Donaldson®

Filtration Solutions

A New CFD Model for Understanding and Managing Diesel Particulate Filter Regeneration

Z. Jason Hou and Ted Angelo

Donaldson Company, Inc.

DPF Technology Development

- Understand Regeneration
  - When?
  - How?
- Characterize Soot Loading and Pressure Drop vs. Time
- System Control
  - Model-Based Feed-Forward Adaptive Control
- Component Development
- Flow Distribution and Thermal Management

DPF Technology Development

- **Understand Regeneration**
  - **When?**
  - **How?**
- Characterize Soot Loading and Pressure Drop vs. Time
- System Control
  - Model-Based Feed-Forward Adaptive Control
- Component Development
- Flow Distribution and Thermal Management

Why Model Regeneration?

- Goal: Achieve Quick, Complete and Safe Regeneration with Minimal Fuel Penalty
- Regeneration is Very Complex
- Experiments are Difficult and Costly
- Modeling Allows Us to Optimize System and Regeneration Strategy

Regeneration Is Complex

- 3-D, Transient Flow
- Three Modes of Heat Transfer
- Porous Layers: Substrate and Soot
- Soot Combustion / Catalyst Effect
- Variable Properties: Porosity, Permeability, etc.
- Sensitive to Operating Parameters:
  - Exhaust flow rate, gas temperature, soot load, oxygen, filter design, etc.

Donaldson.

Filter Failure: Want to Avoid

- Ring-off Cracking of Cordierite

Regeneration Model: I/O

Input:

- Filter configuration: dimensions, cell density, wall thickness
- Soot loading / distribution
- Regeneration condition: inlet gas temp, exhaust flow rate, O_2
- Substrate property: porosity, permeability, thermal, etc.
- Soot property: packing density, permeability, etc.
- Soot reaction kinetics and catalyst effect

Output:

- Spatial and temporal profiles of key variables
  - Temperature, velocity, oxygen, reaction rate, etc.
- Soot distribution (regen efficiency) vs. time
- A tool for parametric and what-if studies

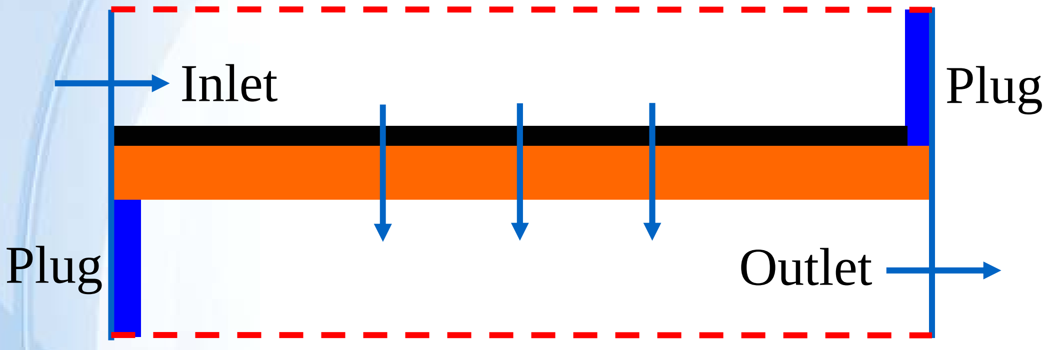
Regeneration Modeling: State of the Art

- Ongoing, lots of good efforts to date
- Mostly 2-D, some 3-D (multiple 2-D channels)
- Lack details at channel level
- Simplified flow equations / Many assumptions
- Single temperature field for all phases: gas, substrate and soot

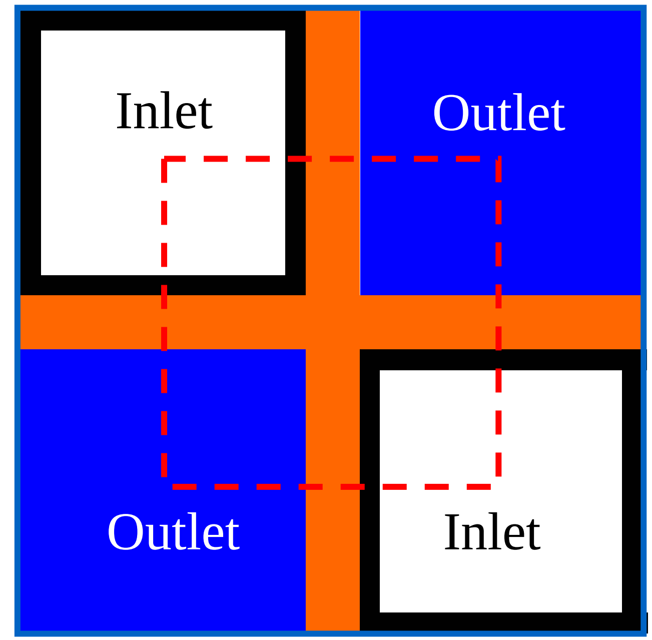
Features in The New Model

- 3-D for one inlet/outlet channel unit
- Porous medium model for substrate and soot layer
- Generic conservation equations for whole domain
- Capable of separate temperature fields for gas and solid via a heat transfer coefficient
- Arrhenius soot reaction with catalytic effect
- Custom CFD code

Computational Domain

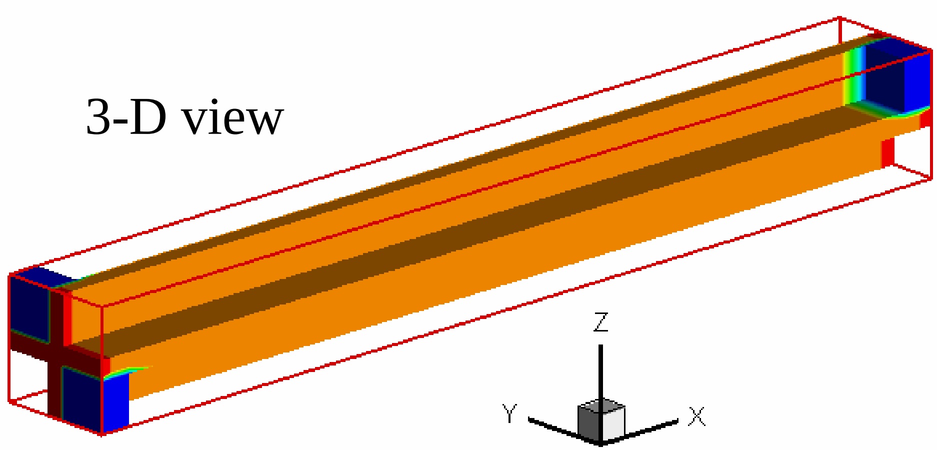


Side View



Cross-section View

3-D view



Conservation Equations

Continuity equation:

$$\frac{1}{\beta}\frac{\partial}{\partial t}(\beta\rho)+\frac{1}{\beta}\frac{\partial}{\partial x_i}(\beta\rho u_i)=\dot{m}'''$$

Momentum equations:

$$\frac{1}{\beta}\frac{\partial}{\partial t}(\beta\rho u_k)+\frac{1}{\beta}\frac{\partial}{\partial x_i}(\beta\rho u_i u_k)=\frac{1}{\beta}\frac{\partial}{\partial x_i}\left(\beta\mu\frac{\partial u_k}{\partial x_i}\right)-\frac{\partial p}{\partial x_k}+S_k$$

Energy equation (single temperature):

