Prediction of Upward Flame Spread over Polymers

Isaac T Leventon

The Fire Problem

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- **The Fire Problem**
- Controlling Mechanisms of Flame Spread
- Purpose of Study

Flame Heat Feedback Model
- Experimental Work
- Experimental Results
- Model Development

Unified Model of Material Burning Behavior
- Modeling Framework
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- Vertical Burning and Upward Flame Spread

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Conclusions and Future Work

- Surface flame spread is a key determinant of early fire growth
- Flame to surface heat feedback controls material burning rate
- Widely used standards assessing material flammability show:
  - Limited predictive capabilities outside of standard test conditions
  - Conflicting assessments between tests

Thermal Model of Upward Flame Spread

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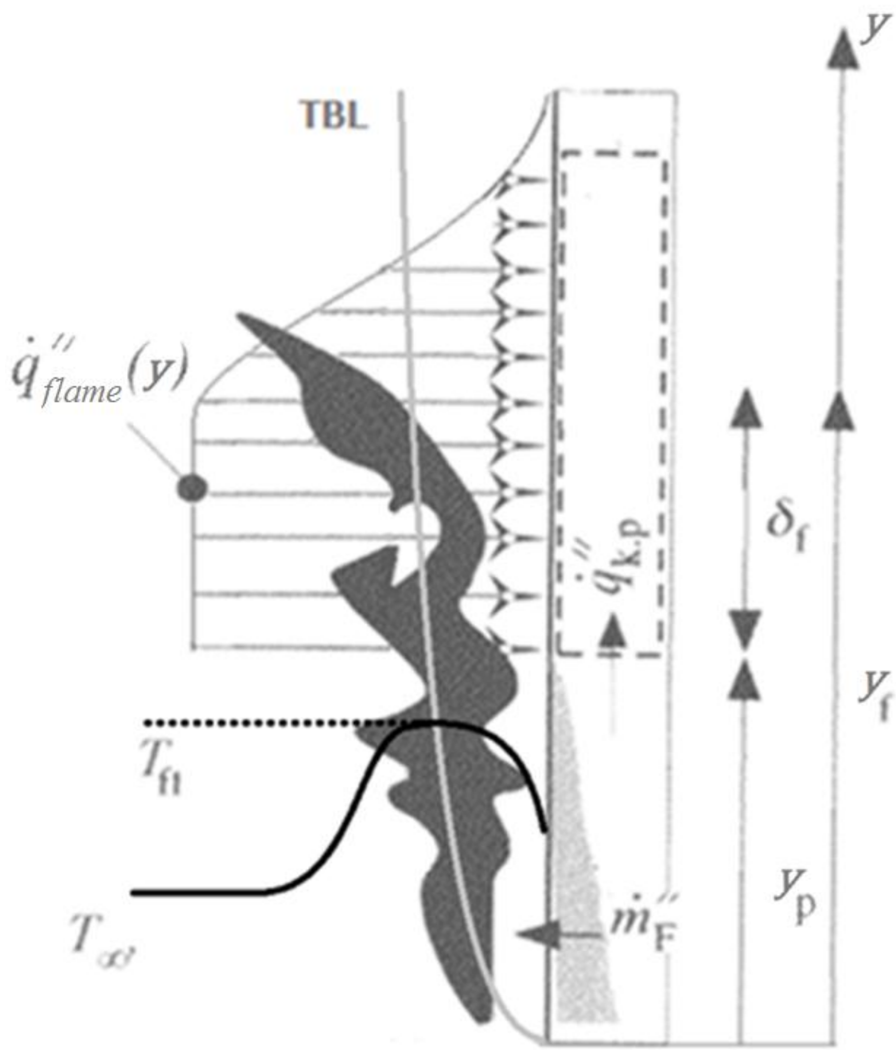

Early Flame Spread Models

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- Early analytical models

$$V_s \approx \frac{4\left(q_f''\right)^2 \delta_f}{\pi(k\rho c_p)\left(T_{ig}-T_s\right)^2}$$

- Additional influences to consider
  - Heat Feedback Distribution
  - Heat Transfer Mechanism
  - Solid Phase Degradation Mechanism
  - Temperature Dependent Material Properties
  - Secondary Burning Behavior
    - Dripping / Polymer Melt flow
    - Soot Formation and Deposition
    - Charring

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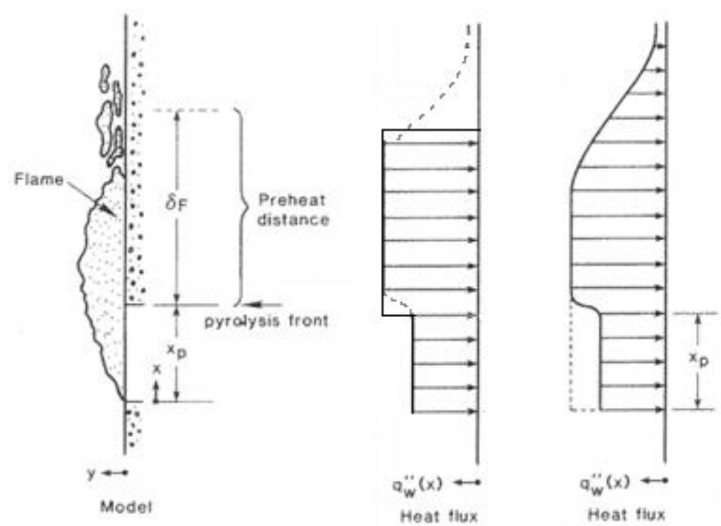
Conclusions and Future Work

- Computational Models
  - Predict material degradation in response to external heat
- How to describe flame heat flux
  - Flame height
  - Heat feedback profile
    - Steady state (peak) heat flux
    - Form/shape, decay region



Hasemi Y., Fire Science and Technology, pp. 75-90 (1984)

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- Better resolve flame to surface heat feedback at the critical length scale

- Predict flame to surface heat feedback solely as a function of material burning rate

$$q''_{flame} = q''\left(y, \frac{dm'}{dt}\right) = \begin{cases} q''_{steady}, & y \le y_f \\ \left(\alpha \times q''_{steady}\right)\left(e^{-\ln(\alpha)\times(y^*)^2}\right), & y > y_f \end{cases}$$

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Conclusions and Future Work

- Couple empirical model of flame heat feedback with pyrolysis model to simulate early stages of upward flame spread
- Generalize wall flame model to describe the burning behavior of a range of materials
- Examine the impact of secondary burning behavior on fire growth

Test Apparatus

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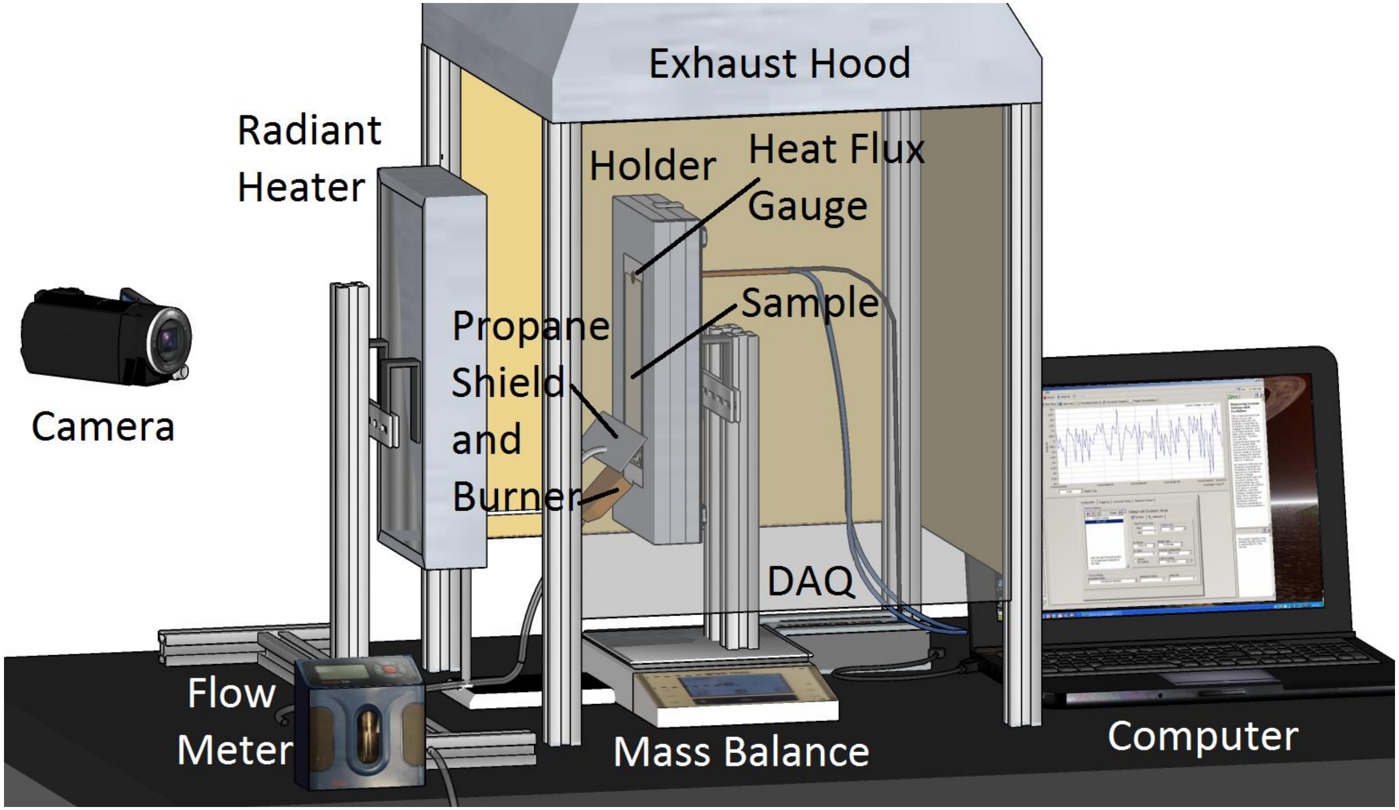

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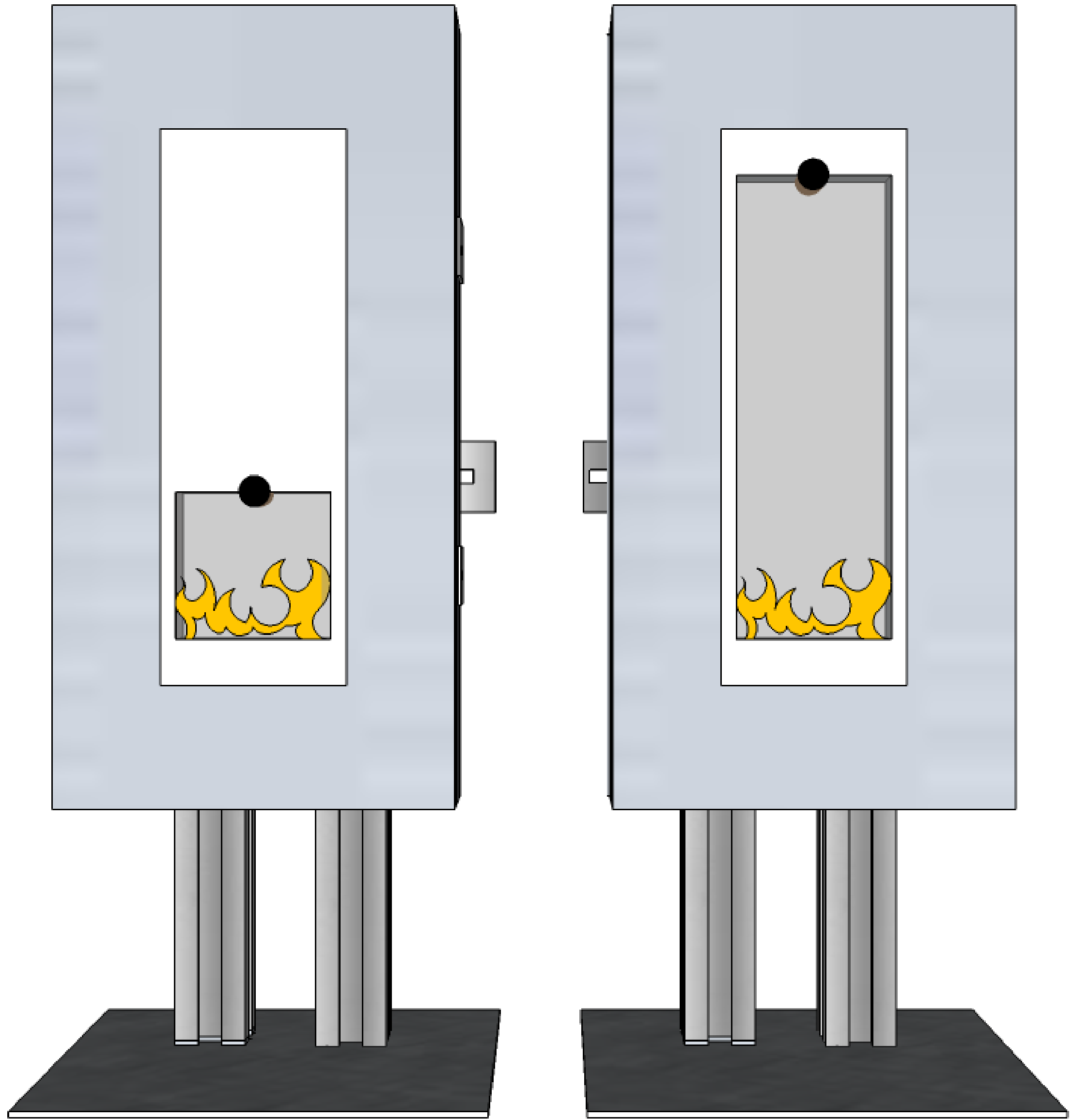

Experiments Conducted

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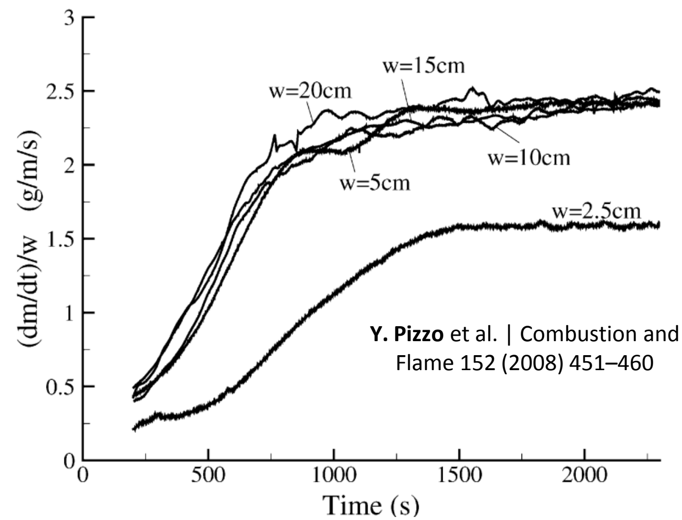
- Materials
  - PMMA (extruded)
- Sample Dimensions
  - Height 3 to 20 cm
  - Width 5 cm
- Experiments
  - Vertical Burning, Upward Flame Spread
  - Measure:
    - Mass Loss Rate
    - Flame Heat Flux



Experimental Procedure

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- Ignite sample base with propane burner; for PMMA, 125 s exposure
- Allow flame to propagate freely until full sample involvement
- Measure flame to surface heat feedback or sample mass loss rate until steady conditions are observed or early sample extinction required (e.g. due to dripping)

Ignition Source Heat Flux Profile

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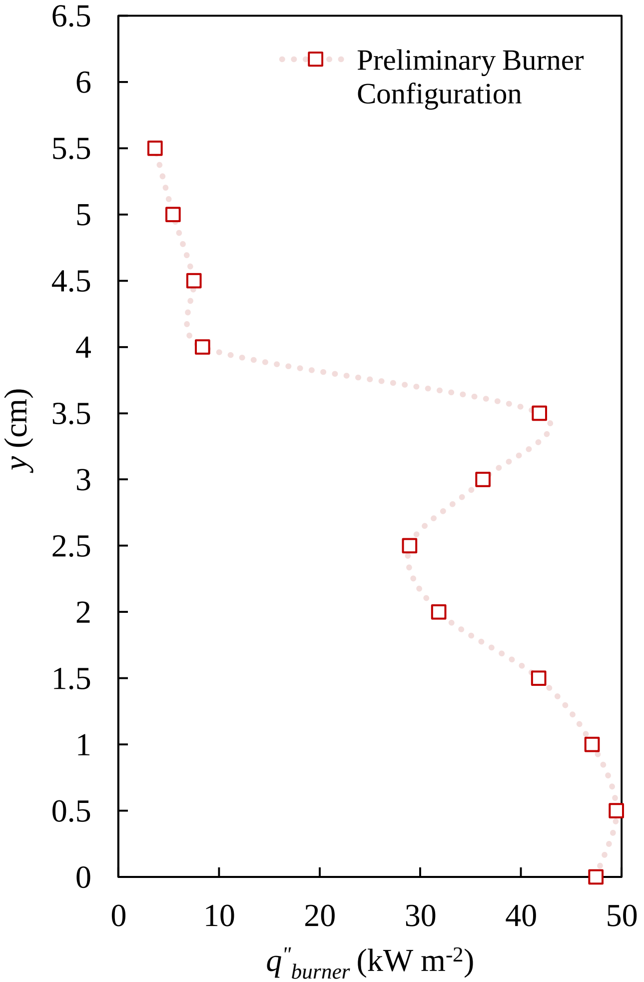
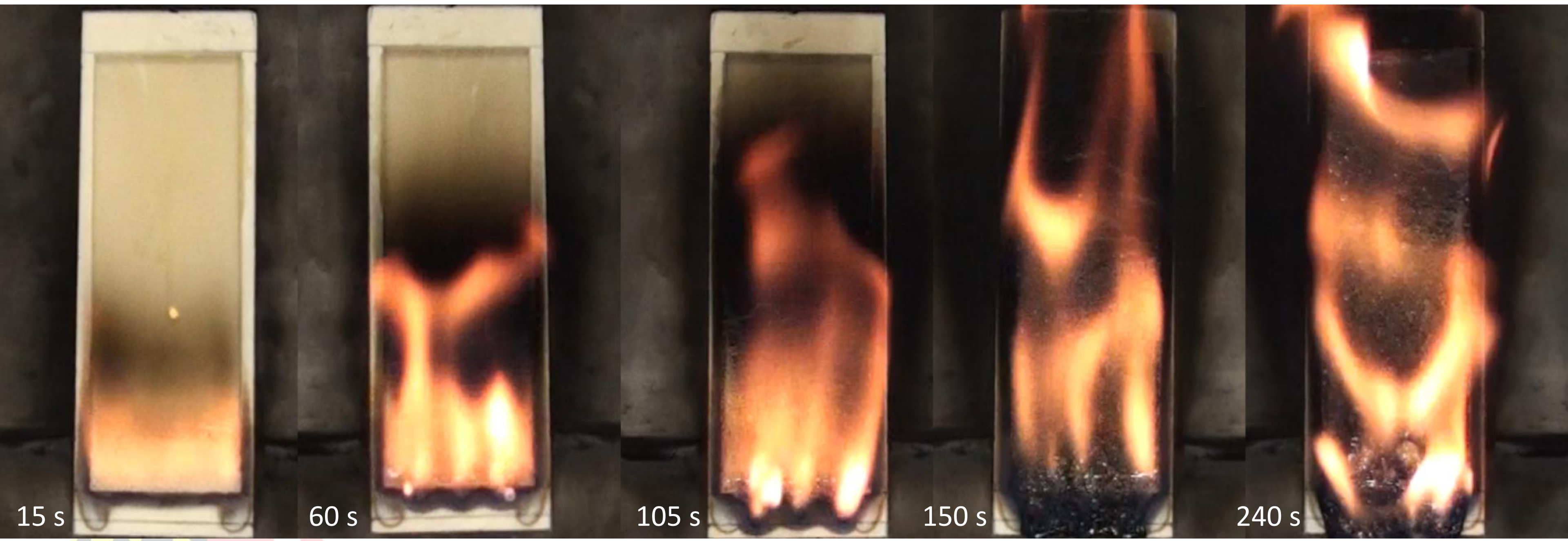


PMMA



PMMA Mass Loss Rate

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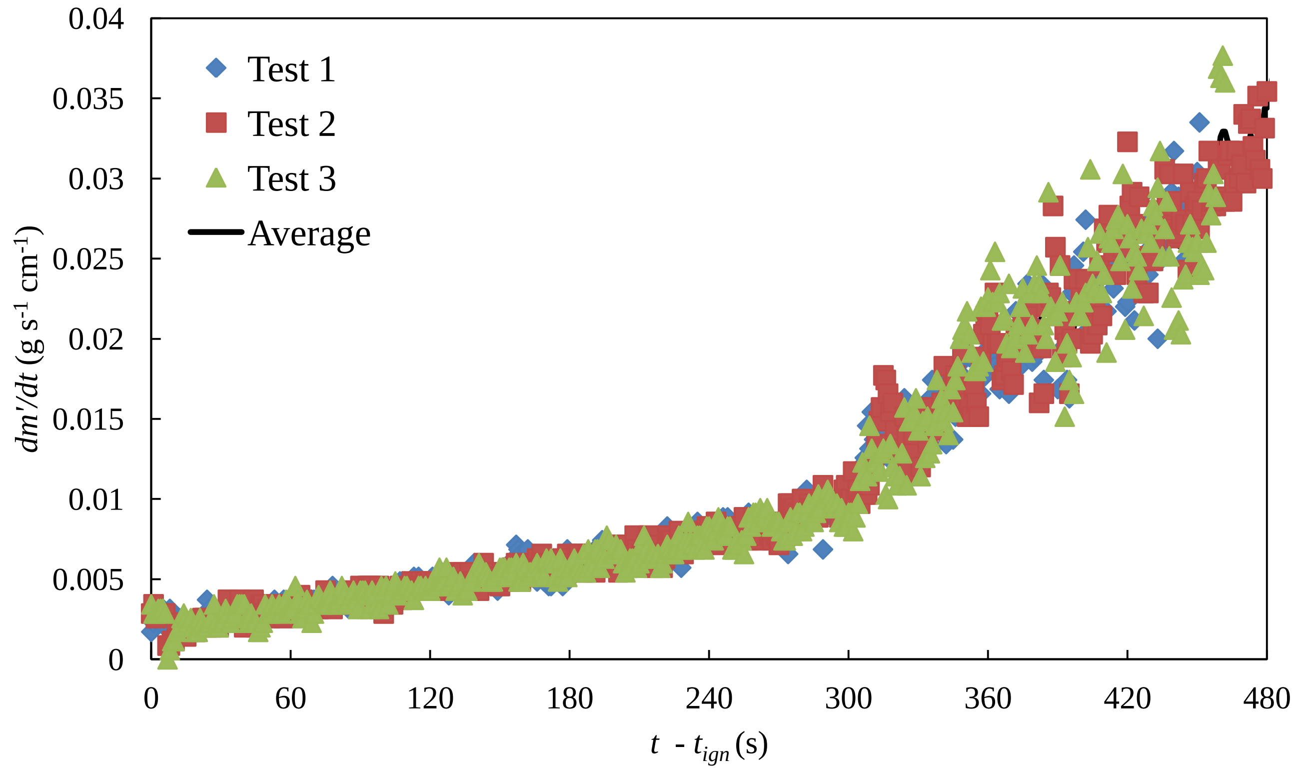

PMMA Mass Loss Rate

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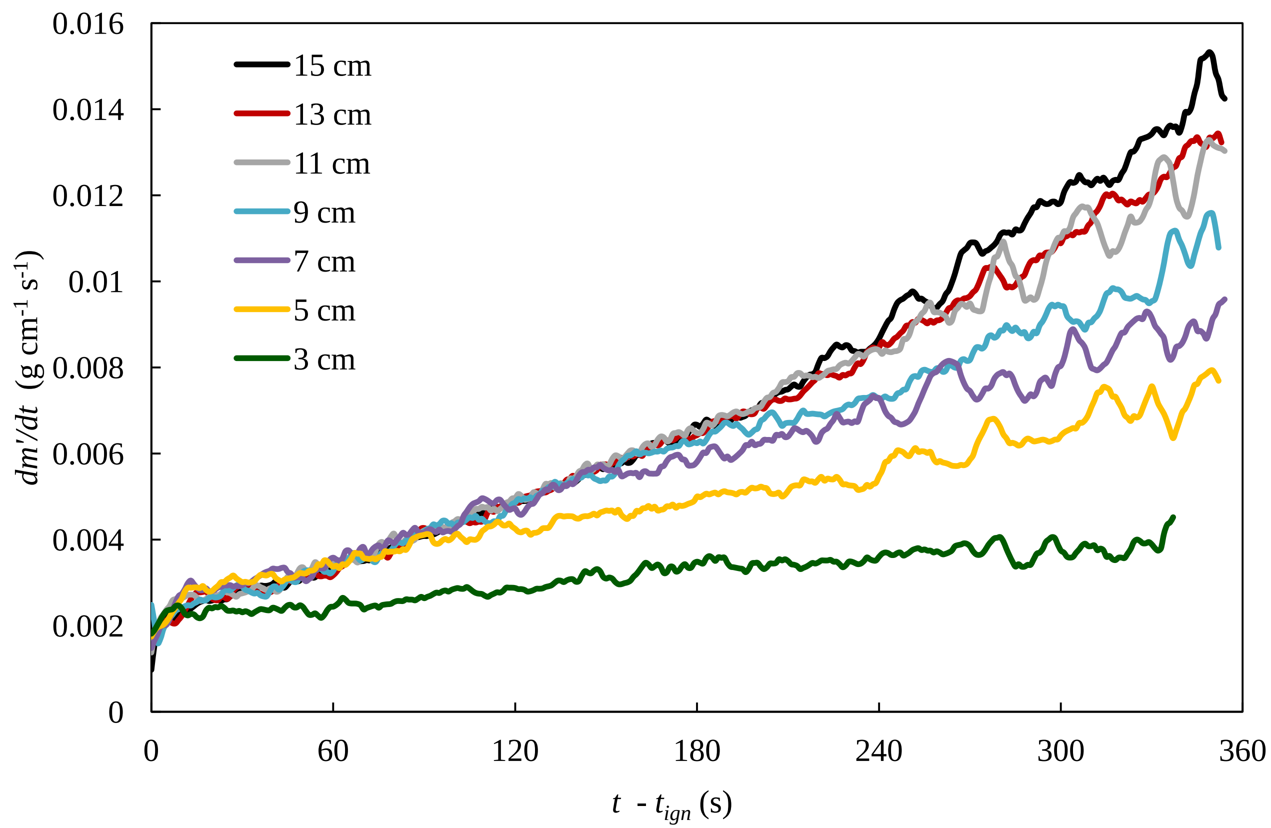

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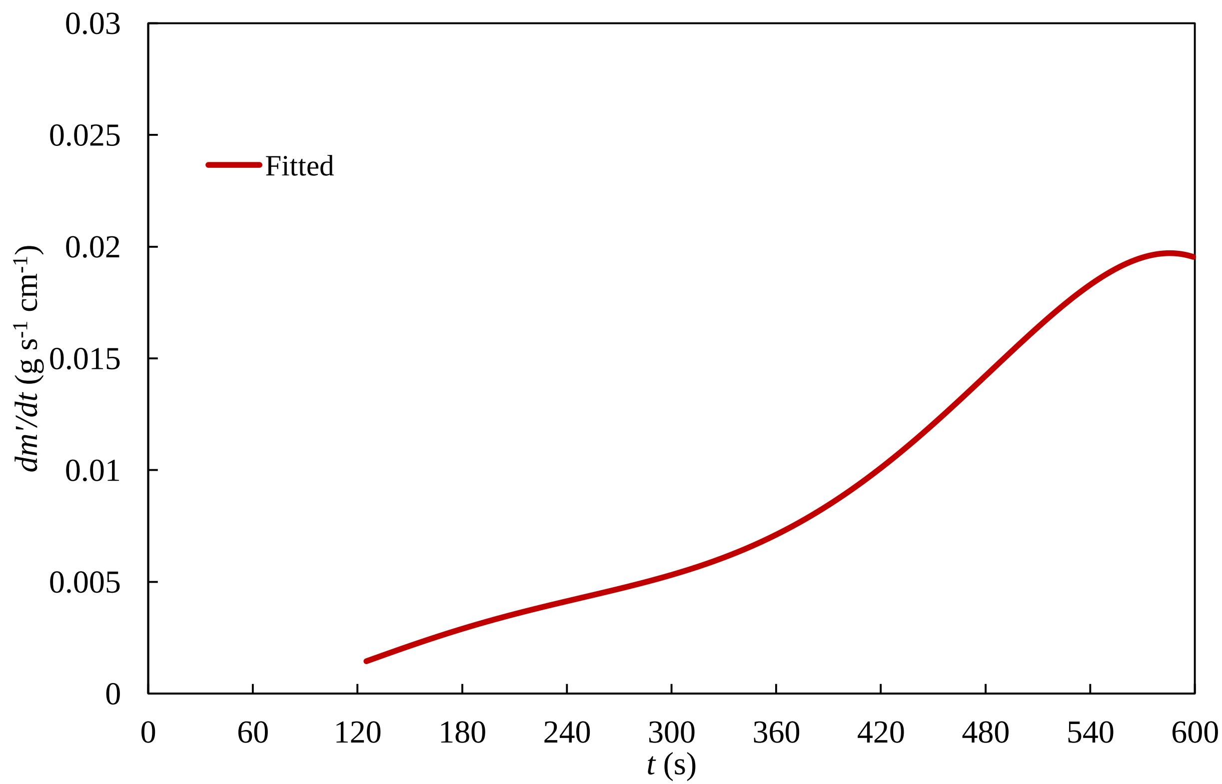

$$\frac{dm'}{dt} = -5.40\times10^{-15}(t-t_{ign})^5 + 4.35\times10^{-12}(t-t_{ign})^4 - 8.13\times10^{-10}(t-t_{ign})^3 + 4.75\times10^{-9}(t-t_{ign})^2 + 2.79\times10^{-5}(t-t_{ign}) + 1.44\times10^{-3}$$

dm'/dt is in g s^{-1} cm^{-1} and t is in s

PMMA Flame Heat Flux

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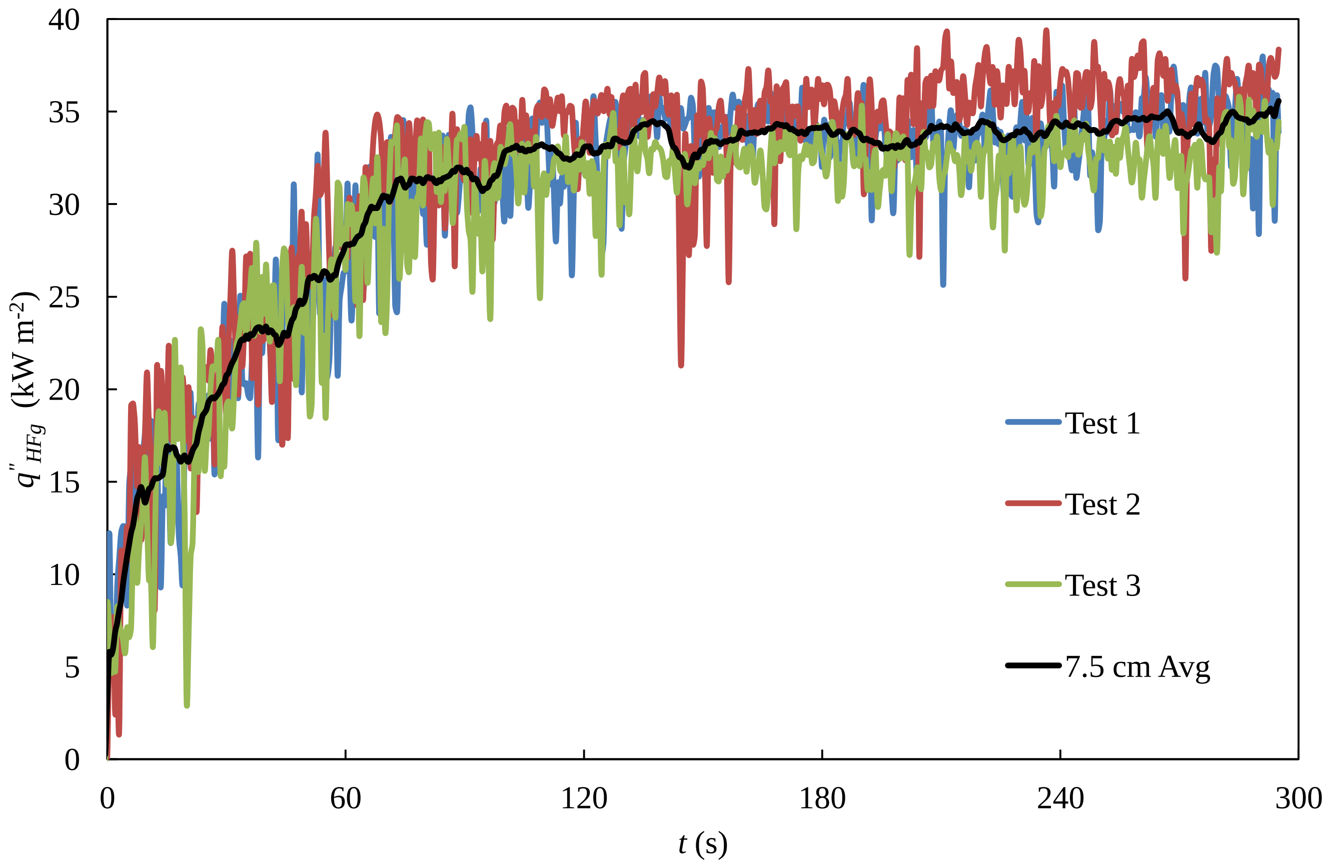
y = 7.5 cm



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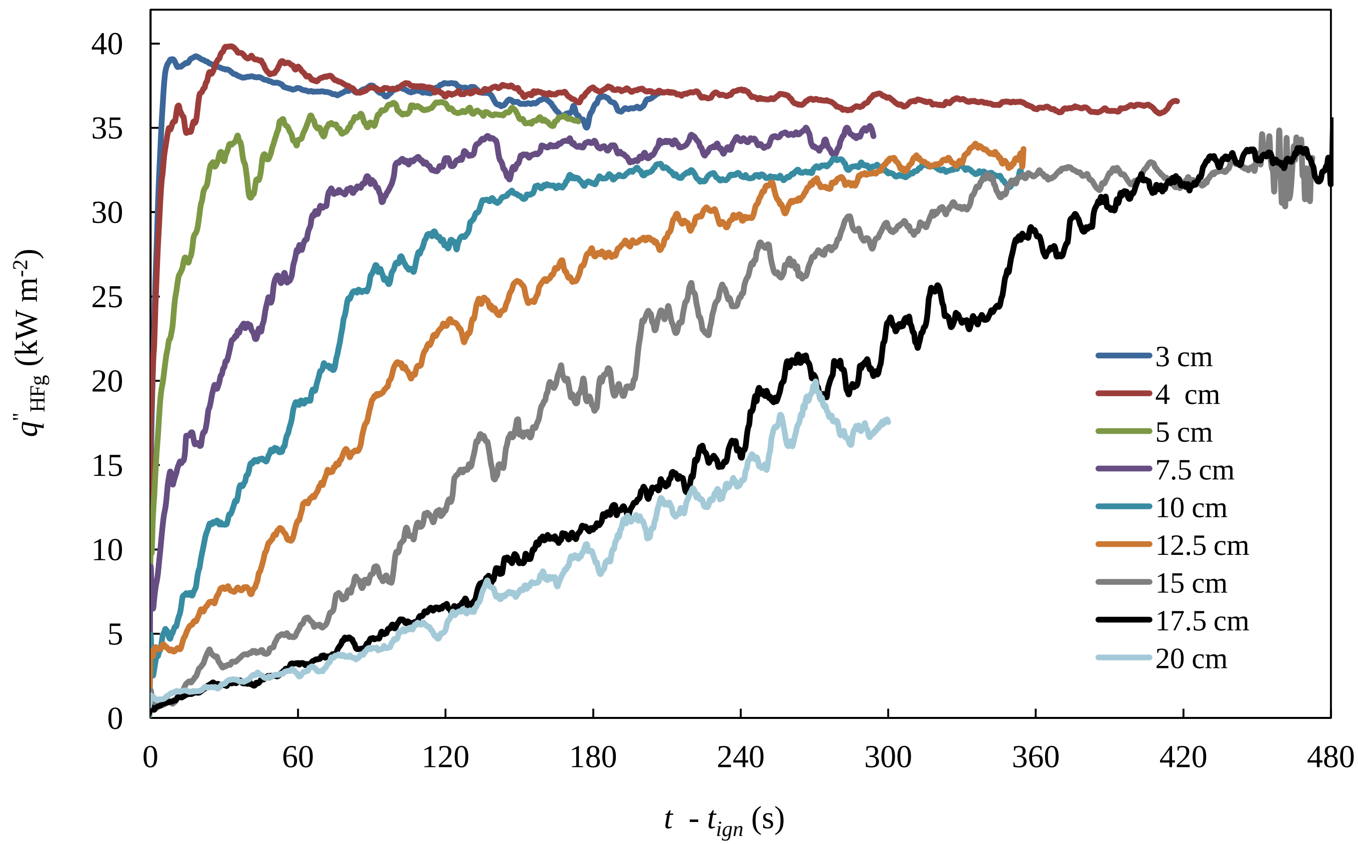

