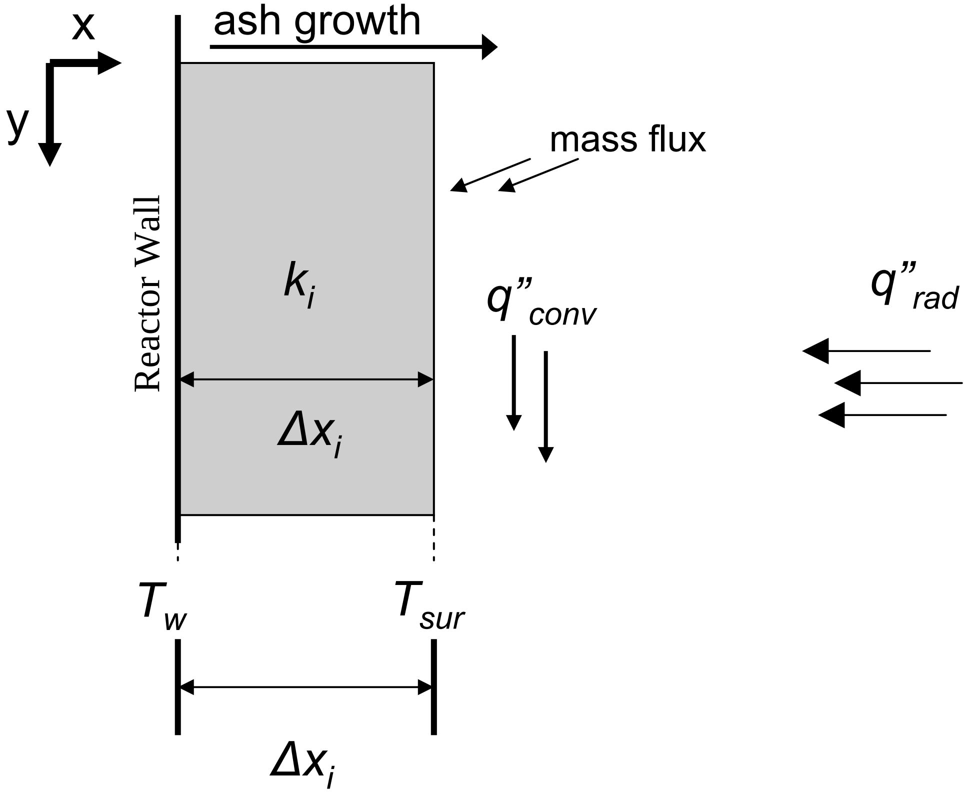
Method – Thermal Transport Analysis

A User Defined Function (UDF) models an ash deposit:

- deposit growth
- thermal transport through the deposit (transient and steady state)

Coupled with FLUENT, the surface temperature (T_{sur}) and heat flux (q'') distributions are determined

Surface temperature and heat flux are calculated after each time step



<u>for the i^{th} layer at position y</u>

- mass balance

$$\Delta x_i(y) = \frac{\dot{m}'' G(\Delta t)}{\rho_a}$$

- wall-normal heat flux

$$\dot{q}''_x(y) = \frac{1}{R_{tot}(y)}(T_w - T_{sur}) = \sum_i \frac{k_i}{\Delta x_i(y)} \Delta T$$

- T_{sur} initially guessed
- FLUENT determines $\dot{q}''_x(y)$
- T_{sur} computed again and compared

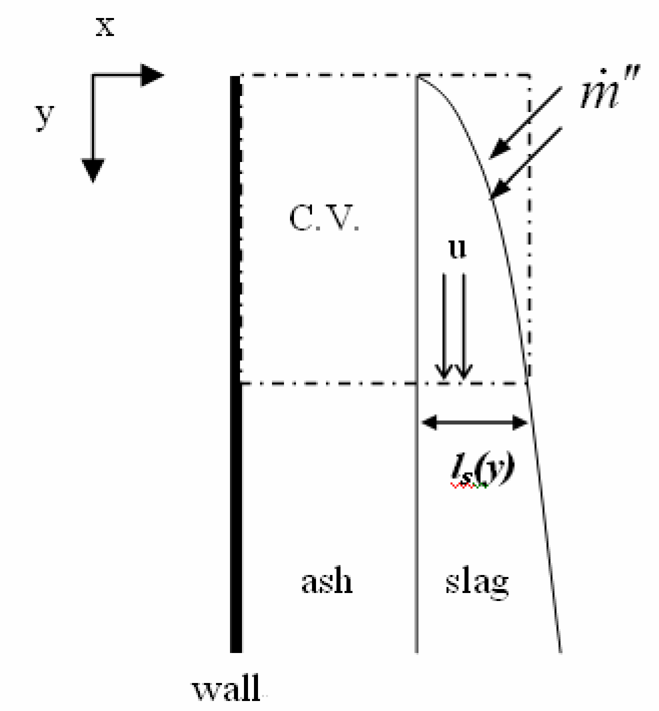
$$q''_{sur} = \dot{q}''_{conv} + \dot{q}''_{rad} = \dot{q}''_x(y)$$

- iteration with FLUENT to convergence of q'' and T_{sur}
- time is incremented and the process is repeated

Method – Steady State Mass Transport Analysis

- Creeping regime

  Reynolds numbers (4.44×10^{-5} to 6.49×10^{-4}), high viscosity and low velocity of the slag
- The surface temperature and heat flux are calculated after each time step as deposit growth progresses in time.



