Experimental and Numerical Study of Flame Spread in the Parallel Panel Geometry

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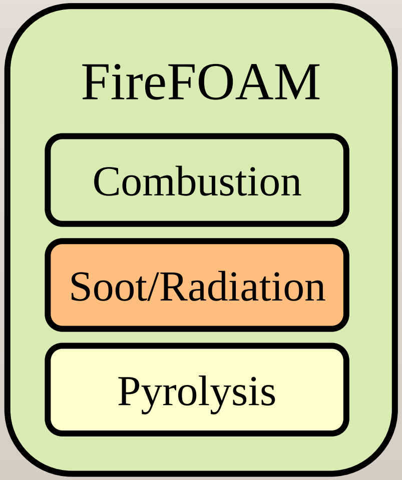
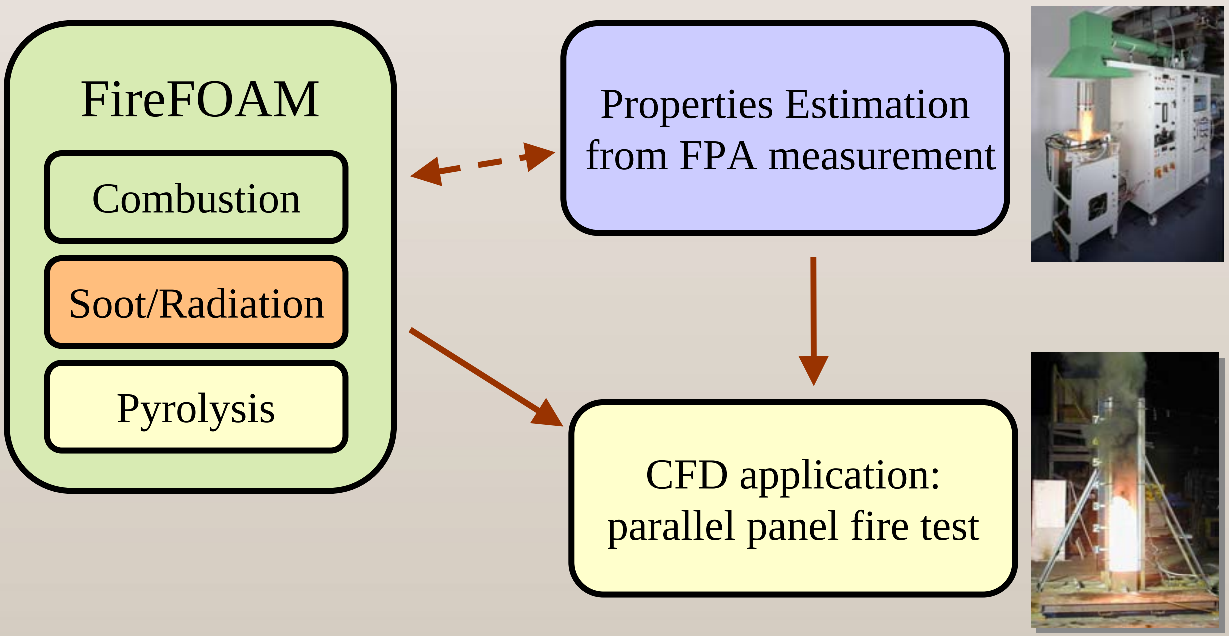
Background

- FM Global fire modeling research program
  - To develop CFD fire modeling capability for large-scale fires including fire growth and extinguishment, which will help FM Global to reduce the number of required large-scale tests
  - FireFOAM (http://code.google.com/p/firefoam-dev)
    - LES solver based on OpenFOAM
      - Basic models for fire spread
      - Unstructured mesh
      - Massive parallelization



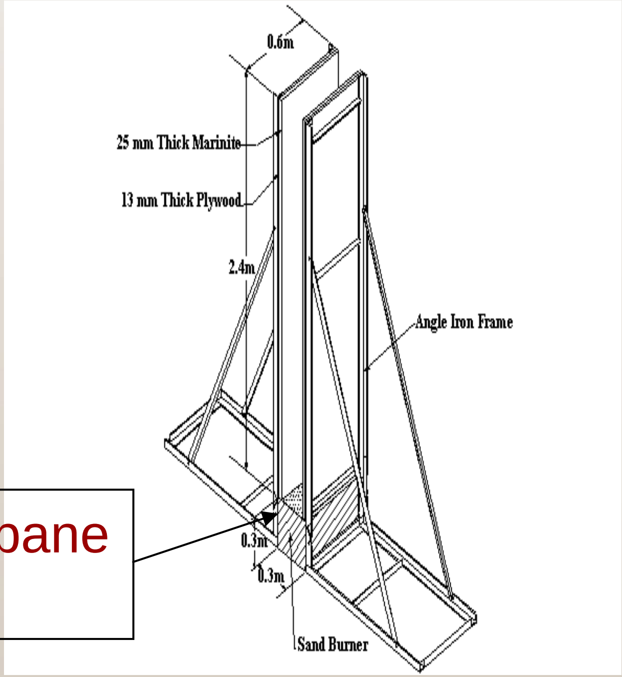
Objective

- Evaluate the overall performance of FireFOAM for flame spread in an intermediate scale fire
  - – Validation experiments (parallel panel)
- Evaluate the pyrolysis model, and effect property estimation approach in real fire test

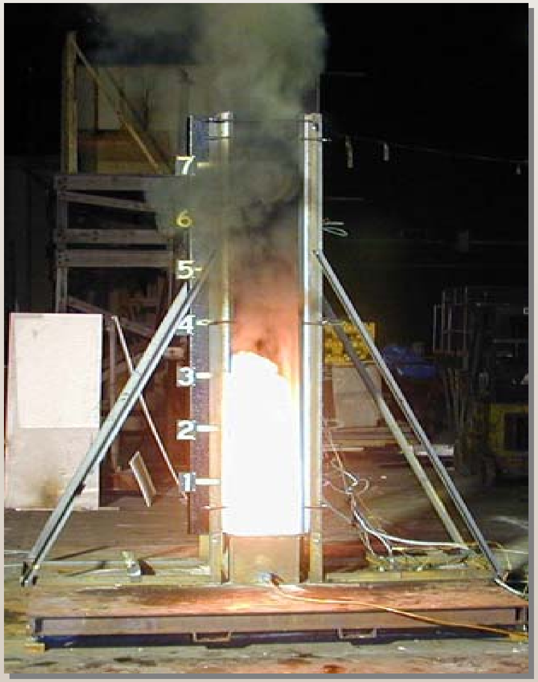


Parallel Panel Configuration

- Standard intermediate test for materials
- Heat flux similar as in large-scale fires
- 0.6 x 0.3 x 2.4 m