PMMA Flame Heat Flux
Effects of Finite Width

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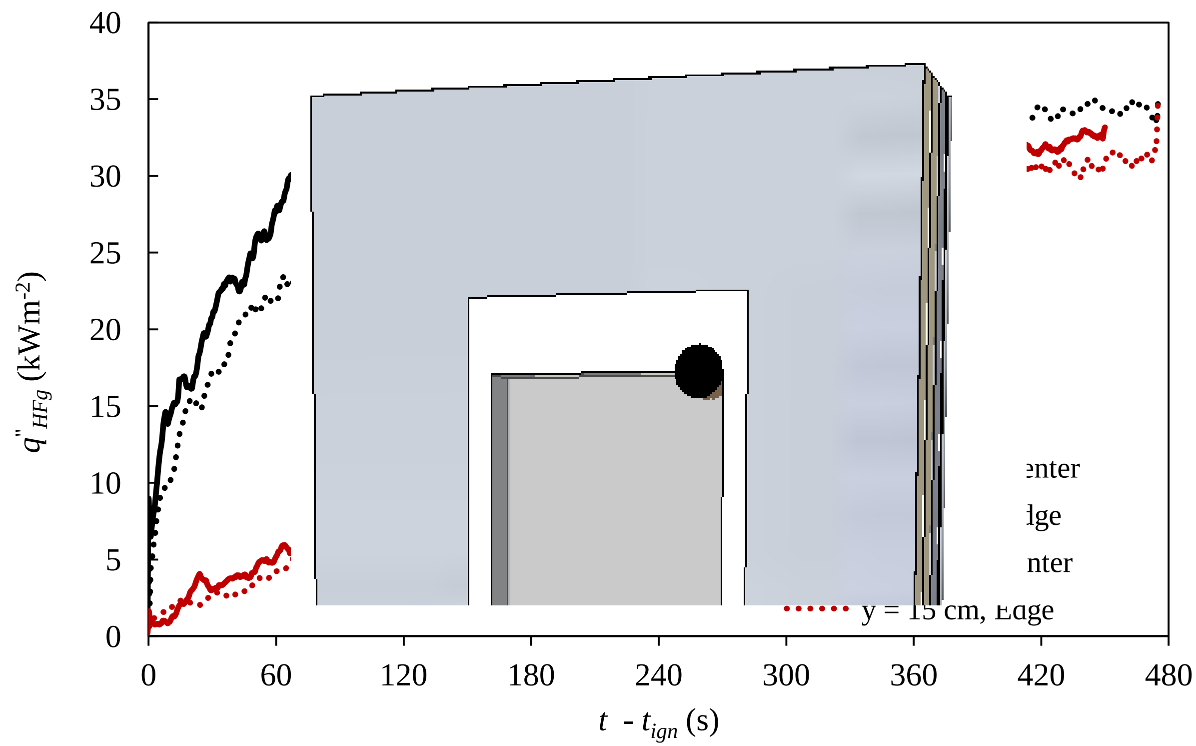

PMMA Flame Heat Flux

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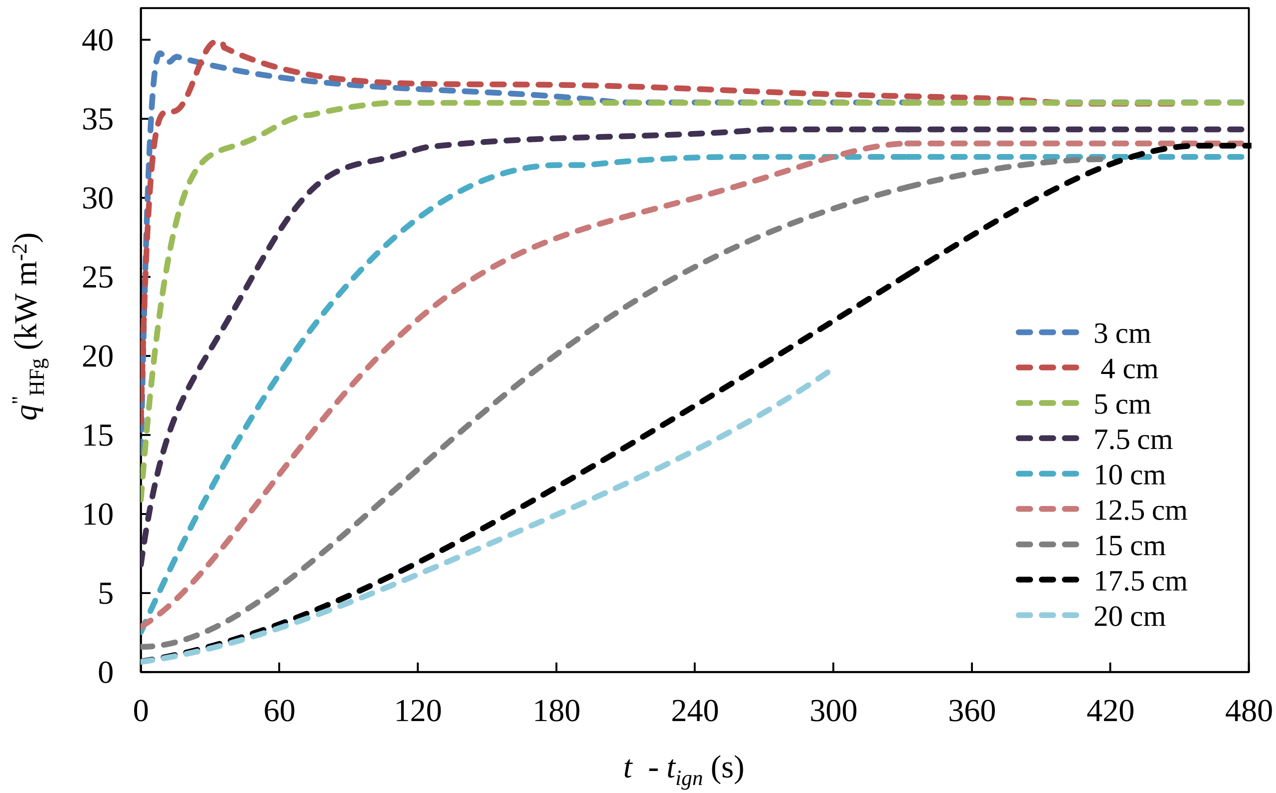

Steady State Flame Heat Flux

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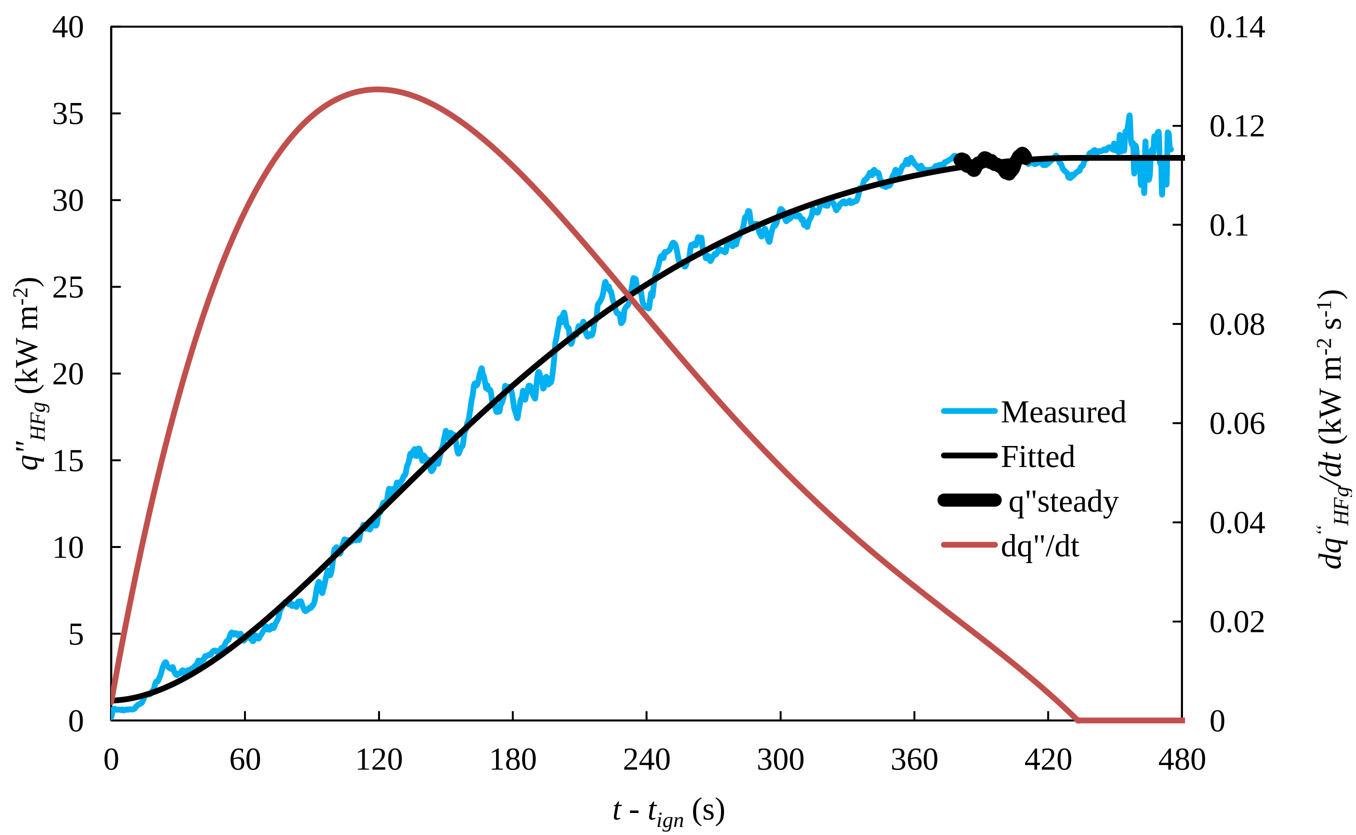
y = 17.5 cm



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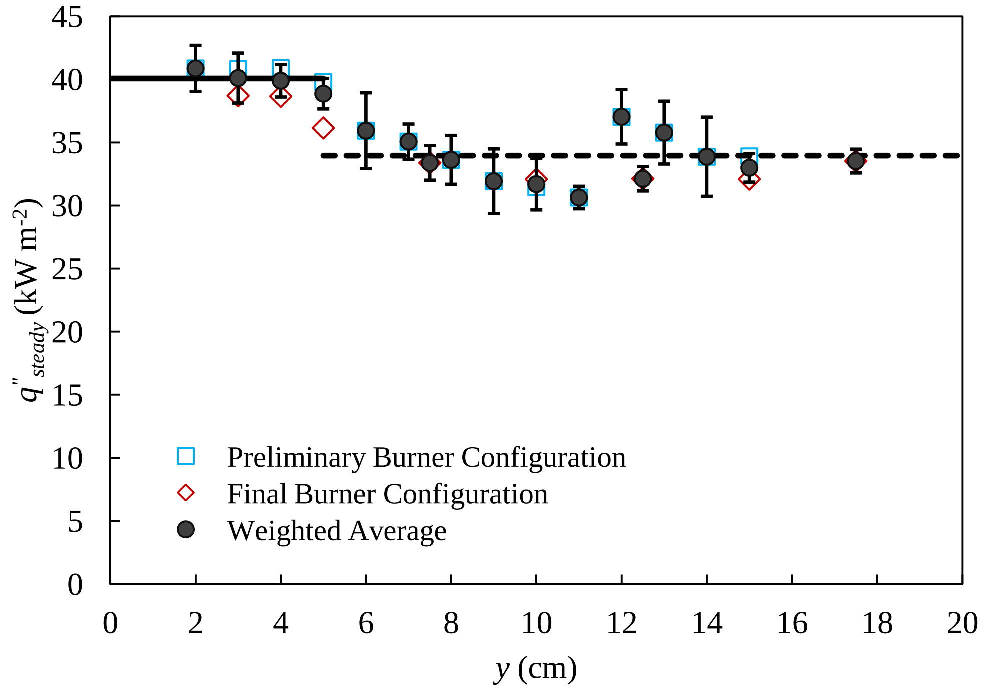
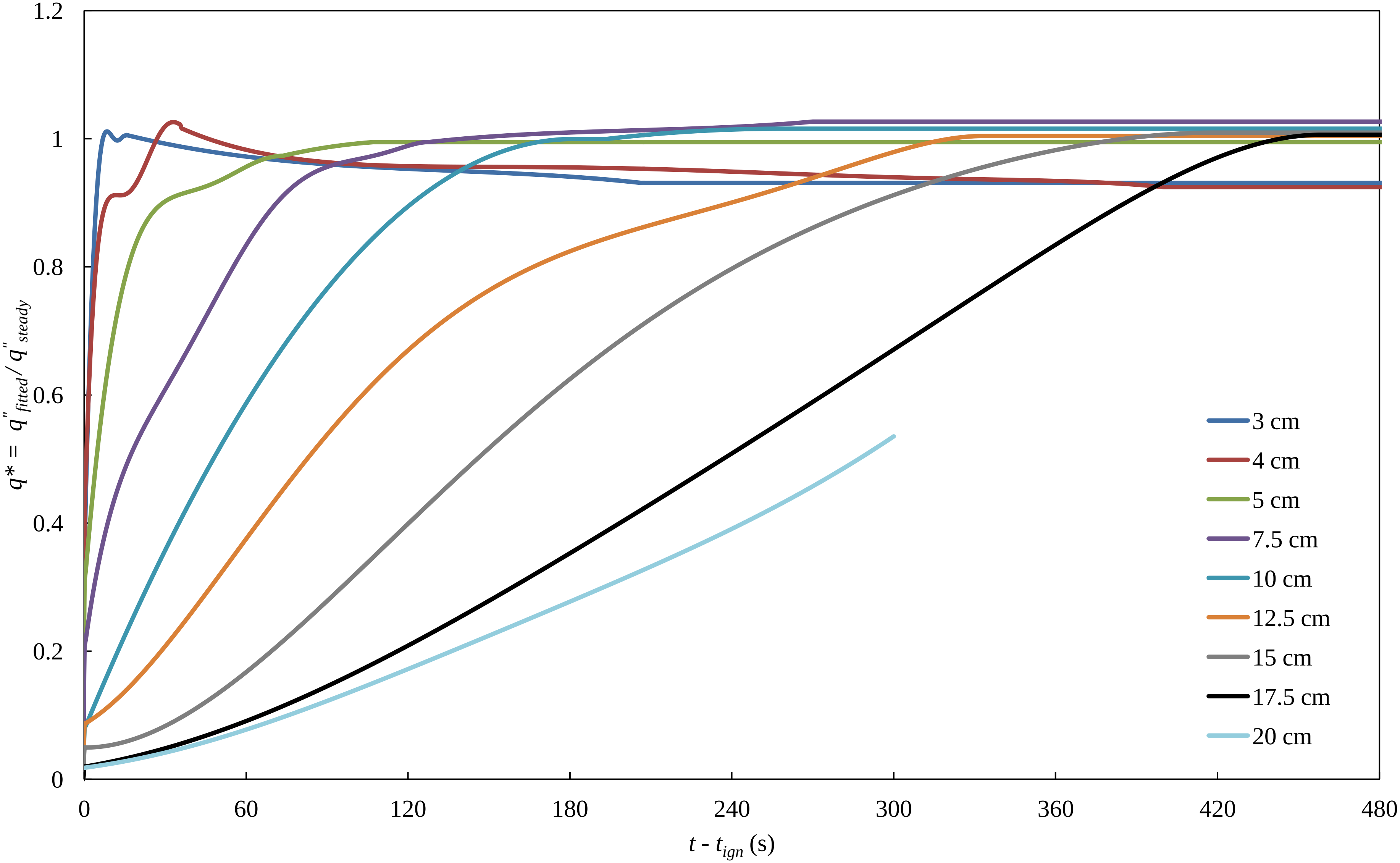


Normalized Flame Heat Flux



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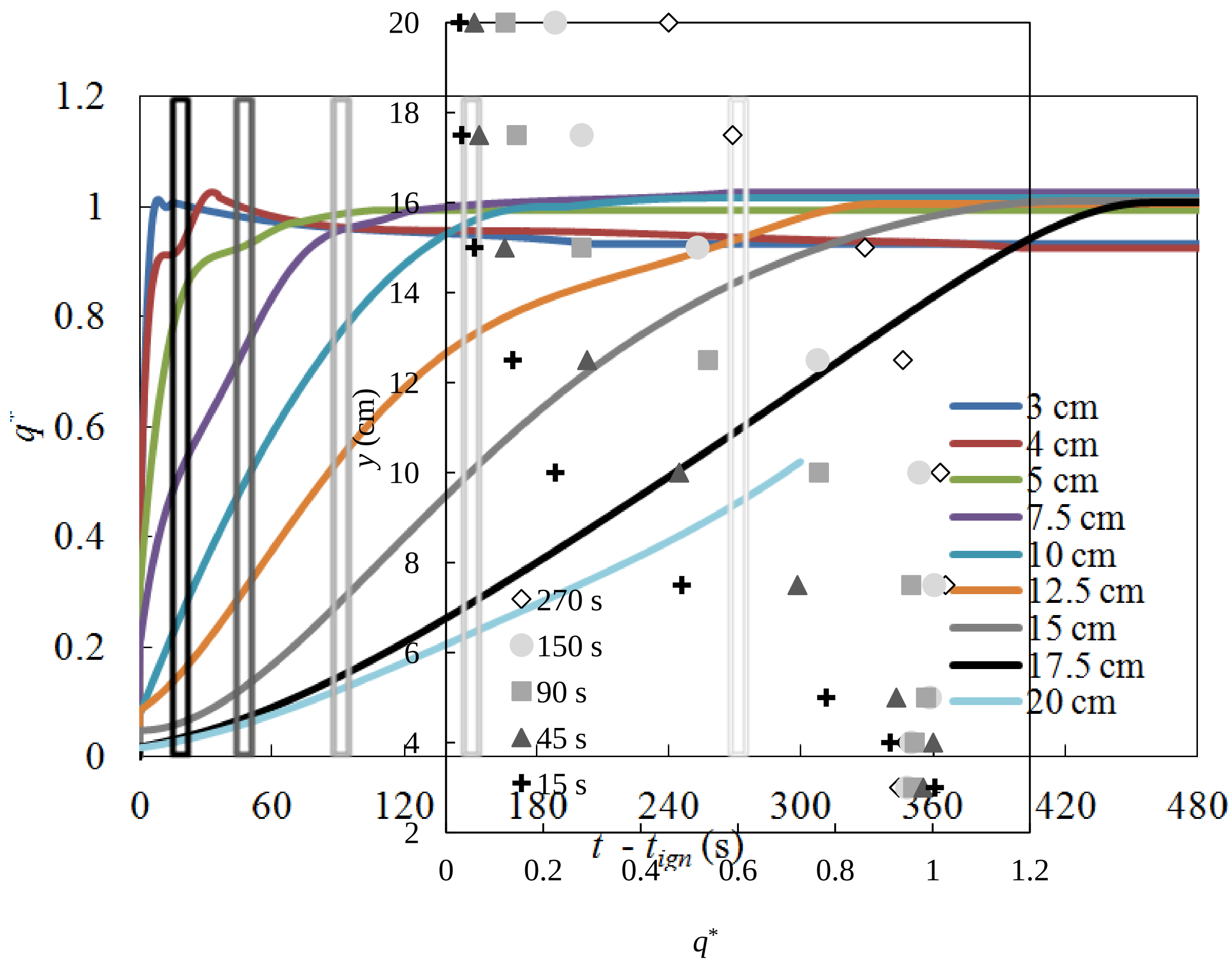

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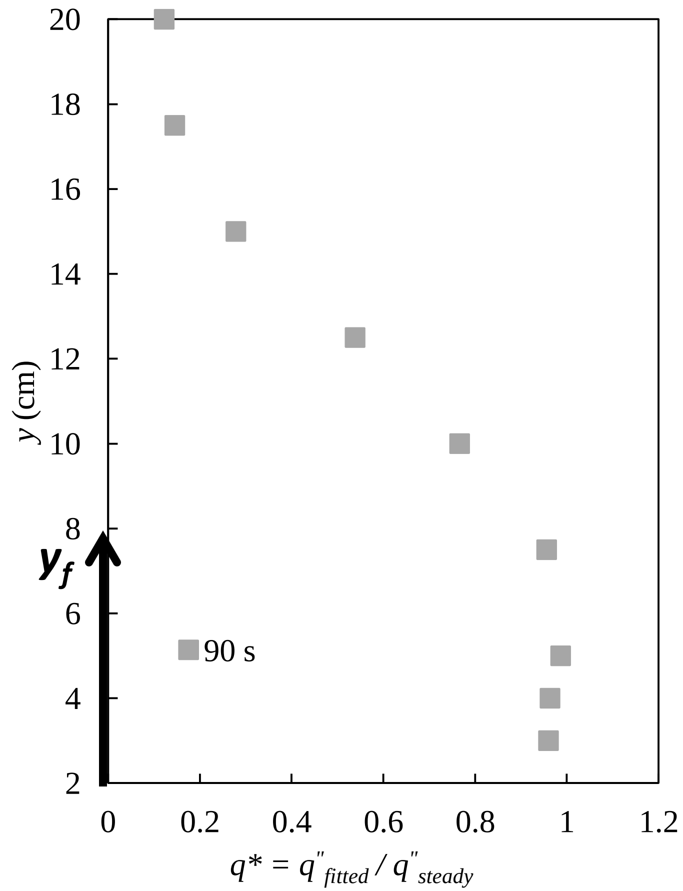

$$q''_{flame} = q''\left(y, \frac{dm'}{dt}\right) = \begin{cases} q''_{steady} \ , & y \le y_f \\ \left(\alpha \times q''_{steady}\right)\left(e^{-\ln(\alpha)\times(y^*)^2}\right) \ , & y > y_f \end{cases}$$

Determining Flame Height, y_f

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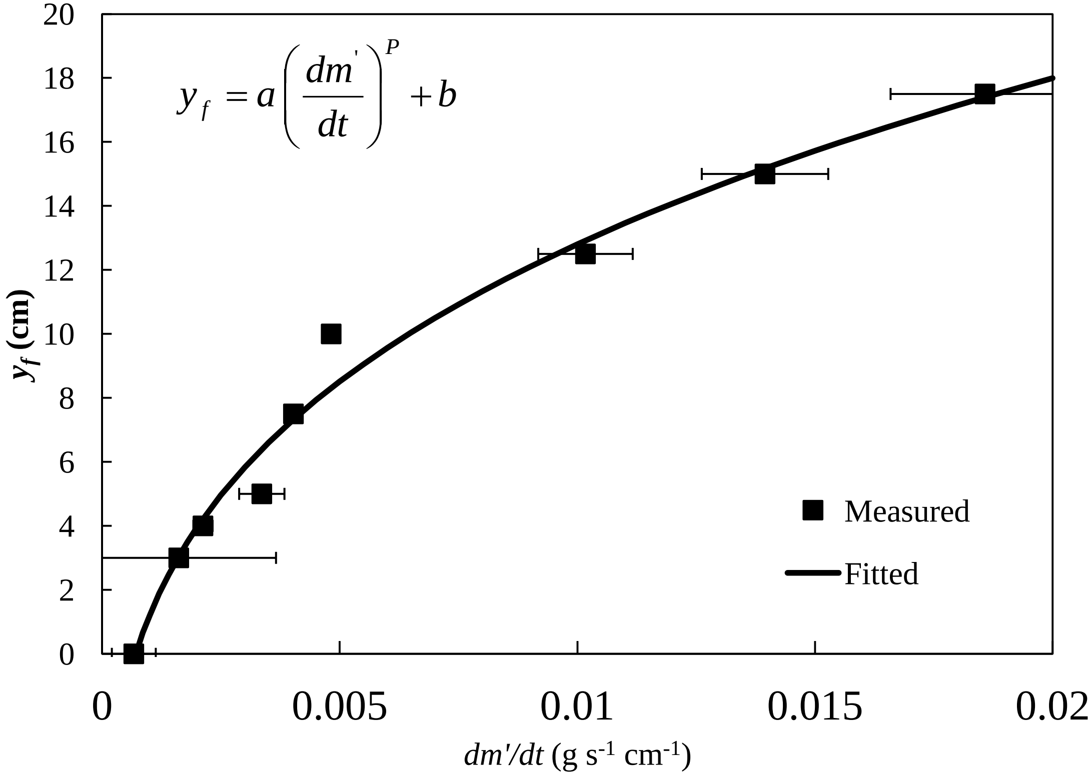
- Flame height is defined as the highest position along the sample at which q''_{HFg} is within 2.5% of q''_{steady}



Flame Heat Flux Beyond y_f

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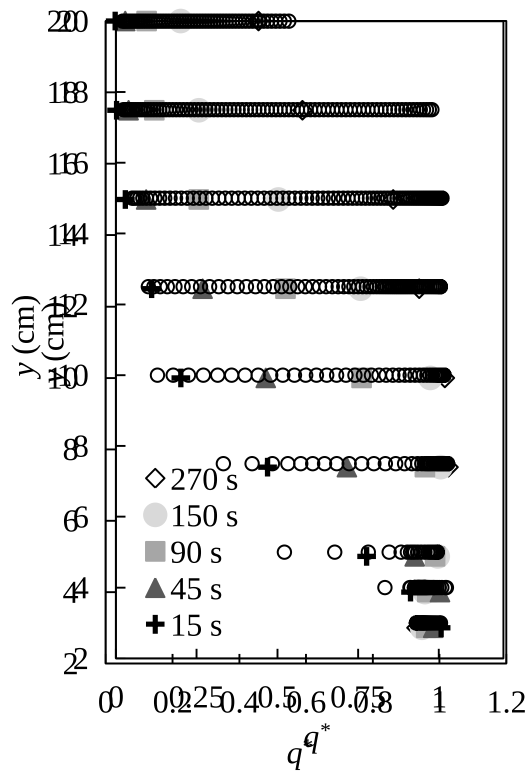

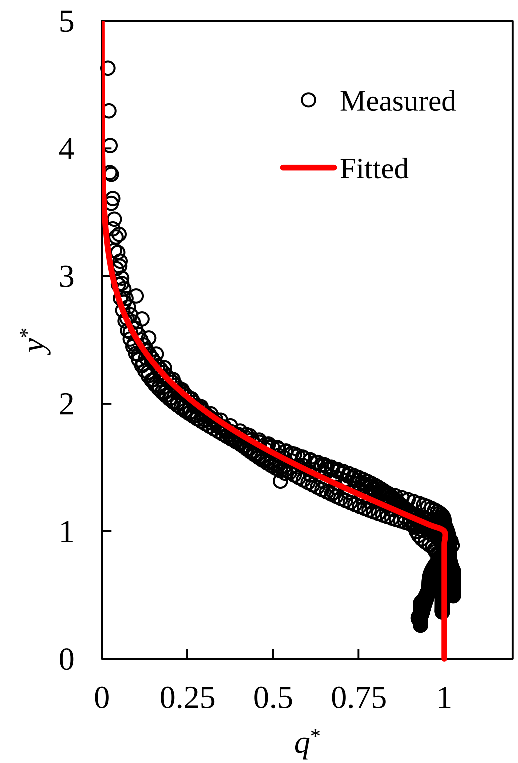

$$\dot{q}''_{flame} = \dot{q}''\left(y, \frac{dm'}{dt}\right) = \begin{cases} \dot{q}''_{steady}, & y \le y_f \\ \left(\alpha \times \dot{q}''_{steady}\right)\left(e^{-\ln(\alpha)\times(y^*)^2}\right), & y > y_f \end{cases}$$

$$y^* = \frac{(y + y_0)}{(y_f + y_0)}$$

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$$q''_{steady} = \begin{cases} 40 \quad \mathrm{kW\,m^{-2}} & ;\ \mathrm{y} \le 5\,\mathrm{cm} \\ 34 \quad \mathrm{kW\,m^{-2}} & ;\ \mathrm{y} > 5\,\mathrm{cm} \end{cases}$$

$$y_f = 87.734\left(\frac{dm'}{dt}\right)^{0.275} - 11.924 \qquad y^* = \frac{(y+2.2)}{(y_f+2.2)}$$

$$q''_{flame} = q''\left(y, \frac{dm'}{dt}\right) = \begin{cases} q''_{steady}\ , & y \le y_f \\ \left(1.54 \times q''_{steady}\right)\left(e^{-\ln(1.54)\times(y^*)^2}\right)\ , & y > y_f \end{cases}$$

Units: y [cm] and $\frac{dm'}{dt}$ [g s^{-1} cm^{-1}]

Flame Heat Feedback Model Predictions

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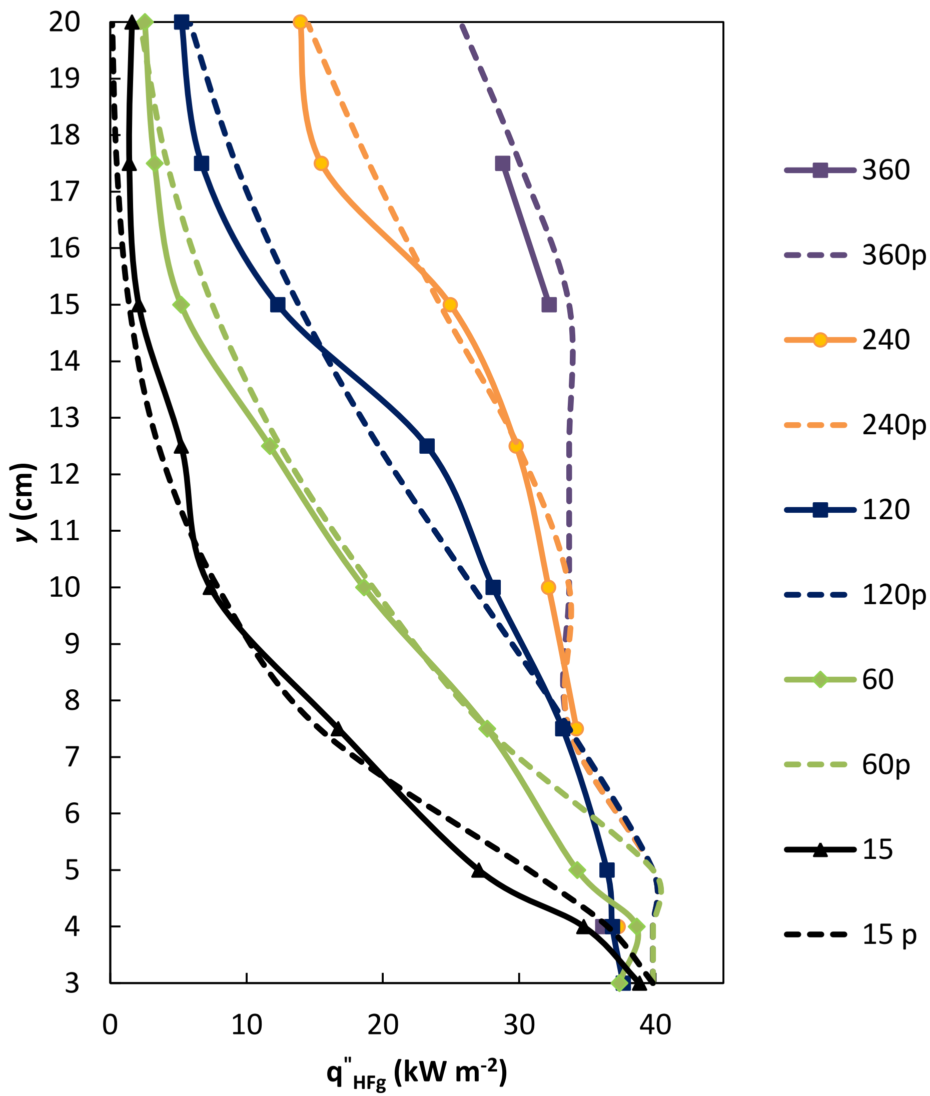

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$$y_f = a\left(\frac{dm'}{dt}\right)^P + b$$

$$q''_{steady} = \begin{cases} 40 \quad \text{kW m}^{-2} & ;\ y \le 5\,\text{cm} \\ 34 \quad \text{kW m}^{-2} & ;\ y > 5\,\text{cm} \end{cases}$$

$$y^* = \frac{(y + y_0)}{(y_f + y_0)}$$

$$q''_{flame} = q''\left(y, \frac{dm'}{dt}\right) = \begin{cases} q''_{steady}\ , & y \le y_f \\ \left(\alpha \times q''_{steady}\right)\left(e^{-\ln(\alpha) \times (y^*)^2}\right)\ , & y > y_f \end{cases}$$

$$\frac{dm'}{dt}$$

Pyrolysis Solver

(ThermaKin)

ThermaKin2D Modeling Framework

Condensed phase is represented by a mixture of components that may interact chemically and physically.

2D heat transfer within solid:

$$q''_{conduction} = -k\frac{\partial T}{\partial x} \quad \text{or} \quad = -k\frac{\partial T}{\partial y}$$

Material degradation mechanism defined by:

- First order Arrhenius reaction rates:

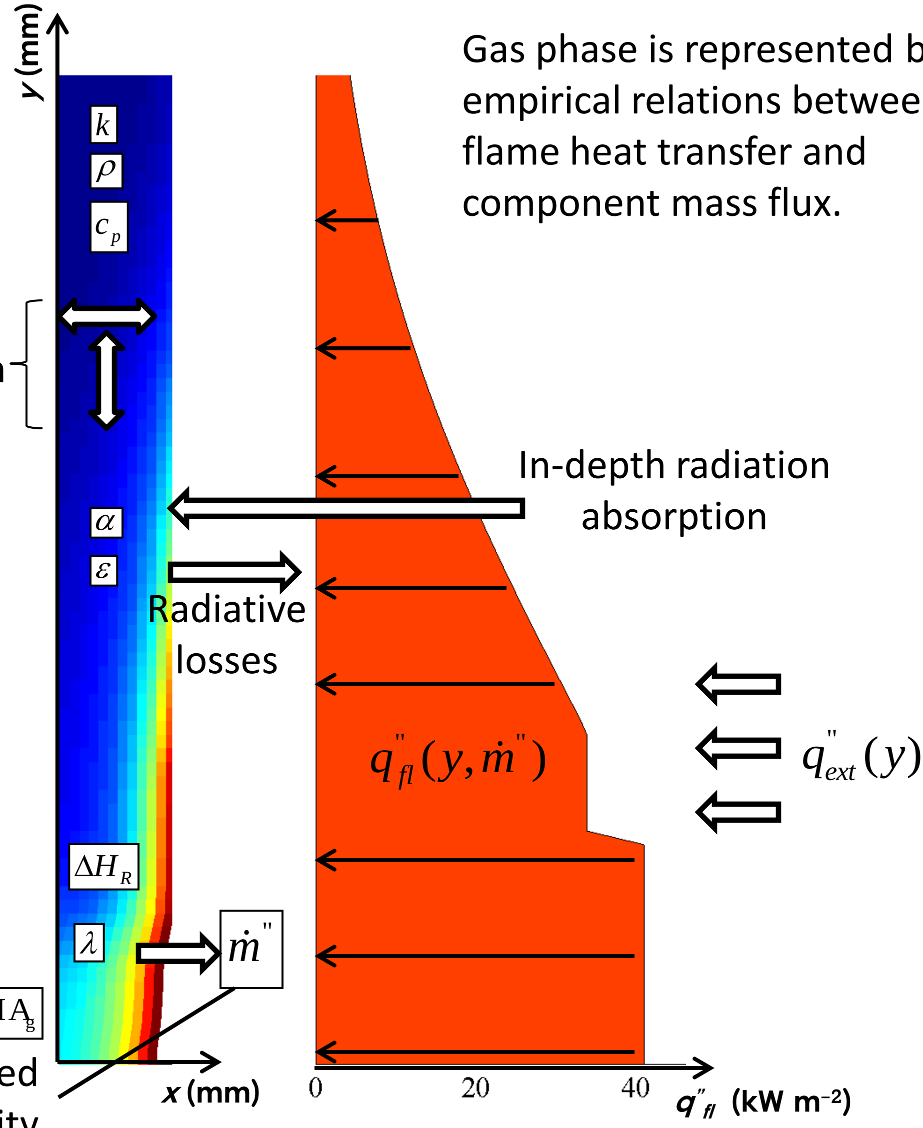
$$r = A\exp\left(-\frac{E}{RT}\right)\xi_{\mathrm{COMP1}}$$

- Temperature dependent material properties (k, ρ, c_p, λ):

$$\text{property} = p_0 + p_1 T + p_2 T^n$$

$$\mathrm{PMMA} \rightarrow \mathrm{PMMA_{ch}} + \mathrm{PMMA_g}$$

Gas phase is represented by empirical relations between flame heat transfer and component mass flux.