- y-component of Navier-Stokes Equations

  (μ evaluated at an average slag temperature)

$$\frac{\partial}{\partial x}\left(\mu \frac{\partial u}{\partial x}\right) = -\rho_{sl} g$$

- integrate twice to obtain slag velocity

$$u = \frac{\rho_{sl} g}{\mu}\left(-\frac{1}{2}x^2 + x l_s(y)\right)$$

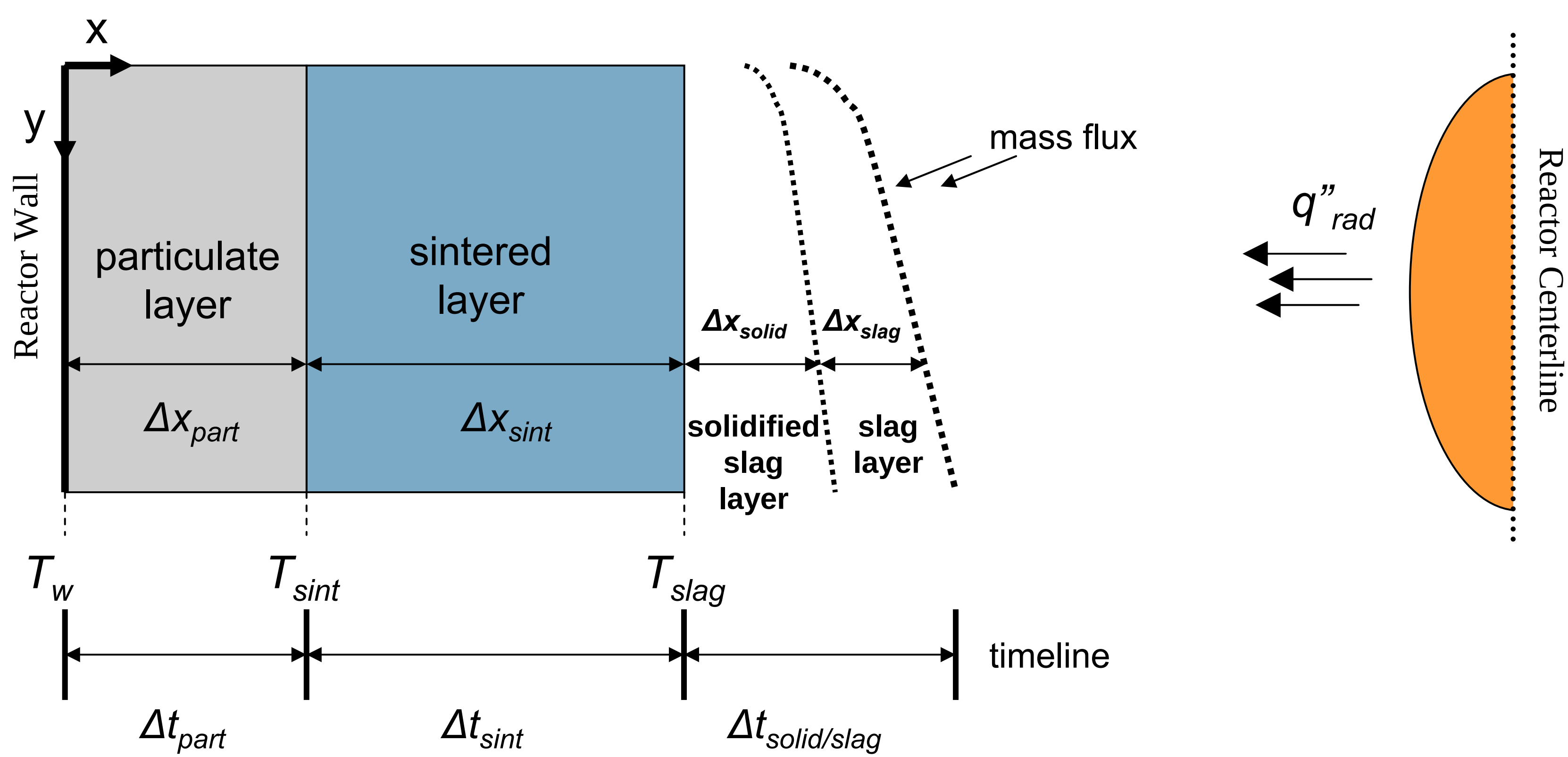
- total mass flow of the slag equals the deposition rate

$$\int_0^{l_s(y)} \rho_{sl} u \, dx = \dot{m}'' y$$

- substituting the velocity distribution and integrating yields the height-dependant slag thickness