60 kW Propane burner

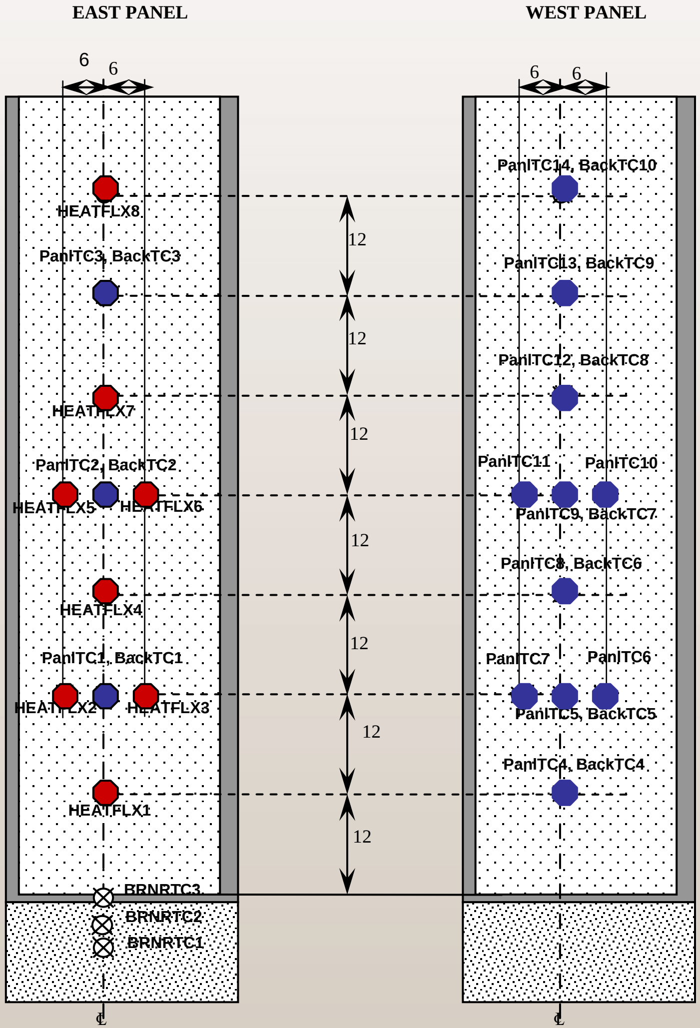


Experiments

- Three materials
  - PMMA (3.18mm)
  - Single-wall corrugated cardboard (3.8mm)
  - CPVC (chlorinated polyvinyl chloride)
- Repeat tests
  - 3 repeat tests for PMMA and corrugated
  - Performed in two different time slots
    - July, November 2009

Corrugated

Instrumentation



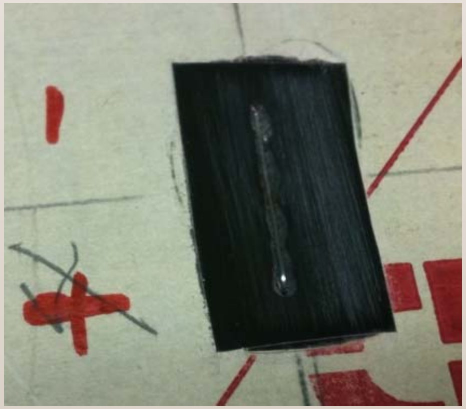
Measurements

- Heat release rates (5 MW FPC)
  - CO-CO_2 generation calorimetry
  - O_2 consumption calorimetery
- Mass loss rate
  - Load cell
- Surface temperatures
  - K-Type thermocouples, 0.8 mm D butt-welded
- Heat fluxes
  - Schmidt-Boelter gage 12.7 mm D

Experimental Challenges

- Exfoliation, warp
  - Thermocouple lost contact
  - View of heat flux gages blocked





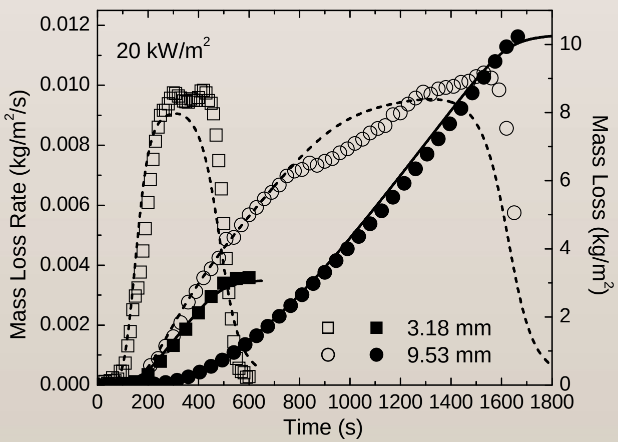

Pyrolysis Model

- 1D, single step, Arrhenius chemistry

$$\frac{\partial}{\partial t}\left(\rho_s C p_s T\right) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial \dot{q}_r''}{\partial x} + \dot{m}''' H_p \qquad \dot{m}''' = -\rho A \exp\left(\frac{-E_a}{RT}\right)$$

- Estimation of model properties

FPA measurement



Model property optimization (SCE)

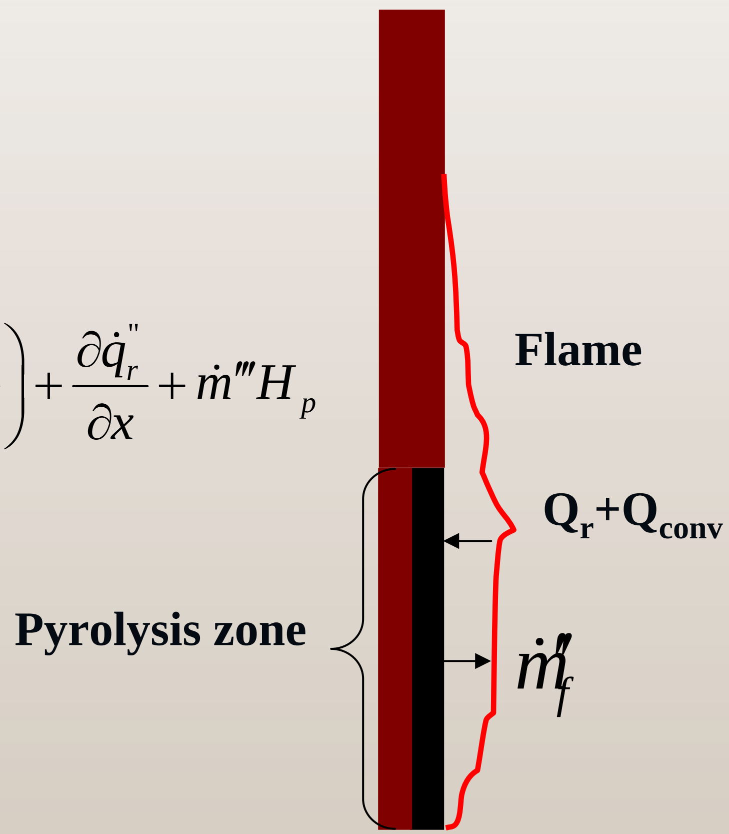
consistency

CFD inputs

Pyrolysis Model: Implementation

- Implemented as boundary conditions
  - *T*, *U*, *Z*

$$\frac{\partial}{\partial t}\left(\rho_s C p_s T\right) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial \dot{q}_r''}{\partial x} + \dot{m}''' H_p$$