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$$q''_{flame} = h_{flame}(T_{fl}^{PMMA} - T_{surf})$$

$$T_{fl,max}^{PMMA} = \begin{cases} T_{fl,adiabatic}^{PMMA} & \forall\ y \le 5\text{ cm} \\ 0.87 \times T_{fl,adiabatic}^{PMMA} & \forall\ y > 5\text{ cm} \end{cases}$$

$$q''_{steady} = \begin{cases} 40\text{ kW m}^{-2} & ;\ y \le 5\text{ cm} \\ 24\text{ kW m}^{-2} & ;\ y > 5\text{ cm} \end{cases}$$

$$y_f = a\left(\frac{dm'}{dt}\right)^p + b \qquad y^* = \frac{y + y_0}{y_f + y_0}$$

$$q''_{flame}\left(y, \frac{dm'}{dt}, T_{surf}\right) = \begin{cases} h_{flame}(T_{fl,max}^{PMMA} - T_{surf}) & \forall\ y \le y_f \\ h_{flame}\left(\alpha\left(T_{fl,max}^{PMMA} - T_{HFg}\right)e^{-\ln(\alpha)(y^*)^2} + T_{HFg} - T_{surf}\right) & \forall\ y > y_f \end{cases}$$

$$q''_{flame}\left(y, \frac{dm'}{dt}\right) = \begin{cases} q''_{steady} & y \le y_f \\ \left(q''_{steady}\right)e^{-\ln(\alpha)(y^*)^2} & y > y_f \end{cases}$$

Degradation Mechanism

Milligram Scale Testing

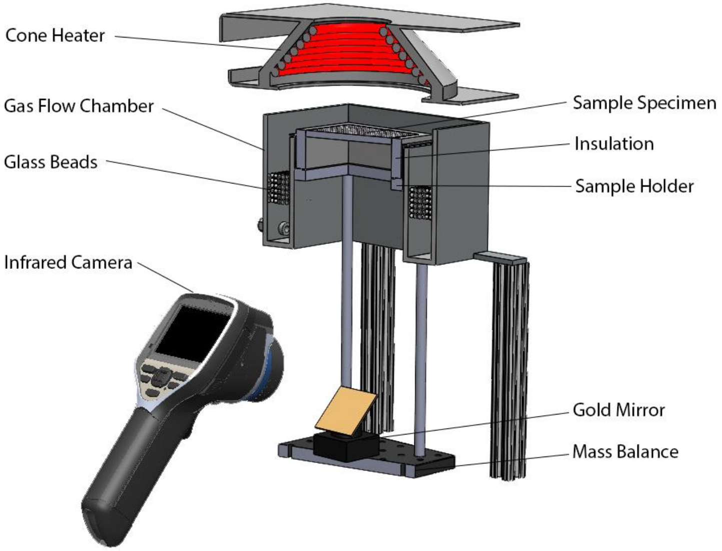
- Thermogravimetric Analyzer (TGA)
  - **Kinetics**: *A*, *E*

$$r = A\exp\left(-\frac{E}{RT}\right)\xi_{\mathrm{COMP1}}$$

- Differential Scanning Calorimetry *(DSC)*
  - **Thermodynamics**
  - Specific heat, C_p
  - Heats of
    - Decomposition, h_{decomp}
    - Melting, h_{melt}

Bench Scale Testing

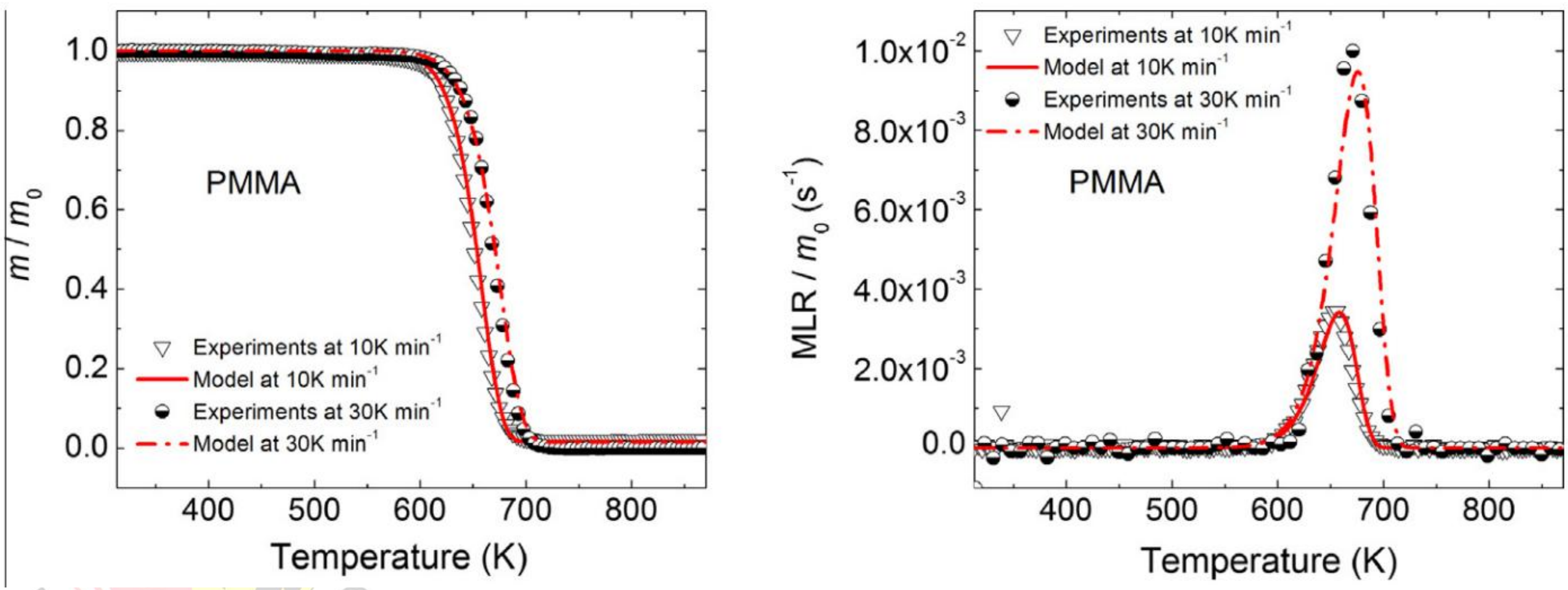
- Gasification Experiments
  - Thermal Conductivity, *k*
  - Absorption coefficient, *a*



Acknowledgements: Jing Li, PhD - University of New Haven

Pyrolysis Model Validation: Milligram Scale Testing (0D)

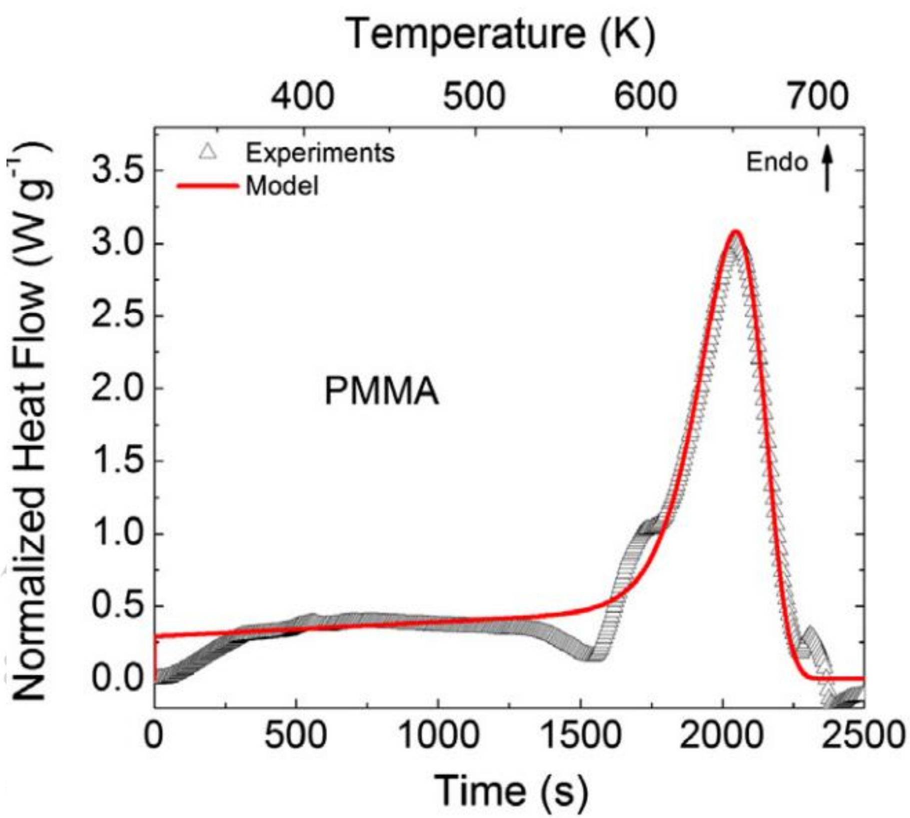
Experimental and simulated TGA of PMMA
at 10 K min^{-1} and 30 K min^{-1}

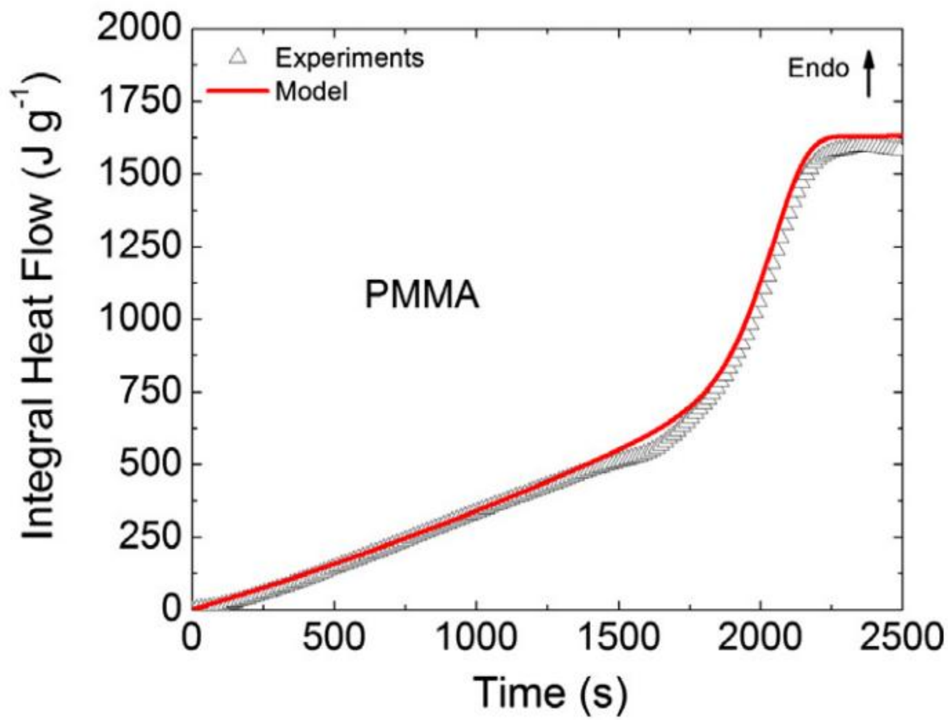


Acknowledgements: Jing Li, PhD - University of New Haven

Pyrolysis Model Validation: Milligram Scale Testing (0D)

Experimental and simulated DSC of PMMA
at 10 K min^{-1} and 30 K min^{-1}





Acknowledgements: Jing Li, PhD - University of New Haven

Flame Heat Flux Validation: Uniform Vertical Burning

Flame Heat Flux Validation: Uniform Vertical Burning

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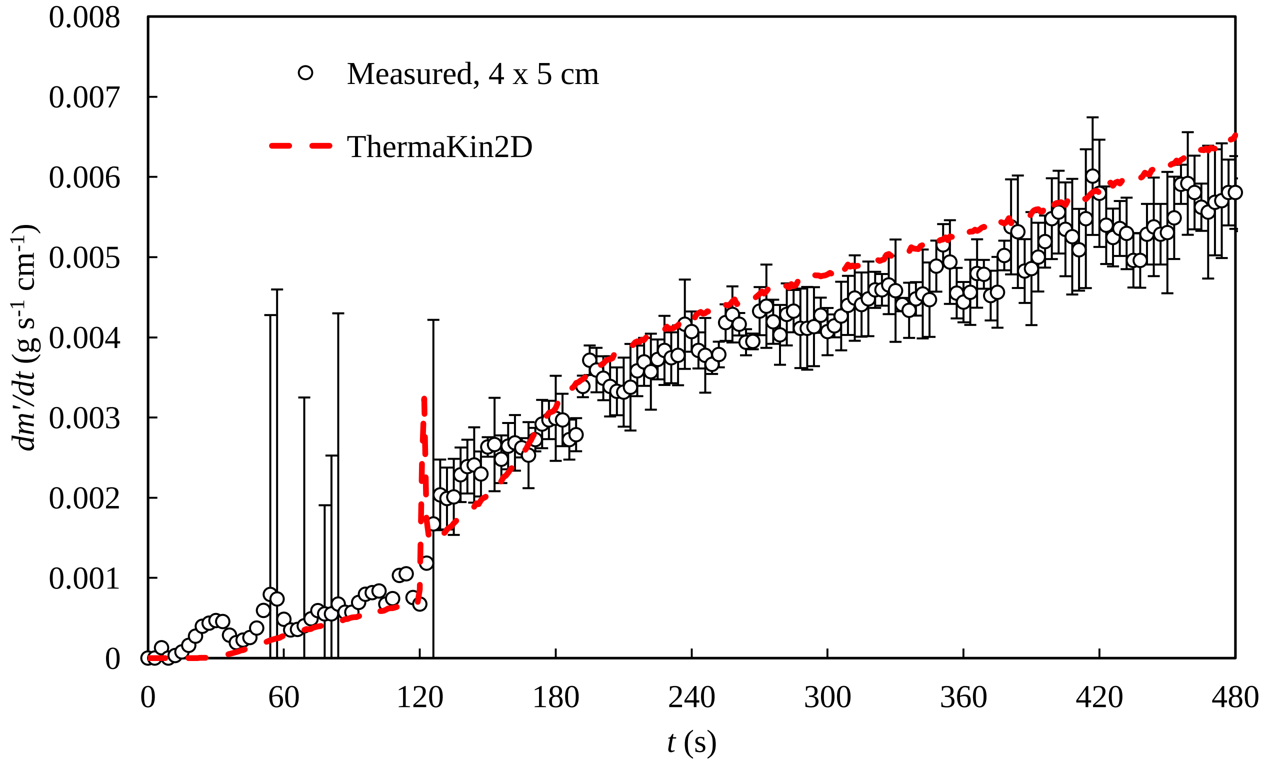

Flame Heat Flux Validation

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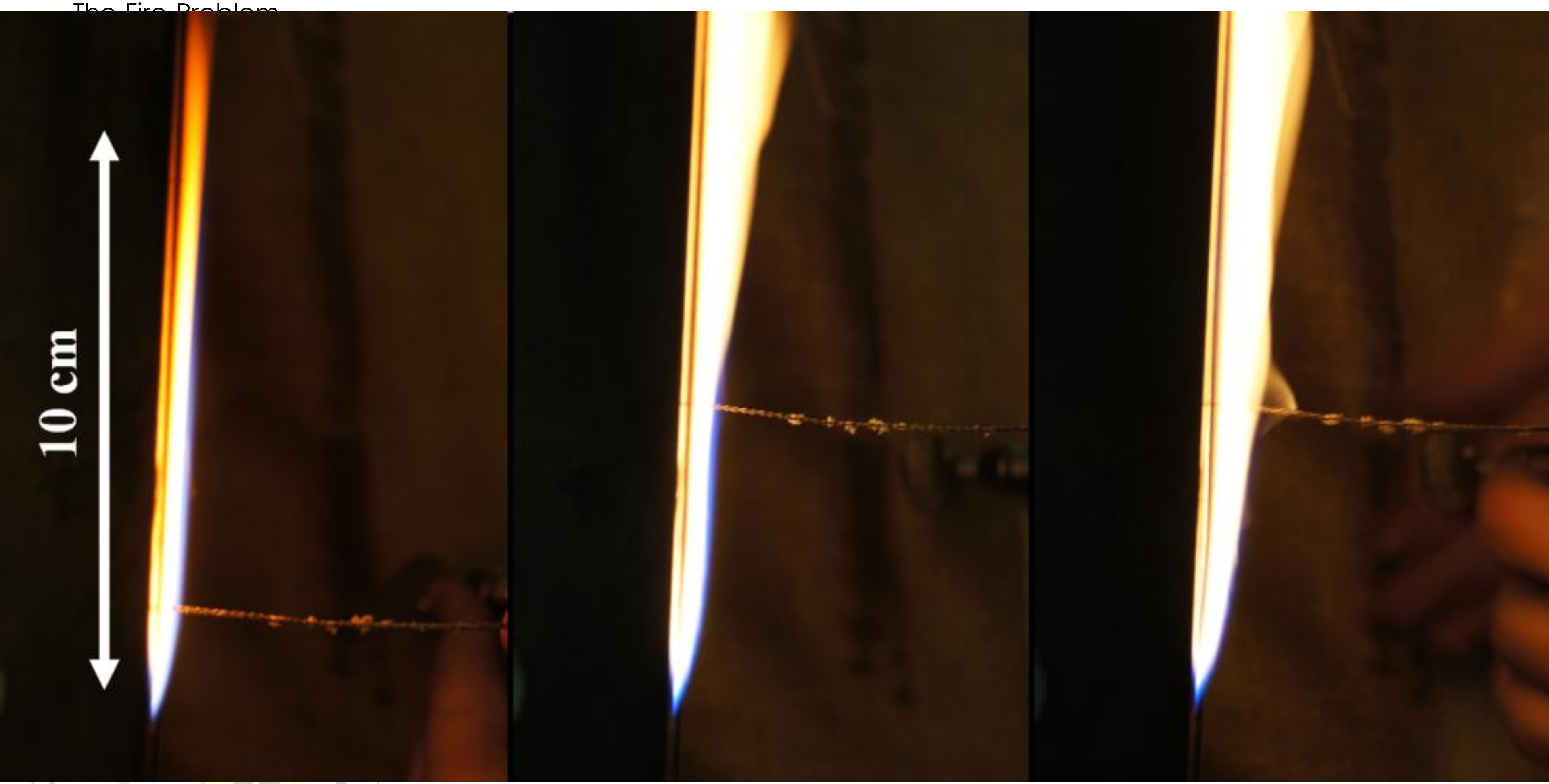
The Fire Problem



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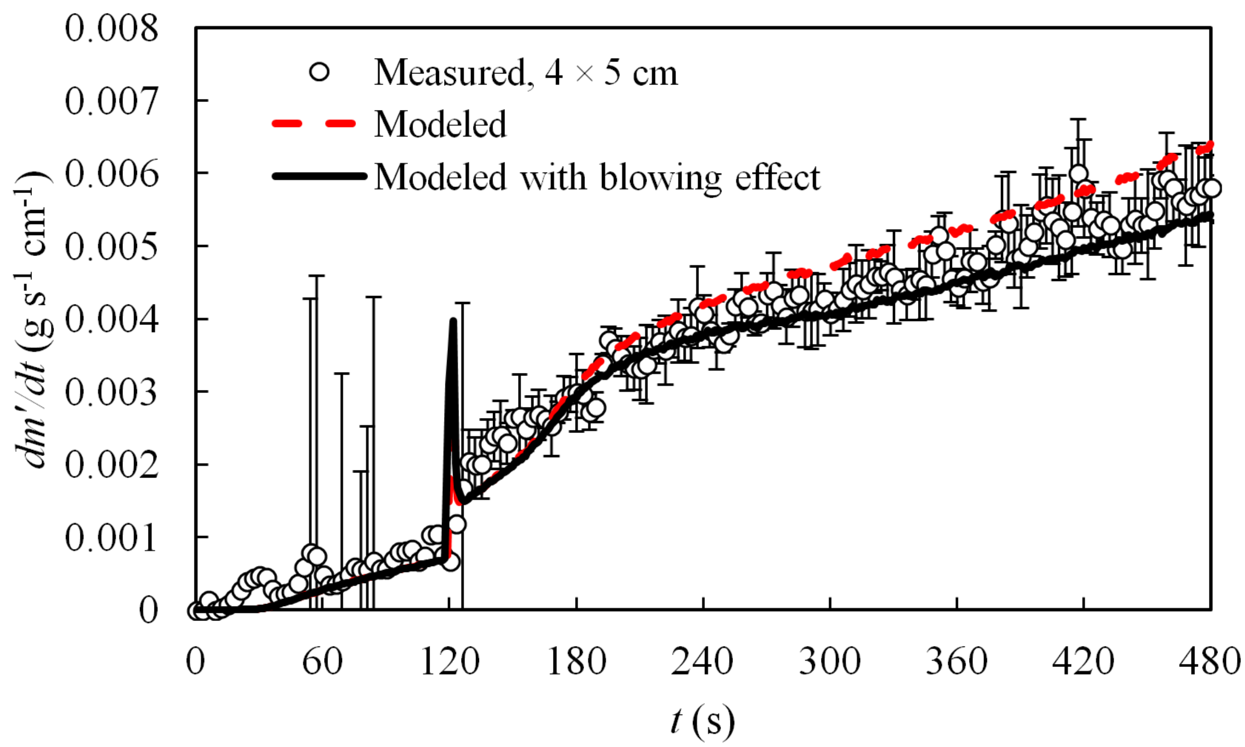

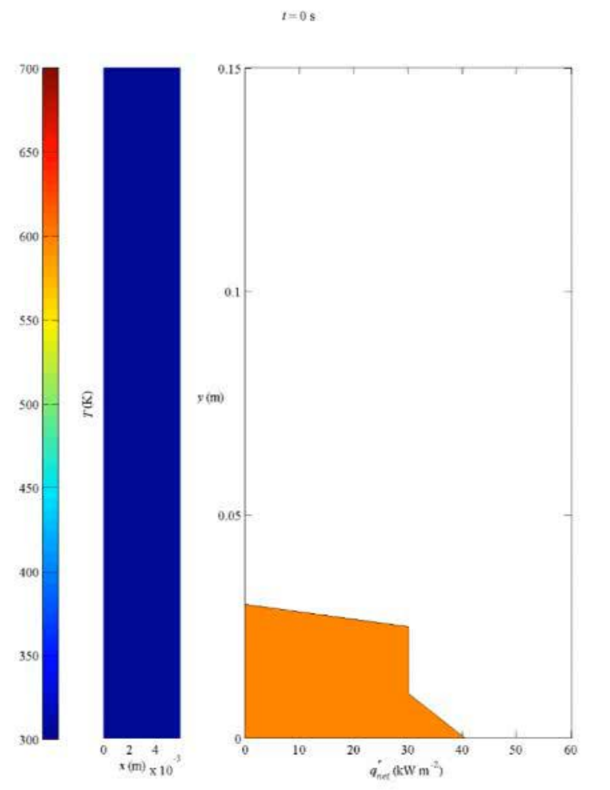

t = 0 s
700
650
600
550
500
450
400
350
300
T (K)
0 2 4
x (m) x 10^-3
y (m)
0.15
0.1
0.05
0
0 10 20 30 40 50 60
q"net (kW m^-2)

Upward Flame Spread

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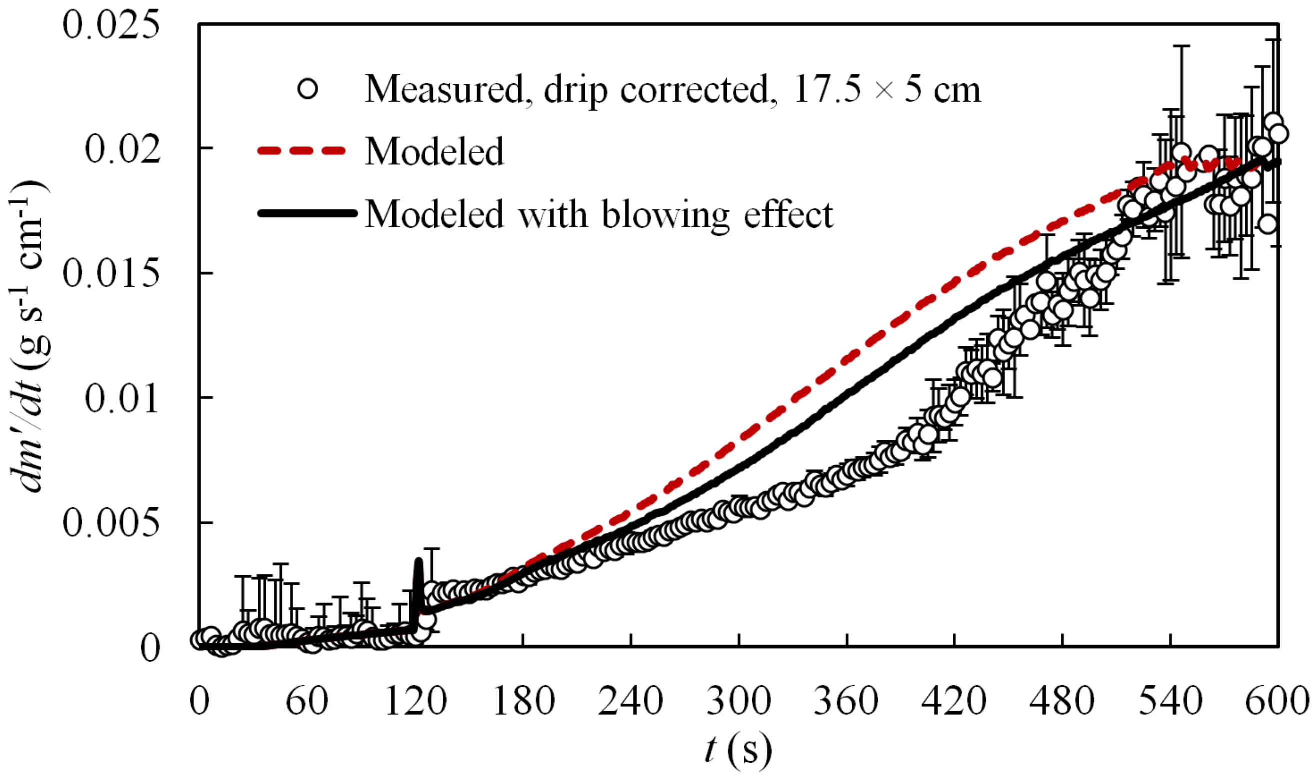

Upward Flame Spread

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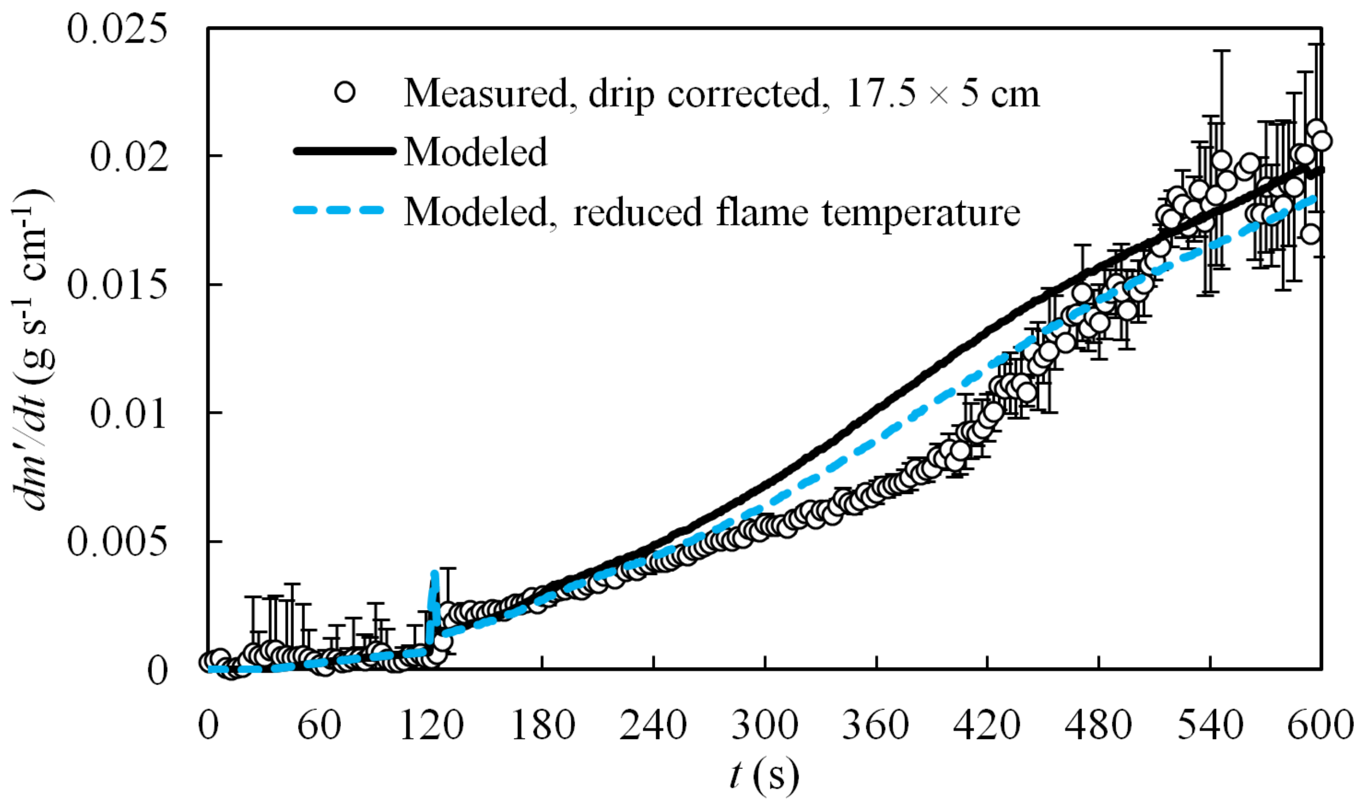
Impact of maximum flame temperature on ThermaKin2D simulations of burning rate during upward flame spread over PMMA



Effect of Dripping on Flame Heat Flux

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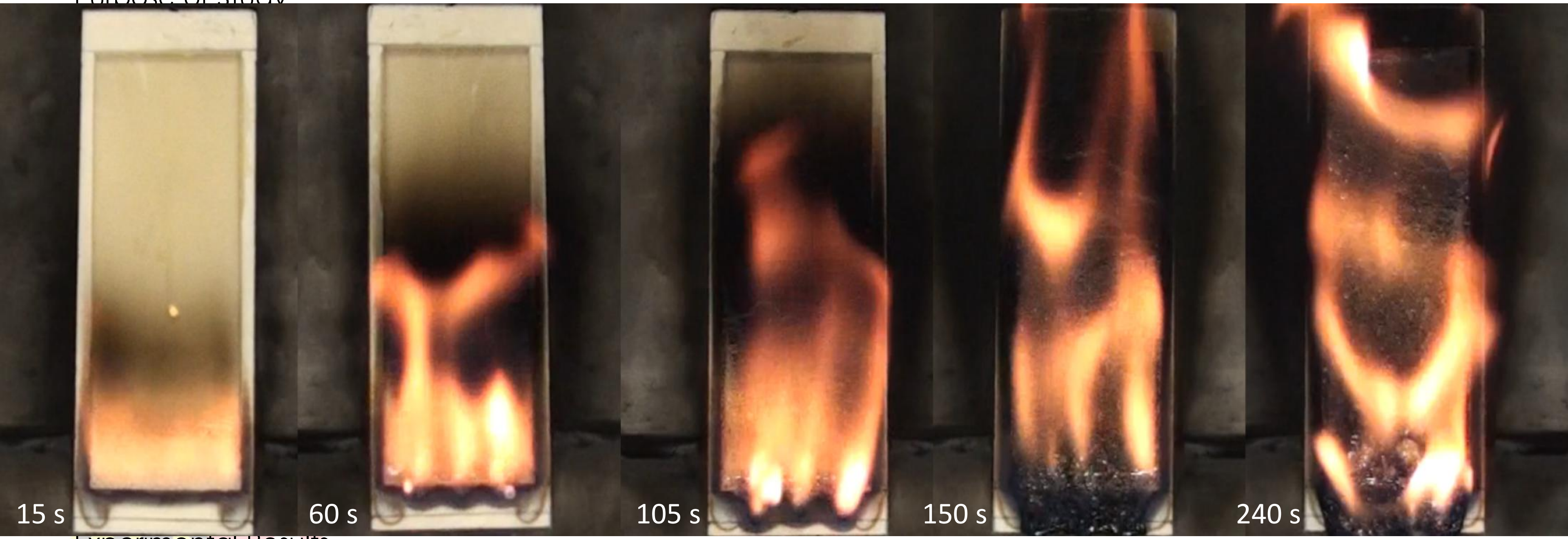

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$$J_{flow} = u \exp\left(-\frac{v}{RT_{surf}}\right)$$