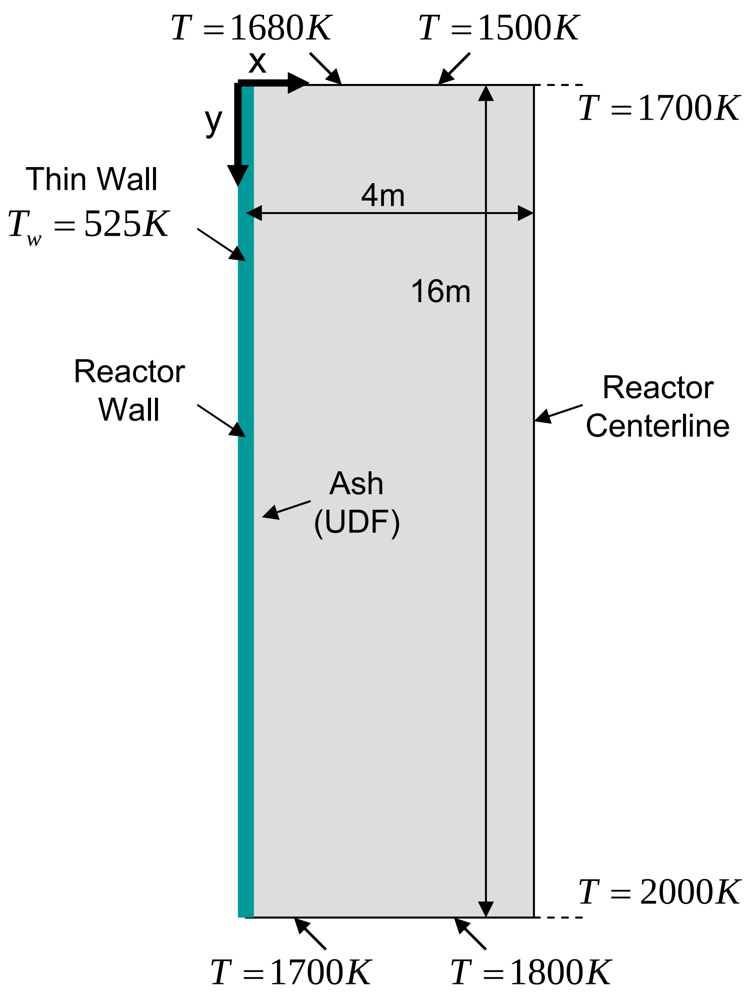
$$l_s(y) = \left(\frac{3\mu \dot{m}'' y}{(\rho_{sl})^2 g}\right)^{1/3}$$

Layer Formation and Temporal Evolution



- The simulation marches through time, adding layers until steady state is attained (slagging conditions may or may not exist

Model Scenario: Industrial Coal-fired Reactor



- Scenario allows for slagging conditions
- Obtained results for transient and steady state conditions

- UDF run in Fluent
  - -2D domain, 4m x 16m
  - -radiation only (surface to surface)
  - -quadrilateral mesh (40 x 20)
- time step of 1.0 min
- typical *k*, *ε*, *ρ* values from literature

Sources

Anderson, et. al Effective Thermal Conductivity of Coal Ash Deposits at Moderate to High Temperatures. *Journal of Engineering for Gas Turbines and Power* 1987, 109, 215-221.

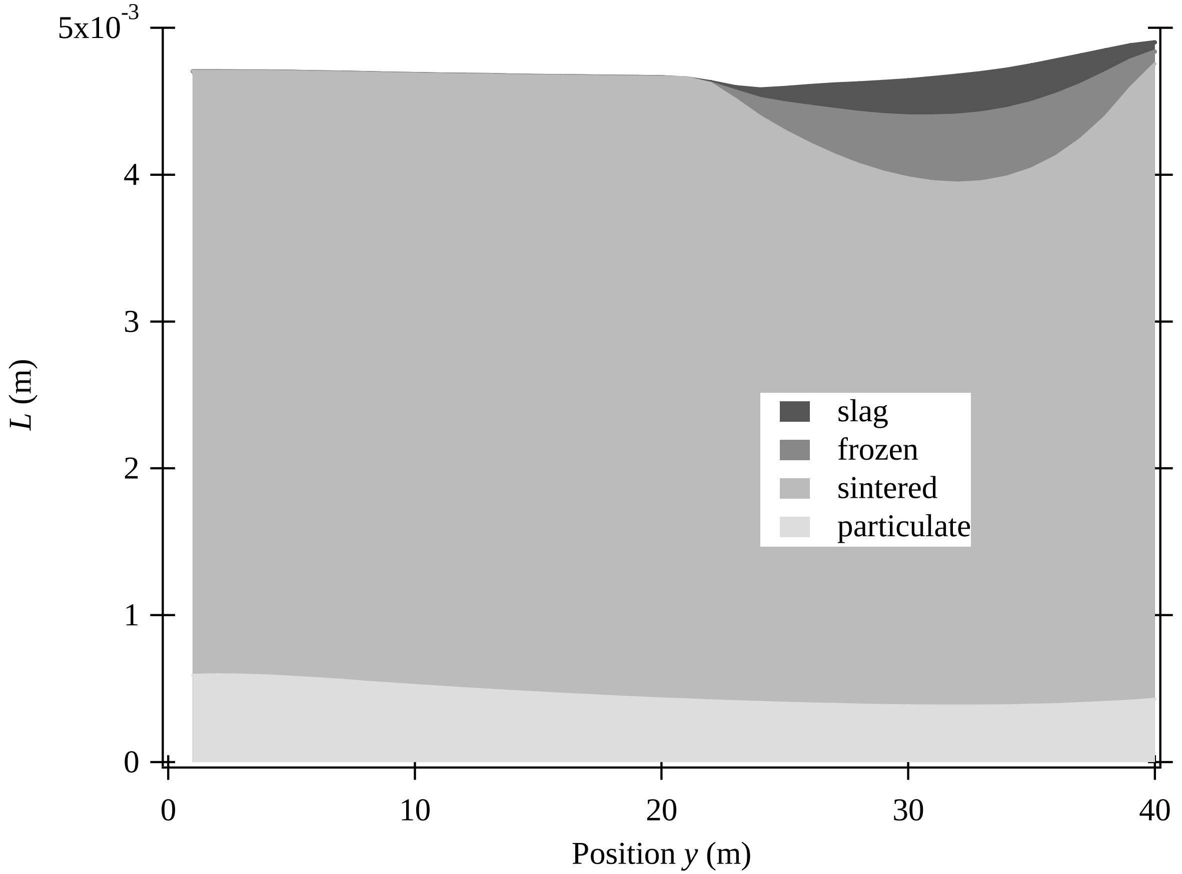
Rezaei,et. al Thermal Conductivity of Coal Ash and Slags and Models Used. *Fuel* 2000, 79, 1697-1710.