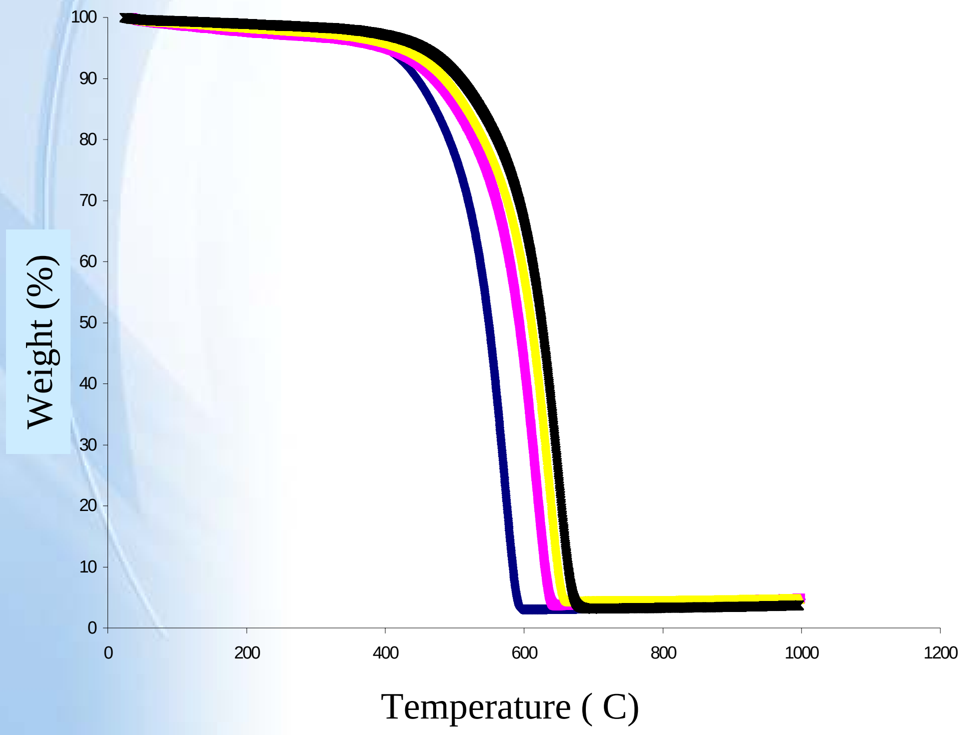
$$\frac{(\rho c_P)}{\beta}\frac{\partial T}{\partial t}+\frac{\beta\rho c_{P,f}}{\beta}u_i\frac{\partial T}{\partial x_i}=\frac{1}{\beta}\frac{\partial}{\partial x_i}\left(k_{eff}\frac{\partial T}{\partial x_i}\right)+S_H$$

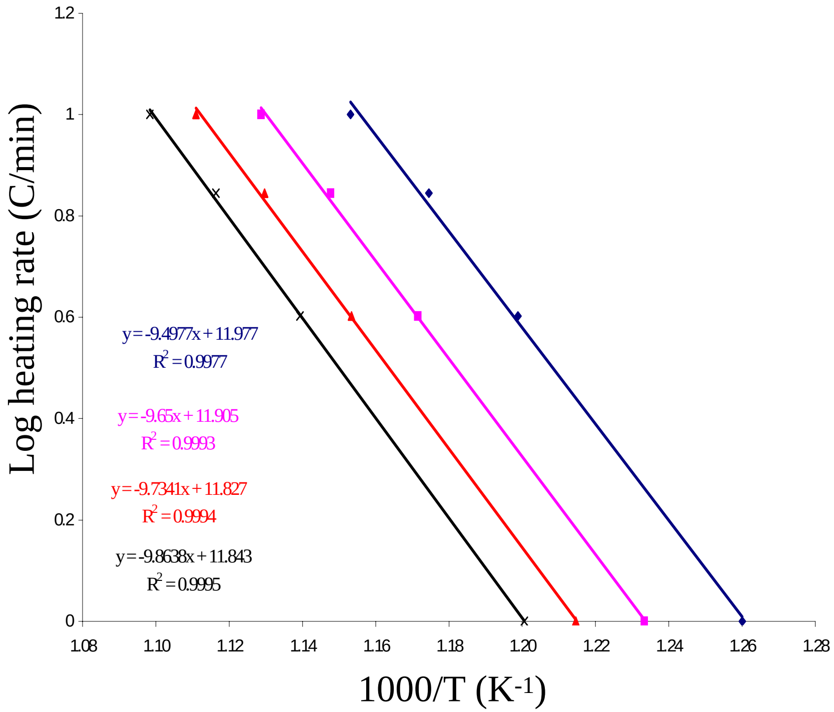
Species continuity equation:

$$\frac{1}{\beta}\frac{\partial(\beta\rho Y)}{\partial t}+\frac{1}{\beta}\frac{\partial(\beta\rho u_i Y)}{\partial x_i}=\frac{1}{\beta}\frac{\partial}{\partial x_i}\left(\beta\rho D\frac{\partial Y}{\partial x_i}\right)+S$$

Required Model Input:

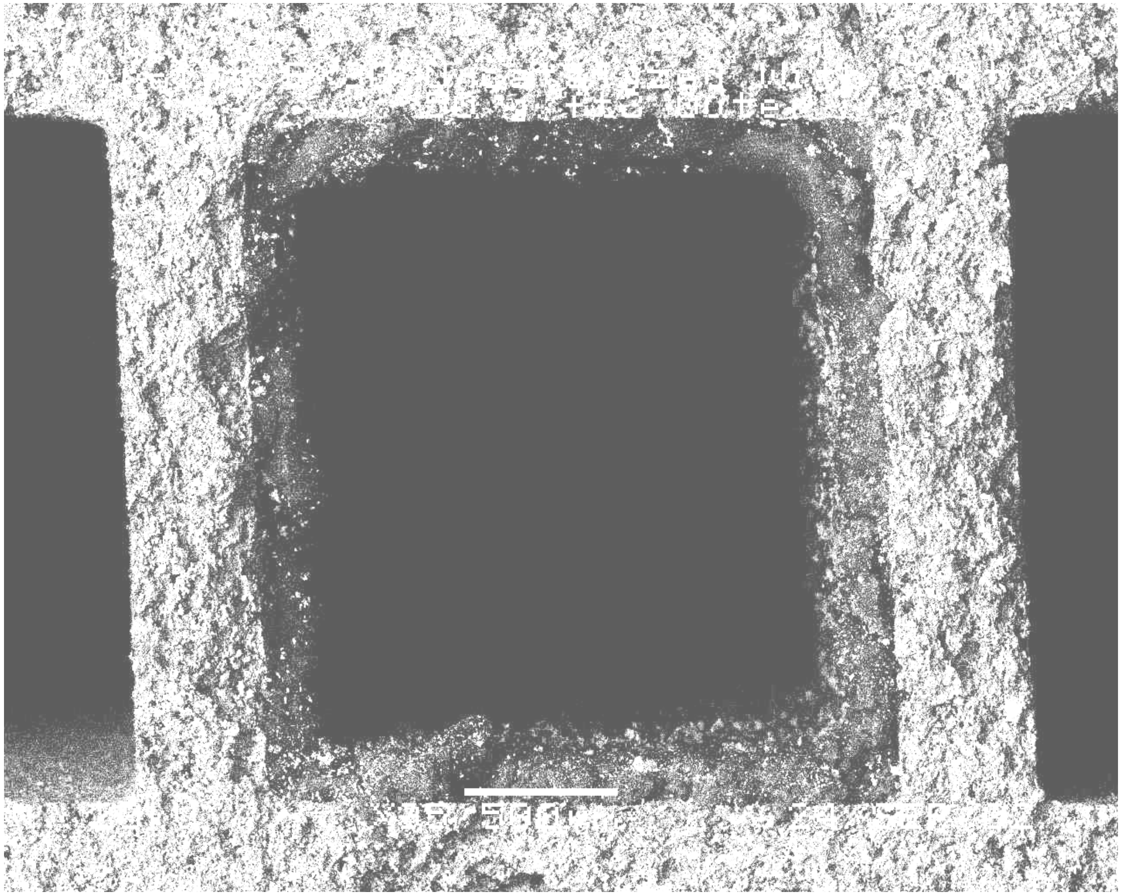
Soot Reaction Kinetics by TGA



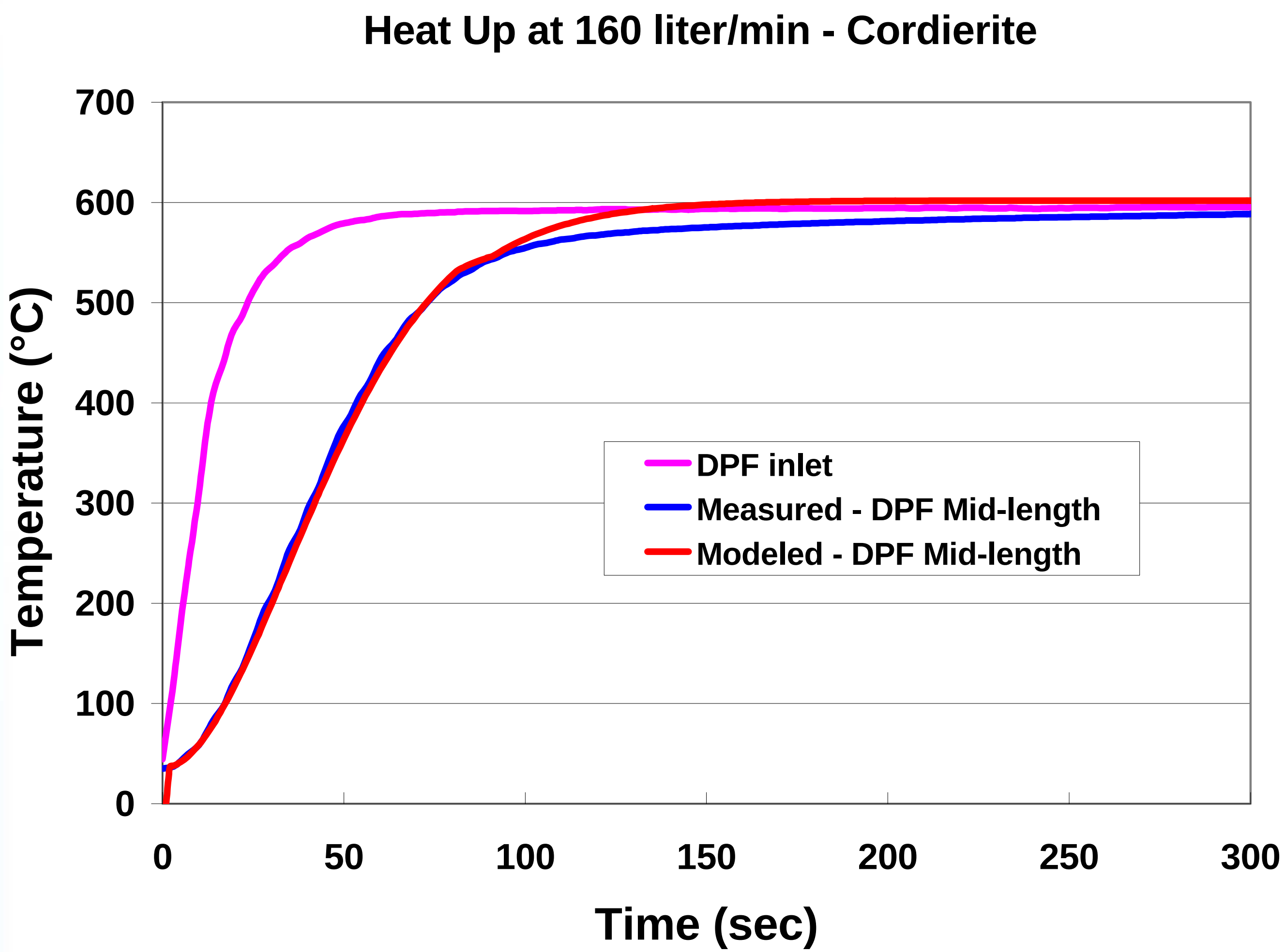


Donaldson.