Effect of Dripping on Flame Heat Flux

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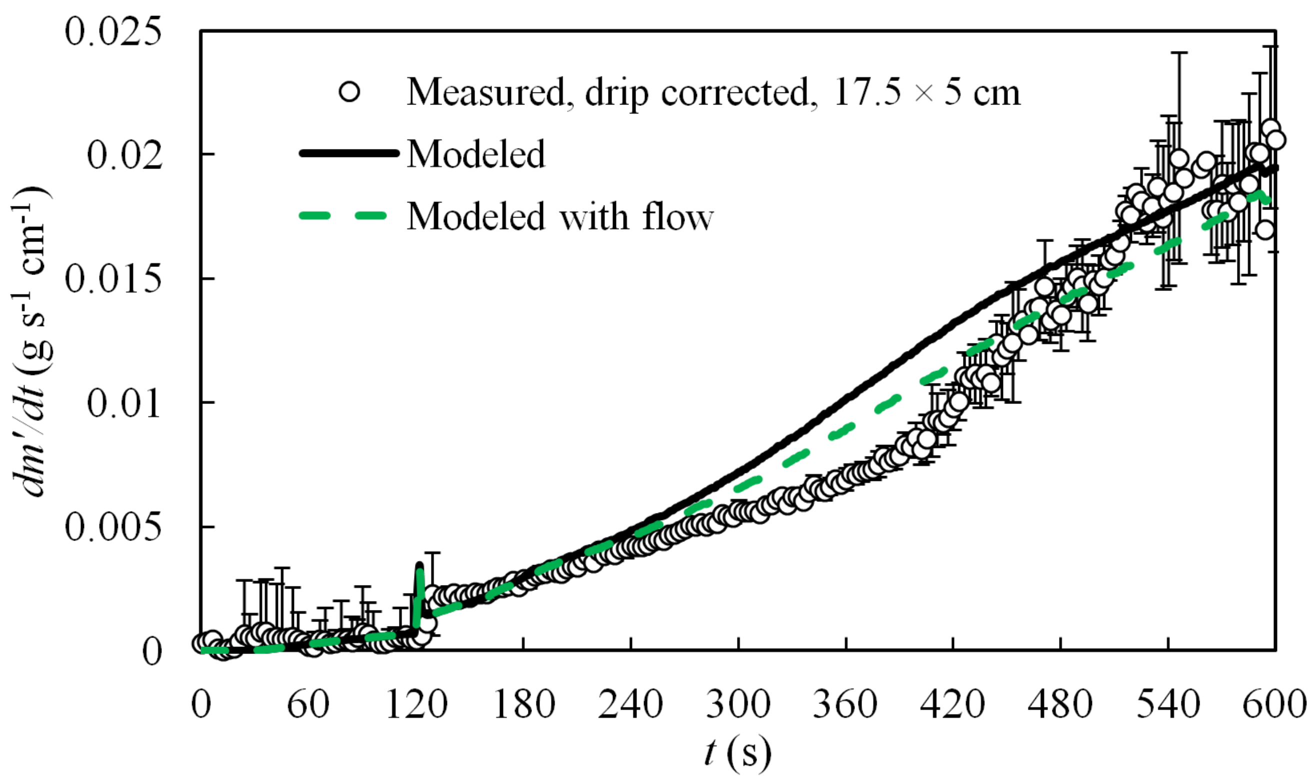
Impact of polymer melt flow on ThermaKin2D simulations of burning rate during upward flame spread over PMMA



A Generalized Wall Flame Model

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- Generalize flame model to predict the behavior of flames supported by a wide range of materials
- Wall flame height is often calculated as a function of heat release rate
- Attempt scaling of model expressions on the basis of the heat of combustion of the gaseous volatiles
  - Flame height
  - Peak heat flux

Experiments Conducted

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- Materials
  - PMMA (cast) ABS, Fiberglass, HDPE, HIPS, PBT, PET, PP, POM
- Sample Dimensions
  - Height 3 to 15 cm
  - Width 5 cm
- Measurements
  - Mass loss rate
  - Flame heat flux
  - Heat of Combustion

Acknowledgements: Kevin Korver - University of Maryland

Test Apparatus

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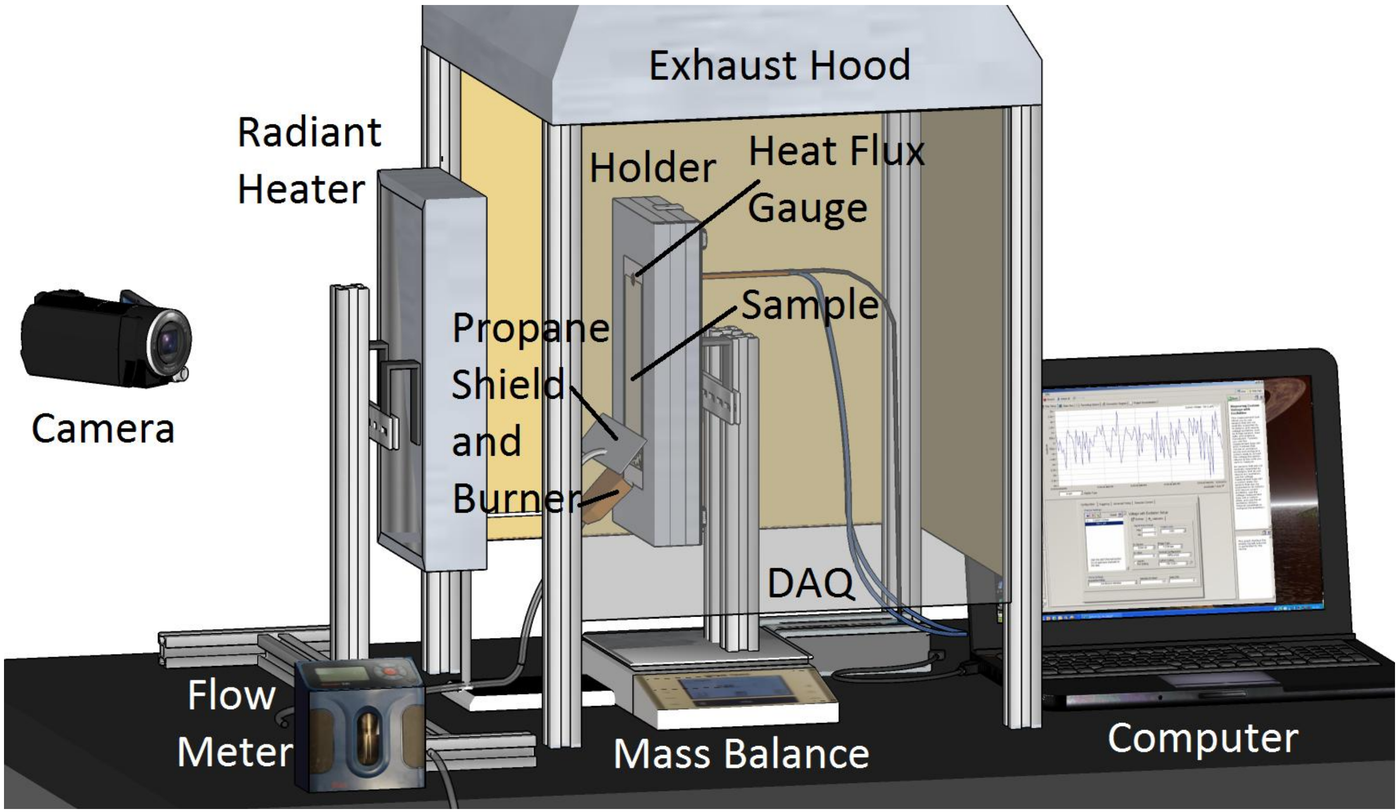

Heat of Combustion Measurements

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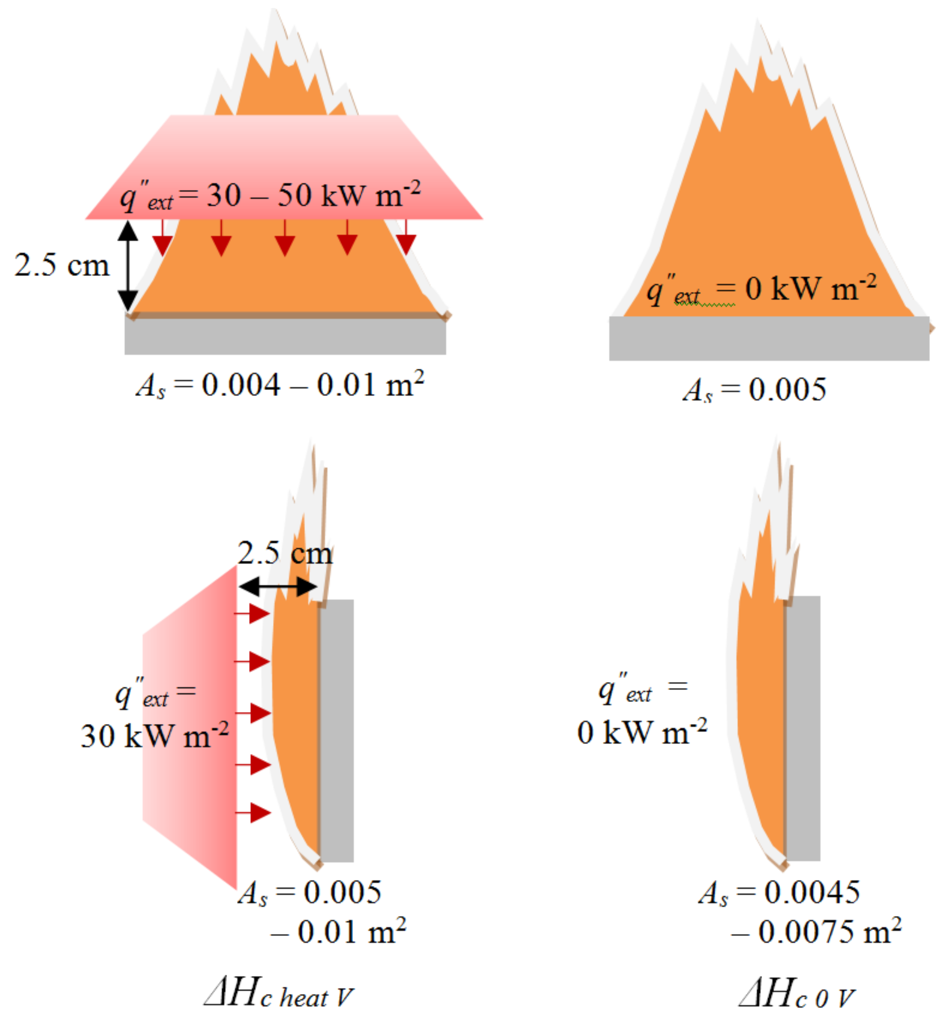

Acknowledgements: Kevin Korver - University of Maryland

Cast PMMA

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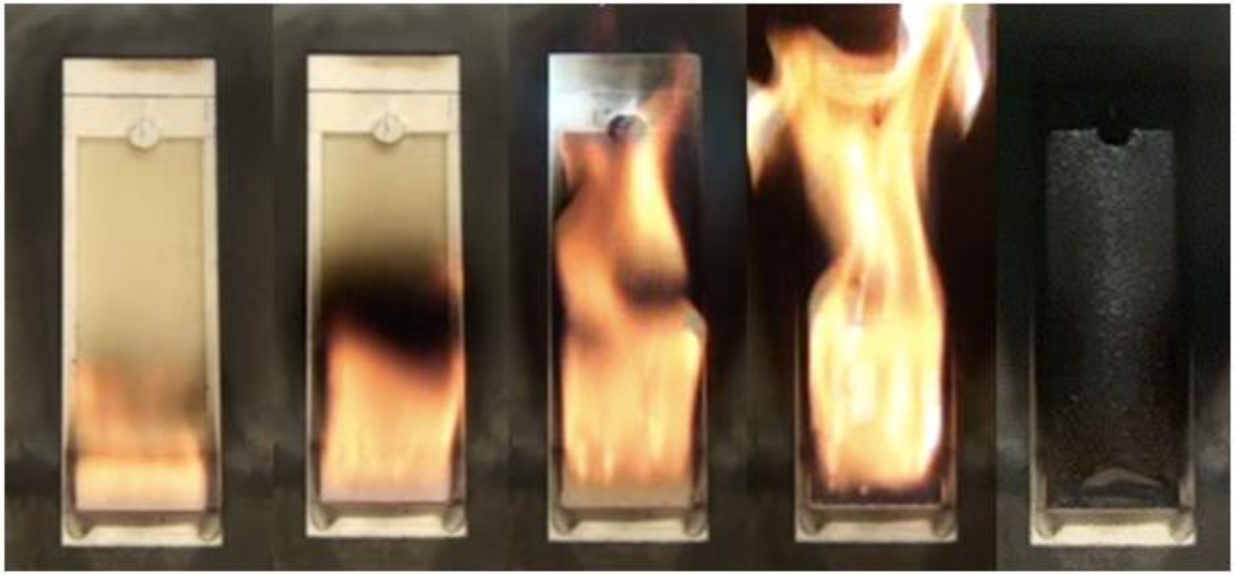
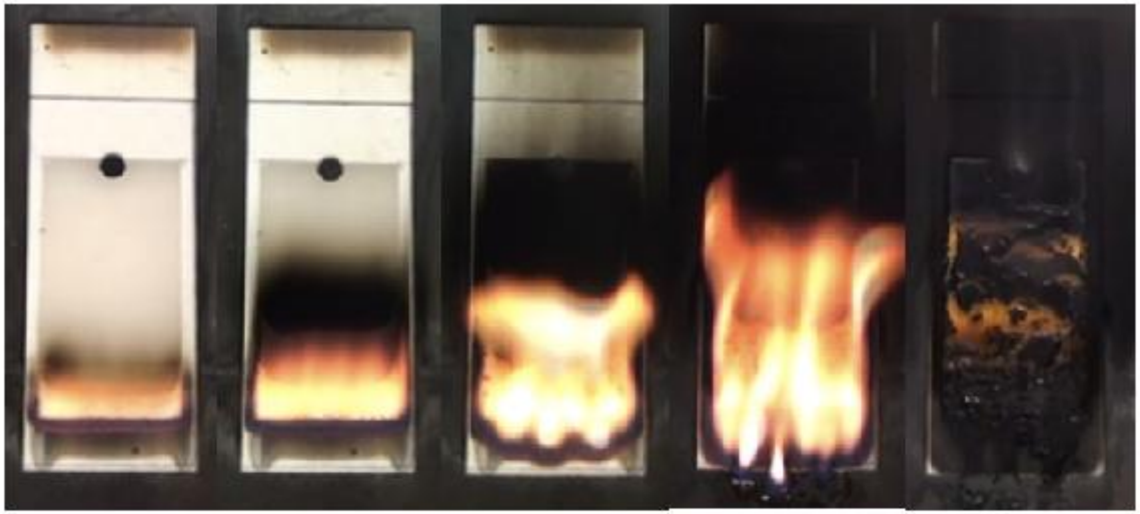


10 s | 60 s | 180 s | 480 s | Extinguish

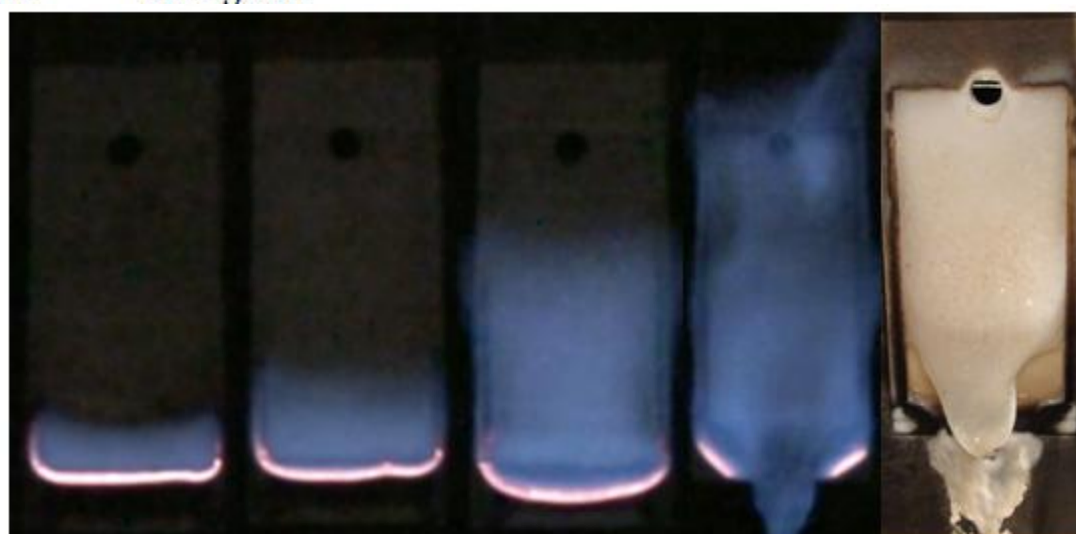
Materials Exhibiting Significant Melt Flow: PP and POM



PP

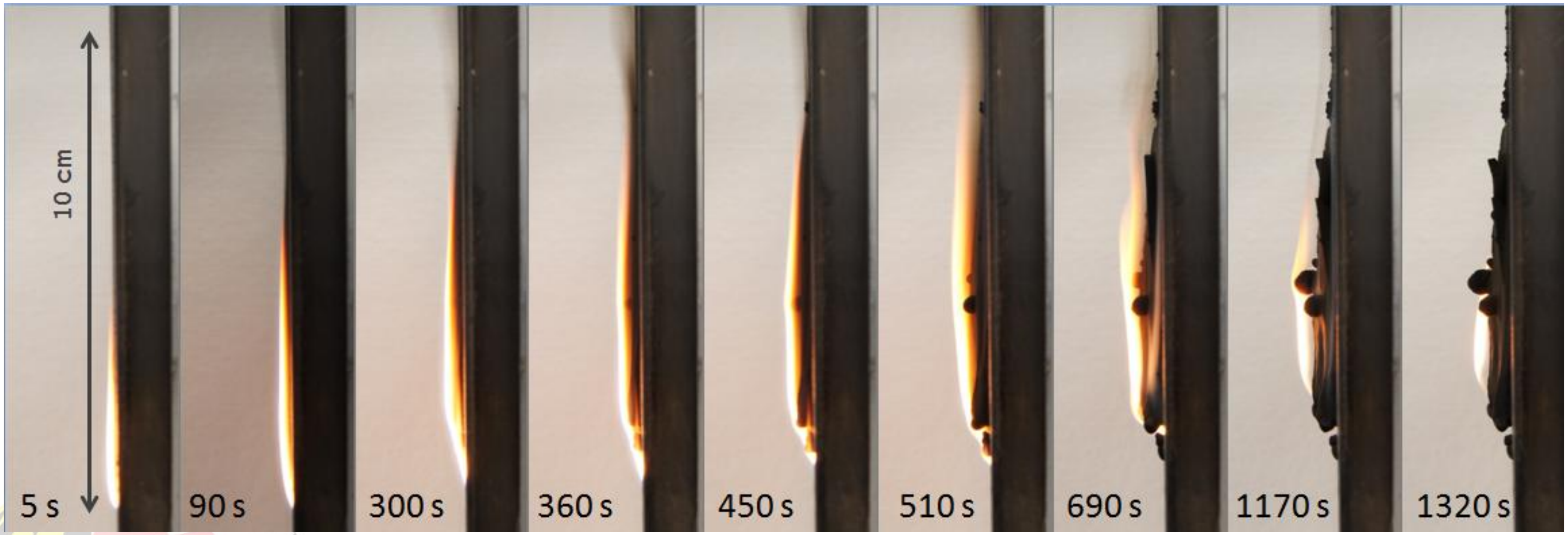
10 s 60 s 180 s 300 s Extinguish

POM

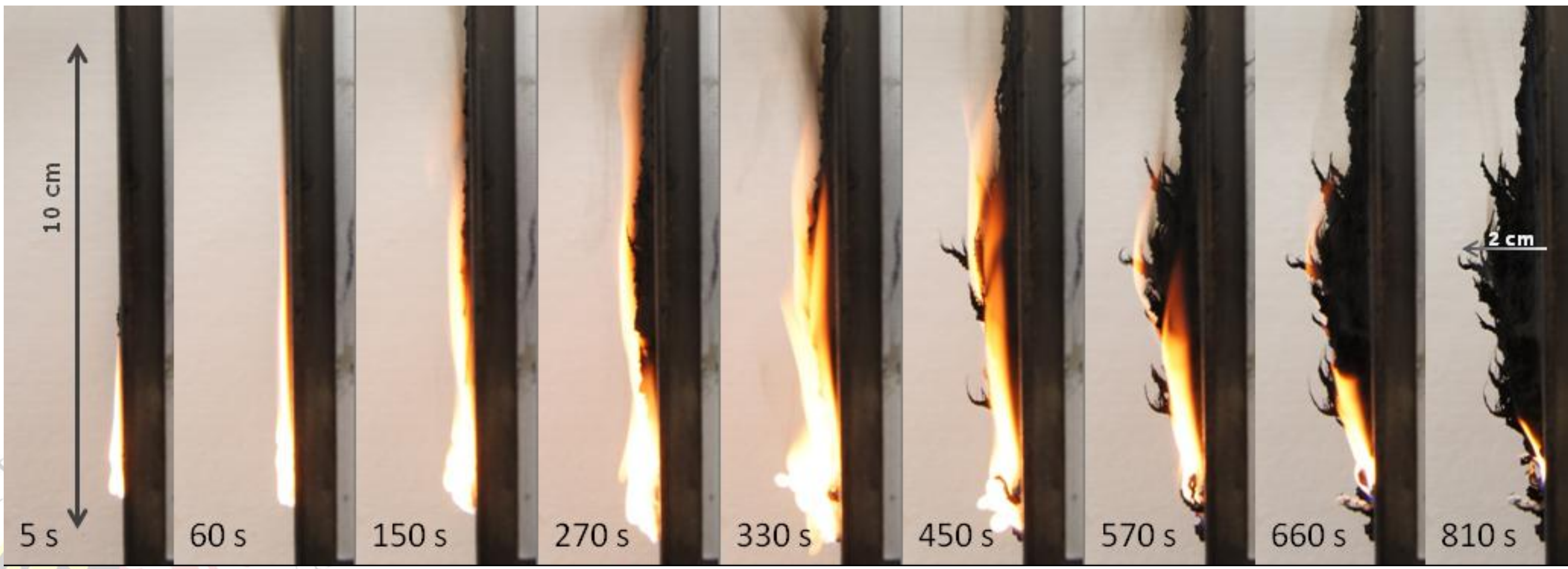


10 s 60 s 180 s 420 s Extinguish

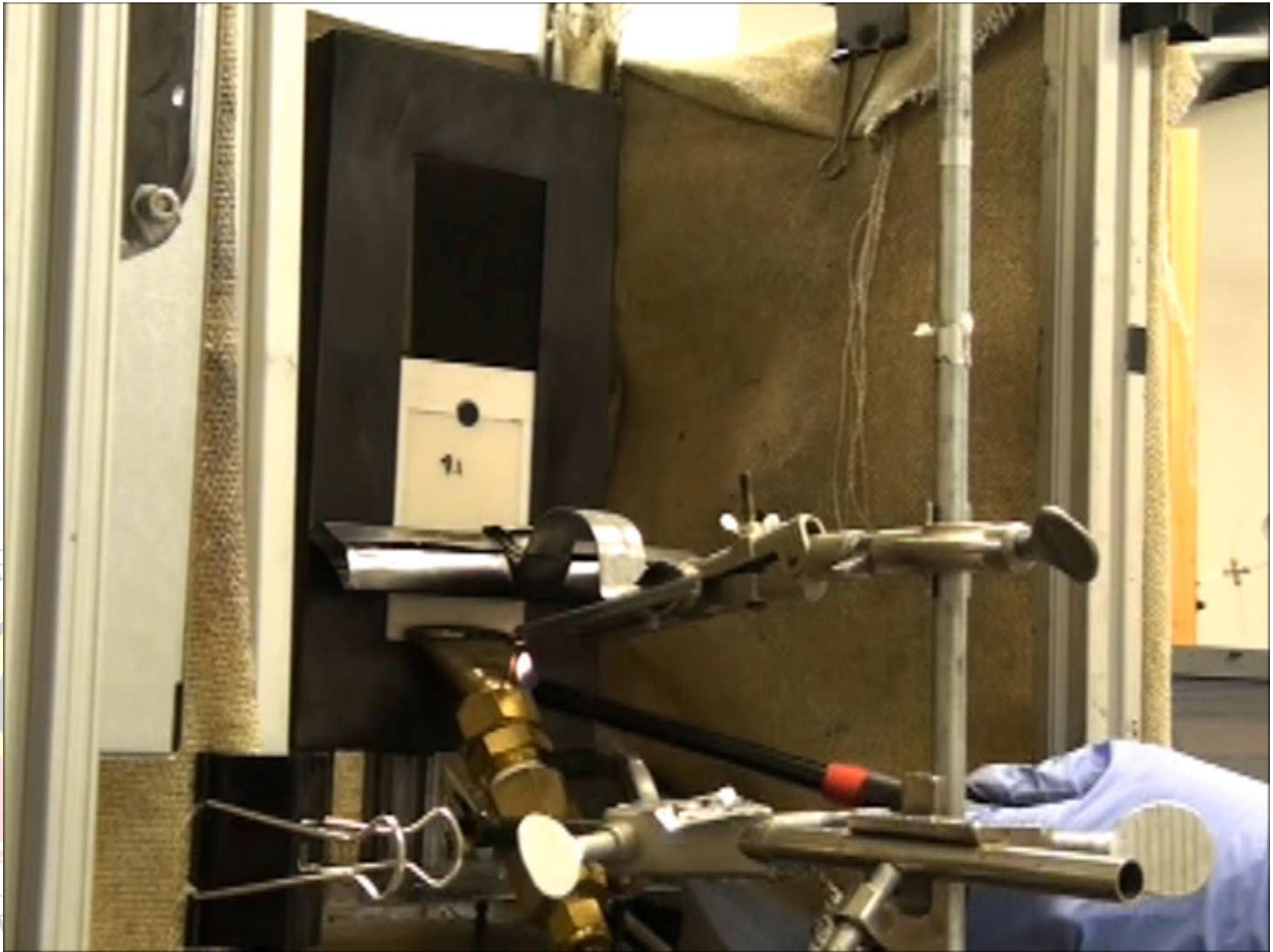
Heavily Sooting Materials: ABS



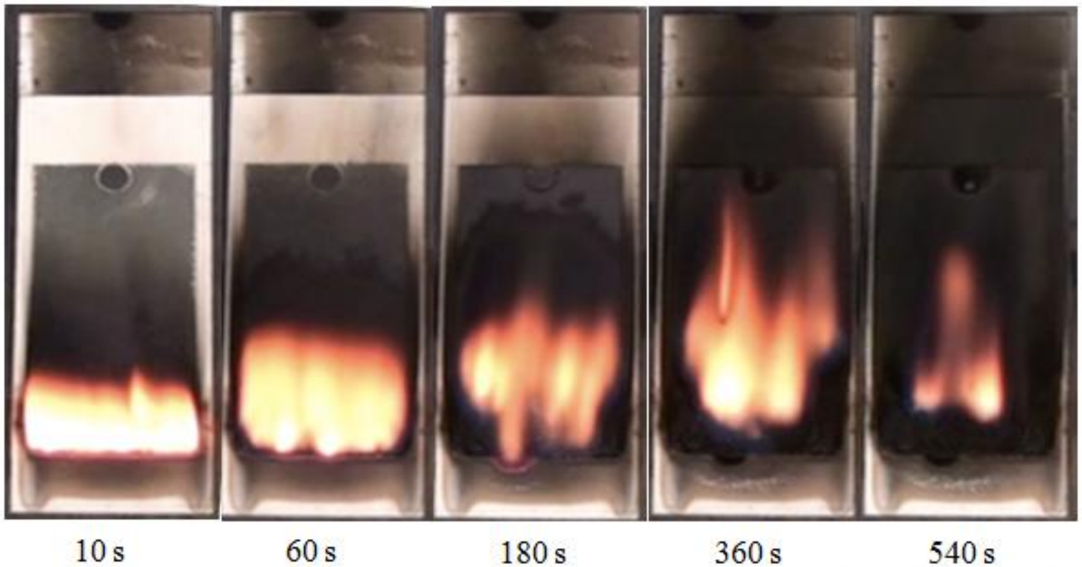
Heavily Sooting Materials: HIPS



Heavily Sooting Materials: Shielded Heat Flux Tests

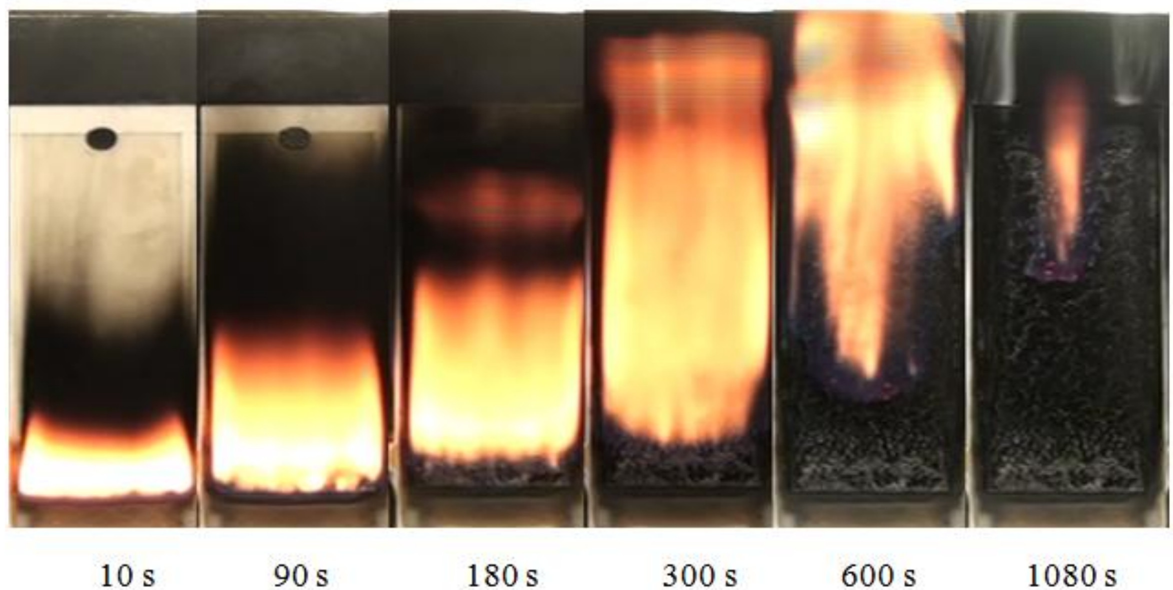


Glass-Reinforced Composite Materials: FRP and PBT



FRP

PBT



Mass Loss Rate

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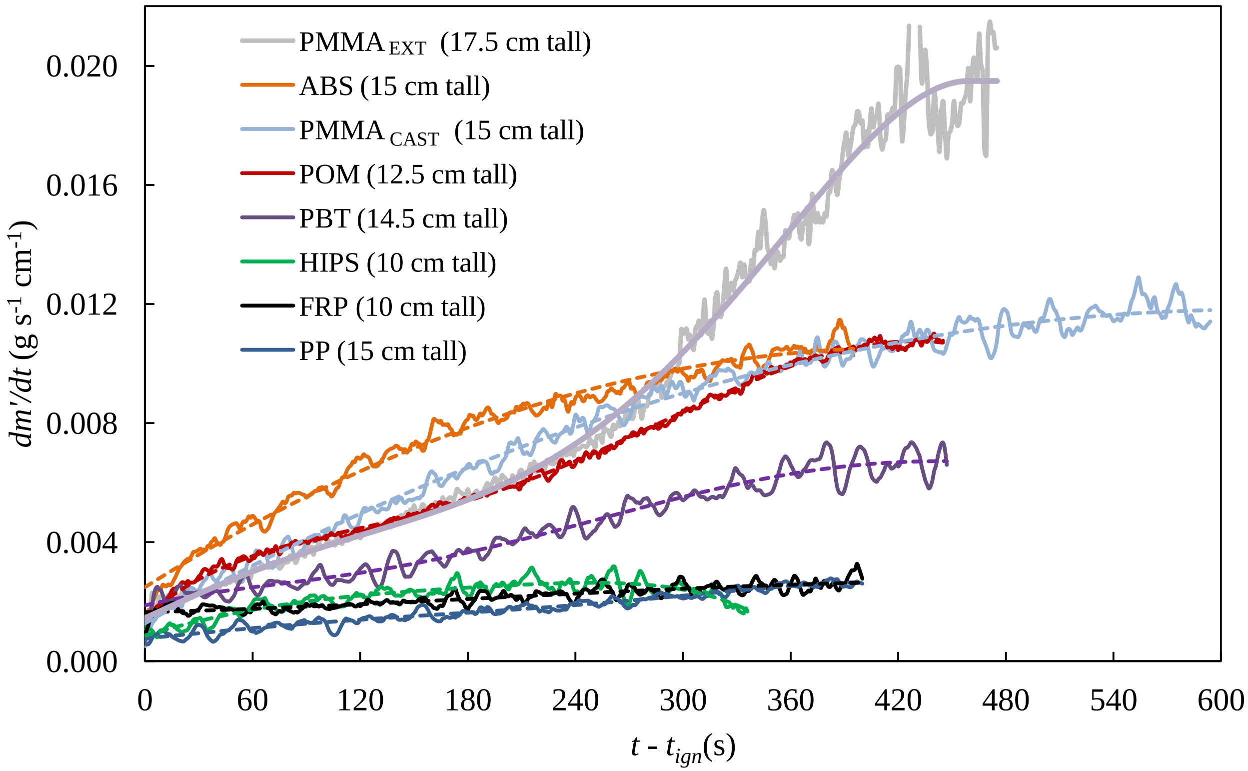

Acknowledgements: Kevin Korver - University of Maryland

Tracking the Location of the Base of the Flame, y_b

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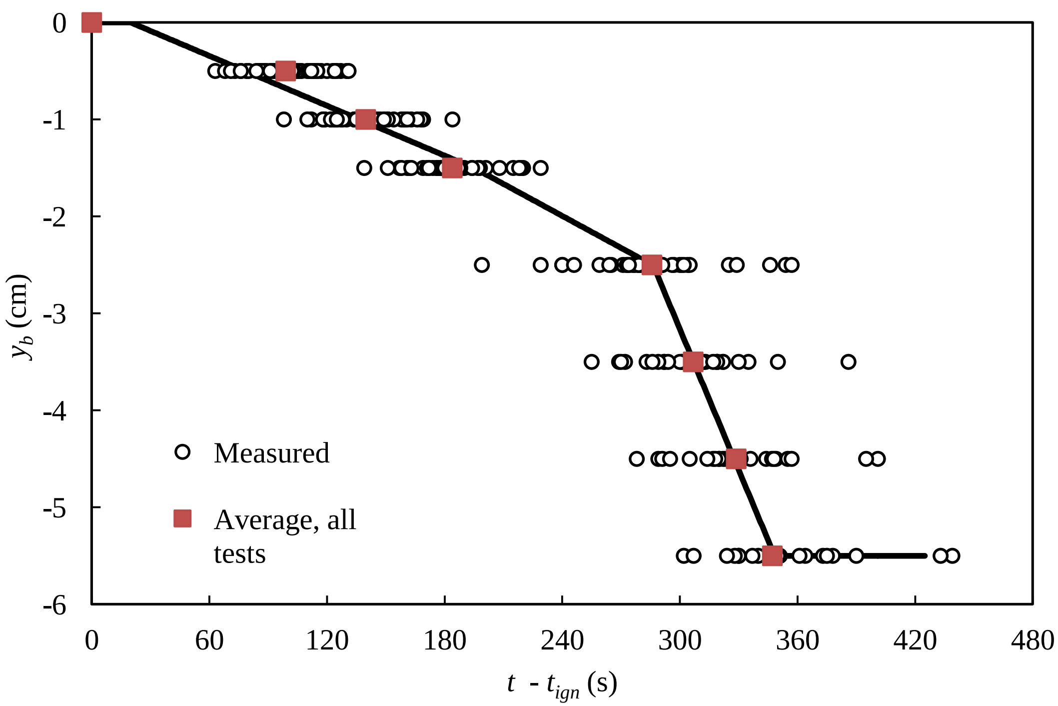