Wall, et.al The Properties and Thermal Effects of Ash Deposits in Coal-Fired Furnaces. *Prog Energy Combust Sci* 1993, 19, 487-504.

Results

Ash Thickness vs. Position

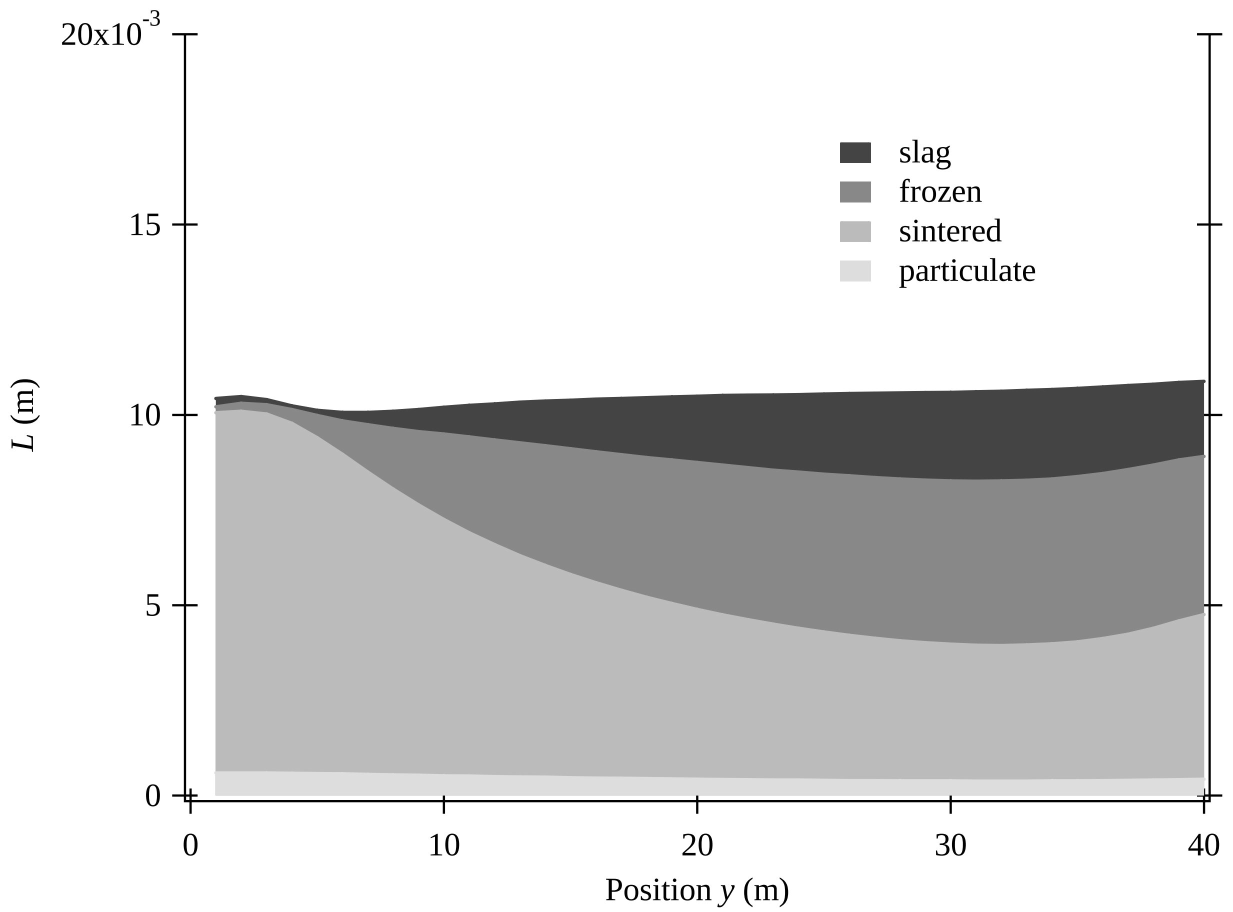
Deposit layers and thicknesses vs. wall position (140 min)