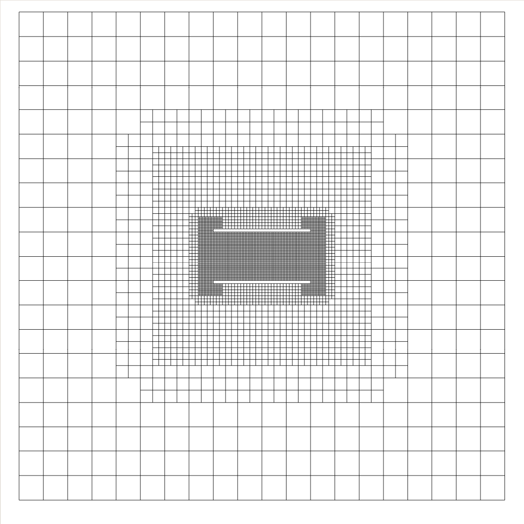


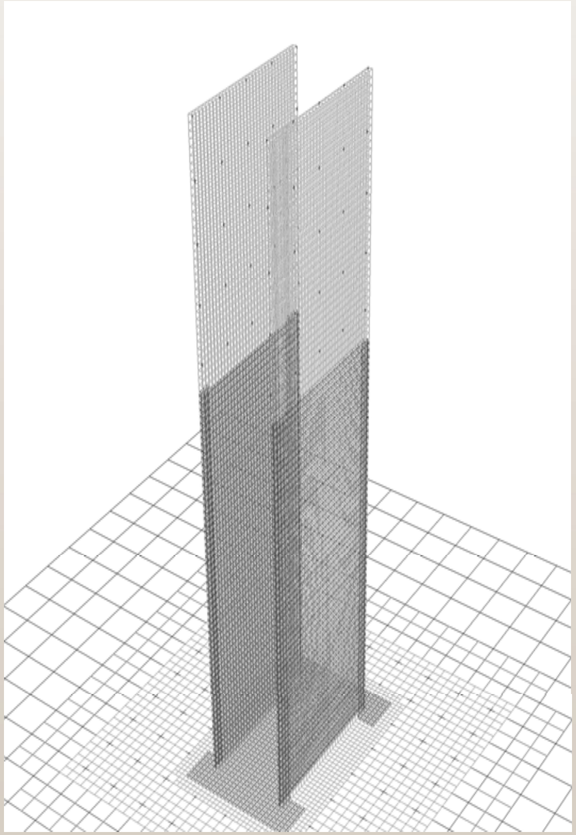
Computational Models: FireFOAM

- Combustion (Wang et. al. P8.3)
  - Infinite fast chemistry model
  - Beta PDF for SGS mixture fraction
- Soot and Radiation (Chatterjee et. al. P30.2)
  - Smoke point based flamelet model
  - Finite volume RTE solver
  - Optically thin, gray gas assumptions
  - 48 angles, solved every 100 time steps

Mesh

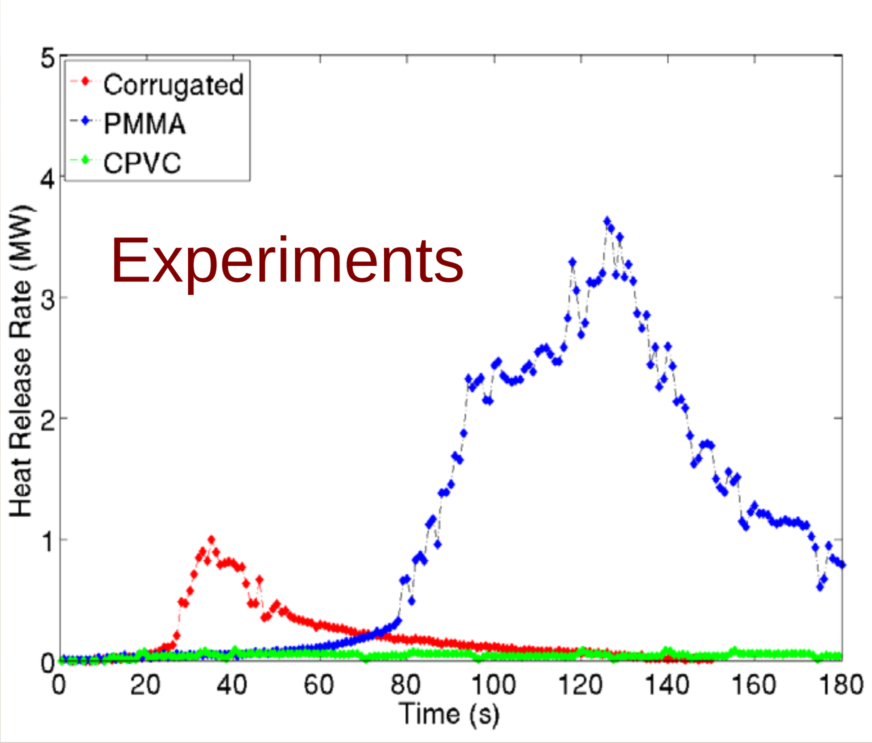
- Domain: 3m x 3m x 4.2m
- SnappyHexMesh: 527k cells
  - 5 refinement levels
  - 1cm x 1cm x 1.25cm
  - 70% cells in the finest region