Tracking the Location of the Base of the Flame, y_b

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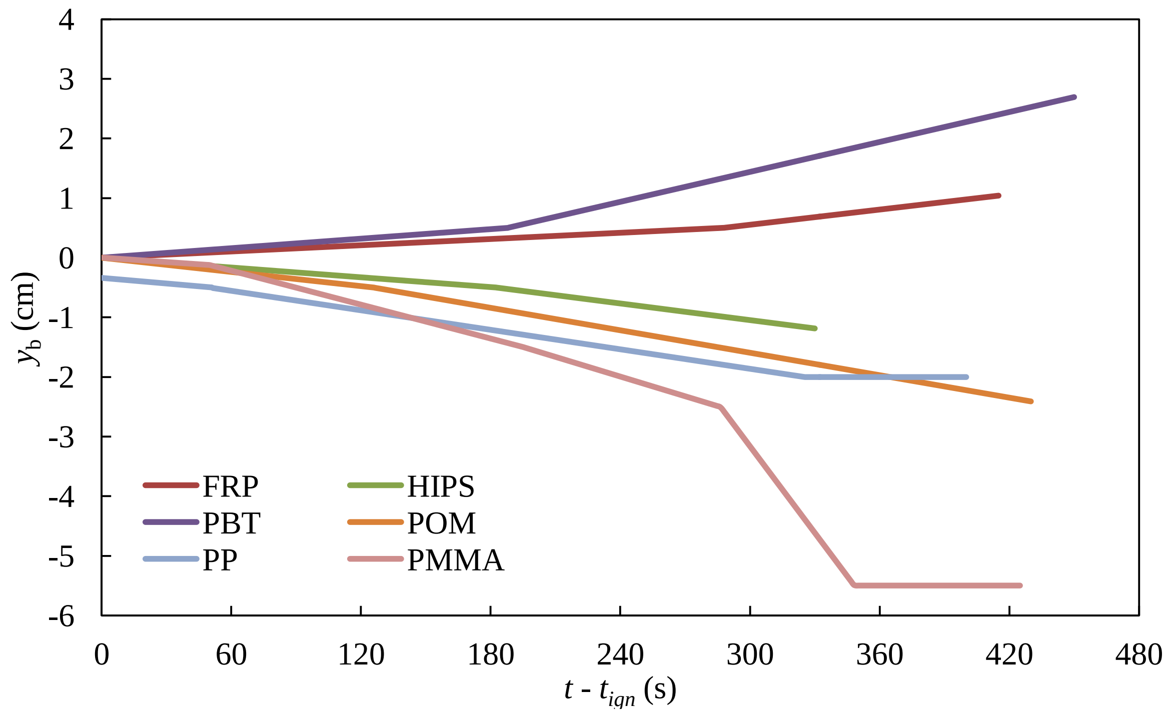
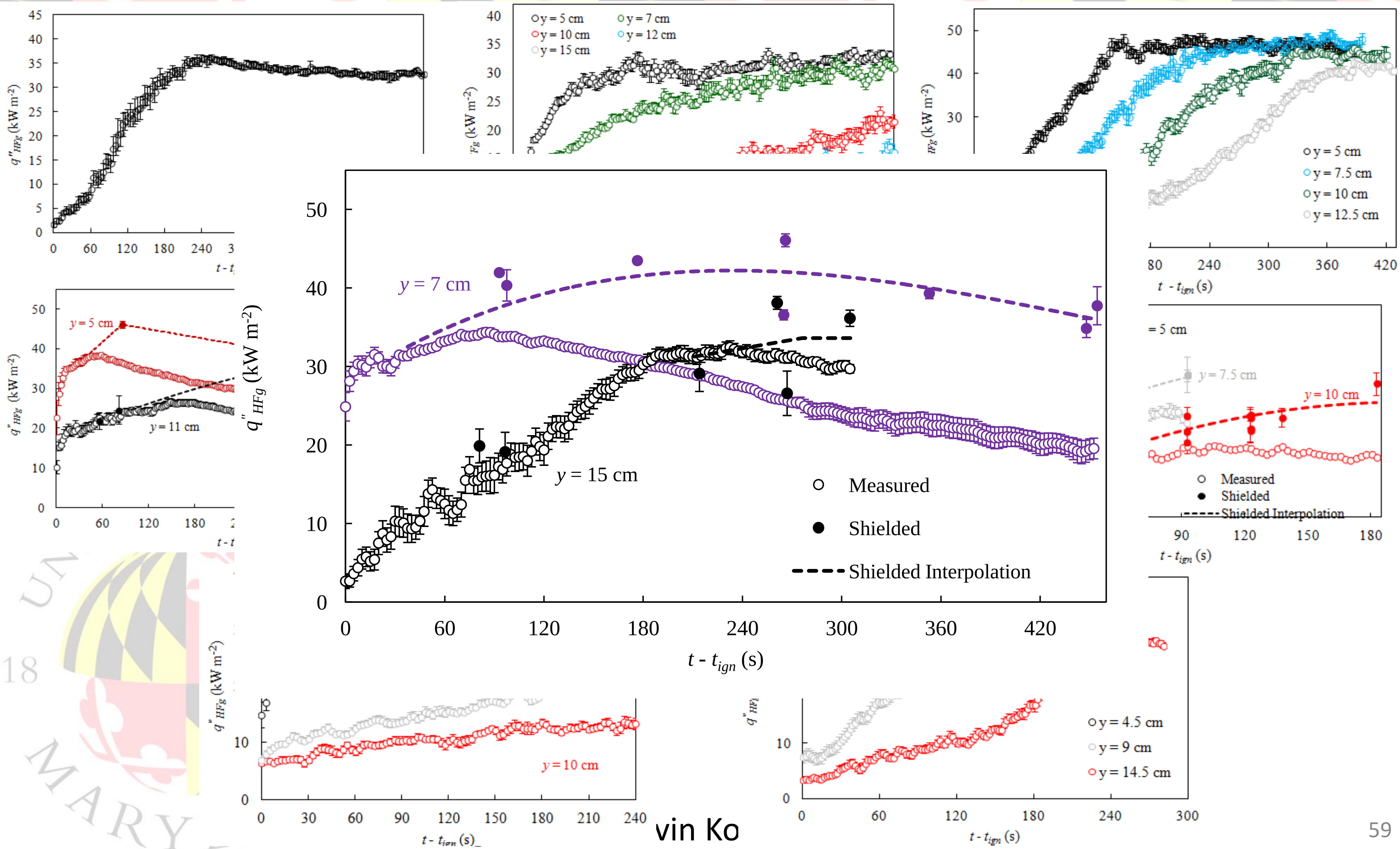
$$y_b = d_0 + d_1 \left(t - t_{ign} \right)$$



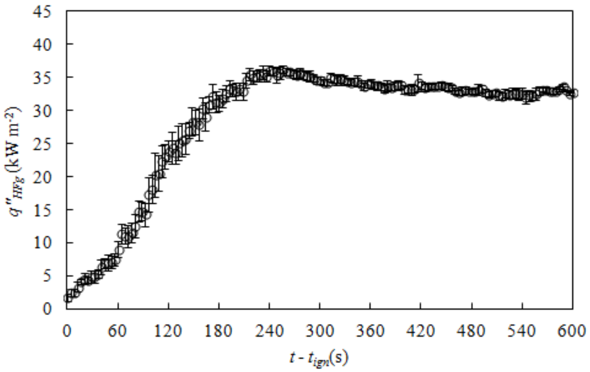
Acknowledgements: Kevin Korver - University of Maryland

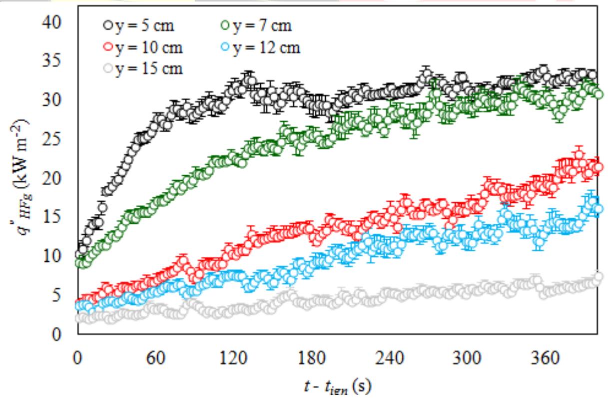
Measured Flame Heat Flux

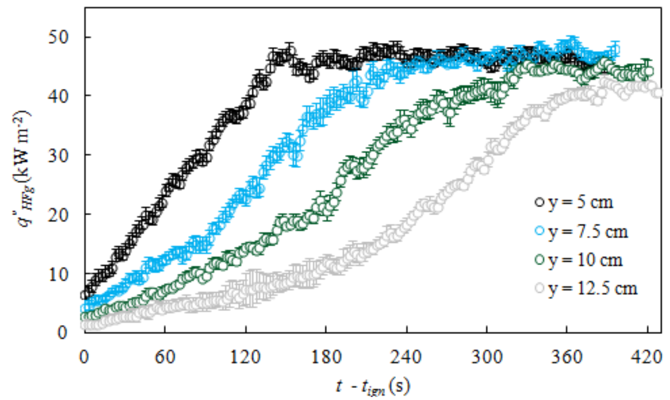


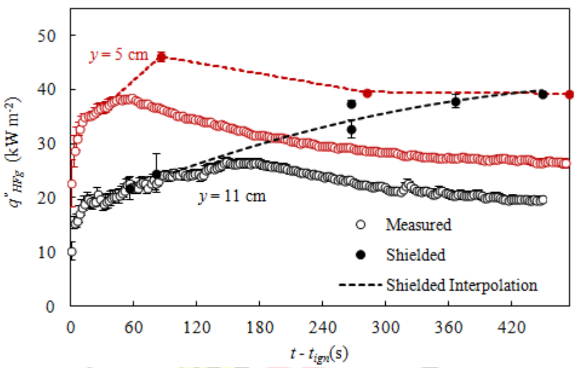
vin Ko

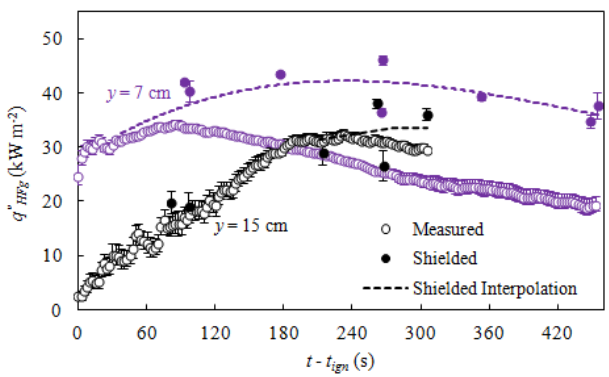
Measured Flame Heat Flux

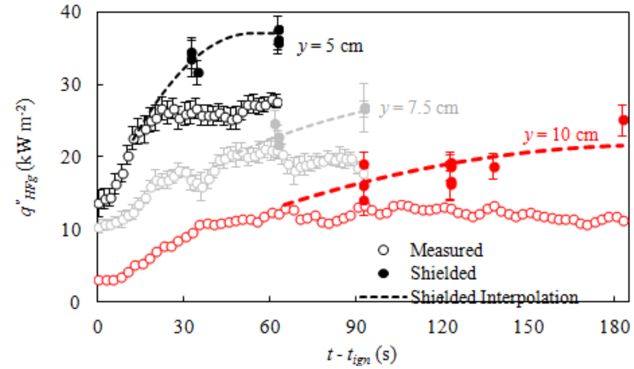


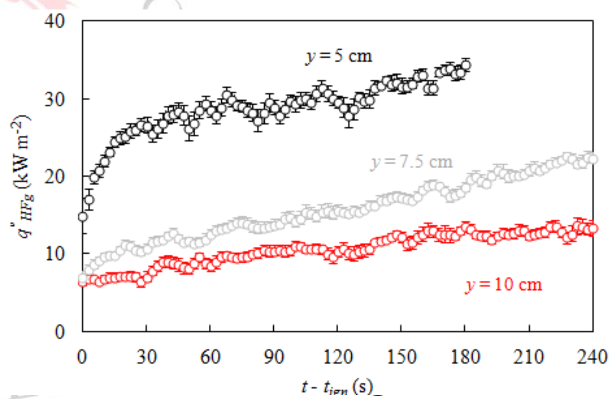


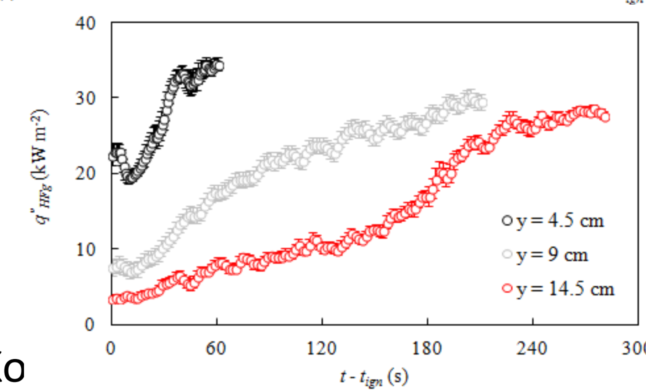












vin Ko

Heat of Combustion

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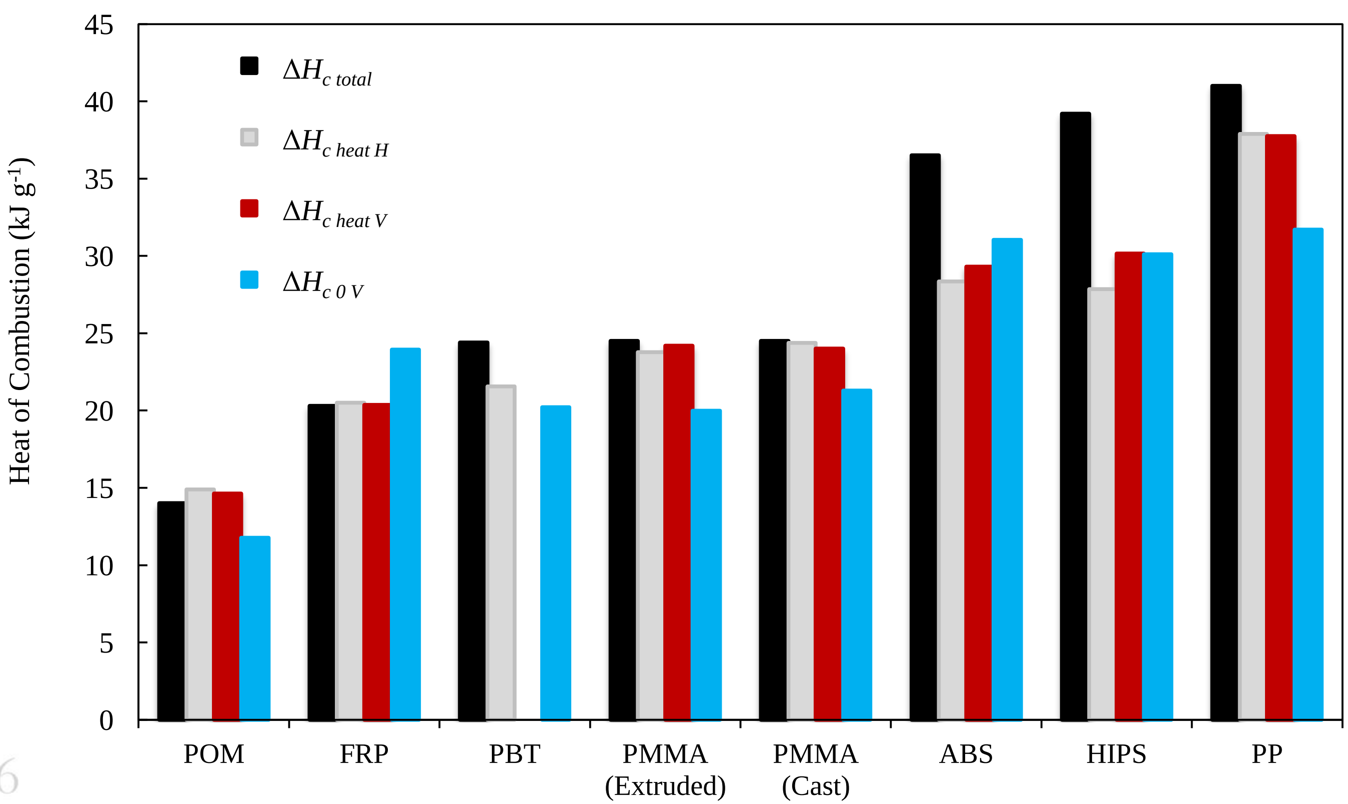

Flame Heat Flux Model

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$$T_{fl,\max}^{PMMA} = \begin{cases} T_{fl,\,adiabatic}^{PMMA} & \forall \; y_{eff} \le 5\text{ cm} \\ 0.87 \times T_{fl,\,adiabatic}^{PMMA} & \forall \; y_{eff} > 5\text{ cm} \end{cases}$$

$$y_{eff} = y - y_b \qquad y_f = a\left(\frac{dm'}{dt}\right)^p + b \qquad y^* \equiv \frac{y_{eff} + y_0}{y_f + y_0}$$

$$q''_{flame} = q''\left(y, \frac{dm'}{dt}, T_{surf}\right) = \begin{cases} h_{flame}(T_{fl,\max}^{PMMA} - T_{surf}) & \forall \; y \le y_f \\ h_{flame}\left(\alpha_f \left(T_{fl,\max}^{PMMA} - T_{HFg}\right) e^{-\ln(\alpha_f)\times\left(y^*\right)^2} + T_{HFg} - T_{surf}\right) & \forall \; y > y_f \end{cases}$$

Flame Height

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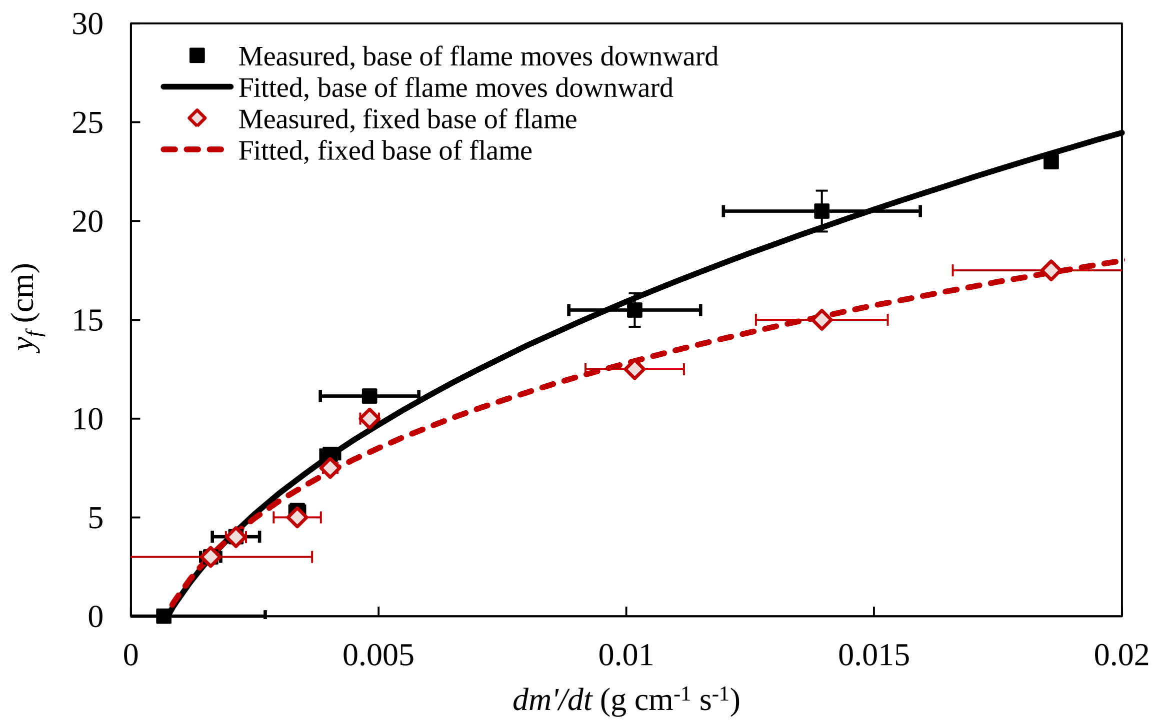
- Flame height, y_f, can be defined as the highest position, y_{eff}, where measured flame heat flux reaches 97.5 % of q''_{steady}



$$y_{eff} = y - y_b$$

Flame Model Predictions Extruded PMMA

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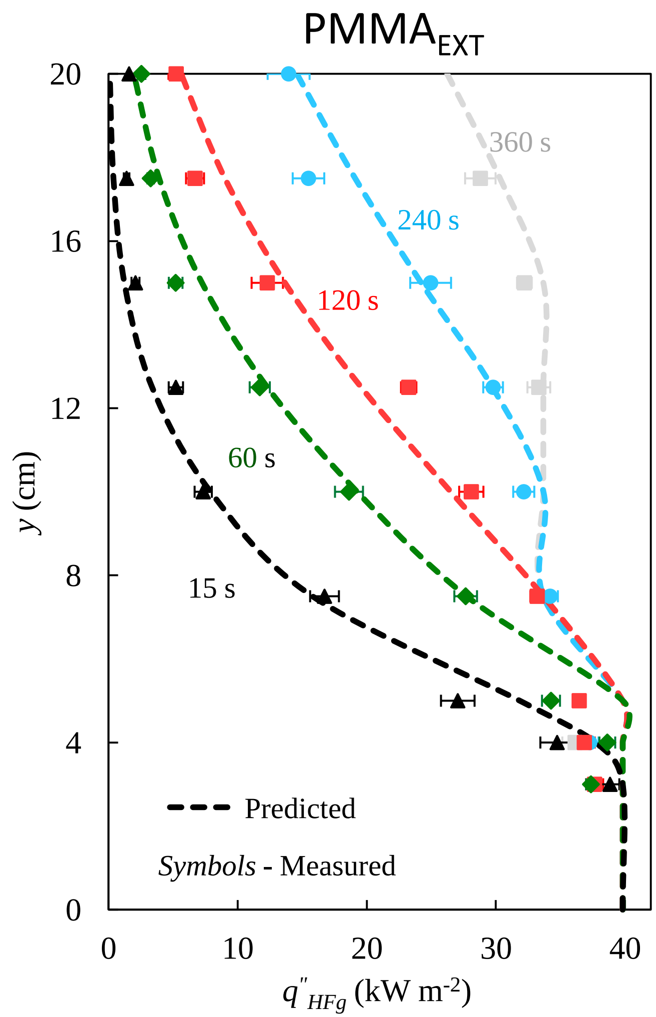

Flame Model Predictions
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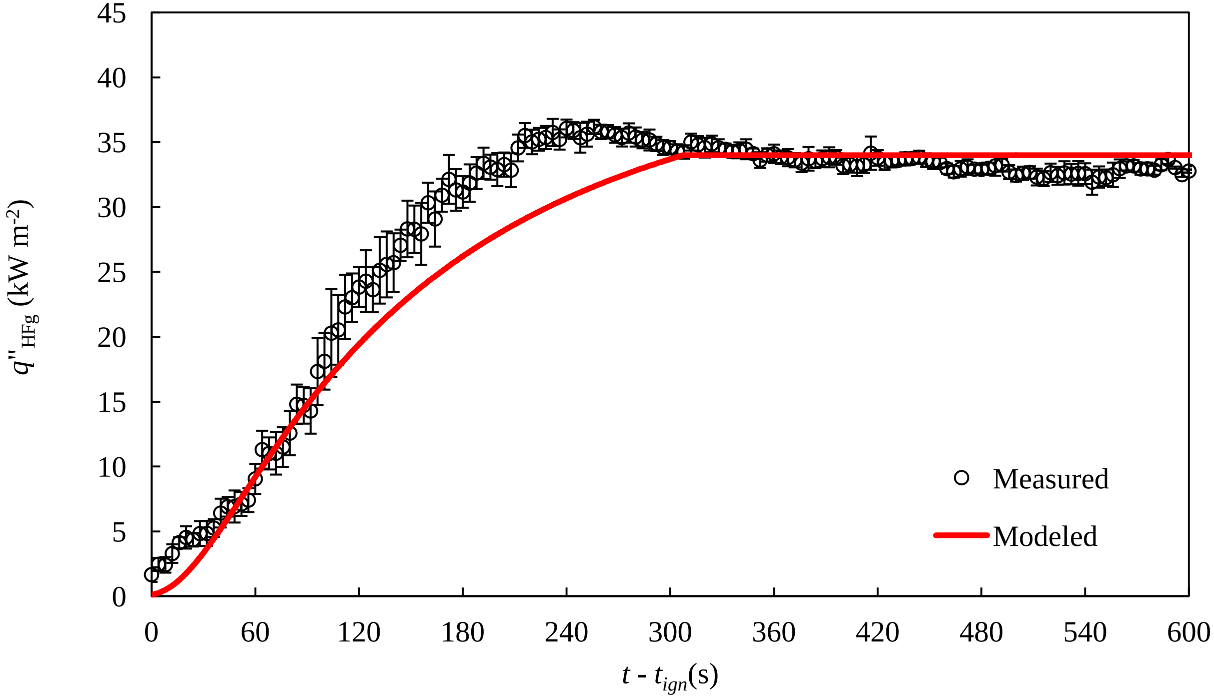

Generalized Flame Model

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$$T_{fl,\max}^{MATL} = \begin{cases} T_{fl,adiabatic}^{MATL} & \forall\ y_{eff} \le 5\,cm \\ 0.87 \times T_{fl,adiabatic}^{MATL} & \forall\ y_{eff} > 5\,cm \end{cases}$$

$$y_{eff} = y - y_b \qquad y_f = a\left(\frac{\Delta H_c^{MATL}}{\Delta H_c^{PMMA}}\frac{dm'}{dt}\right)^P + b \qquad y^* = \frac{y_{eff} + y_0}{y_f + y_0}$$

$$\dot{q}''_{flame} = \dot{q}''\left(y_{eff}, \frac{dm'}{dt}, T_{surf}\right) = \begin{cases} h_{flame}\left(T_{fl,\max}^{MATL} - T_{surf}\right) & \forall\ y_{eff} \le y_f \\ h_{flame}\left(\alpha_f\left(T_{fl,\max}^{MATL} - T_{HF,g}\right)e^{-\ln(\alpha_f)\times(y^*)^2} + T_{HF,g} - T_{surf}\right) & \forall\ y_{eff} > y_f \end{cases}$$

Model Accuracy

Material	*Method 1* $y_f \sim \Delta H_{c\ total}$ $T_{fl} \sim \Delta H_{c\ total}$	*Method 2* $y_f \sim \Delta H_{c\ heat\ H}$ $T_{fl} \sim \Delta H_{c\ heat\ H}$	*Method 3* $y_f \sim \Delta H_{c\ 0\_V}$ $T_{fl} \sim \Delta H_{c\ 0\_V}$	*Method 4* $y_f \sim (1-X_r)\ \Delta H_{c\ heat\ H}$ $T_{fl} \sim (1-X_r)\ \Delta H_{c\ heat\ H}$	*Method 5* $y_f \sim (1-X_r)\ \Delta H_{c\ heat\ H}$ $T_{fl} \sim \Delta H_{c\ total}$
ABS	5.4	6.6	5.9	10.8	6.6
FRP	1.6	4.0	12.4	5.1	4.0
HIPS	3.7	9.2	2.4	14.9	9.2
PBT	5.2	5.1	6.3	5.1	5.1
$PMMA_{CAST}$	2.1	2.0	2.1	2.0	2.0
POM	9.3	7.8	8.7	7.0	7.8
PP	1.7	2.1	2.2	6.1	2.1
Average	**4.2**	**5.2**	**5.7**	**7.3**	**5.2**

Model Accuracy

Material	*Method 1* $y_f \sim \Delta H_{c\ total}$ $T_{fl} \sim \Delta H_{c\ total}$	*Method 2* $y_f \sim \Delta H_{c\ heat\ H}$ $T_{fl} \sim \Delta H_{c\ heat\ H}$	*Method 3* $y_f \sim \Delta H_{c\ 0\ V}$ $T_{fl} \sim \Delta H_{c\ 0\_V}$	*Method 4* $y_f \sim (1-X_r)\ \Delta H_{c\ heat\ H}$ $T_{fl} \sim (1-X_r)\ \Delta H_{c\ heat\ H}$	*Method 5* $y_f \sim (1-X_r)\ \Delta H_{c\ heat\ H}$ $T_{fl} \sim \Delta H_{c\ total}$
ABS	5.4	6.6	5.9	10.8	6.6
FRP	1.6	4.0	12.4	5.1	4.0
HIPS	3.7	9.2	2.4	14.9	9.2
PBT	5.2	5.1	6.3	5.1	5.1
$PMMA_{CAST}$	2.1	2.0	2.1	2.0	2.0
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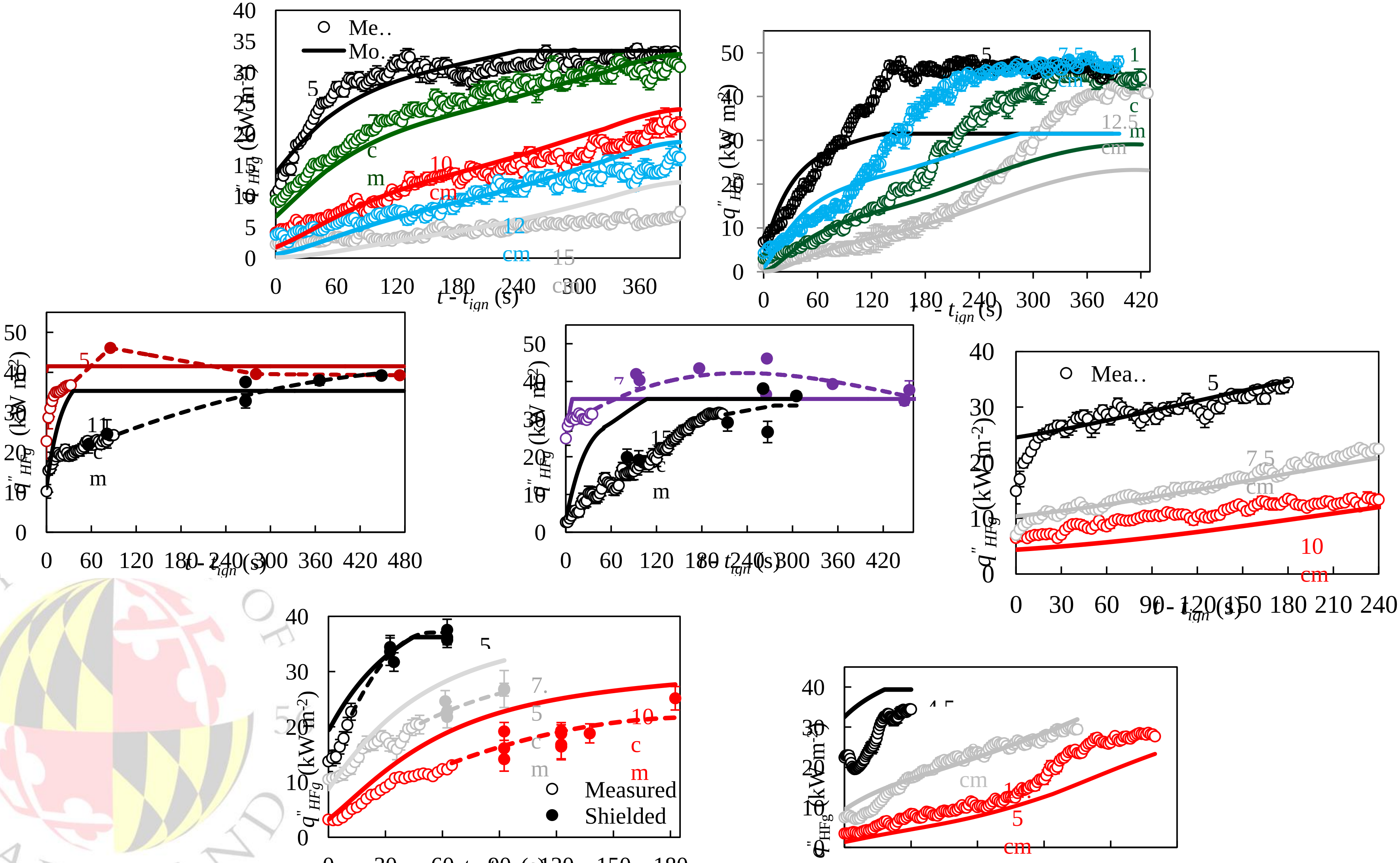
Average	**4.2**	**5.2**	**5.7**	**7.3**	**5.2**

Model–Predicted Flame Heat Flux



Generalized Flame Model

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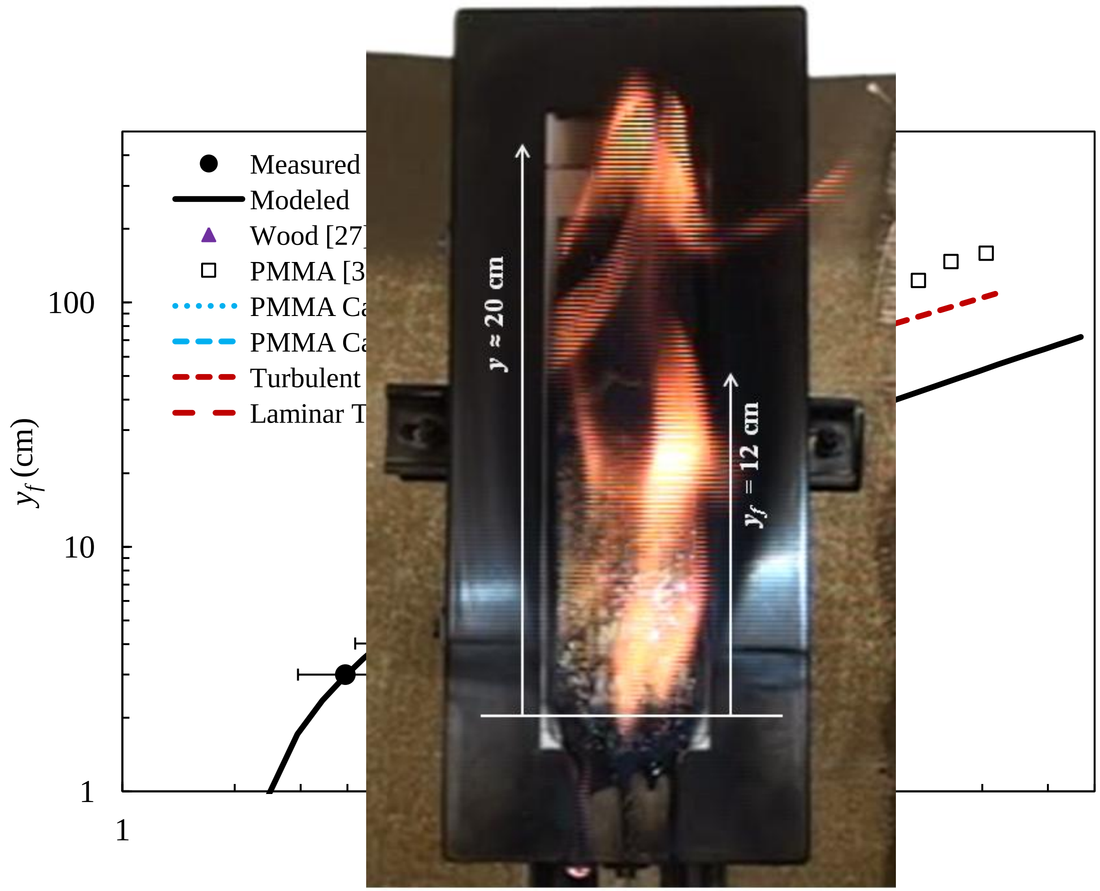

Modeling of Standard Flammability Tests – ISO9705, UL 94

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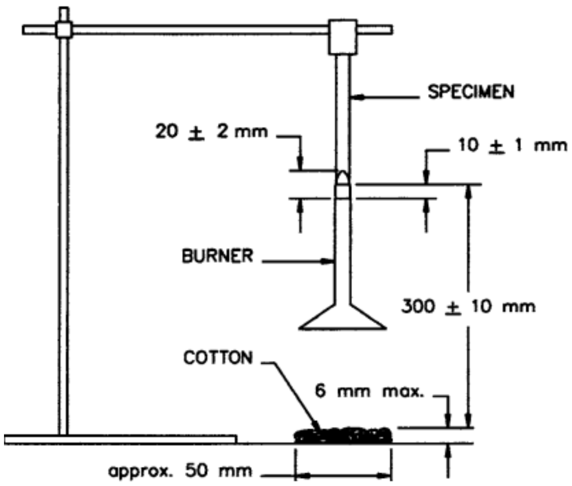