Results

Ash Thickness vs. Position

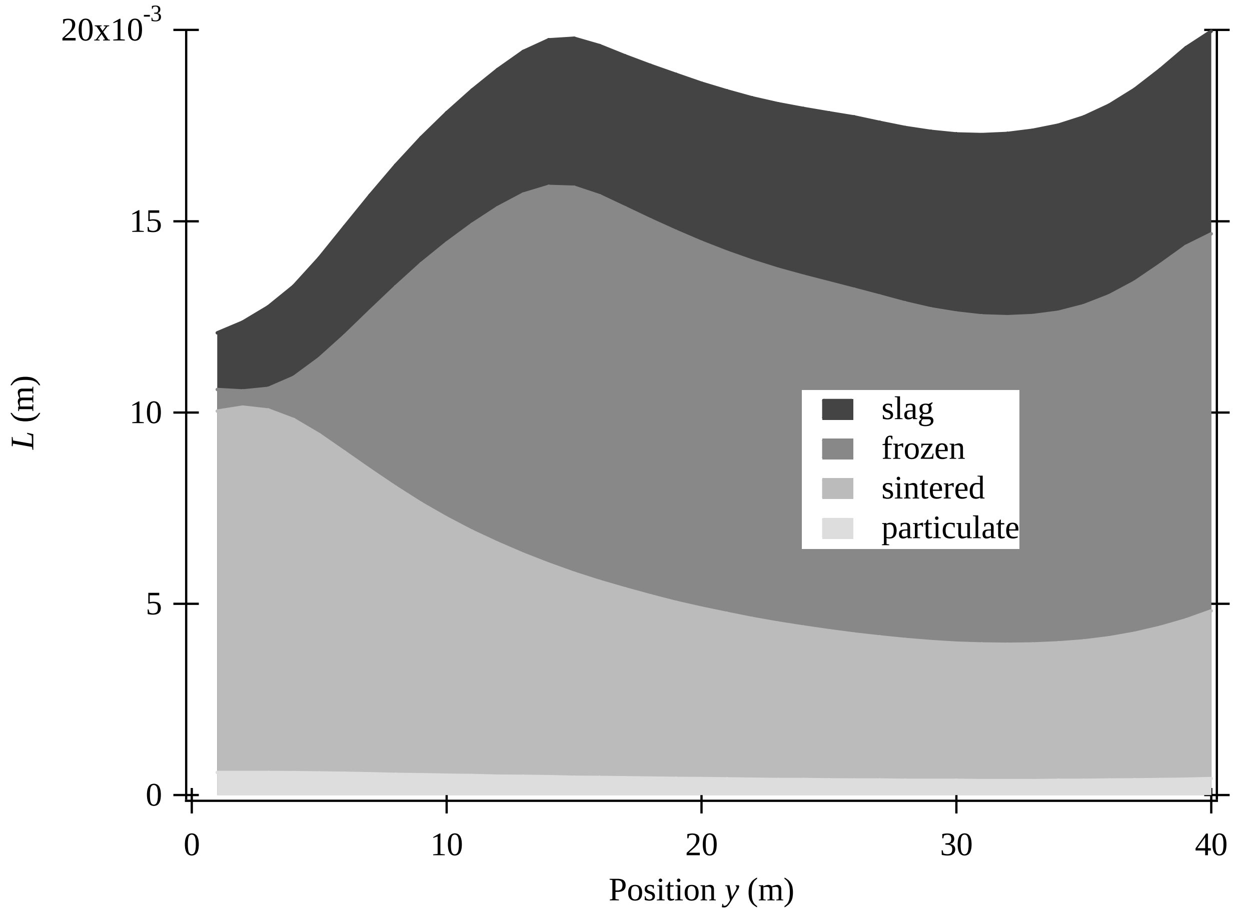
Deposit layers and thicknesses vs. wall position (318 min)



Results

Ash Thickness vs. Position

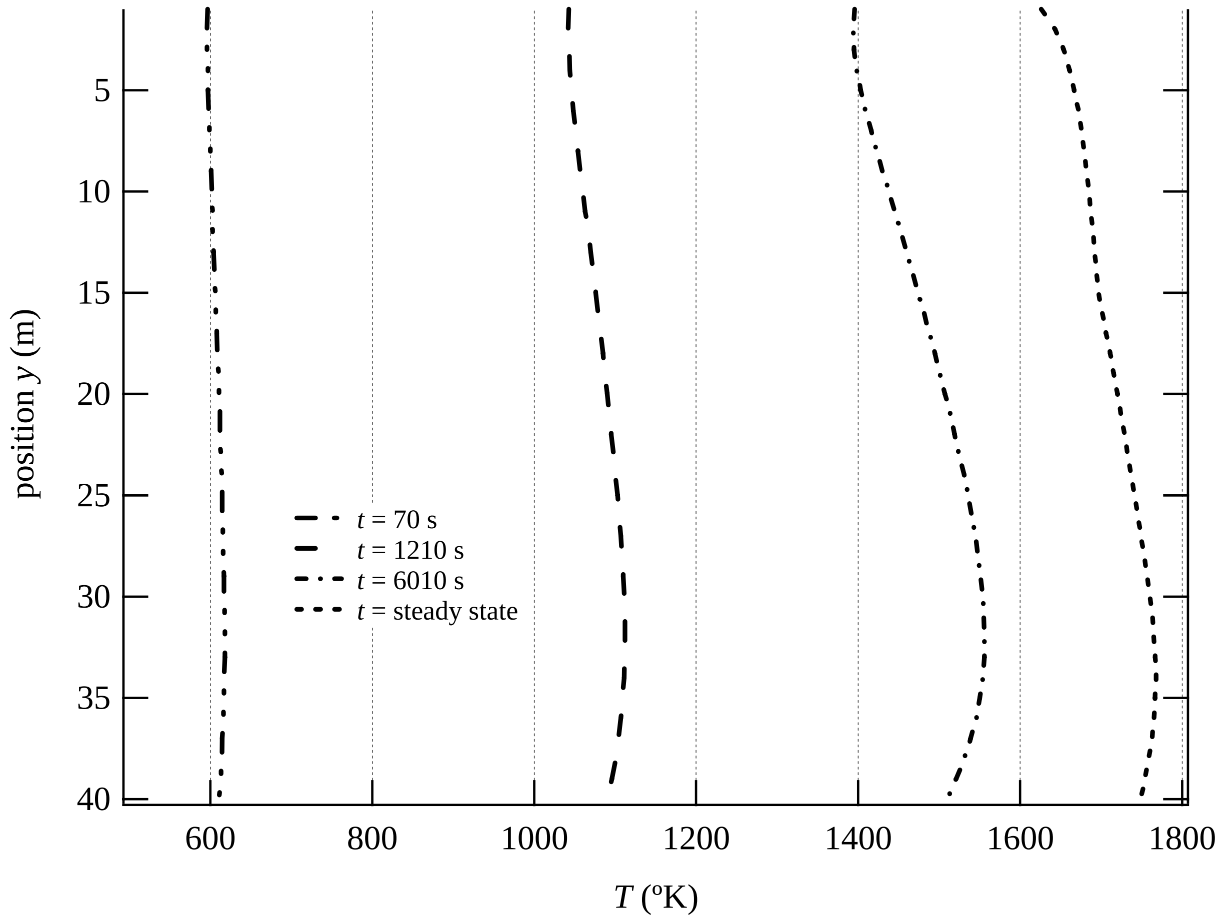
Deposit layers and thicknesses vs. wall position (10 hrs)