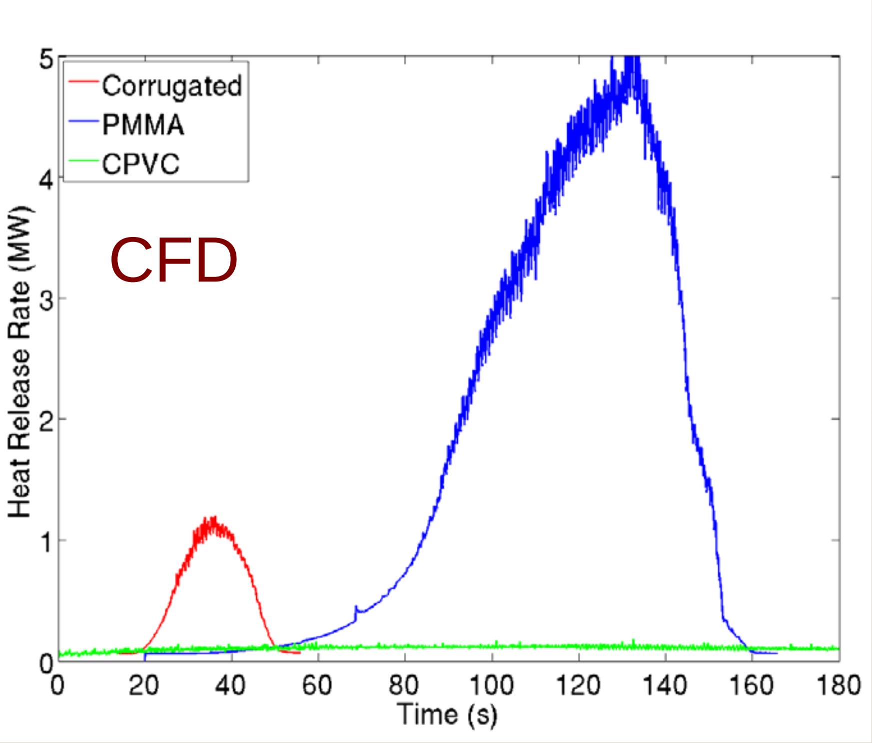




HRR of Three Materials

- Single-wall corrugated cardboard
- PMMA
- CPVC

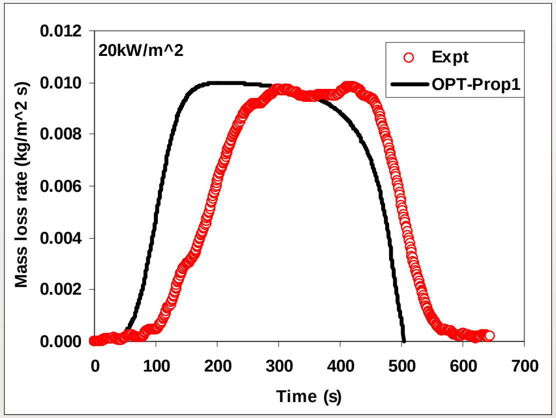


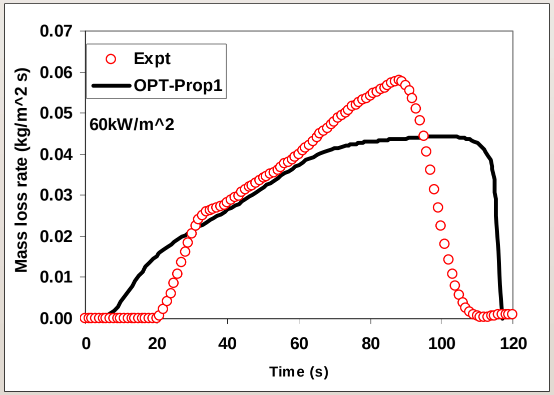


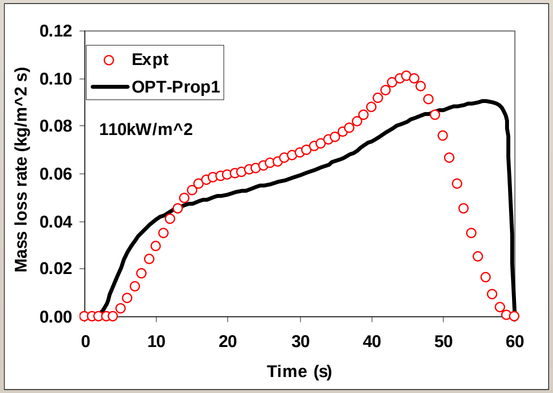
PMMA: Model Properties

– No in-depth radiation
– Adiabatic back boundary

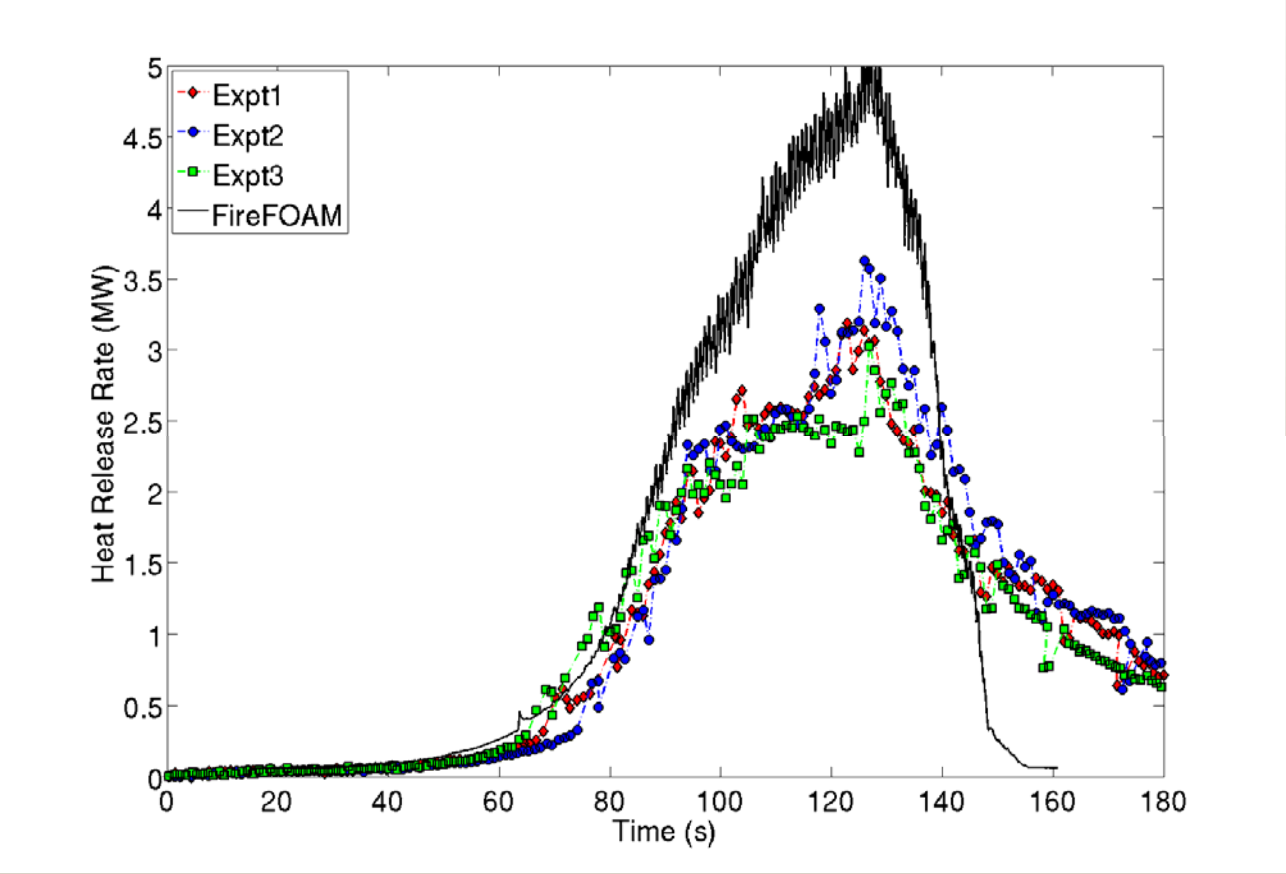
Property	Optimized value	Uncertainty
Thermal Conductivity (W/m K)	0.152	± 0.008
Density (kg/m^3)	1112.8	± 7
Specific Heat Capacity (J/kg K)	1462	± 33
Heat of Vaporization (J/kg)	8.22×10^5	$\pm 2.9 \times 10^4$
Emissivity	0.992	± 0.09
Pre-exponential Factor (1/s)	1.19×10^6	$\pm 1.5 \times 10^6$
Activation Energy (J/mol)	9.4×10^4	$\pm 6.6 \times 10^3$