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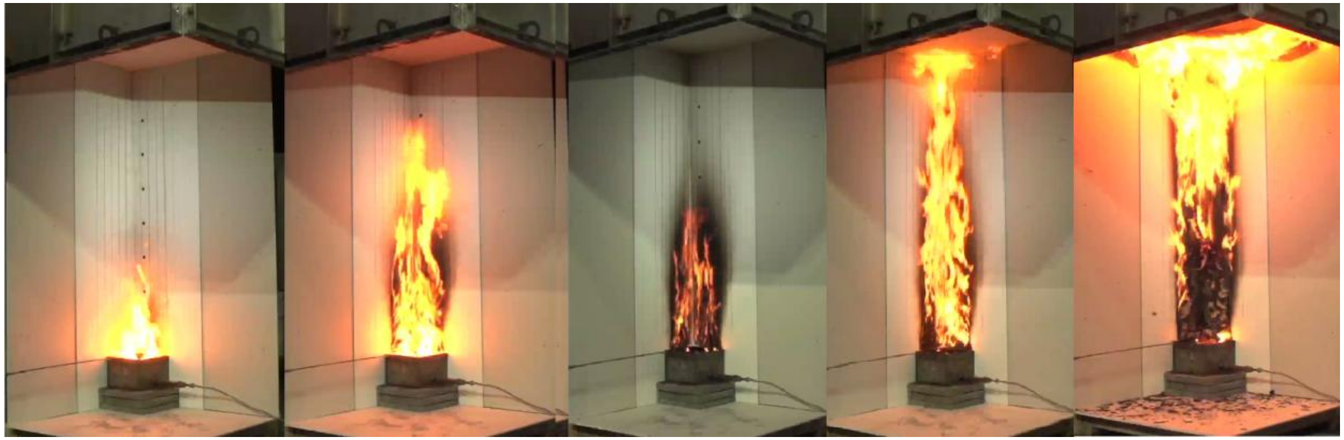

110 s | 227 s | 245 s | 347 s | 533 s

Acknowledgements: Chad Lannon - University of Maryland

Modeling of Standard Flammability Tests – ISO9705, UL 94

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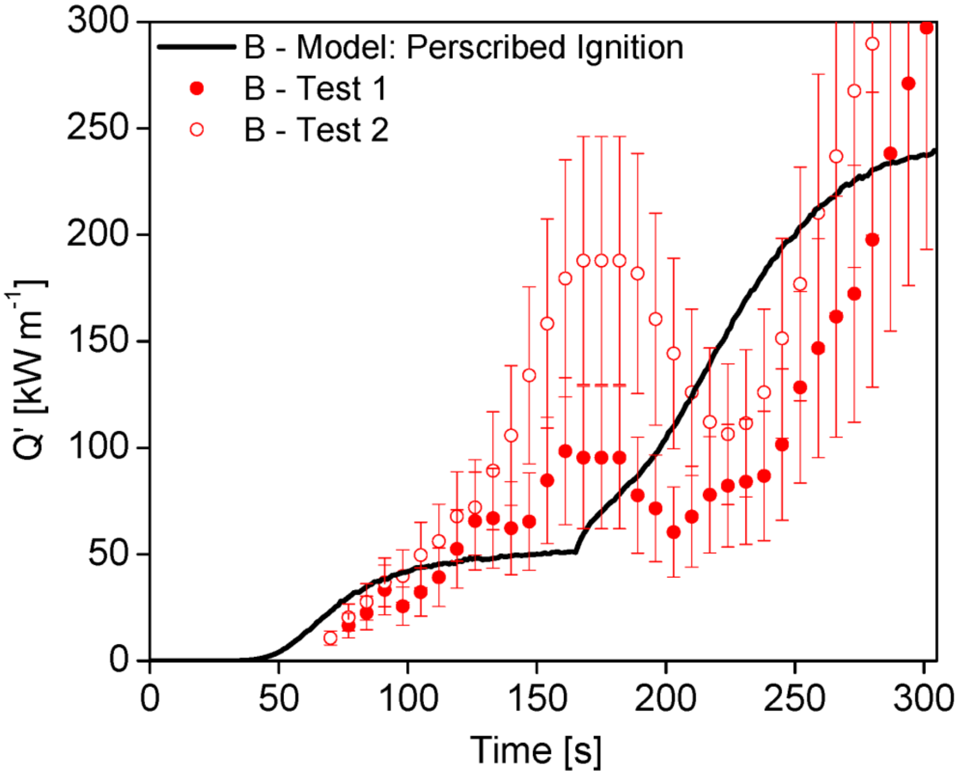

Mechanisms of Action of Flame Retardants During Flame Spread

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  - Flame height, y_f
  - Peak flame heat flux (q''_{steady}) at $y < y_f$
  - Flame stability

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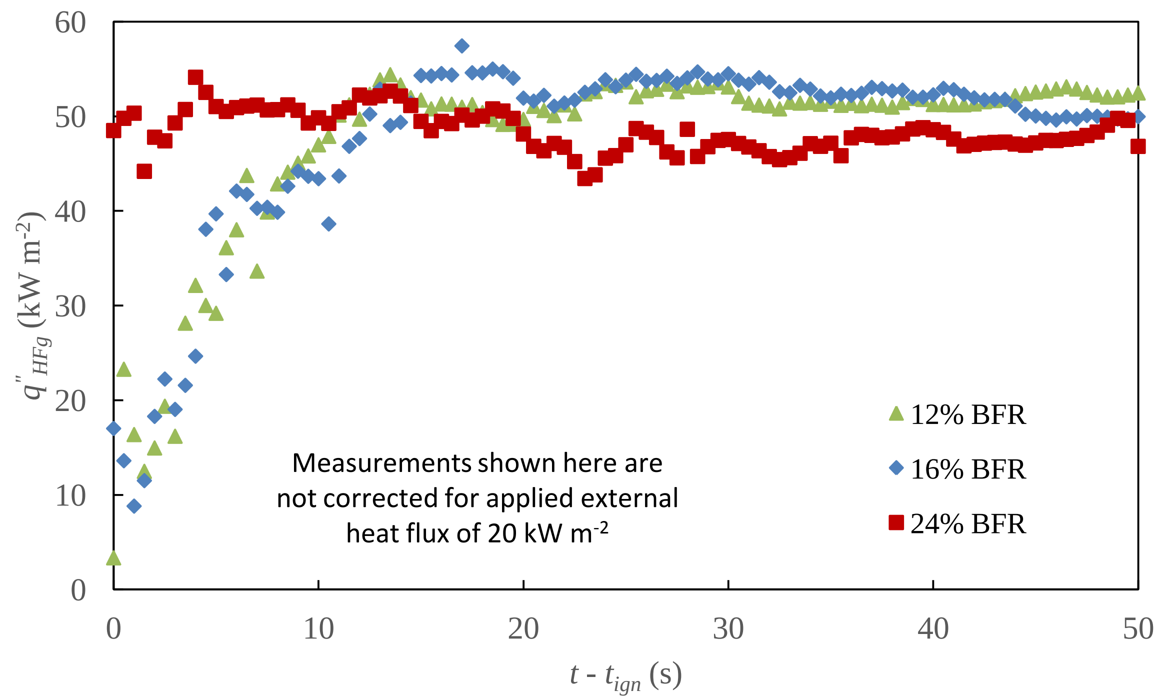

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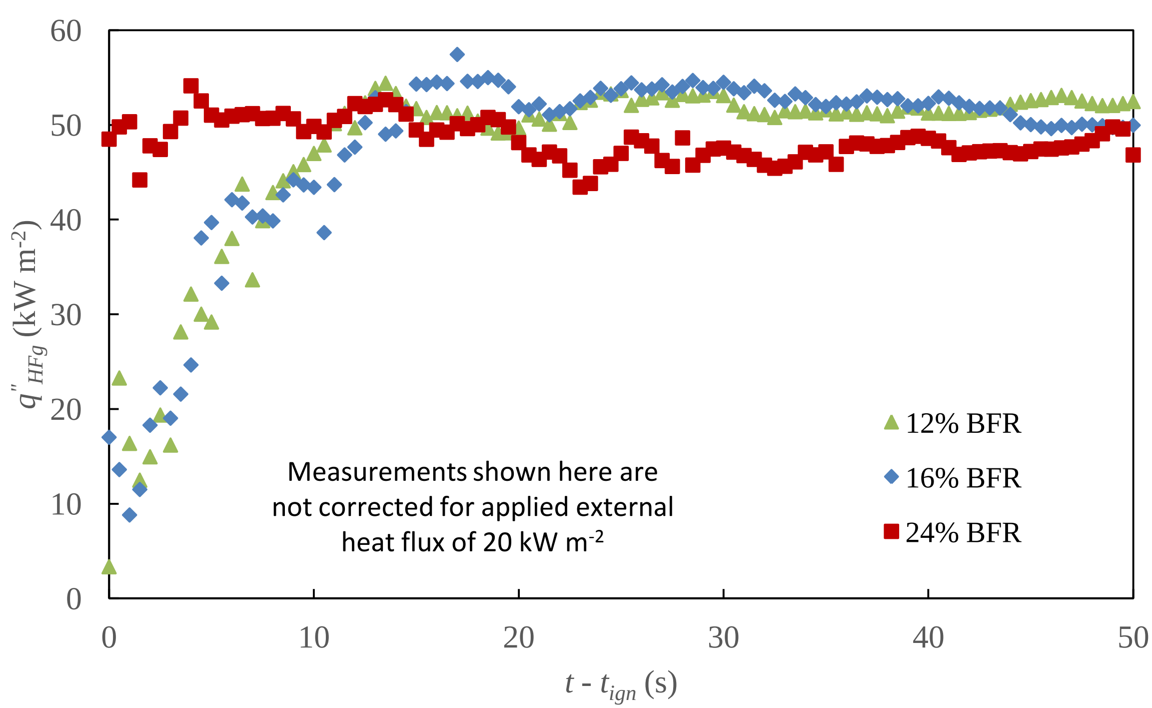

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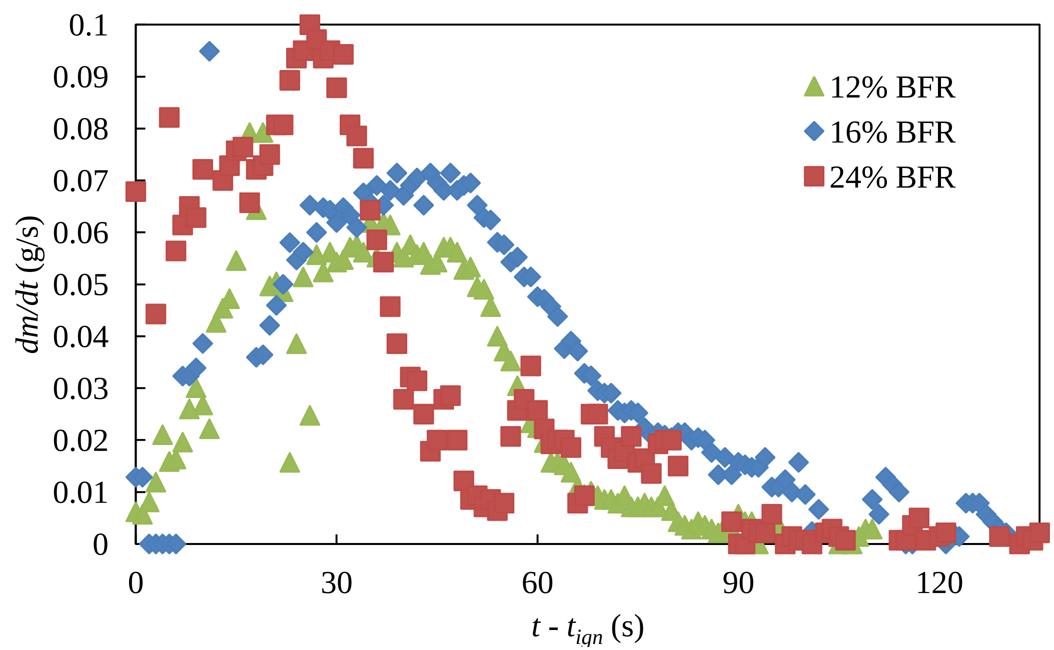

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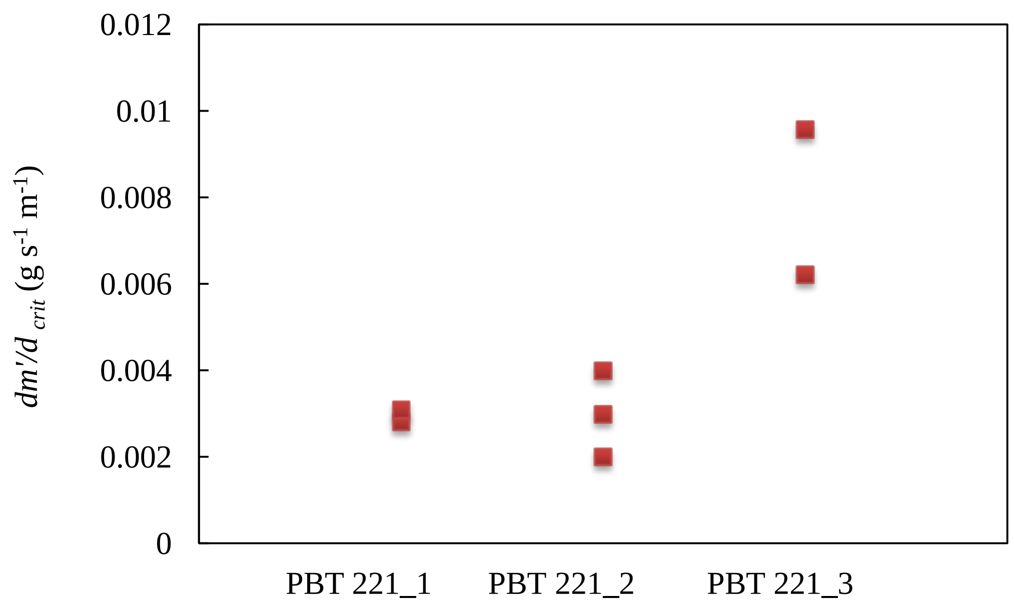
  - <u>Flame stability</u>



FDS Simulations

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- sensitivity of FDS simulation results to user decisions during model development and indicate the experimental measurements needed to parameterize key inputs required for accurate predictions of laminar wall fire behavior.

[Filler text; pretty graphs coming soon]

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- Obtained highly resolved measurements of flame to surface heat feedback during upward flame spread

- Developed a flame model that relates flame heat feedback (as a function of distance above the base of the flame) to width–normalized mass loss rate

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- Coupled flame heat flux model with the solid phase pyrolysis solver ThermaKin2D
  - This unified model simultaneously predicts outcome of thermal analysis, gasification, and vertical flame spread experiments
  - Accurate predictions of time to ignition, initial, peak, and rate of rise of burning rate during upward flame spread
  - This model bridges a range of scales and offers a path for development of rigorous quantitative relationships between various flammability test standards

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- Generalized flame model to describe heat feedback from wall flames supported by a wide range of materials
  - Significant melt flow/dripping: POM, PP
  - Heavy soot formation/deposition: ABS, HIPS
  - Composite materials: FRP, PBT
- Model–predicted flame heat flux, shown to match experimental measurements with an average accuracy of 4.2 kW m^{-2} (approximately 10 – 15 % of peak measured flame heat flux)

Ongoing work

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- Prediction of material burning behavior in Standard Flammability tests (e.g. UL 94, ISO 9705)

- Characterize mechanisms of action of gas phase flame retardants
  - Flame height
  - Flame heat feedback
  - Flame stability

- Quantify flame heat transfer mechanism (convection vs. radiation) of wall flames across a range of scales

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- Leventon I. T., Li J., Stoliarov S. I., *A Flame Spread Simulation Based on a Comprehensive Solid Pyrolysis Model Coupled with a Detailed Empirical Flame Structure Representation;* Combustion and Flame 162: 3884–3895 (2015)
- Stoliarov, S.I., Leventon, I.T., and Lyon, R.E., *Two-Dimensional Model of Burning for Pyrolyzable Solids*, Fire and Materials 38: 391–408 (2013)
- Leventon I.T., Stoliarov S.I., *Characterization of Flame Growth on ABS by Measurement of Surface Heat Feedback*, Proceedings of the Seventh International Seminar on Fire and Explosion Hazards (ISFEH 7): 242–251 (2013).
- Leventon I.T., Stoliarov S.I., *Evolution of flame to surface heat flux during upward flame spread on poly(methyl methacrylate)*, Proceedings of the Combustion Institute 34: 2523–2530 (2013).

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- Leventon I. T., Korver K.T., Stoliarov S. I., *A Generalized Model of Flame to Surface Heat Feedback for Laminar Wall Flames;* Combustion and Flame (In preparation)
- Lannon, C.M., Leventon I. T., Stoliarov S. I., A Methodology for Determining the fire Performance Equivalency Amongst Similar Materials During a Full-scale Fire Scenario Based on Bench-scale Testing (In preparation)
- Prediction of Material Performance in the UL94V Standard Test Configuration (Planned)
- Mechanisms of Action of Bromine- and Phosphorous-Based Flame Retardants on Laminar Wall Flames (Planned)
- *Dependence of* Heat Transfer Mechanism in *Small to Intermediate Scale* Wall Fires (Planned)

Flame Heat Transfer Mechanism

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$$q''_{net} = h(T_{flame} - T_{surf}) + \varepsilon q^{rad}_{flame} - \varepsilon\sigma T^4_{surf}$$

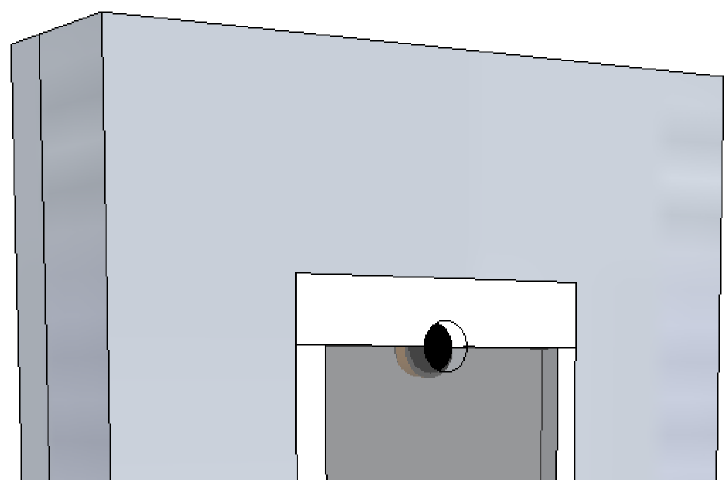
- Determine radiative fraction of total flame to surface heat flux

$$\varphi = 0.77 +/- 0.05$$

- The heat flux gauge is recessed, determine radiation view factor:

$$q''_{HFG} = q''_{rad} + q''_{conv}$$

  - Recess the heat flux gauge 0.64 cm to limit convective heat transfer



Recessed Heat Flux Gauge Measurements

Recessed Heat Flux Gauge Measurements

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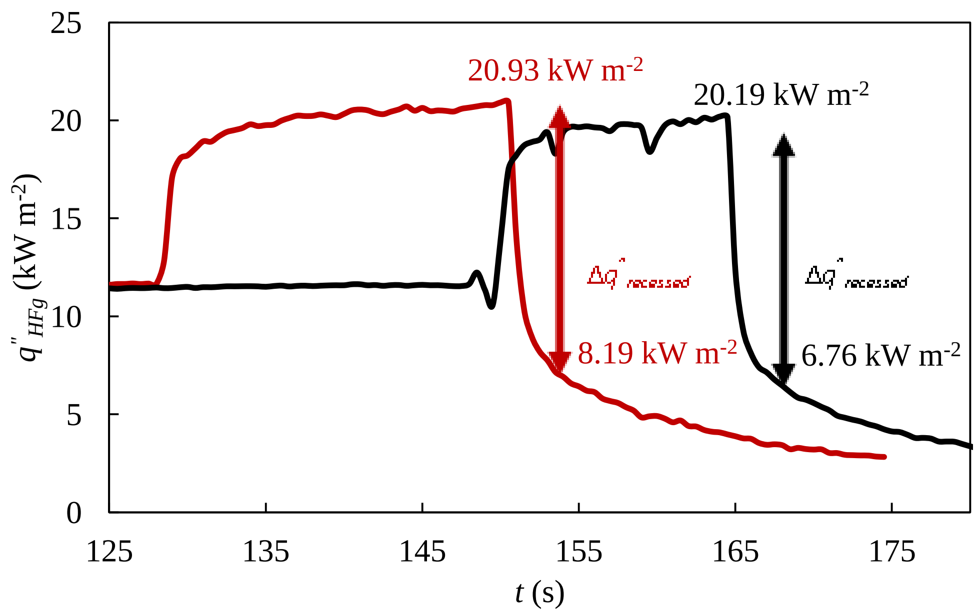

$$q_{rad}^{\%} = 100 \times \left(\frac{q_{rad}^{flame}}{q''_{steady}} \right)$$

Recessed Heat Flux Gauge Measurements

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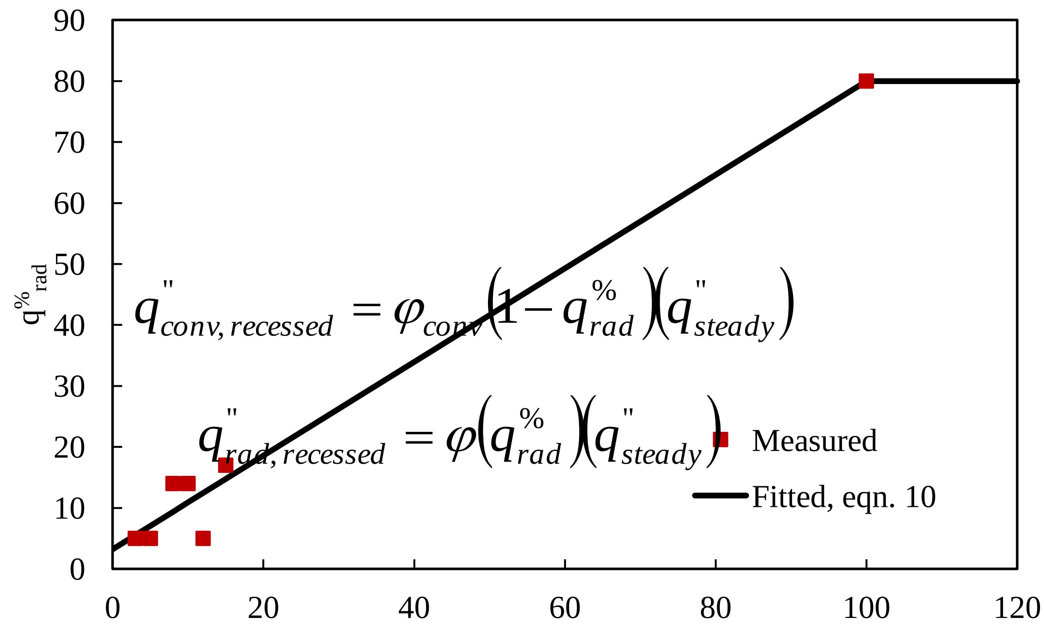

$$q''_{conv,\,recessed} = \varphi_{conv}\left(1 - q^{\%}_{rad}\right)\left(q''_{steady}\right)$$

$$q''_{rad,\,recessed} = \varphi\left(q^{\%}_{rad}\right)\left(q''_{steady}\right)$$

$$q''_{recessed} = q''_{conv,\,recessed} + q''_{rad,\,recessed}$$

Similarity of Burning Behavior of Different Sized Samples

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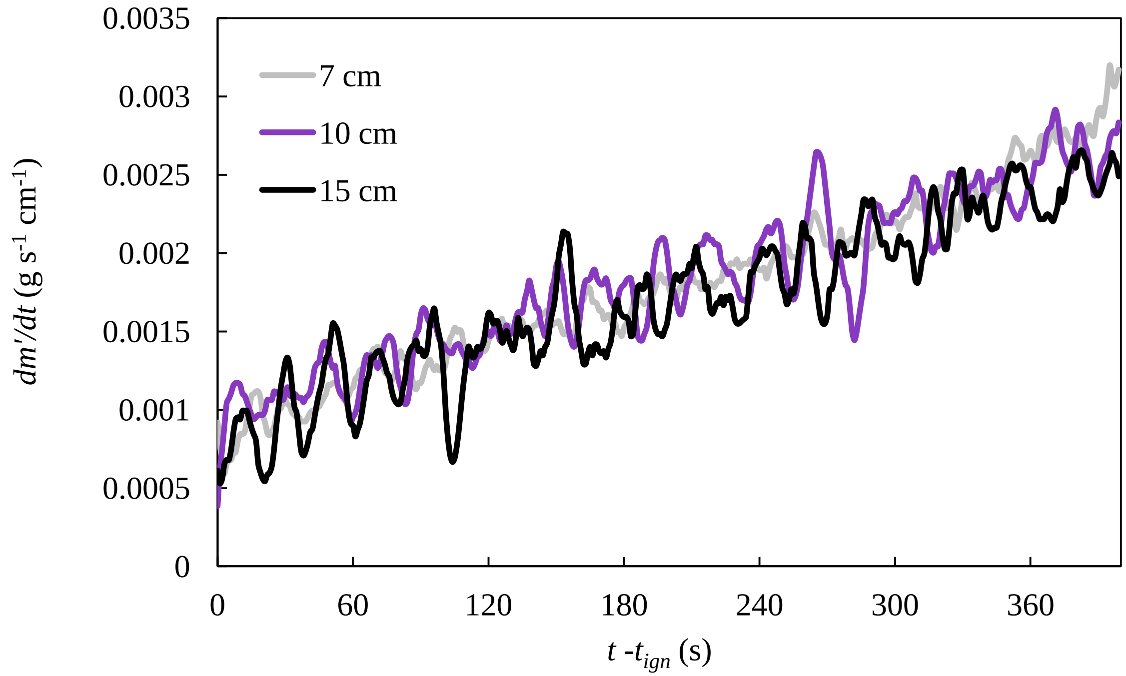

Measured width-normalized mass loss rate of PP samples of different heights

Similarity of Burning Behavior of Different Sized Samples

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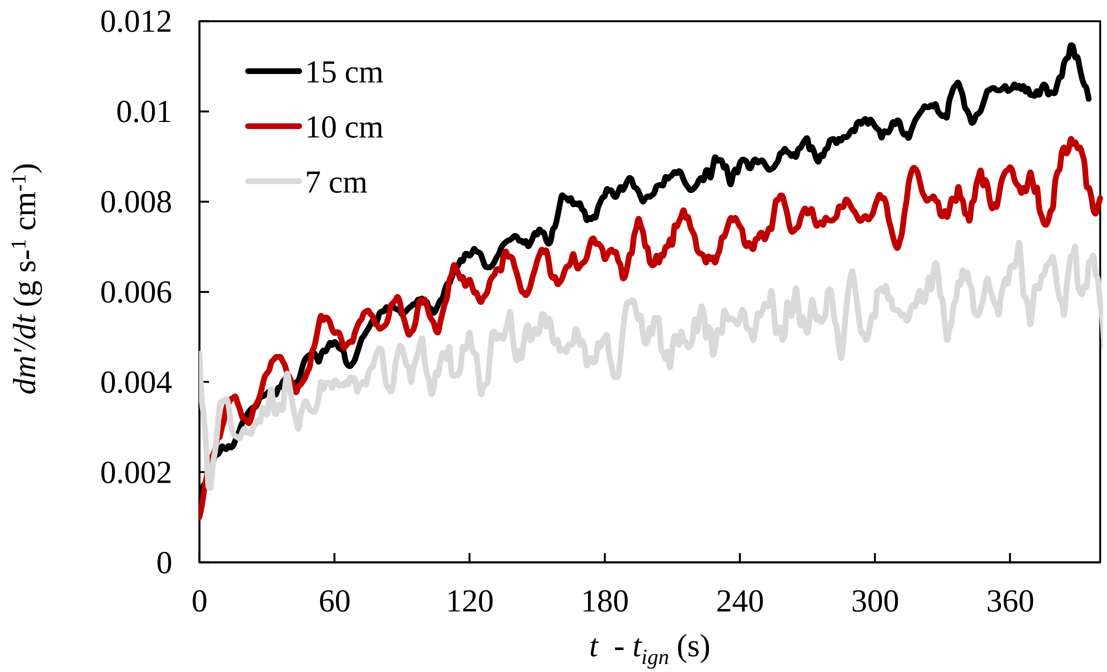
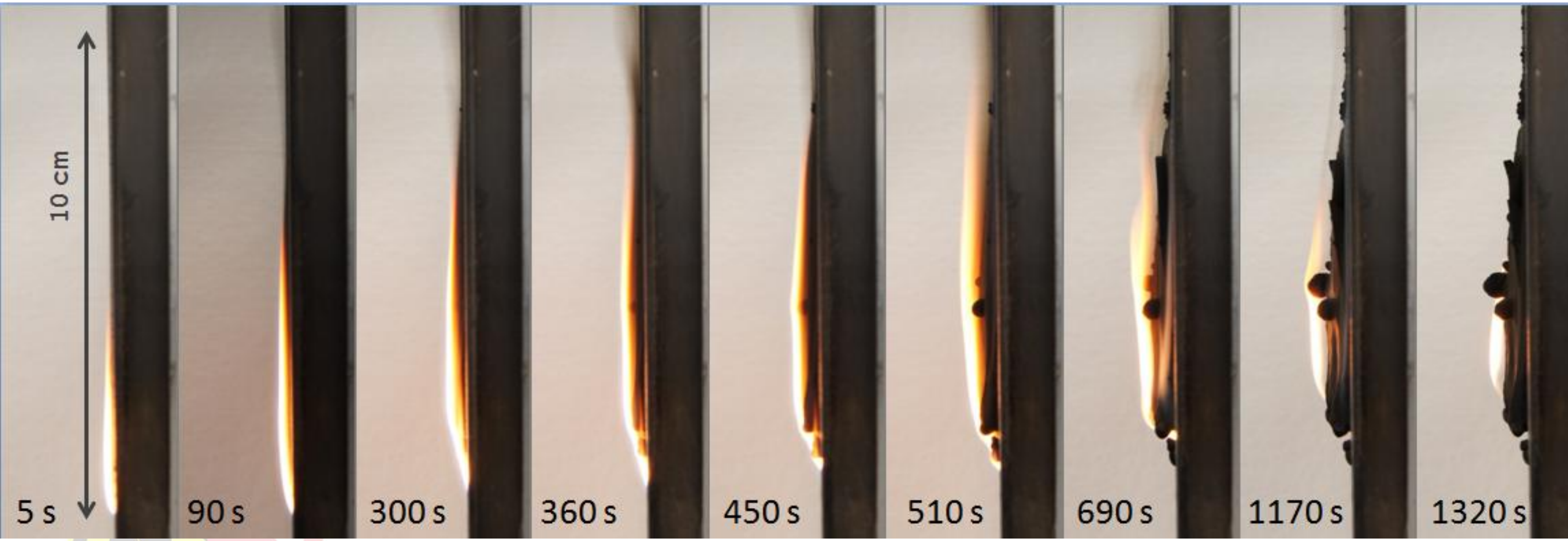


Measured width-normalized mass loss rate of ABS samples of different heights

ABS



ABS

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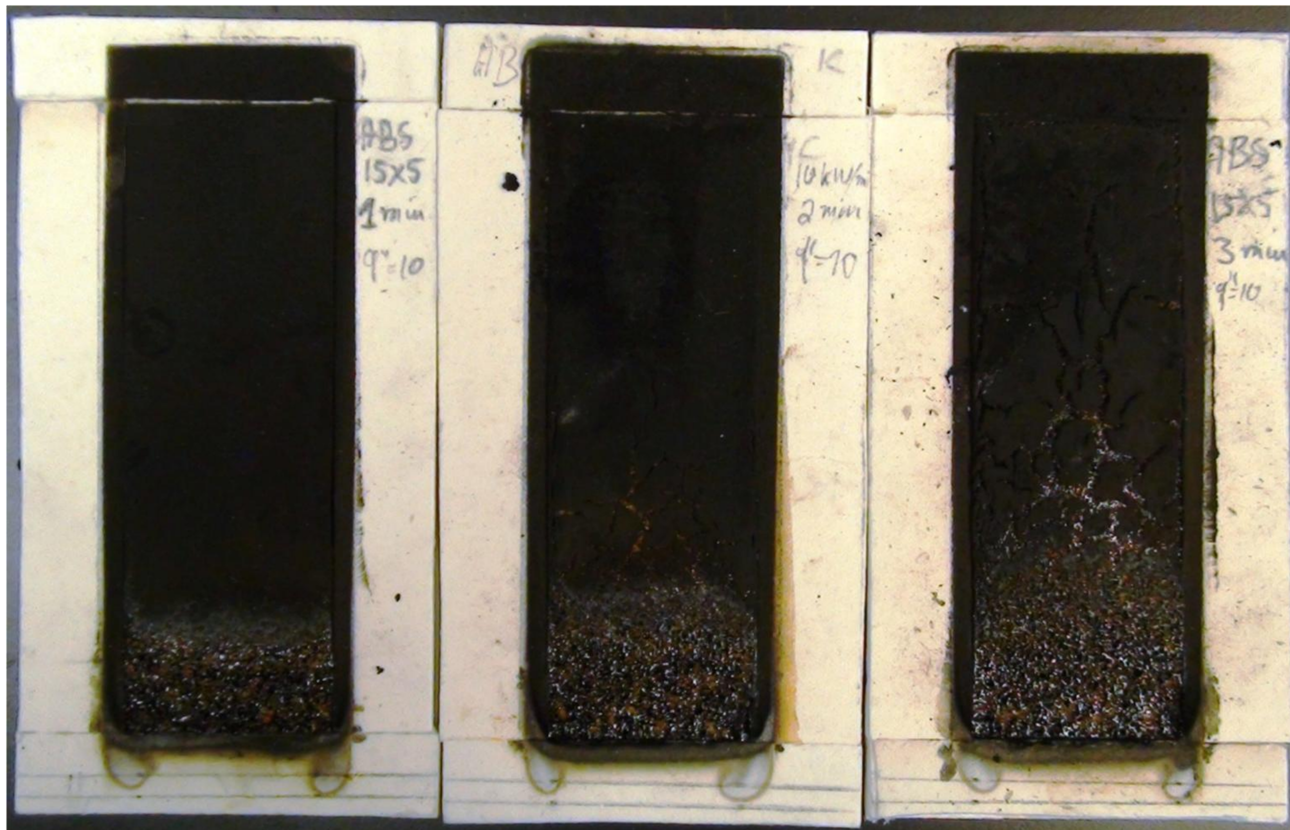
- Flame Spread
- Additional Materials

Conclusions and Future Work

$$q''_{ext} = 10 \text{ kW m}^{-2}$$



60 s | 120 s | 180 s

ABS

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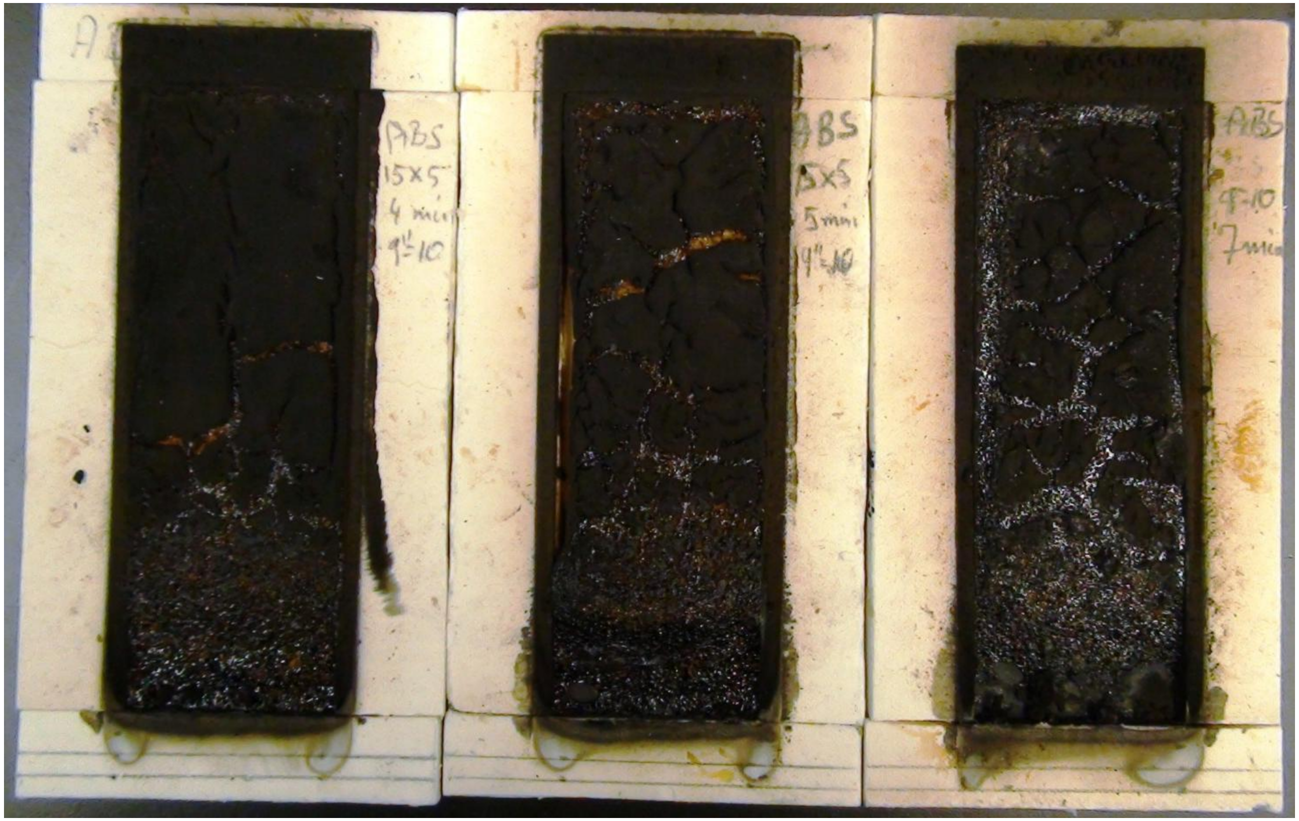