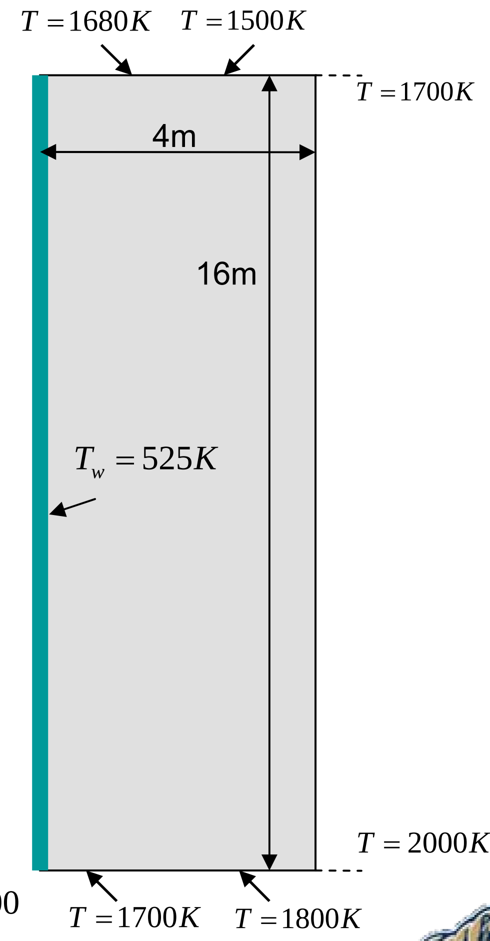


Results

Ash Surface Temperature vs. Position

Ash surface temperature profiles at t = 70 s, 1210 s, 6010 s, and at steady state