Required Model Input:
Soot Cake Shape and Porosity by SEM

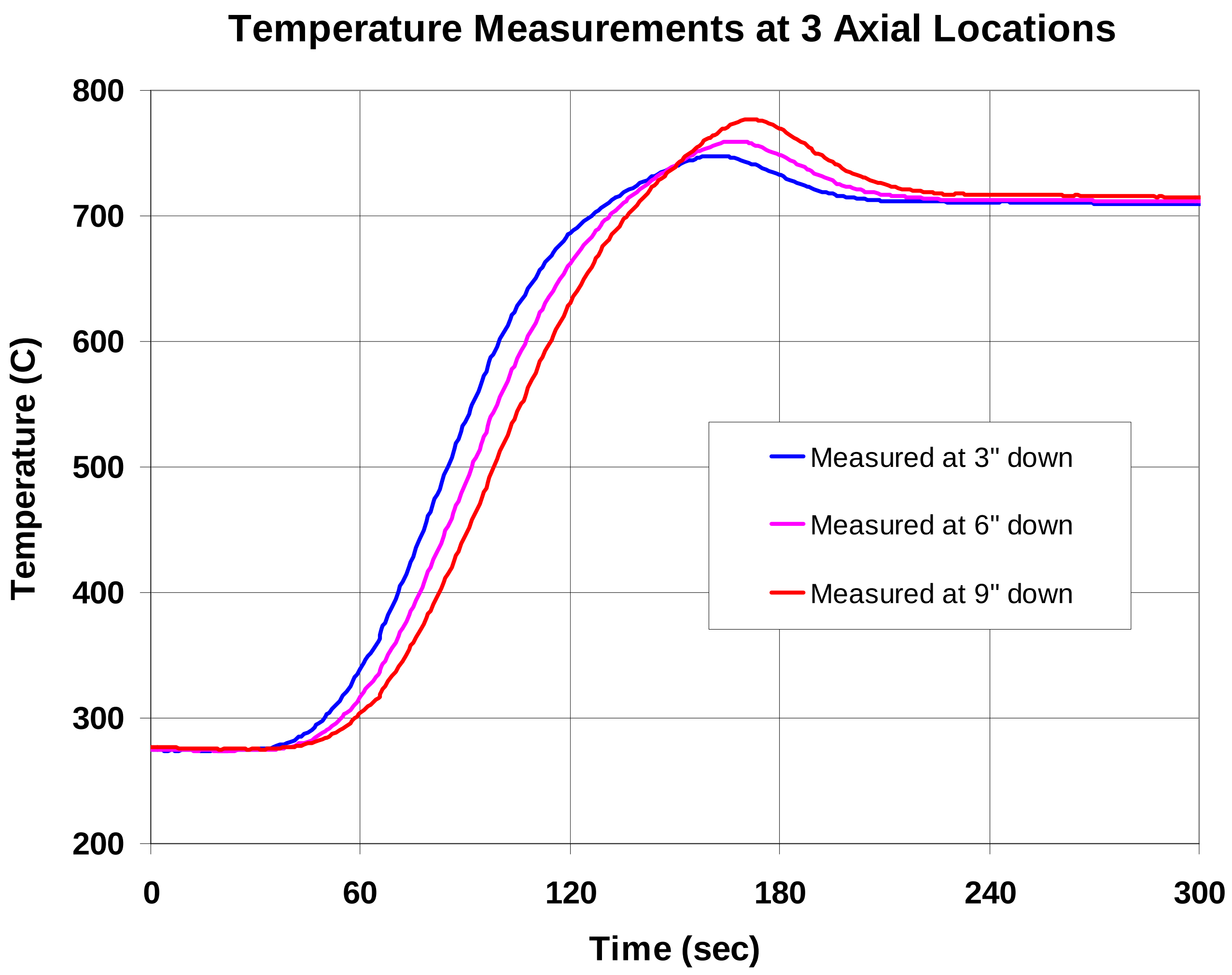


Model Validation:
Step 1. Heat-up w/o Regeneration



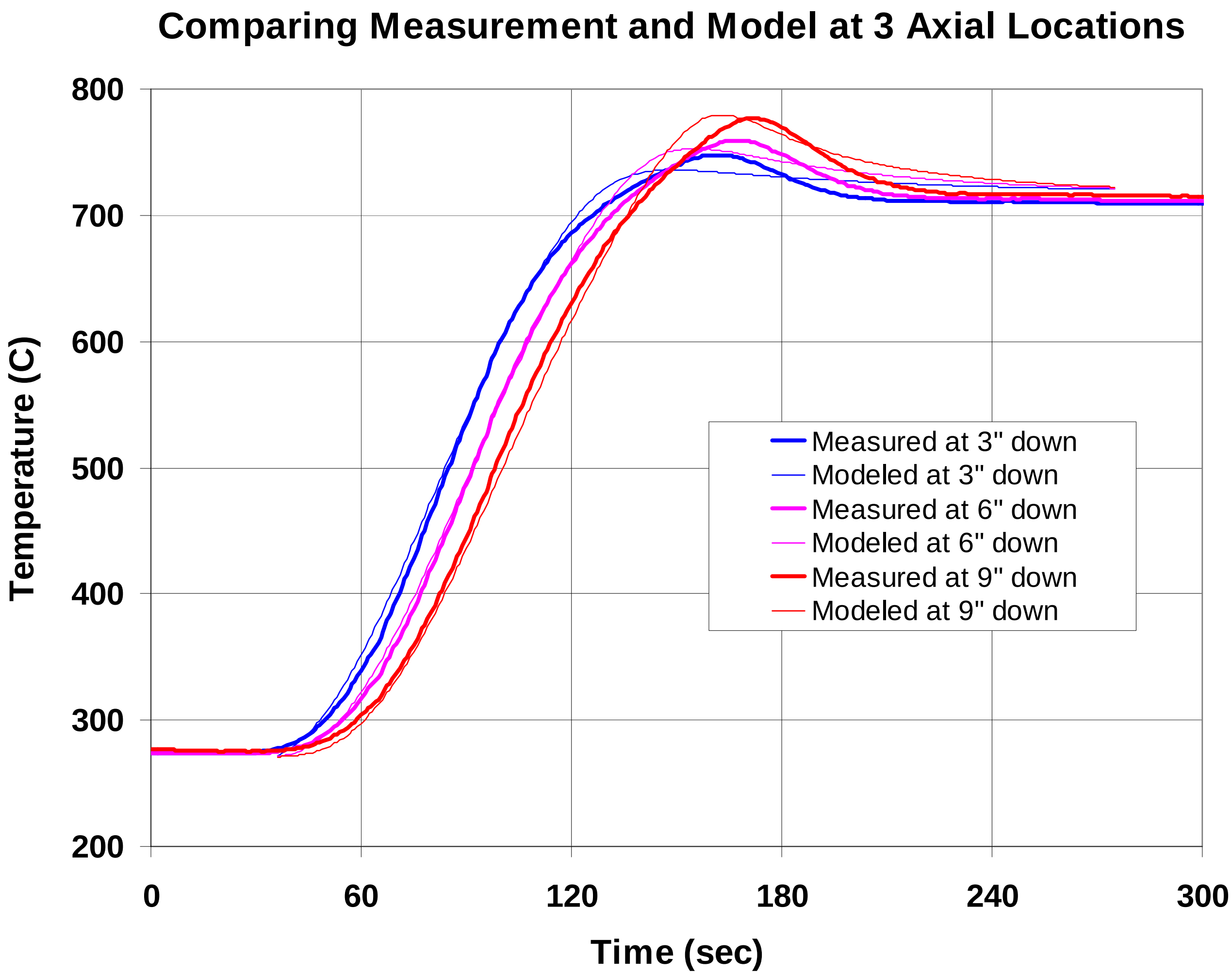
Donaldson.

Model Validation:
Step 2. Regeneration



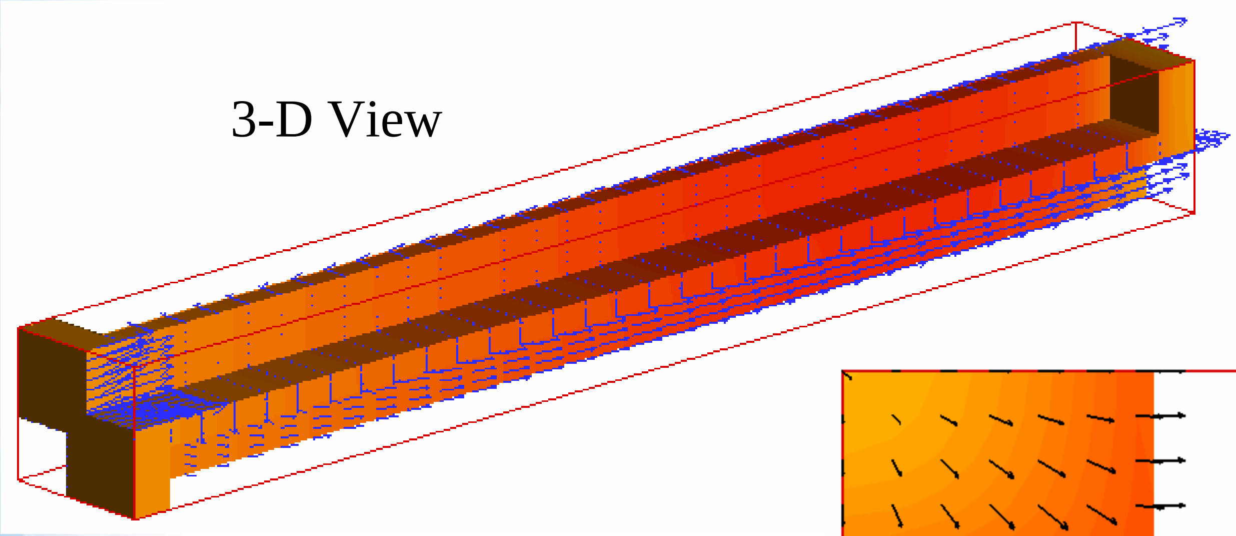
Donaldson.

Model Validation:
Step 2. Regeneration

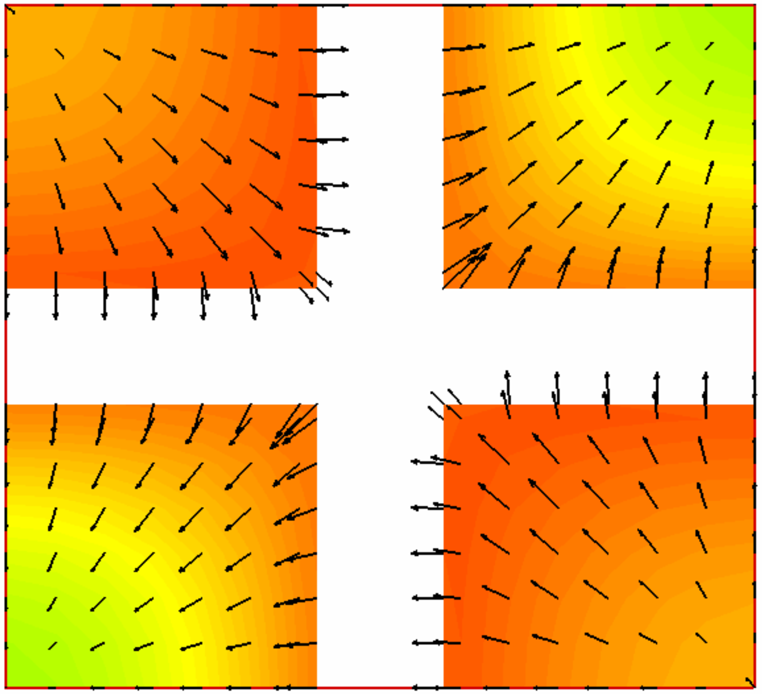


Donaldson.