240 s   300 s   420 s

HIPS

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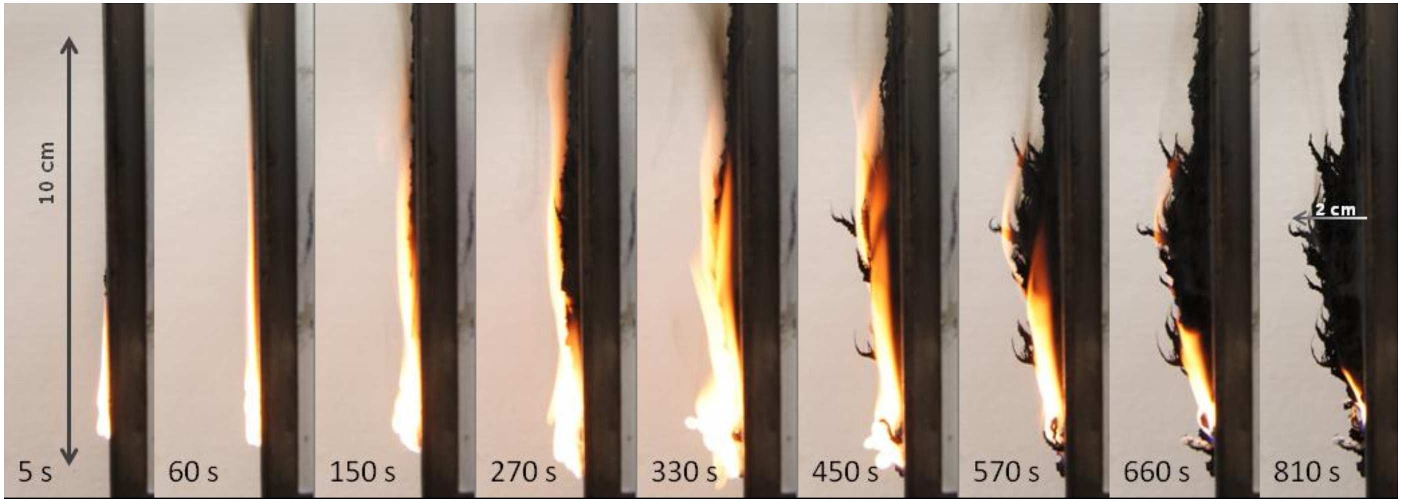
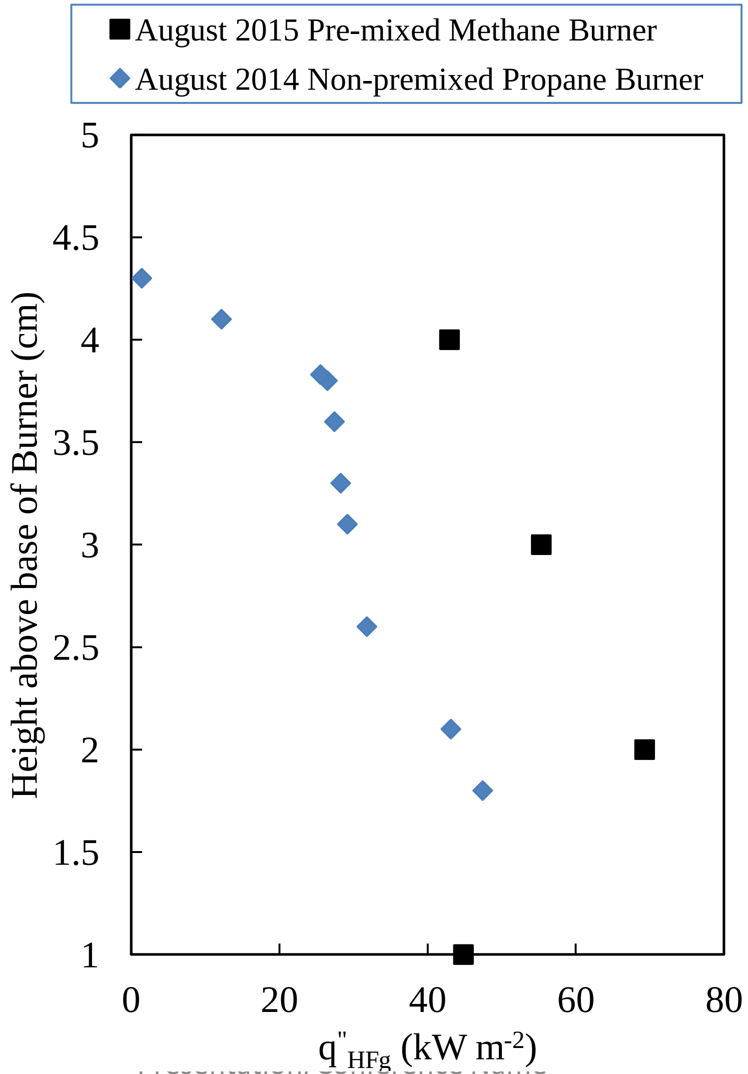


Cracks in the soot layer of ABS samples spread upwards from the base of the sample

Cracks in the soot layer of HIPS samples do not present a preferred growth direction.

New Ignition Source



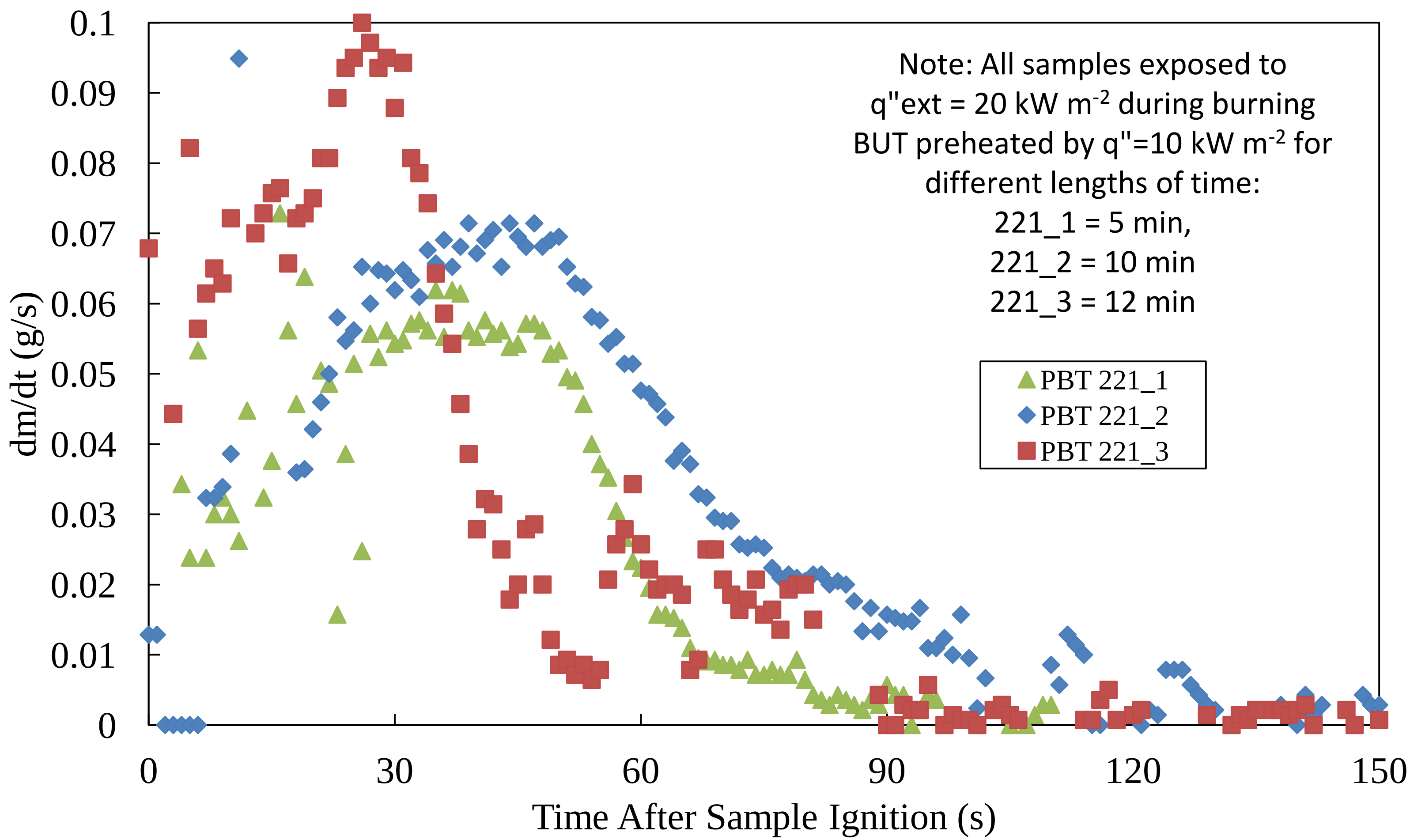
221 Series (Pure Polymer + 12, 16, or 24% Bromiertes Acrylat FR)

	Sample Preheat Duration ($q''_{preheat}$ = 10 kW m^{-2})	Burner Application (Methane, premixed)	External Heat Flux (q''_{ext} = 20 kW m^{-2})
PBT 221_1	5 minutes	30 s	Apply immediately after sample ignition
PBT 221_2	10 minutes	20 s	Apply immediately after sample ignition
PBT 221_3	12 minutes	Propane Hand Torch (~8 s)	Reposition heater, then apply propane torch

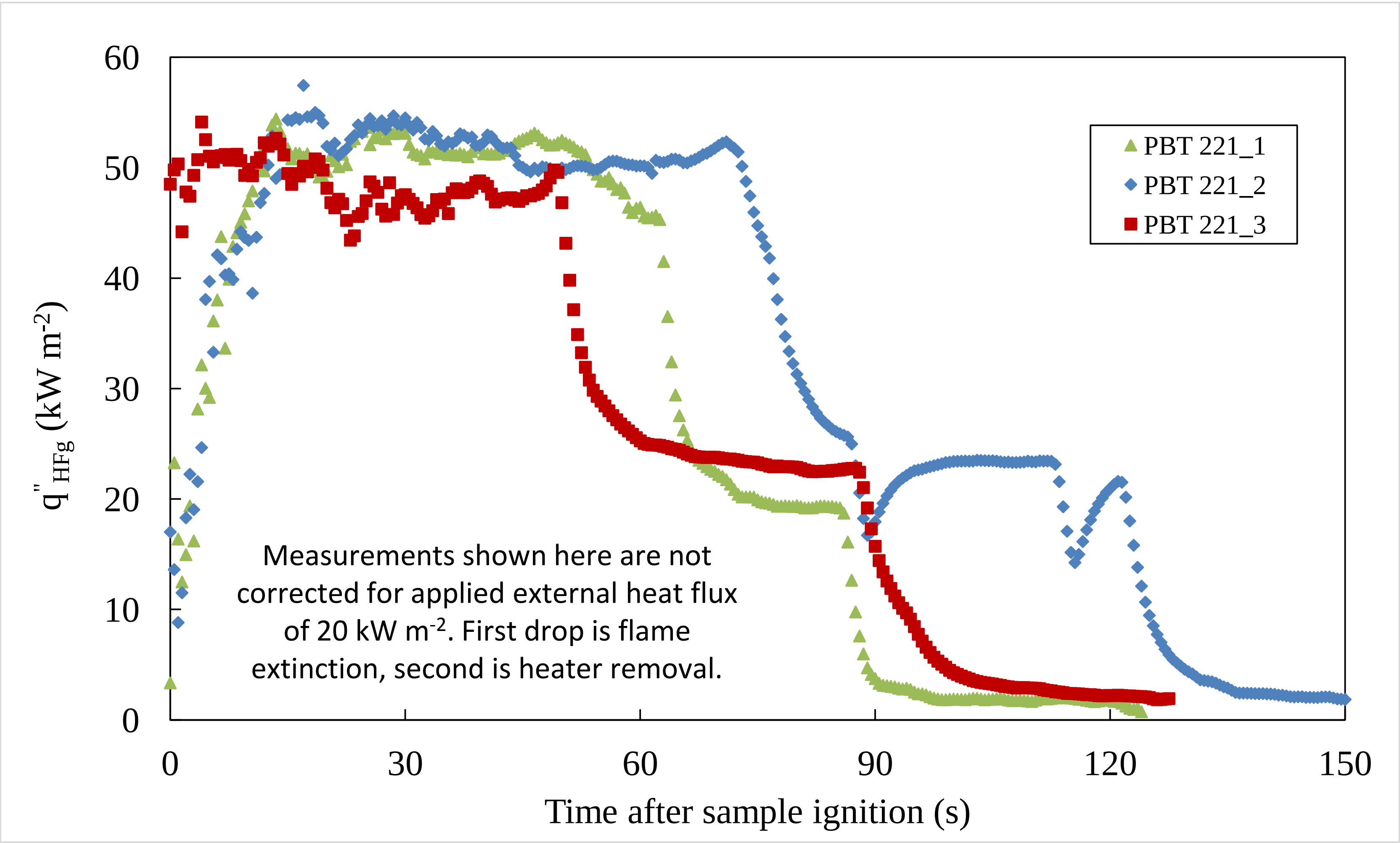
- Typical burning & extinction behavior, see:

  PBT 221_1 7x5 cm 20150820 1110am

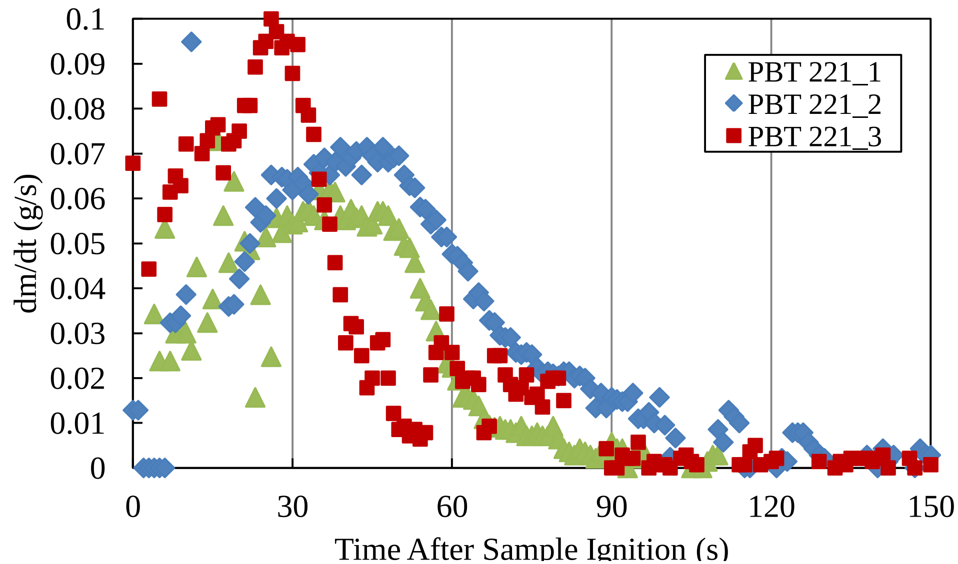
221 Series (Pure Polymer + 12, 16, or 24% Bromiertes Acrylat FR)

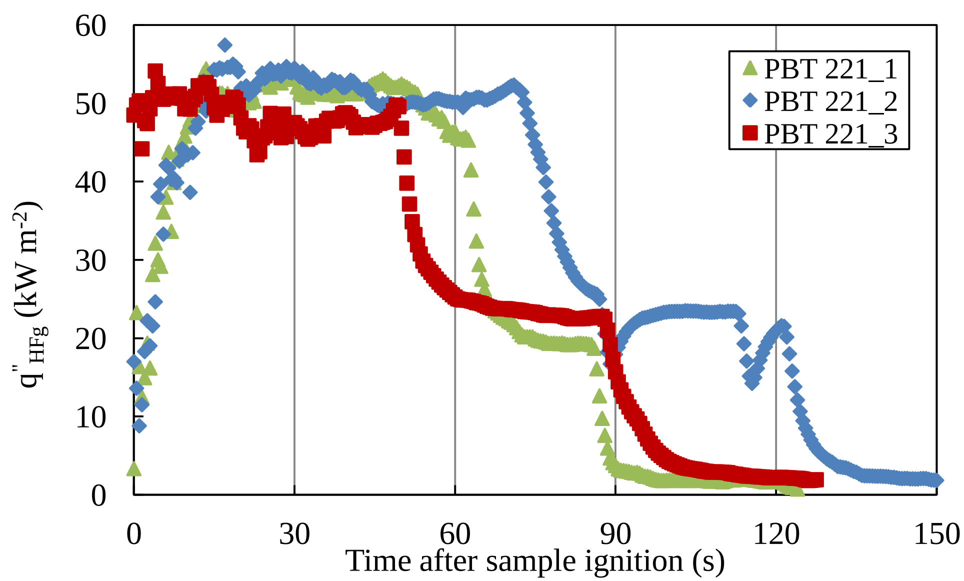


221 Series (Pure Polymer + 12, 16, or 24% Bromiertes Acrylat FR)



221 Series (Pure Polymer + 12, 16, or 24% Bromiertes Acrylat FR)

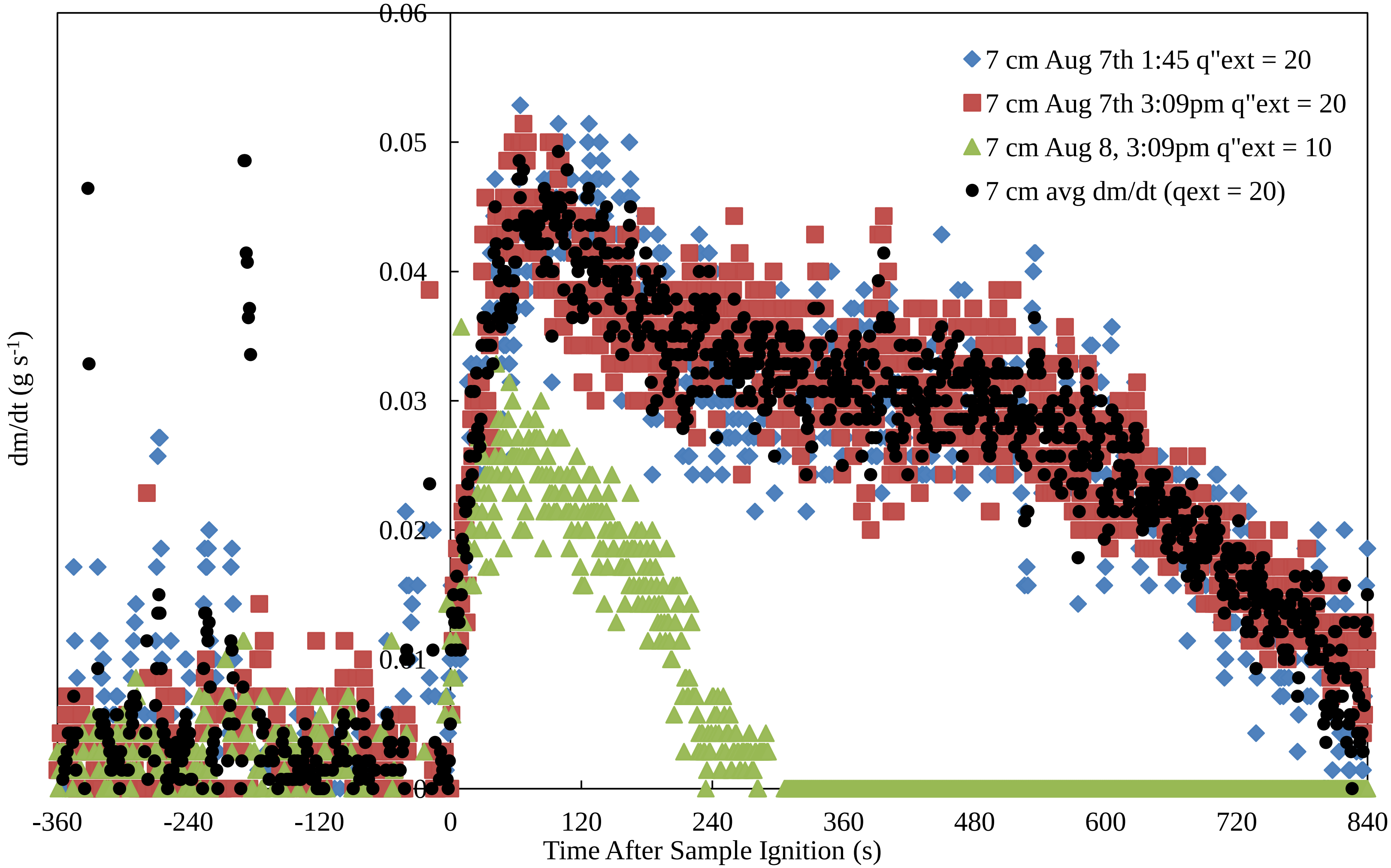




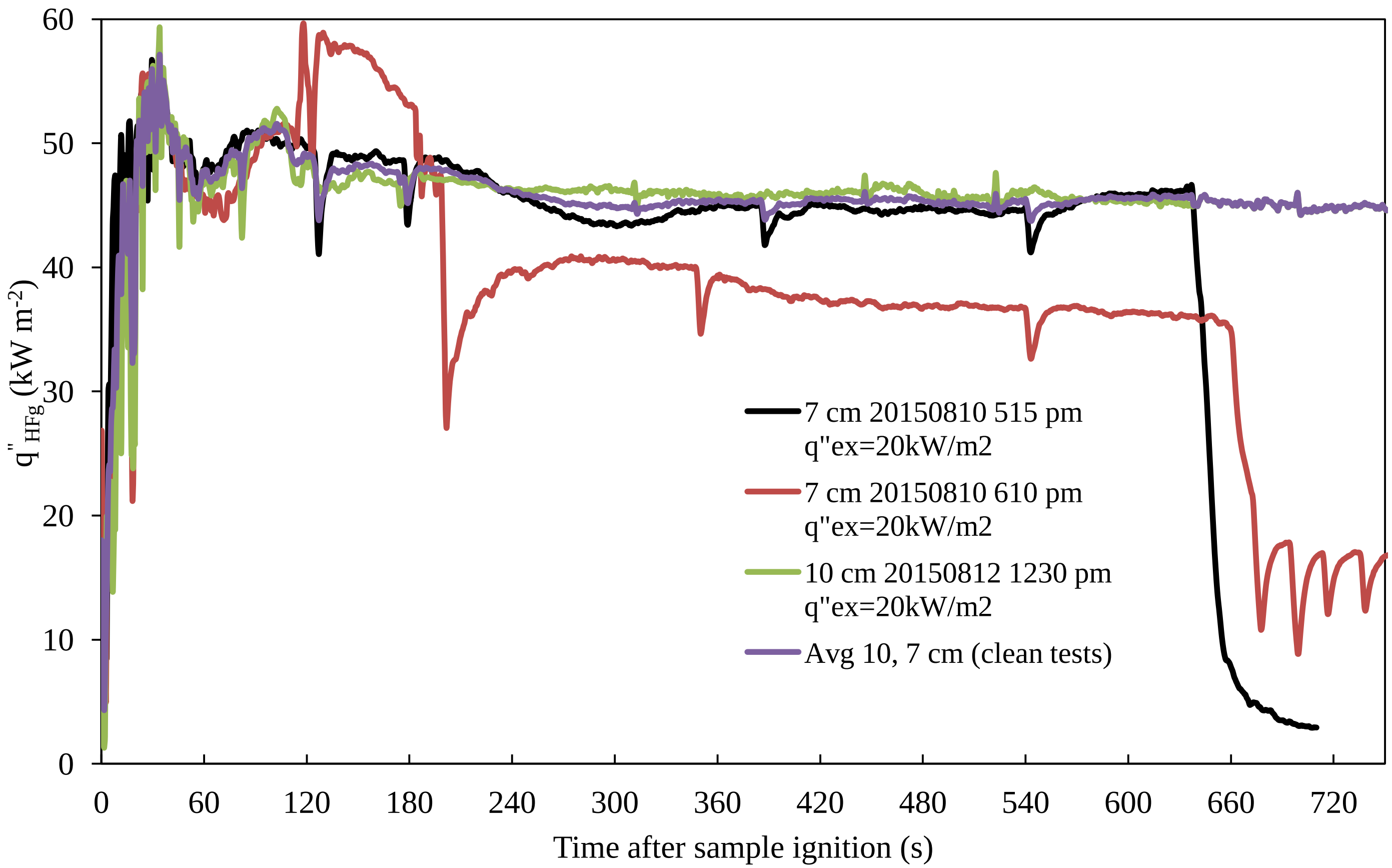
220 Series (Pure Polymer + 8, 12, 16, or 20 % Exolit OP 1230)

PBT 220_1	Non-premixed Propane Burner (120 s)		
Material	Sample Preheat Duration ($q''_{preheat}$ = 10 kW m^{-2})	Burner Application (Methane, premixed)	External Heat Flux (q''_{ext} = 20 kW m^{-2})
PBT 220_2	7 minutes	20 s	Apply immediately after sample ignition
PBT 220_3	7 minutes	40 s	Apply immediately after sample ignition
PBT 220_4	10 minutes	55 s	Apply immediately after sample ignition
PBT 220_5	10 minutes	70 s	Apply immediately after sample ignition

PBT 220_2 (8 % Exolit)
Mass Loss Rate



PBT 220_2 (8 % Exolit) Flame Heat Flux

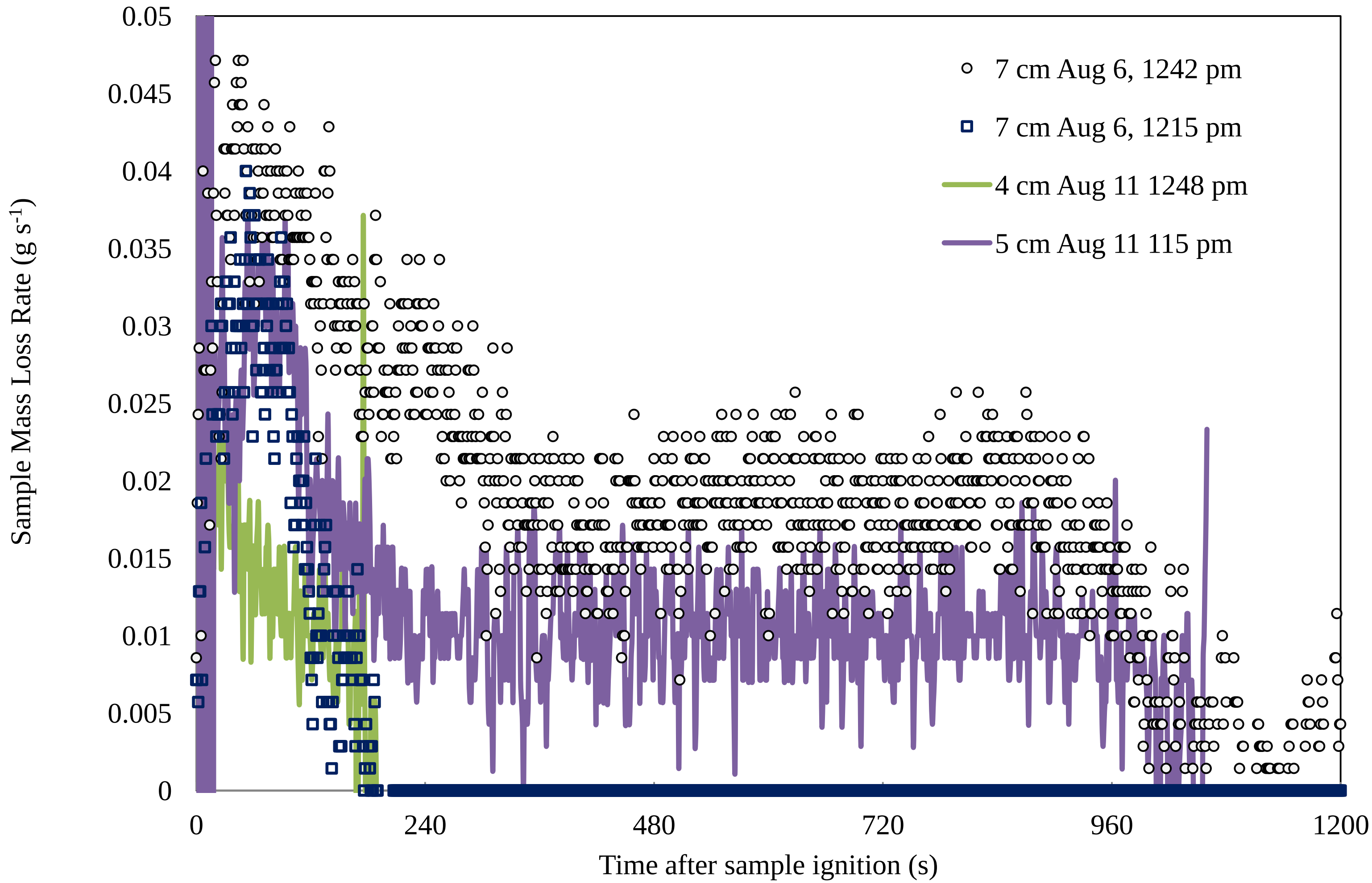


PBT 220_2 (8 % Exolit)

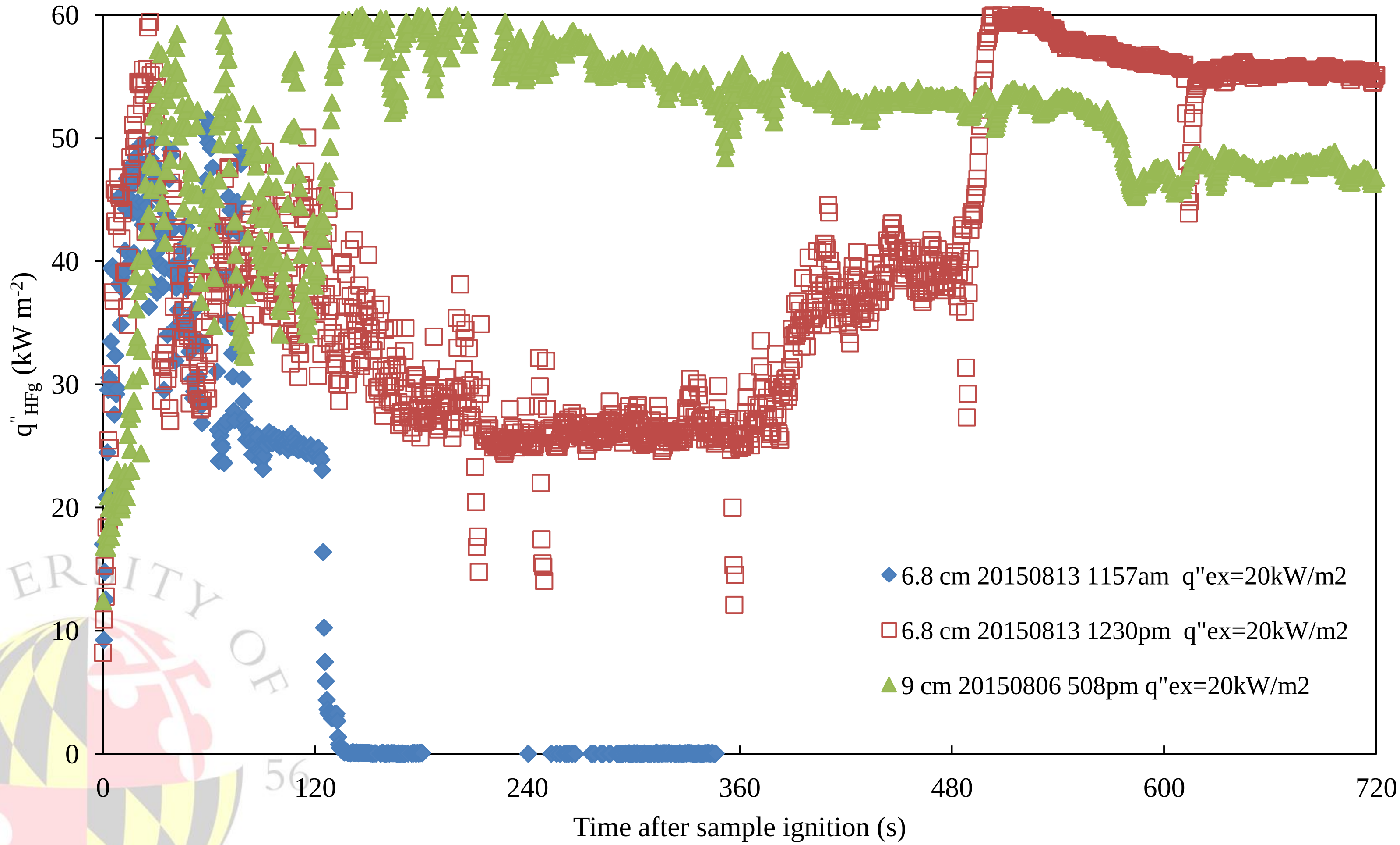
t = 0 s (ignition)	t = 60 s	t = 180 s	t = 300 s (vertical flickering)	t = 390 s (attempted reginition of vapors)