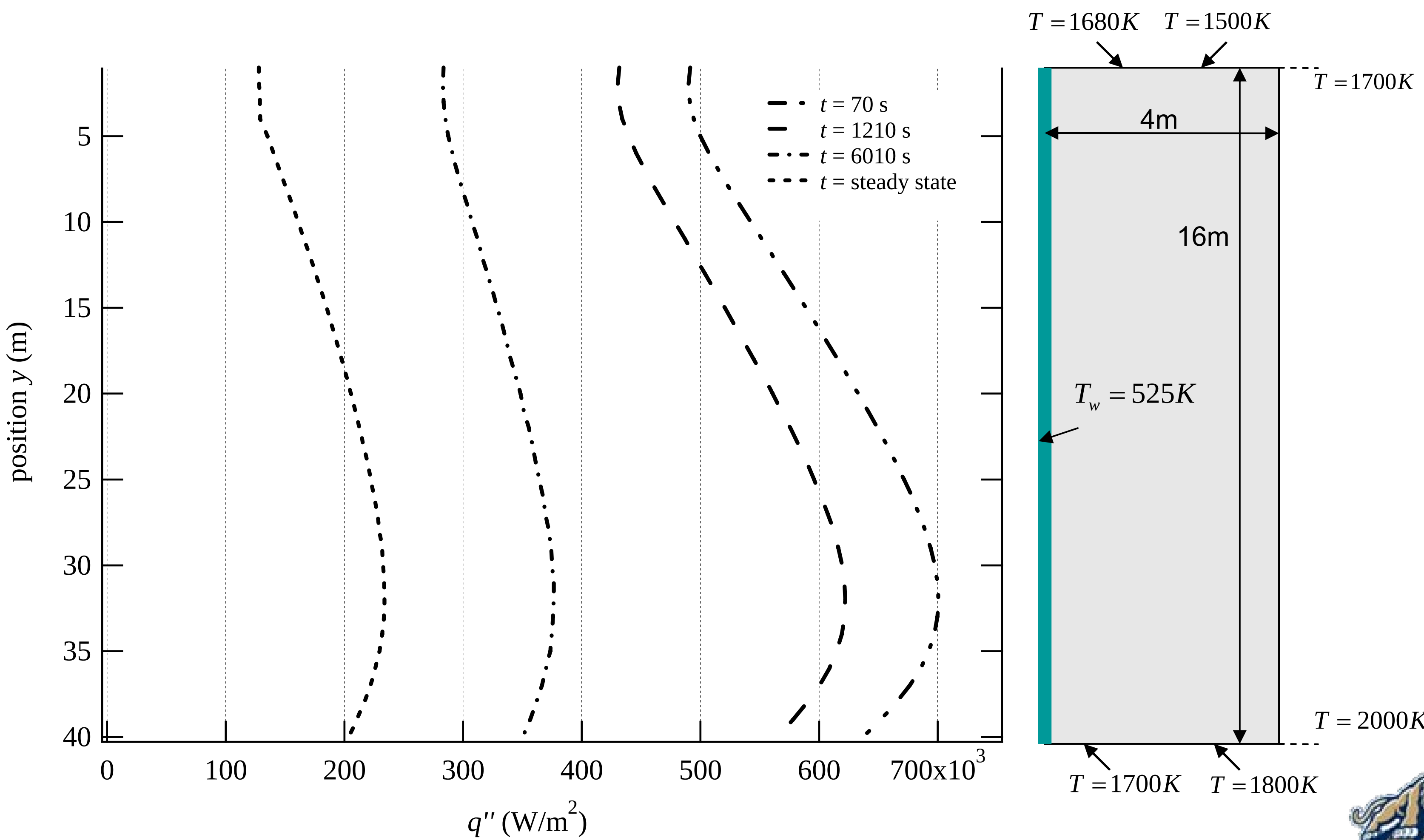




Results

Heat Flux vs. Position

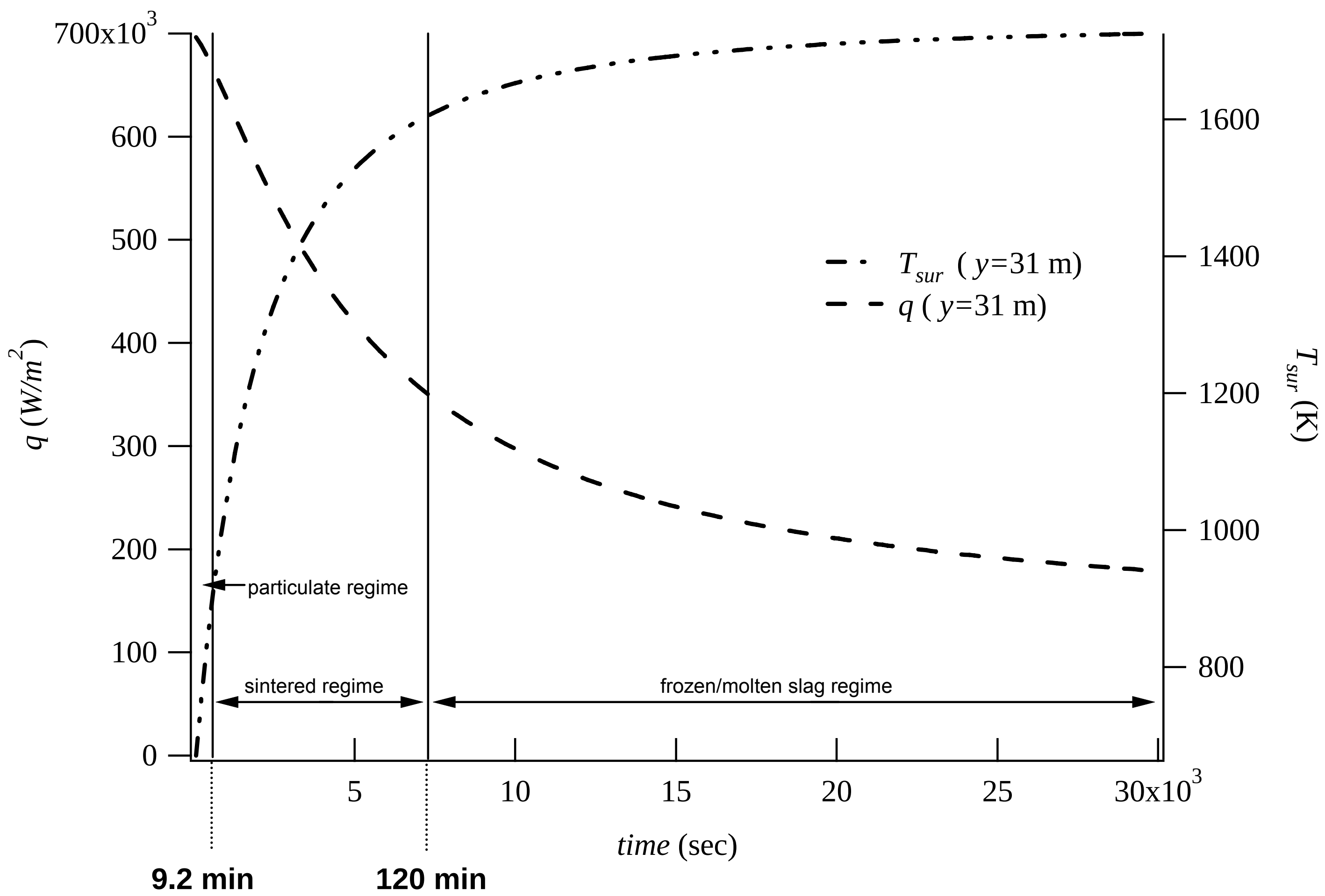
Wall heat flux profiles at t = 70 s, 1210 s, 6010 s, and at steady state



Results

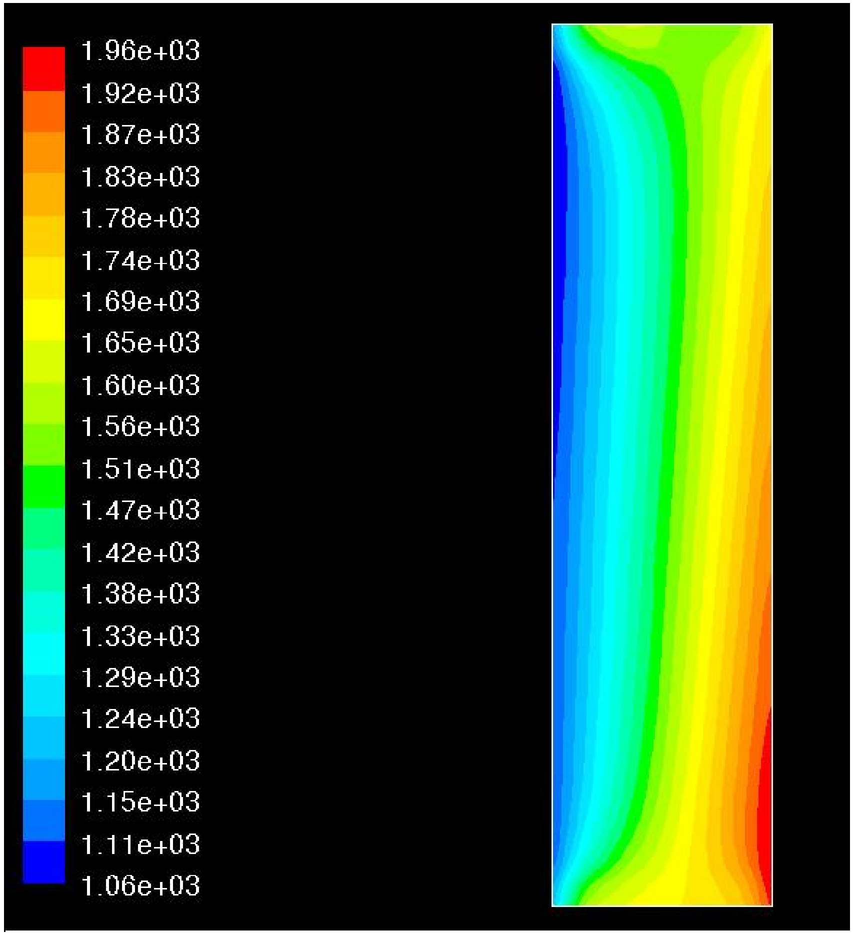
Heat Flux and Surface Temperature vs. Position