Model Results:
Velocity and Temperature Fields

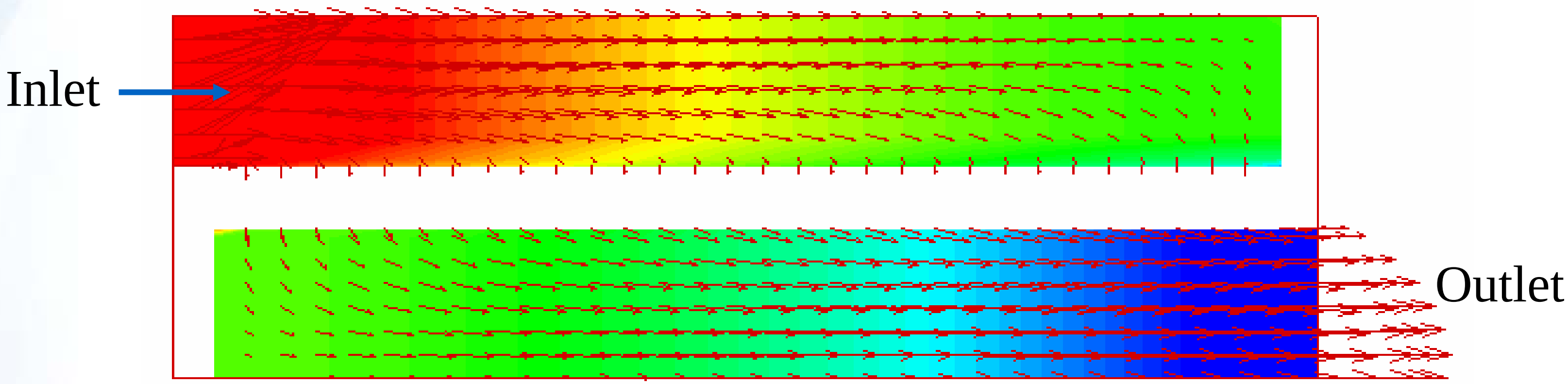

3-D View

Colored by Temperature

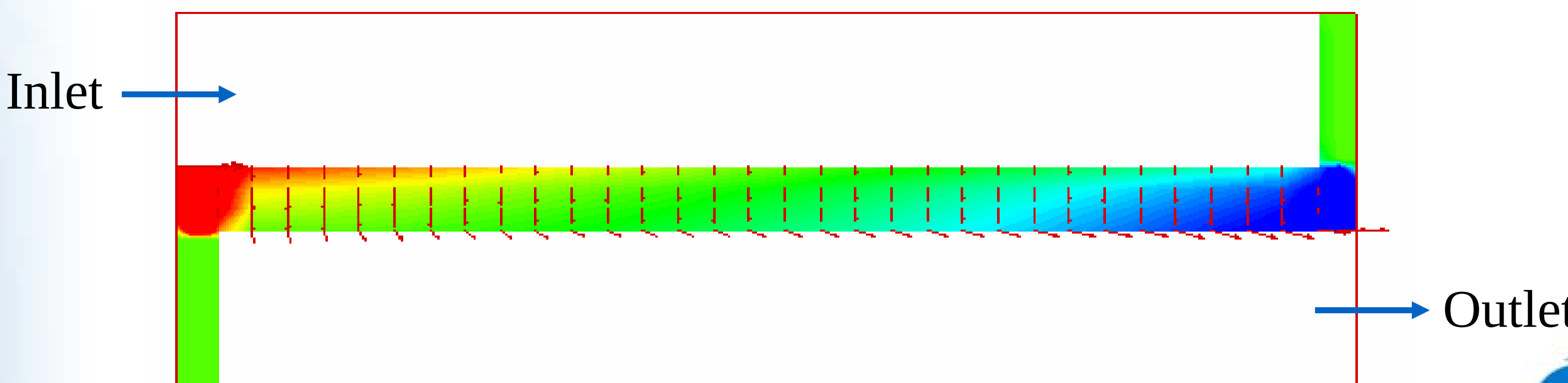

Cross-sectional View

Model Results:
Velocity and Pressure Field

Colored by Pressure