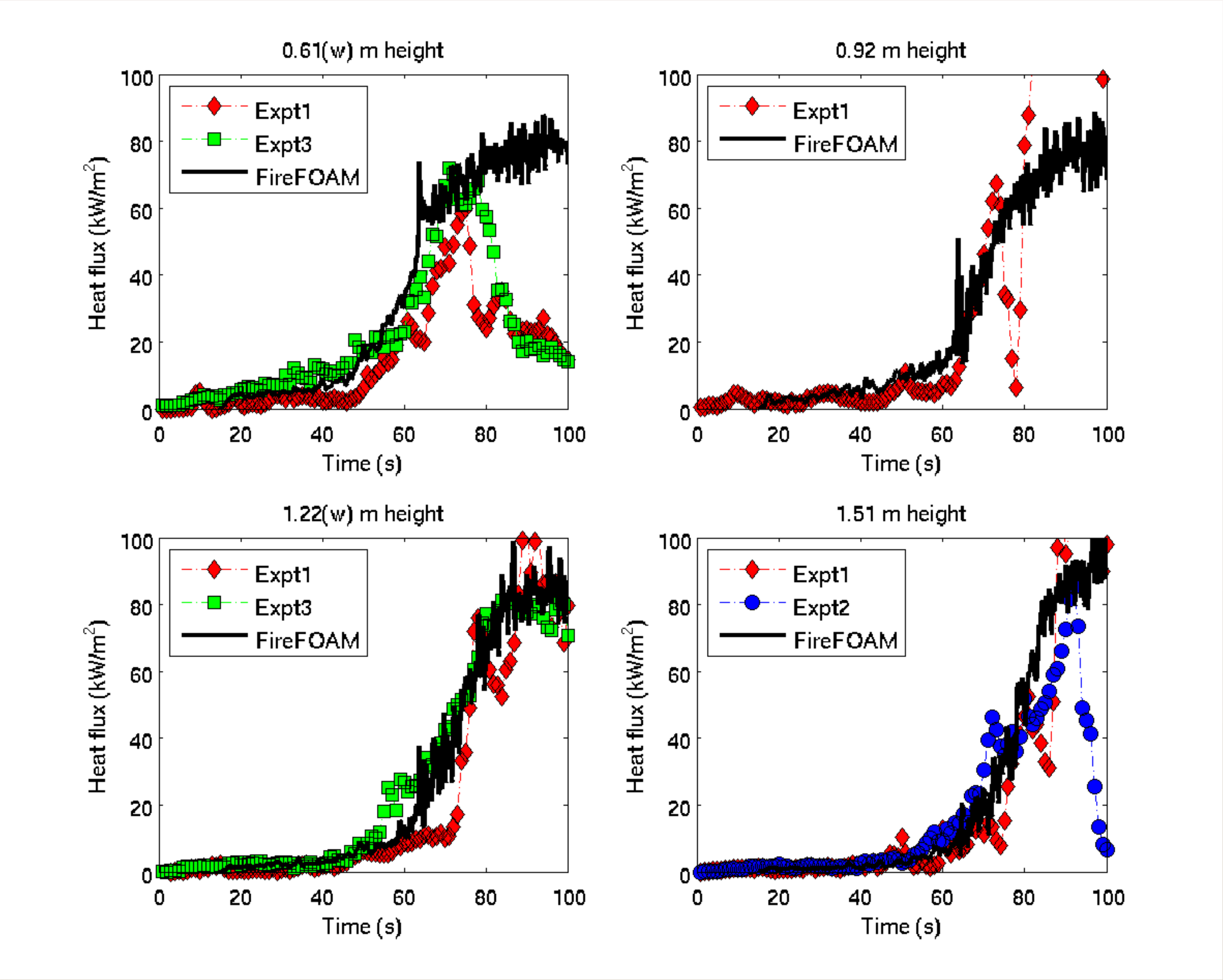
PMMA: Heat Release Rate



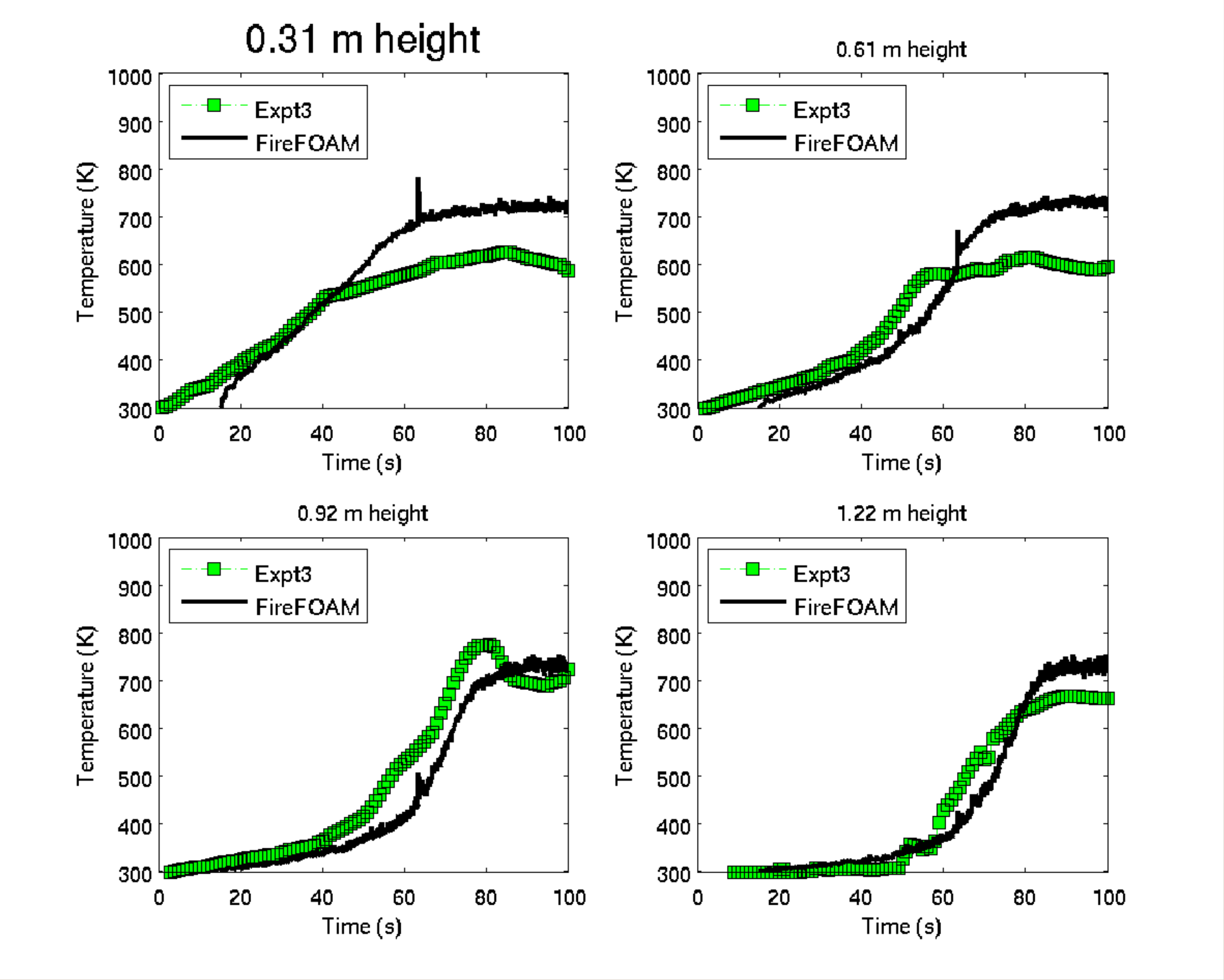
$HRR = \exp(b\Delta t)$; b_{expt} = 0.0798±0.006; b_{sim} = 0.084