Heat flux (left axis) and ash surface temperature (right axis) as a function of time, at position y = 31m.

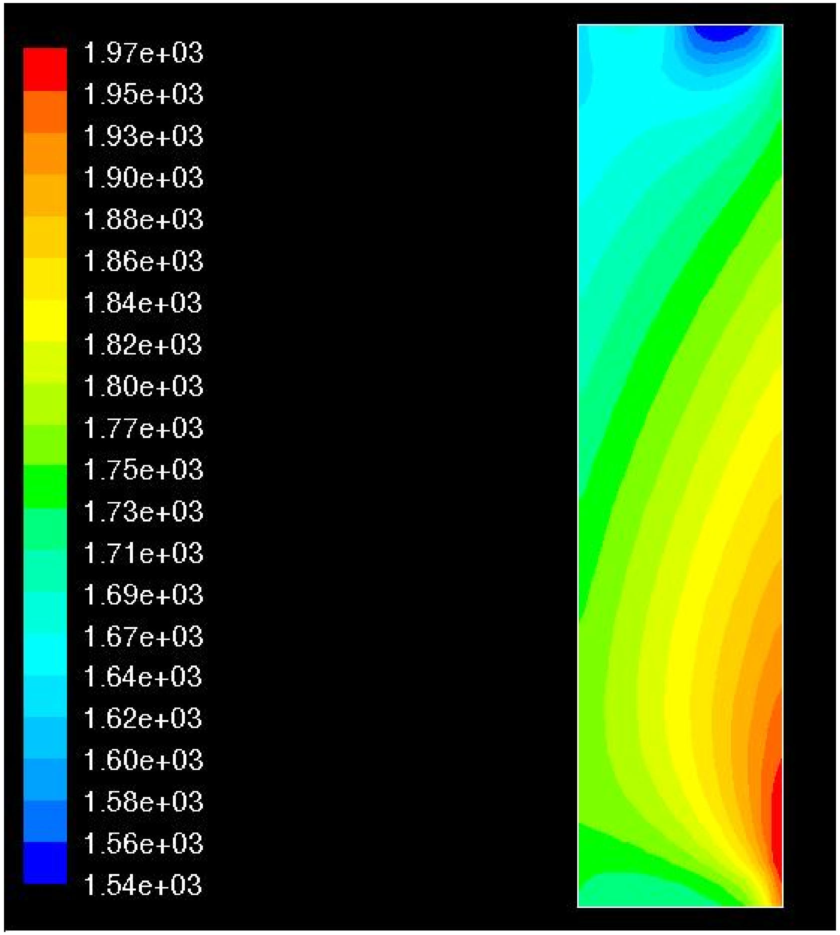


Results

Temperature Distribution



(20 min)



(10 hrs)

Work in Progress

- Implementation of a continuous model for the effective thermal conductivity (*k*) which captures the dependence on ash properties.

  Investigation of Preliminary models for (*k*)
  - Packed Beds
  - Empirical data
  - Conduction and radiation models

  examples
    - Random two continuous phase model (Brailsford, Major)
    - based on porosity and *k* values of two continuous (gas and solid) phases

$$k_e = \left\{(3p_g - 1)k_g + (3p_s - 1)k_s + \left[\{(3p_g - 1)k_g + (3p_s - 1)k_s\}^2 + 8k_g k_s\right]^{1/2}\right\}/4 \qquad p_s = 1 - p_g$$

    - Laubitz model
    - models radiation combined with an existing conduction model
    - based on particle diameter, porosity, and temperature

$$k_e = 2k_{(cond)} + 4\sigma T^3 \varepsilon \frac{d_p}{p}(1 - p^{2/3} + p^{4/3})$$

- incorporation of emittance and deposition models/UDF's within FLUENT
- Obtain experimental data to further model development and for validation

Summary

- Developed a model (UDF) to describe the behavior of a temporally-varying ash deposit
- Model coupled thermally with FLUENT through wall heat flux and temperature
- The thermal transport and changes in deposit morphology were determined
- Model exercised on an industrial coal-fired boiler (with slagging conditions)
- Spatial and temporal profiles obtained for
    - deposit thickness
      (steady state thickness of 15 - 20 mm)
    - surface temperature
      (maximum temperatures above 1700 K)
    - heat flux
      (approximately 60% reduction in maximum heat flux)