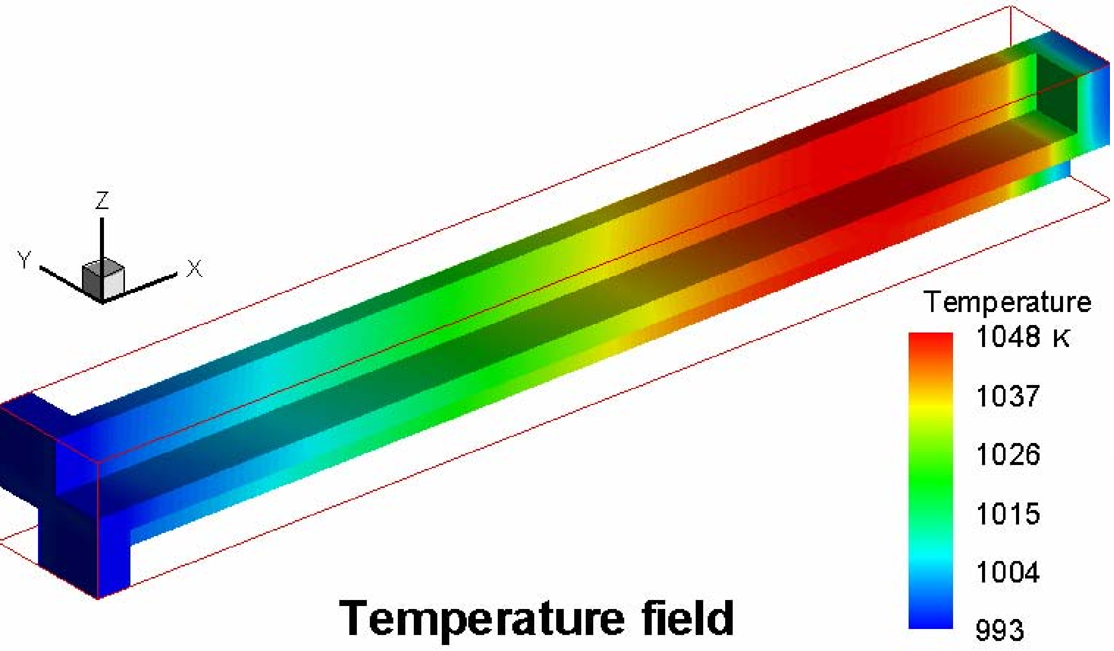


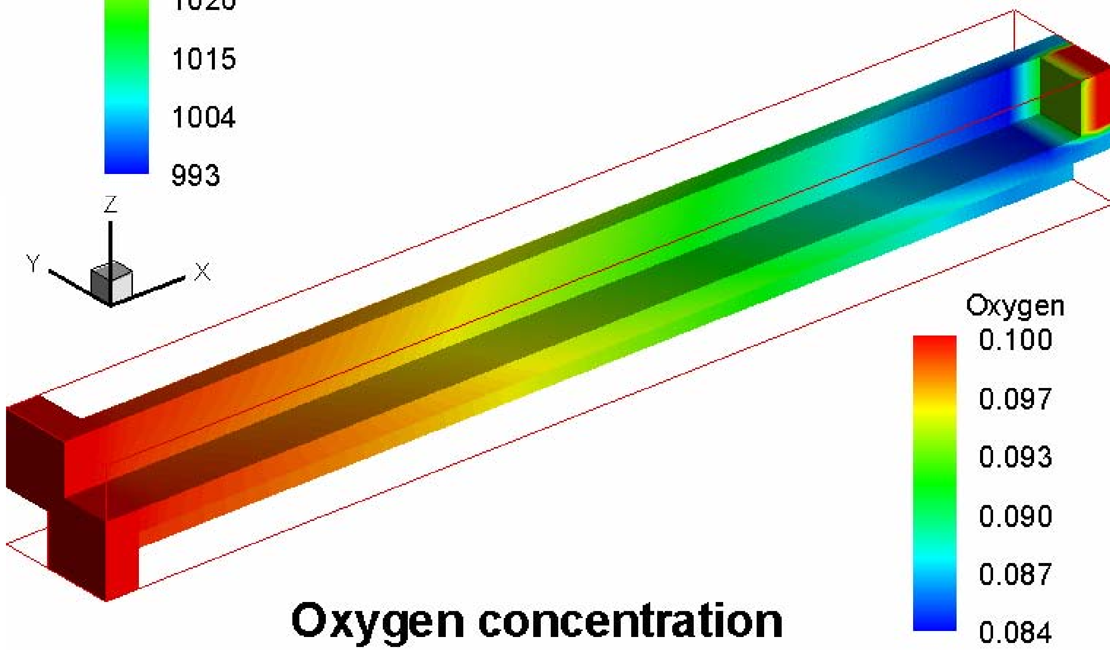
Side view – Gas Zone



Side view – Porous Zone

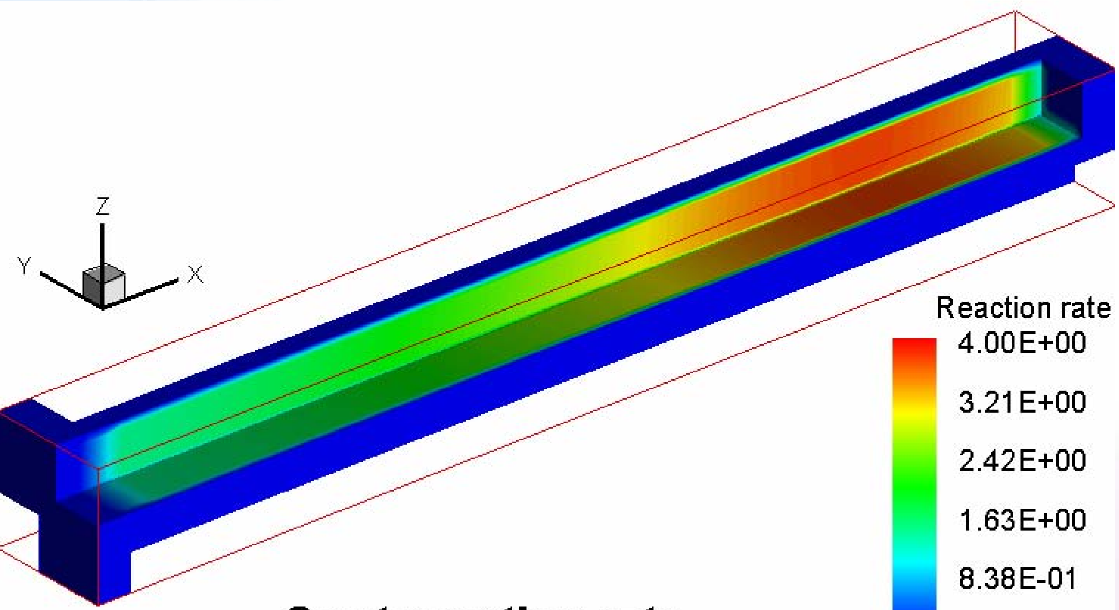
Model Results:
Temperature and Oxygen Distribution



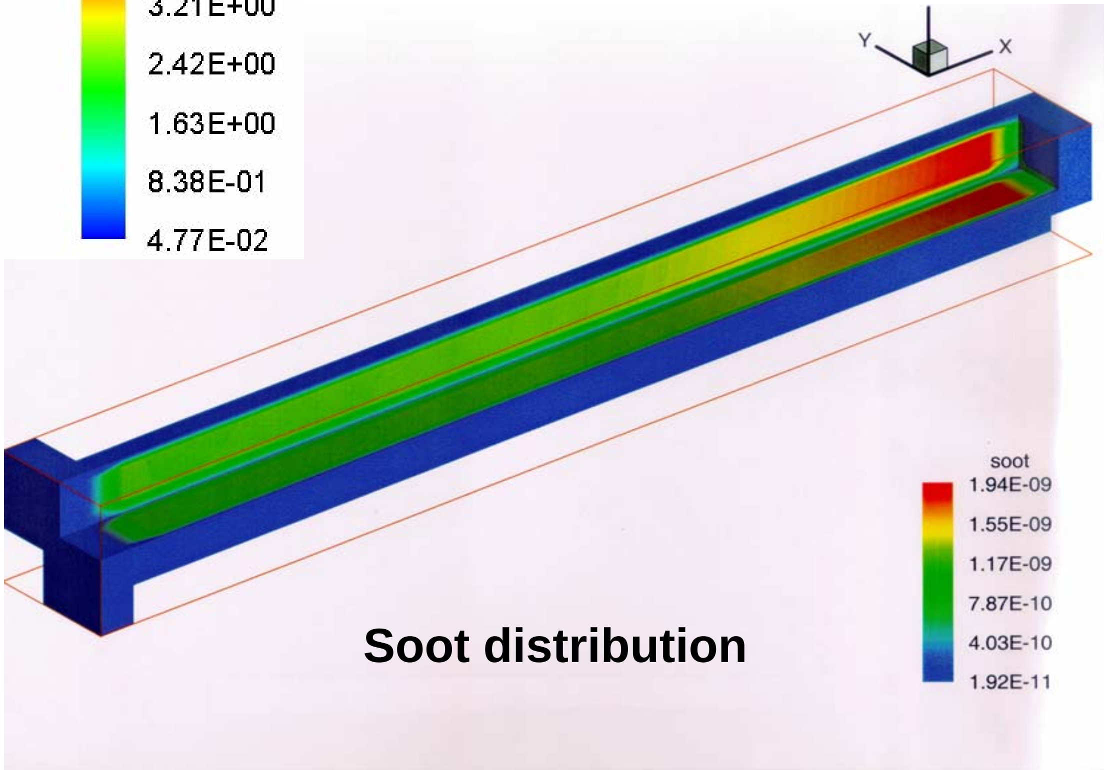


Donaldson.