Exponential growth rate observed between 60-90 seconds

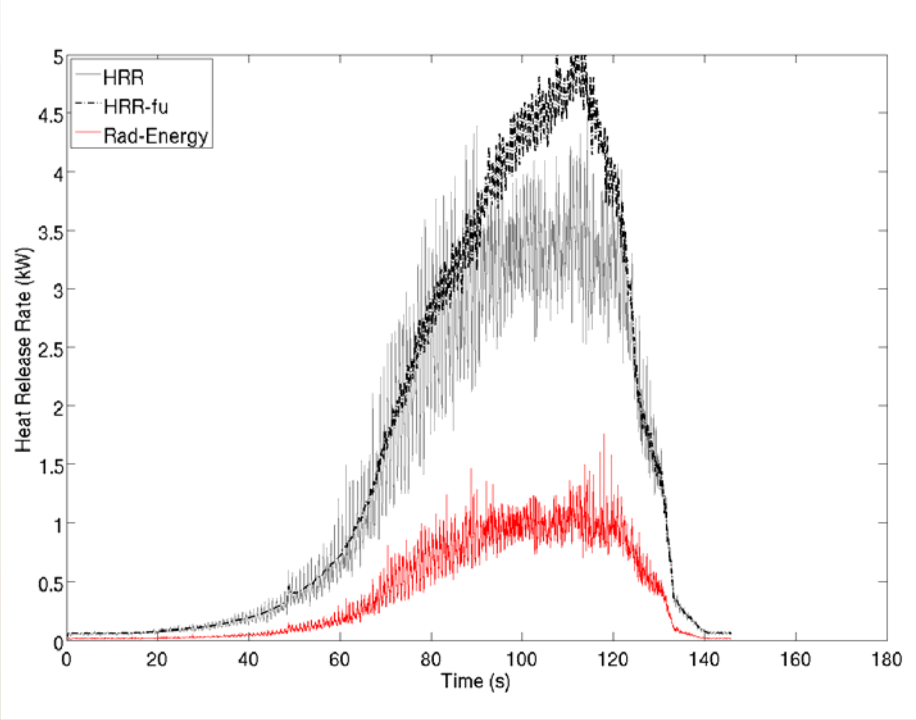
PMMA: Heat Flux

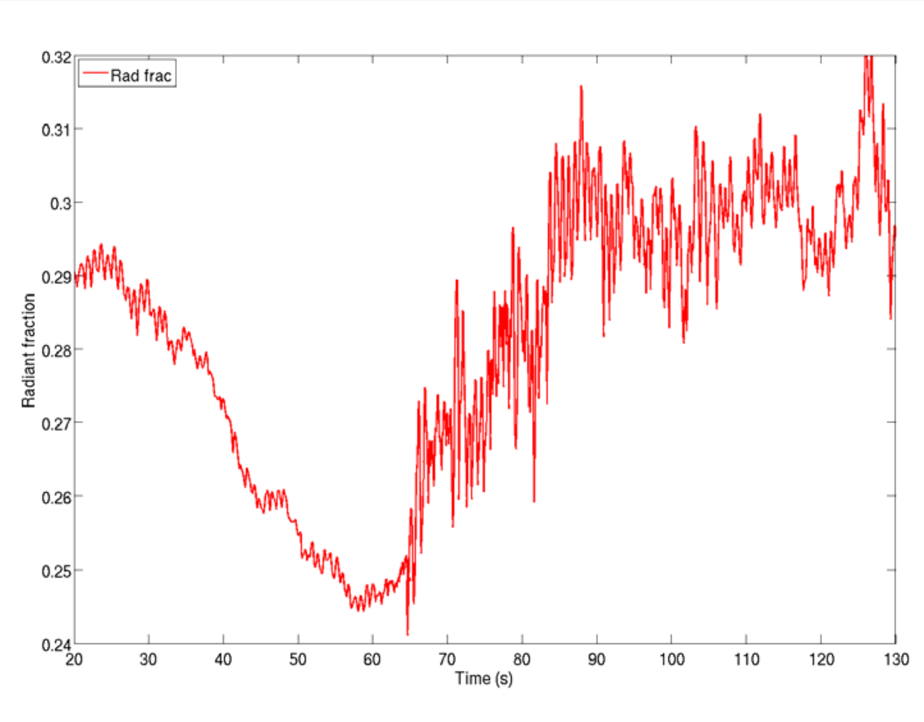


PMMA: Surface Temperature



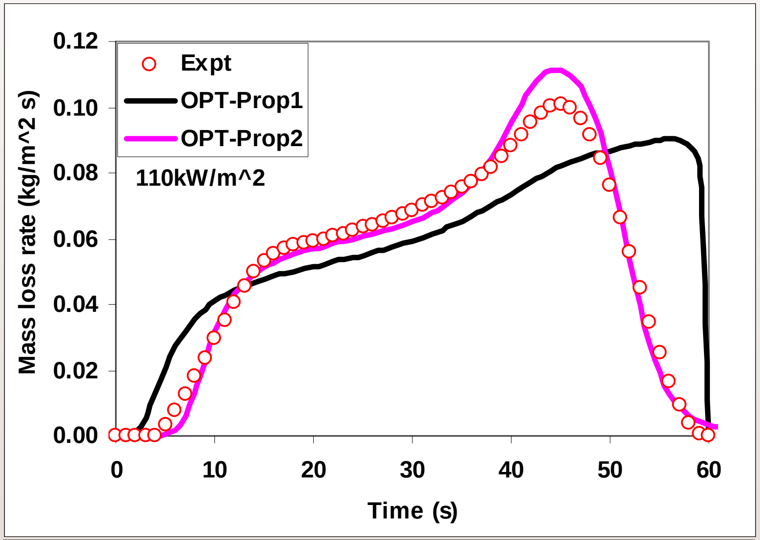
PMMA: Radiant Fraction

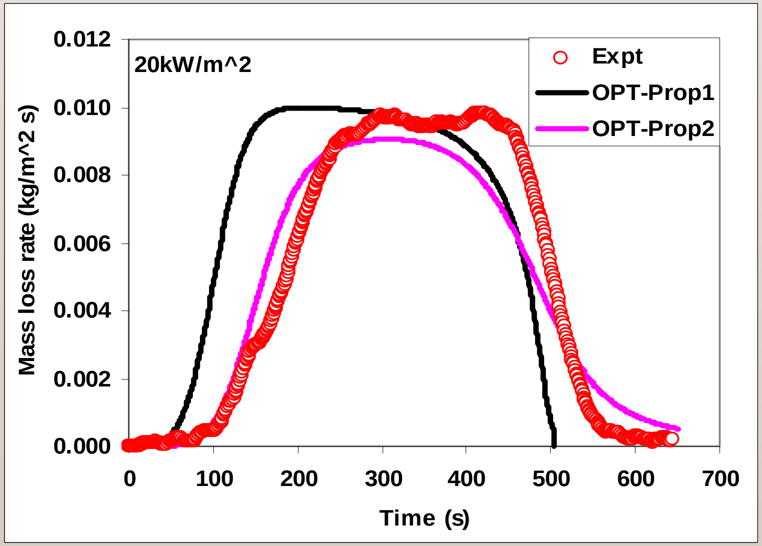


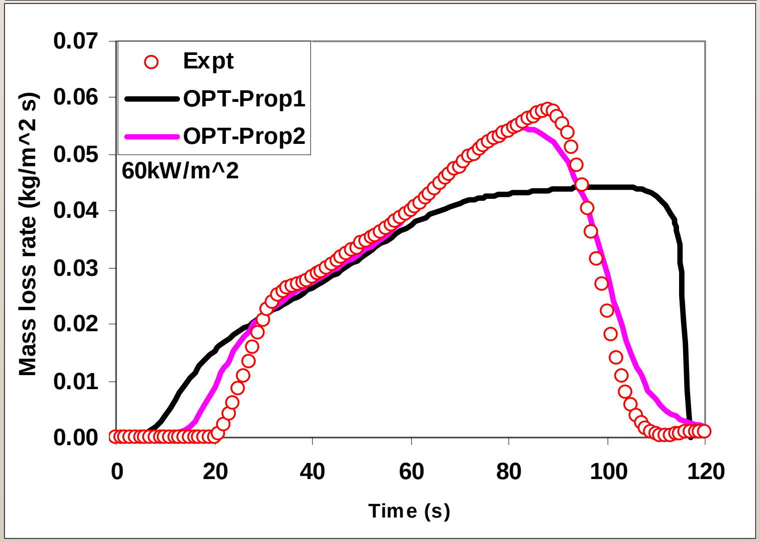


PMMA: Improved Model Properties

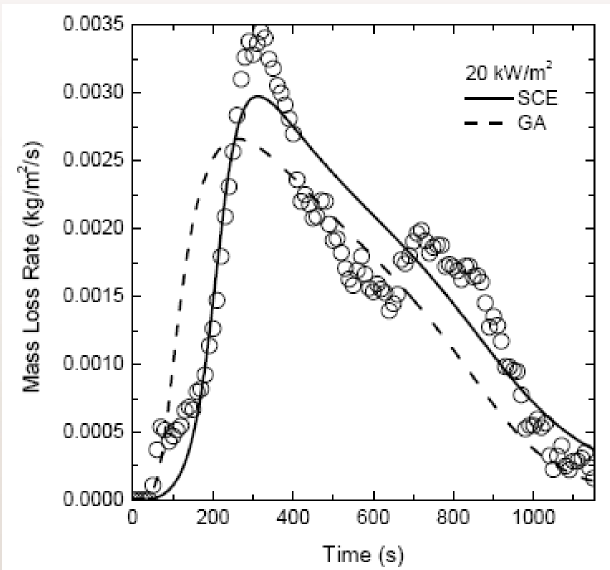
- Shuffled Complex Evolution (SCE) algorithm
- In-depth radiation
- Heat transfer to back boundary
- Cumulative mass loss included in objective function