Model Results:
Reaction Rate and Soot Distribution



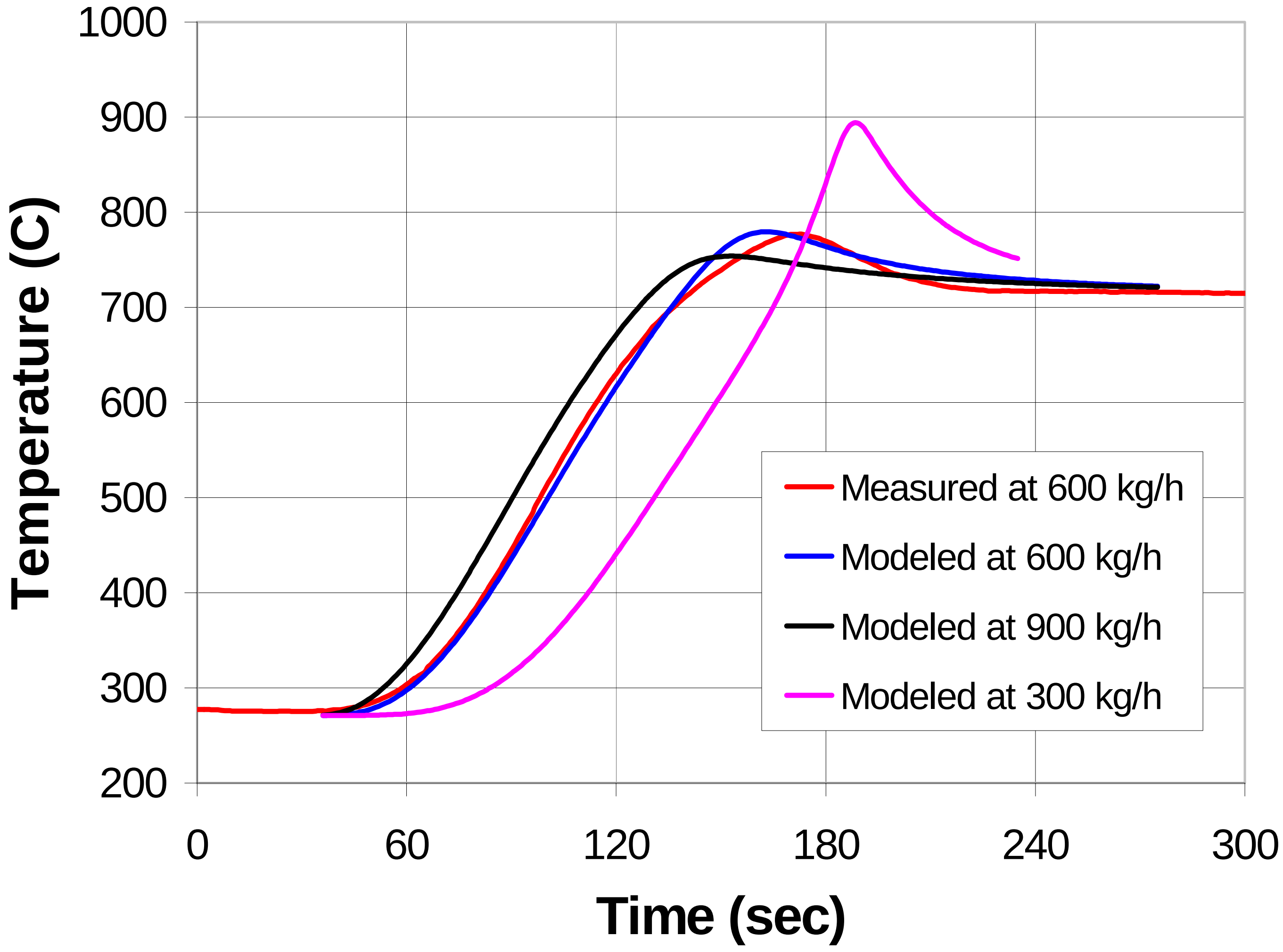
Soot reaction rate



Soot distribution

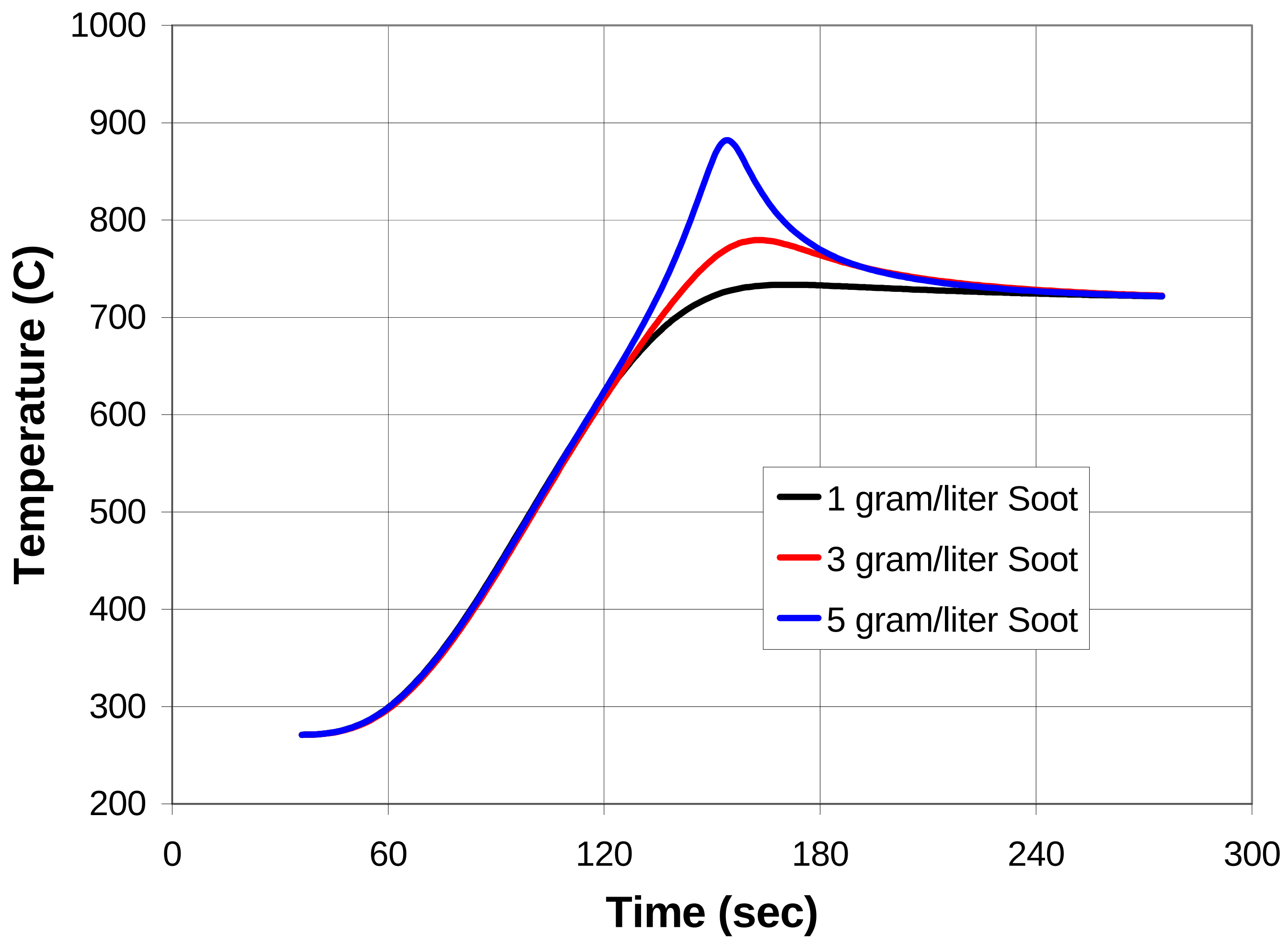
Parametric Study:

Effect of Flow Rate



Donaldson.

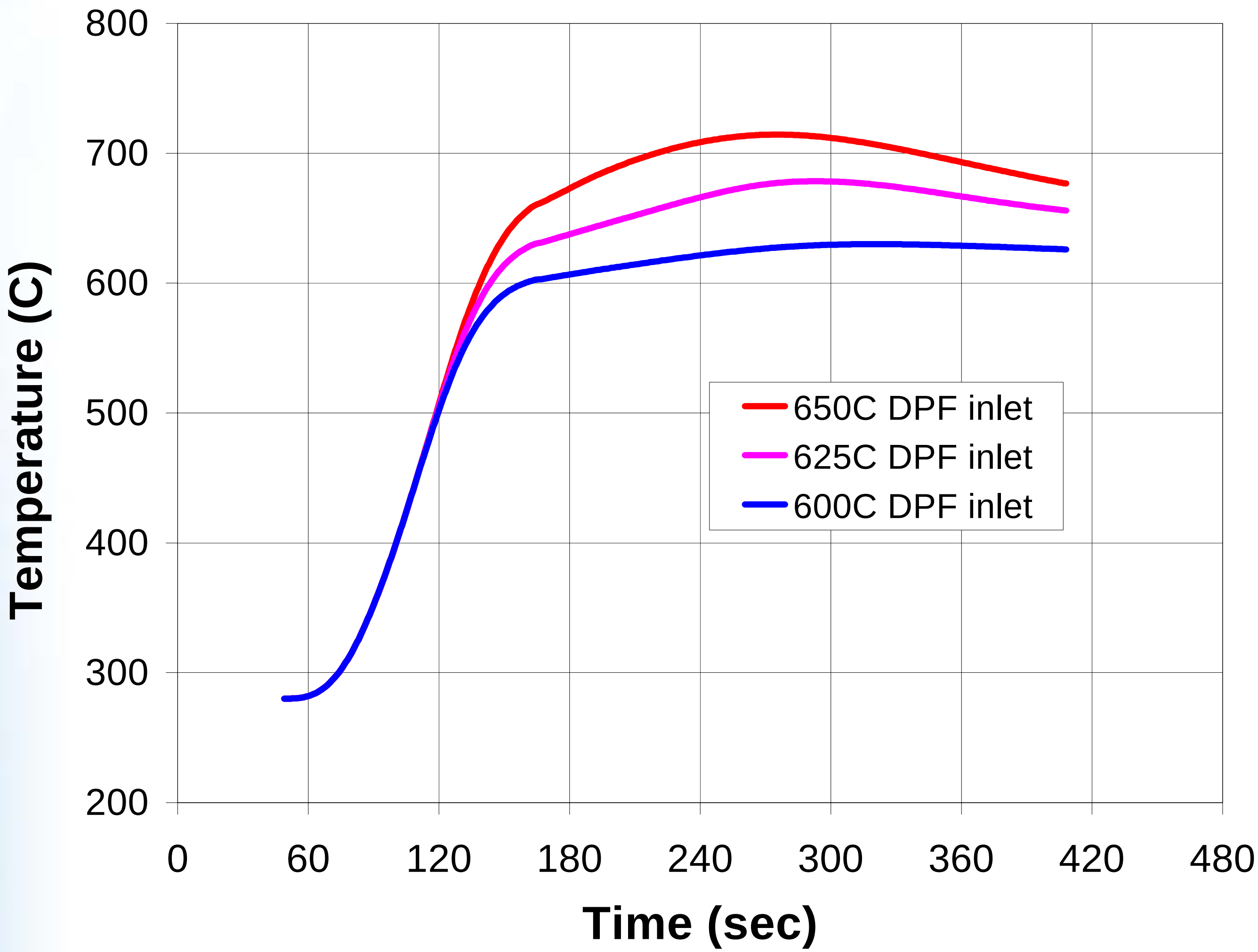
Parametric Study:
Effect of Soot Loading



Donaldson.

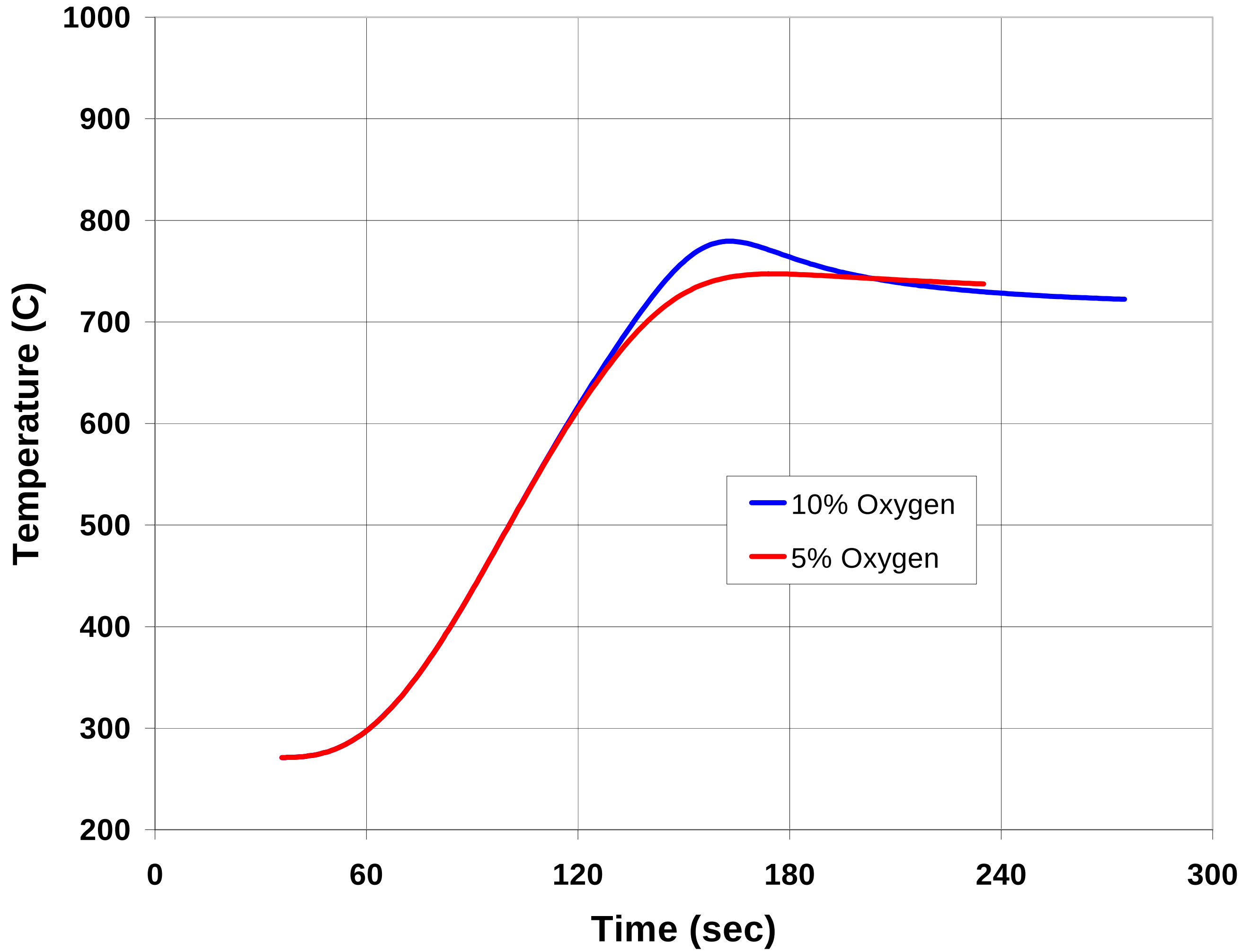
Parametric Study:

Effect of DPF Inlet Temperature



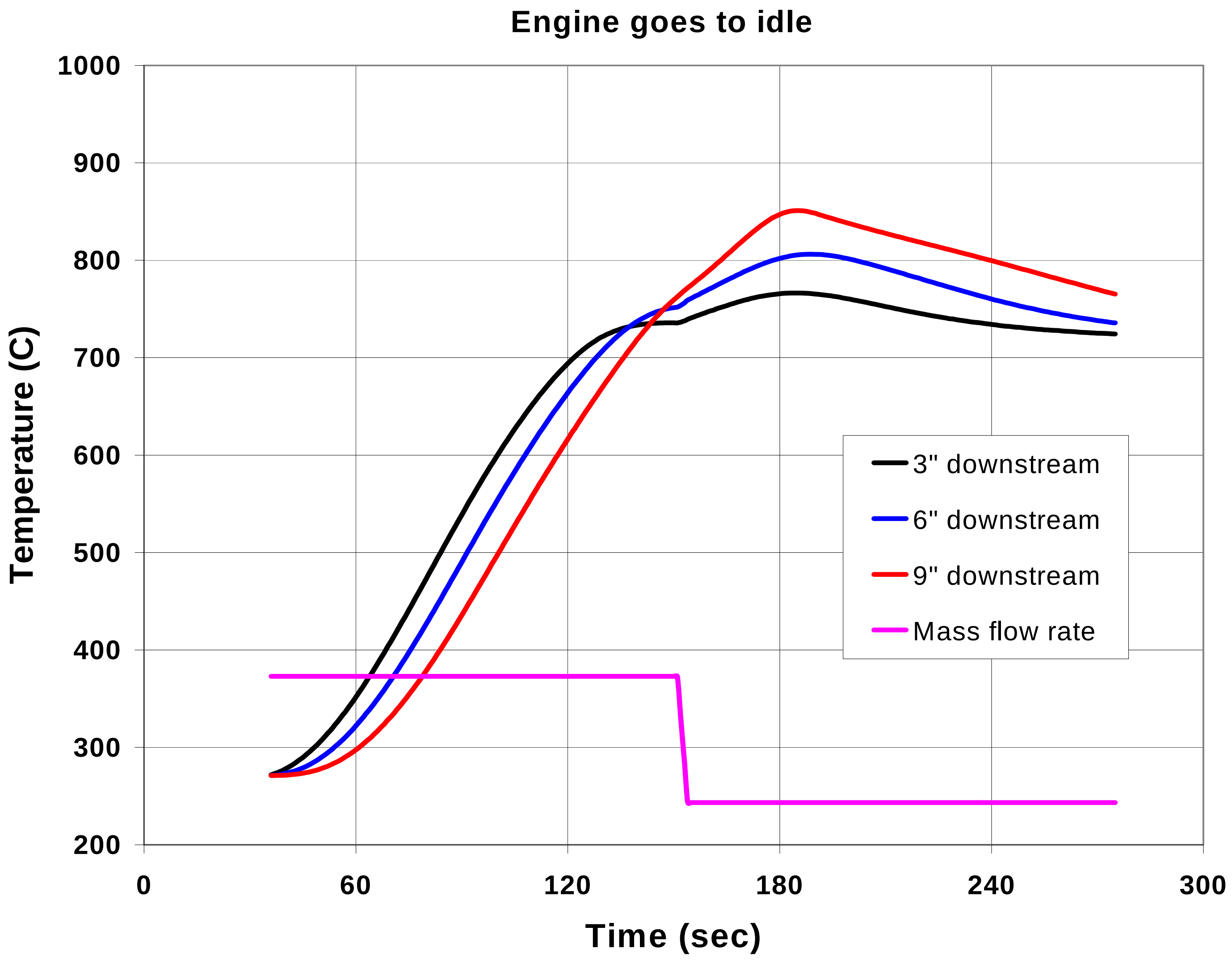
Donaldson.

Parametric Study:
Effect of Oxygen



Donaldson.

What-If Study:
Runaway Regeneration?



Summary

- A new regeneration model was developed and validated
- Features include: (1) 3-D; (2) A porous model; and (3) Generic equations solved
- The model provides detailed prediction of spatial and temporal distributions of key parameters such as temperature, as well as regeneration efficiency
- The model was shown to be effective in parametric and what-if studies
- A good model is useful in the design and operation of DPF systems, hence shortening development cycle