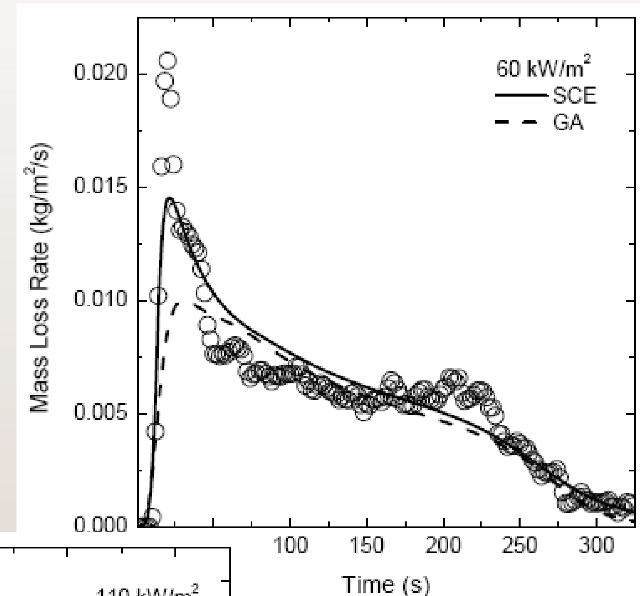


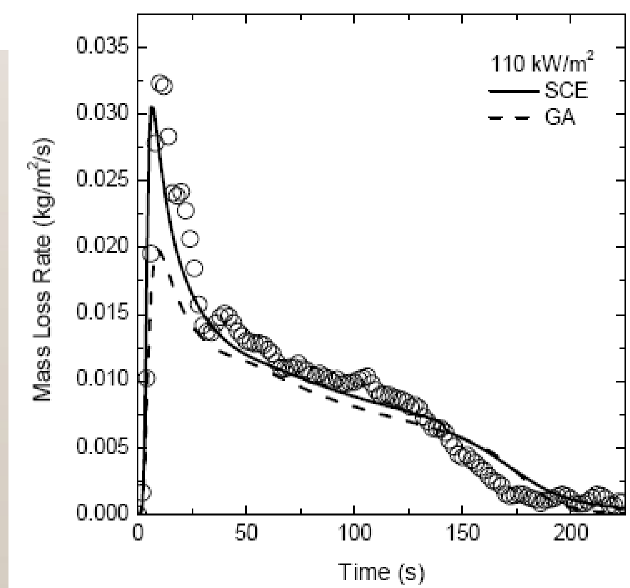




Corrugated: Sensitivity to Properties

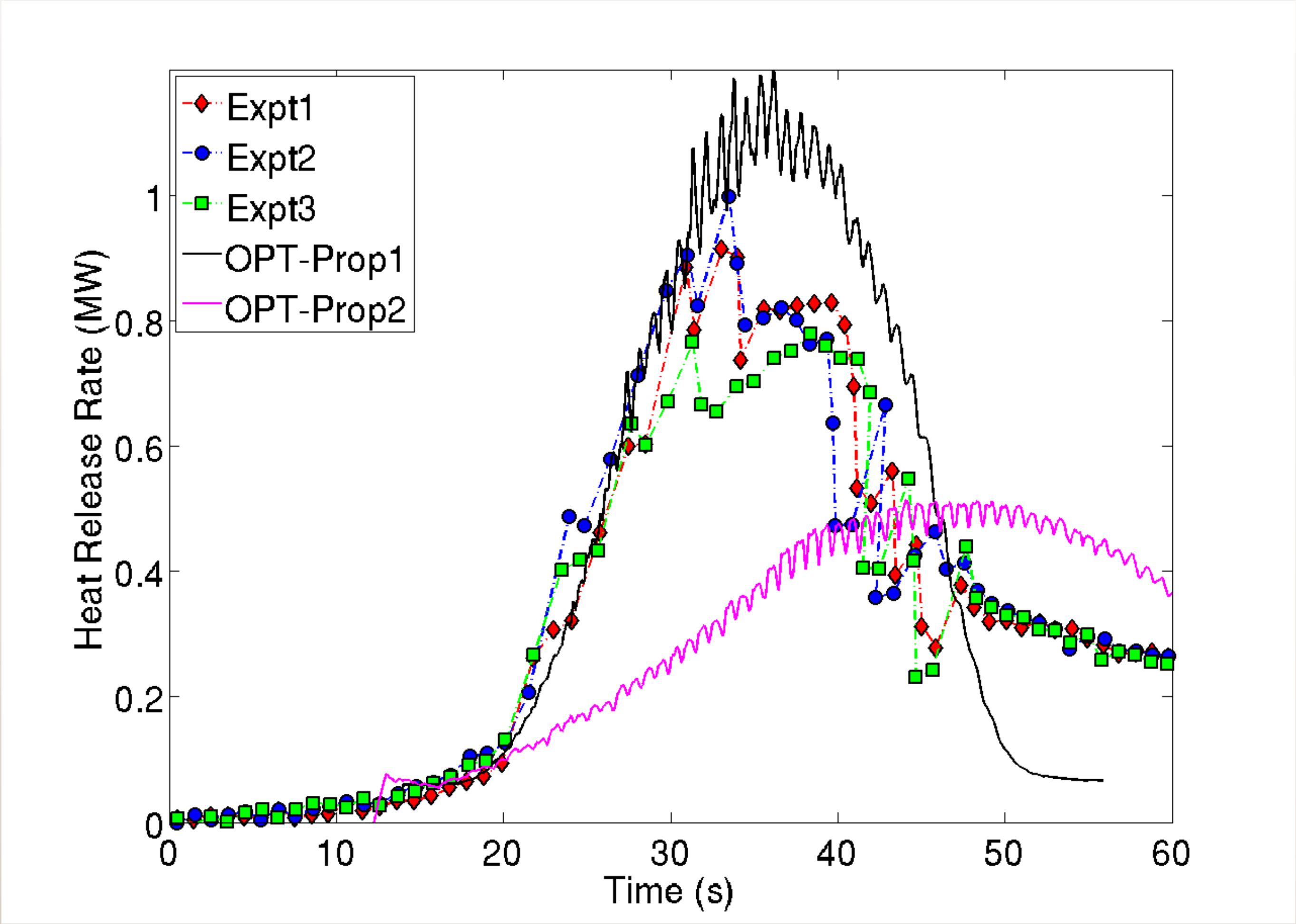




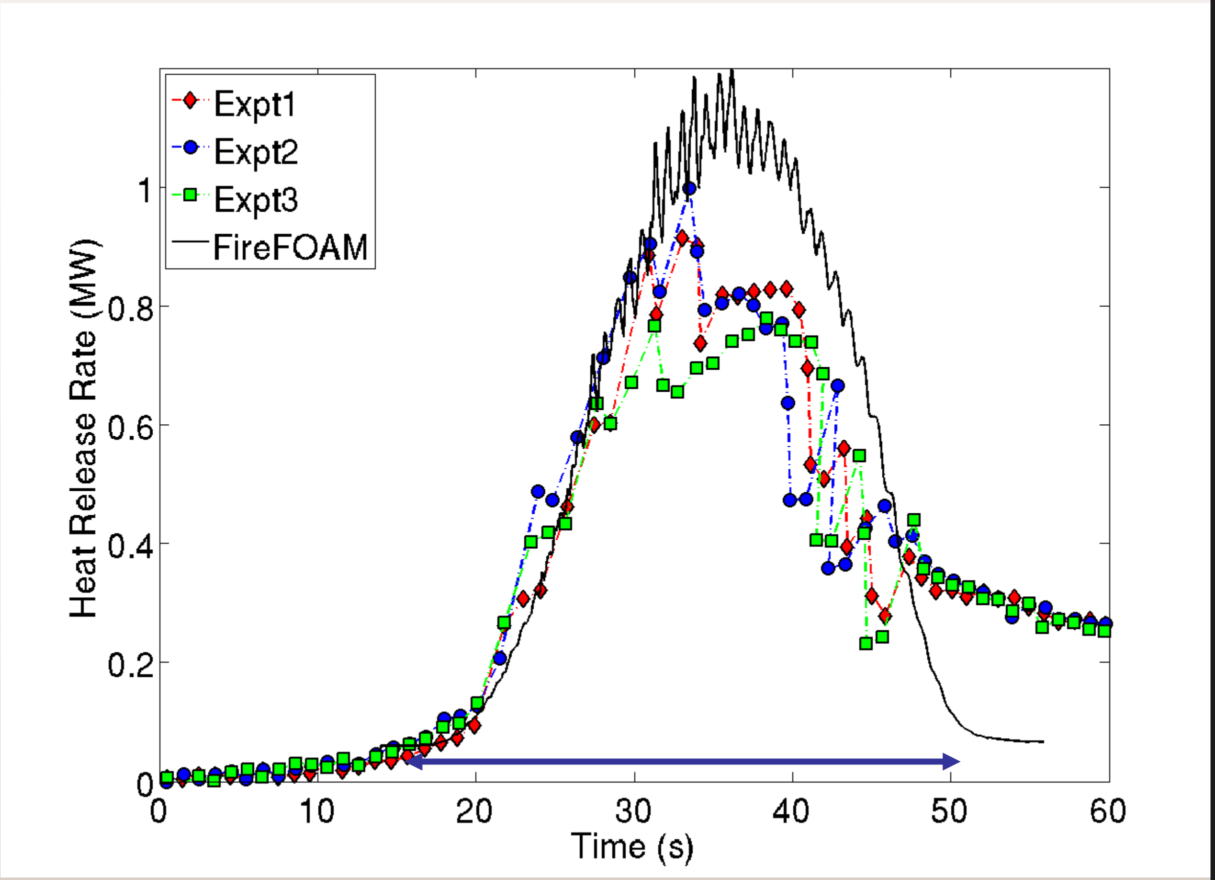


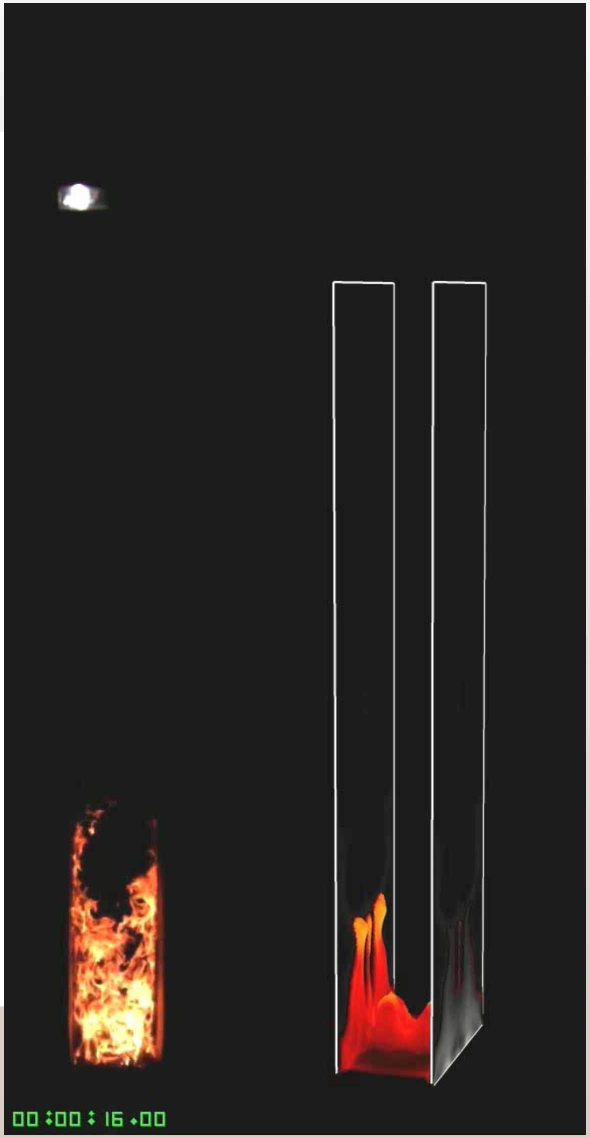
- Cumulative mass loss included in objective function
- Shuffled Complex Evolution (SCE) algorithm

Sensitivity to Properties: HRR in PP



Heat Release Rate: Corrugated





Summary and Future Work

- FireFOAM with coupled submodels is used to model flame spread behavior in the parallel panel geometry

- Feasibility of the extraction of material properties from bench-scale experiments for use in intermediate-scale has been demonstrated.

- Additional physics for pyrolysis models and improved optimization algorithm improved model prediction. Simulation for PMMA with improved properties ongoing.

- Systematic study of property uncertainty planned

Acknowledgement

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  - FM Global Strategic Research Program on fire modeling

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