- PBT 220_2 10 x 5 cm 20150812 325pm

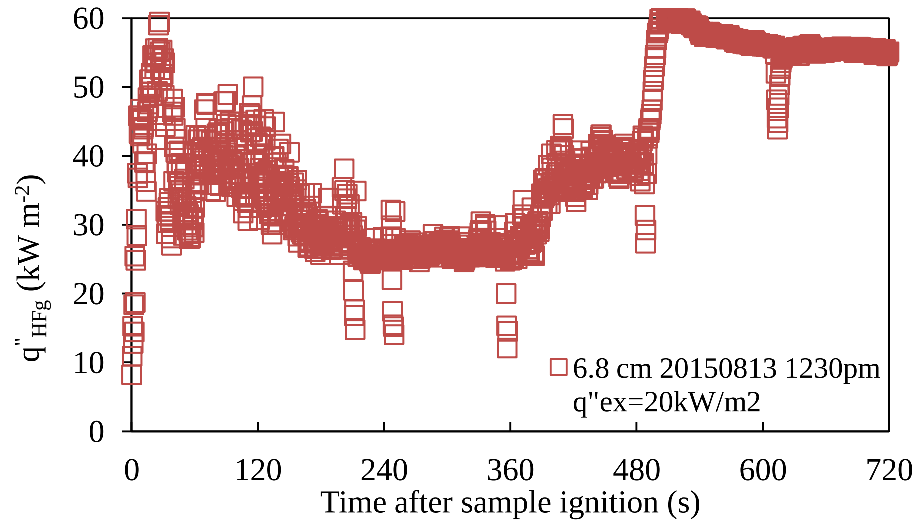
PBT 220_3 (12 % Exolit) Mass Loss Rate

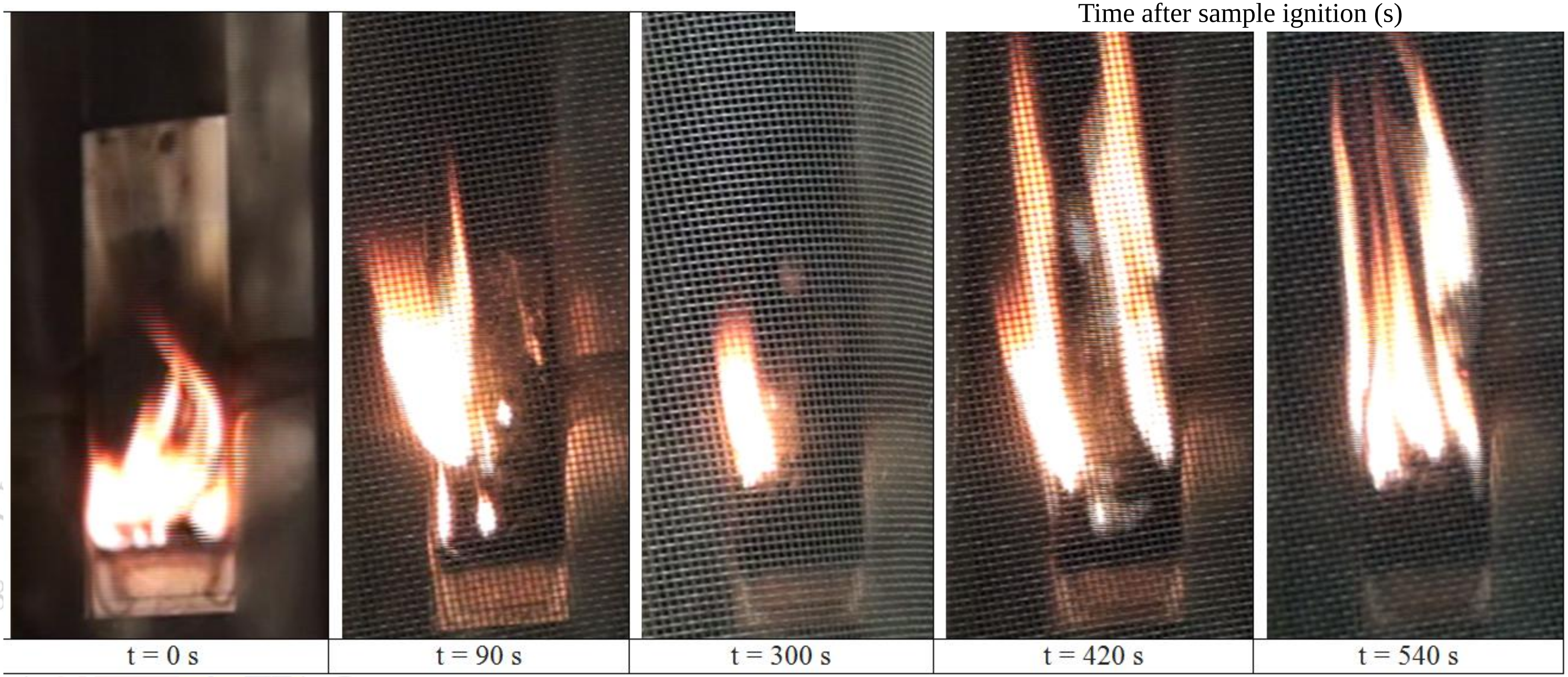


PBT 220_3 (12 % Exolit) Flame Heat Flux



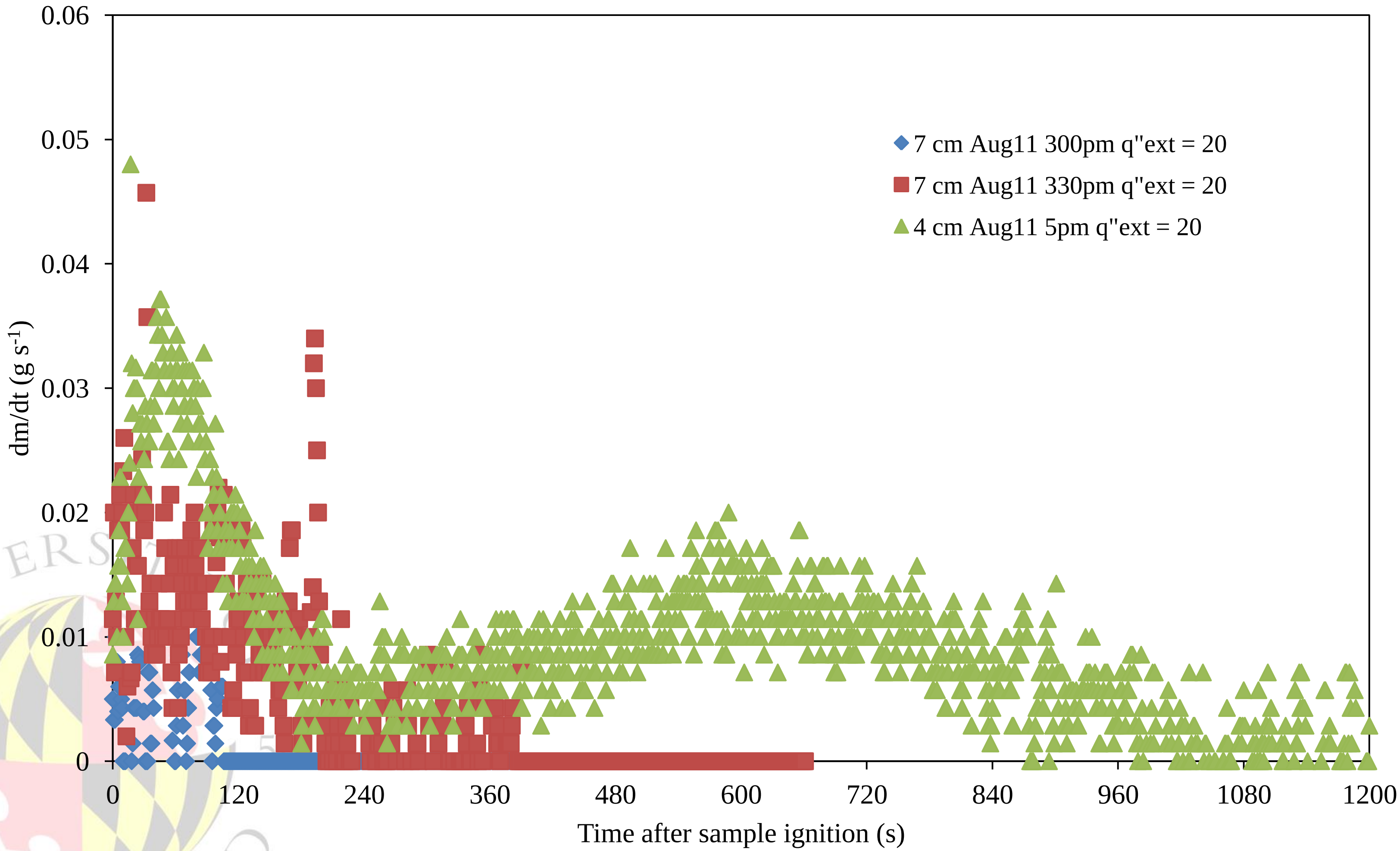
PBT 220_3 (12 % Exolit)



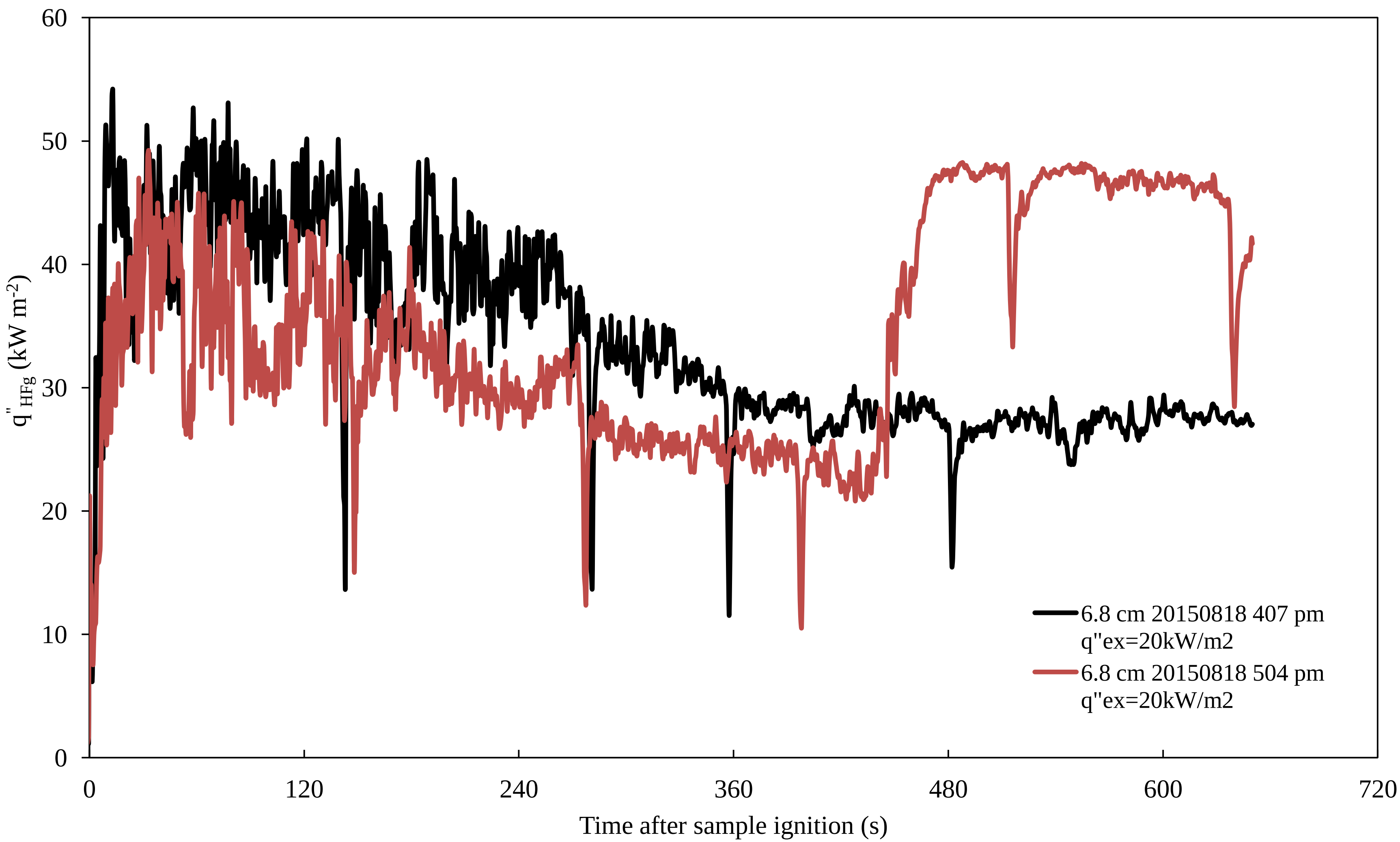


- PBT 220_3 6.8x5 cm 2015081 1230pm

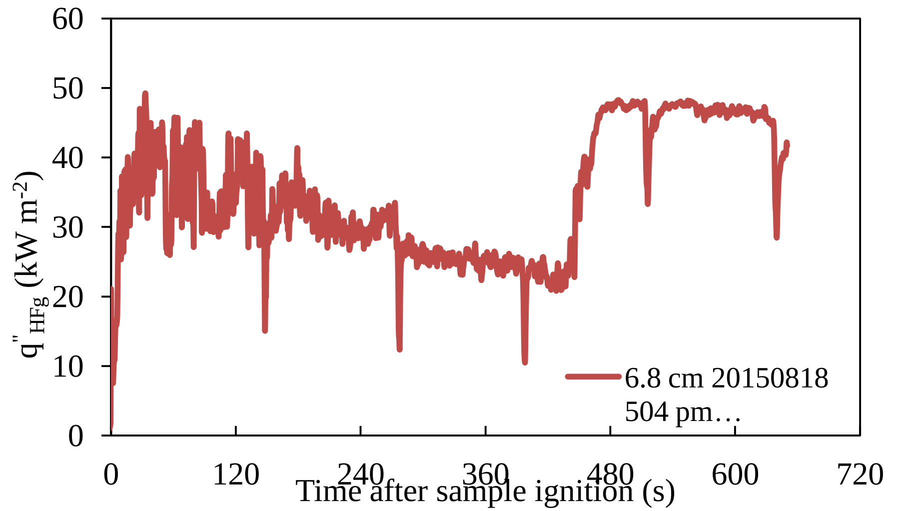
PBT 220_4 (16 % Exolit) Mass Loss Rate

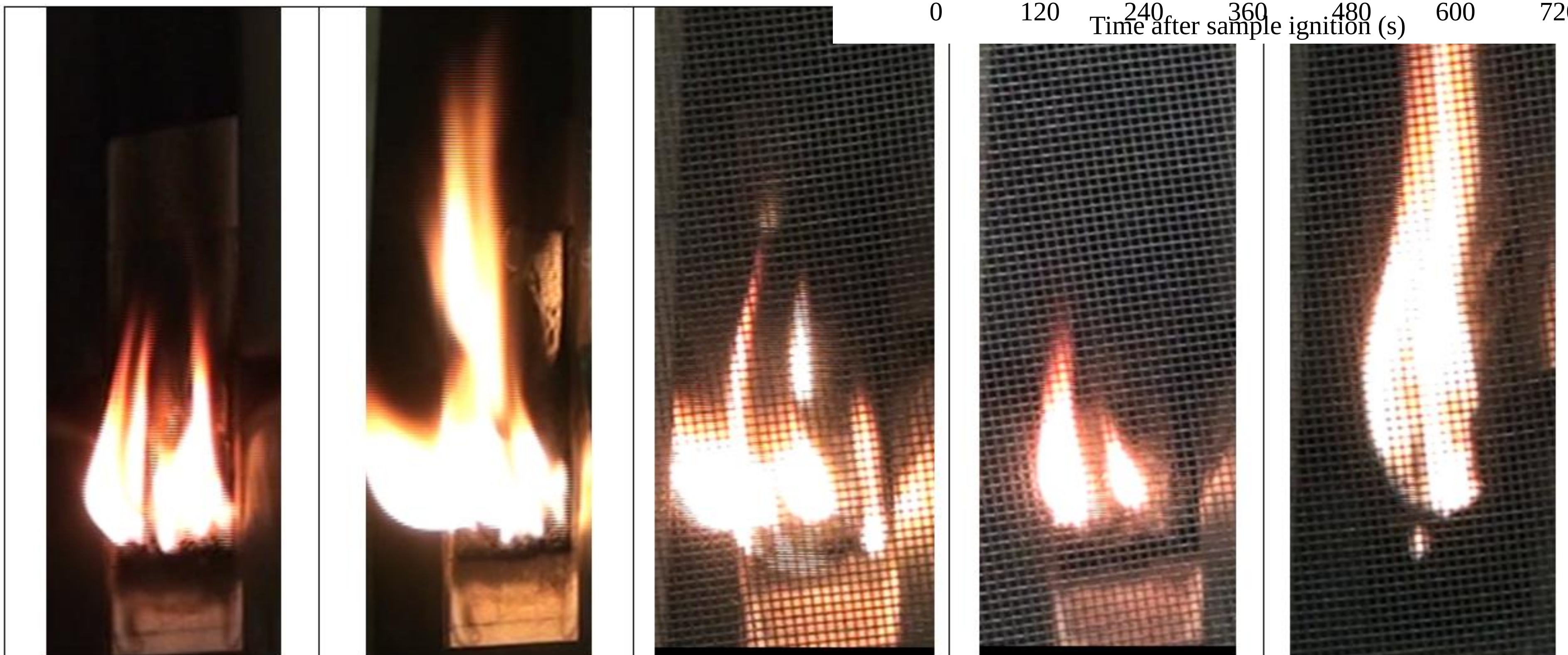


PBT 220_4 (16 % Exolit)
Flame Heat Flux



PBT 220_4 (16 % Exolit)

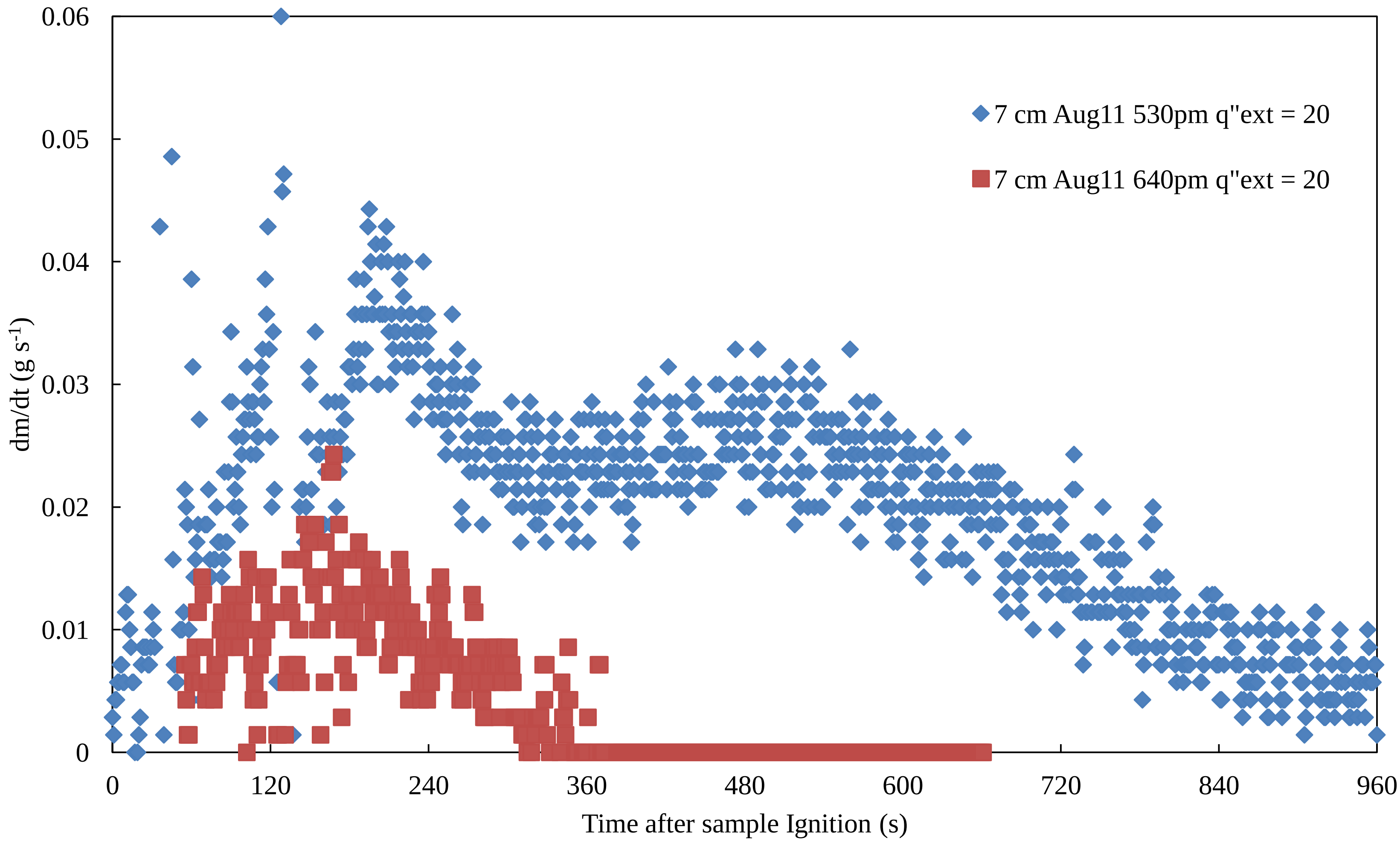




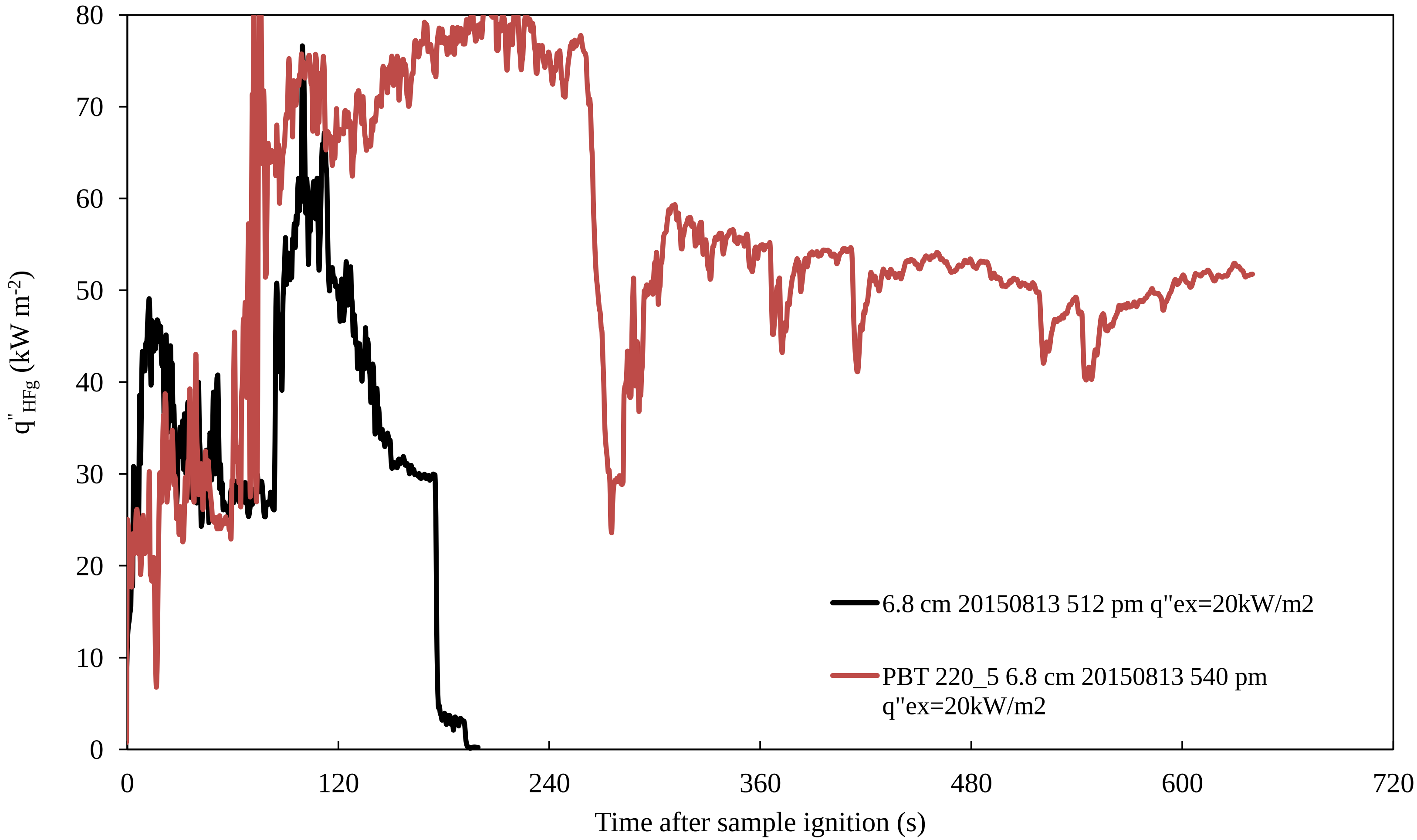
t = 5 s | t = 30 s | t = 180 s | t = 400 s | t = 480 s

- PBT 220_4 6.8x5 cm 20150818 504pm

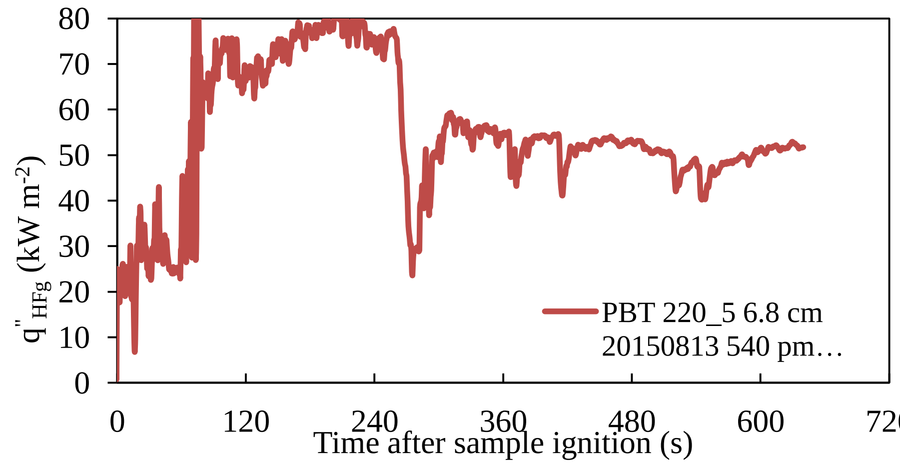
PBT 220_5 (20 % Exolit) Mass Loss Rate

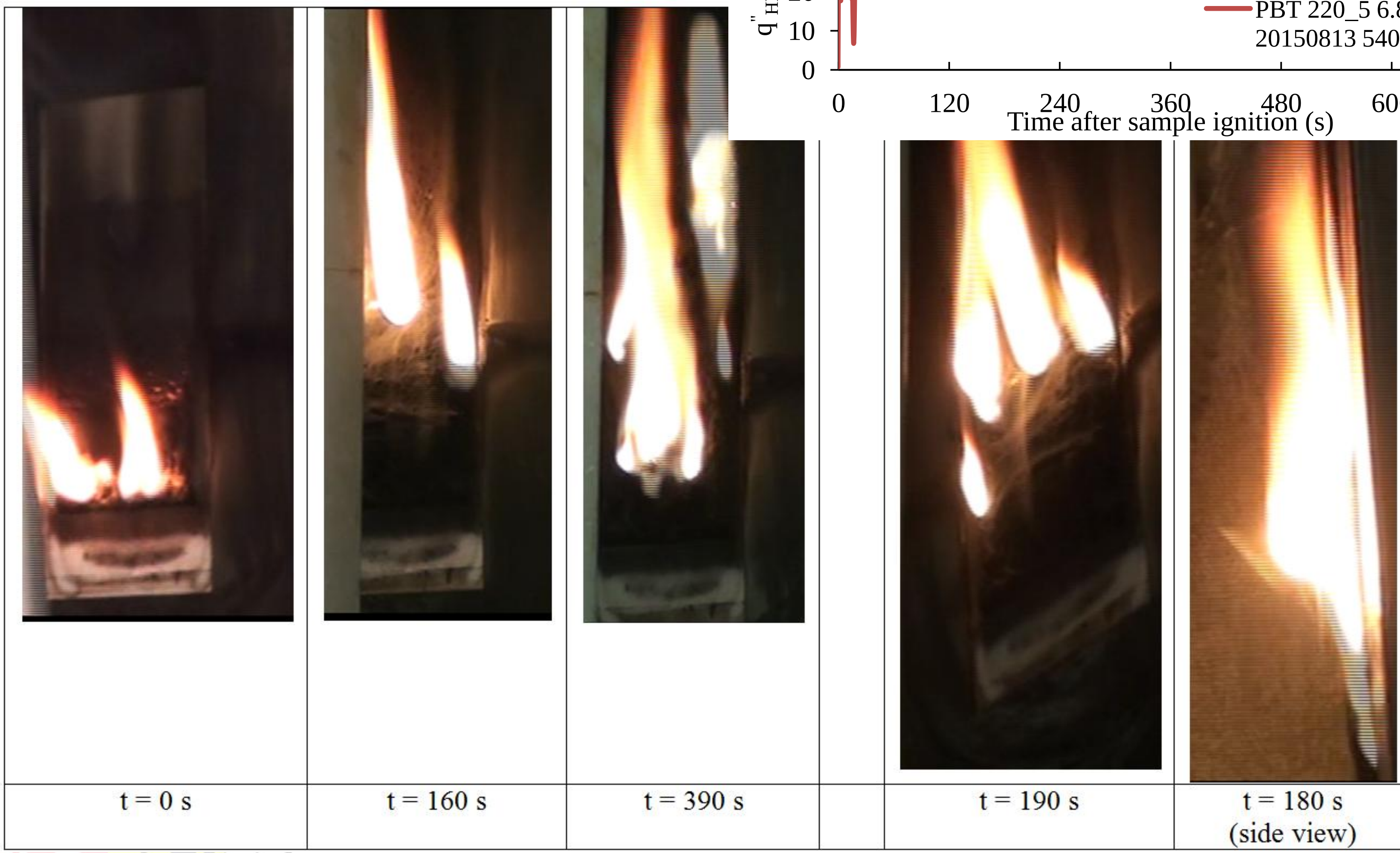


PBT 220_5 (20 % Exolit) Flame Heat Flux



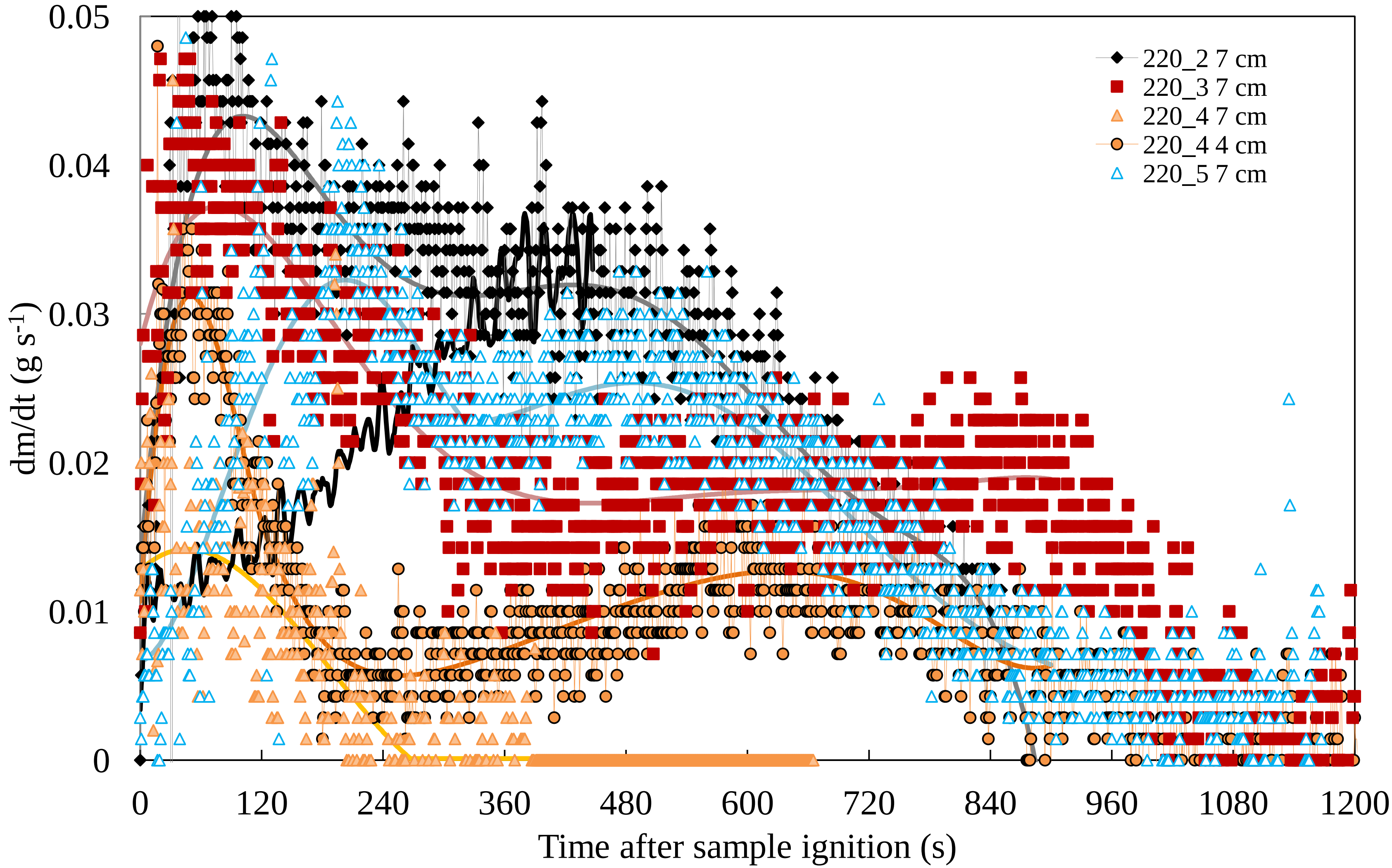
PBT 220_5 (20 % Exolit)



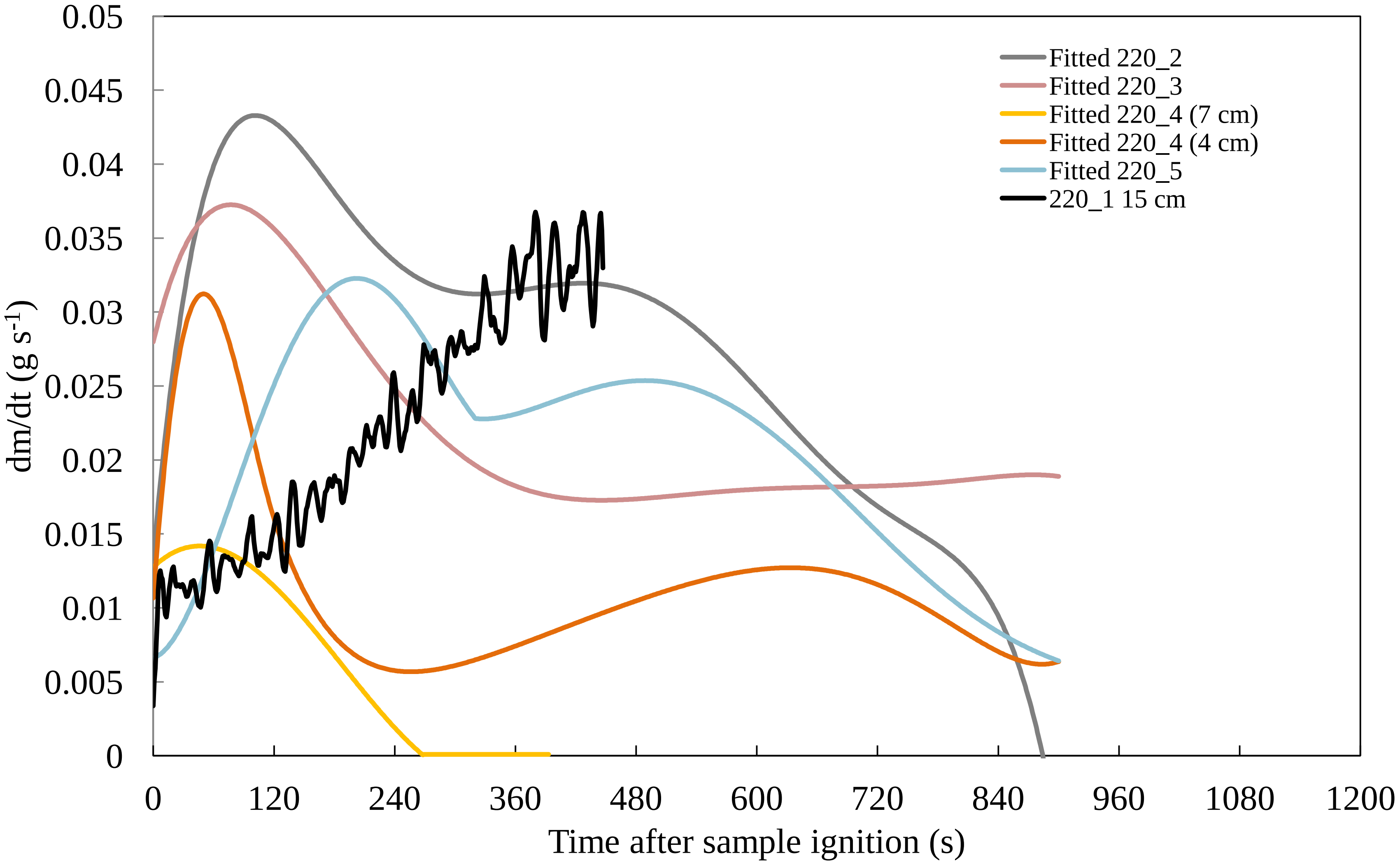


- PBT 220_5 7x5cm 20150811 533 pm

PBT 220 Series (Exolit) Mass Loss Rate



PBT 220 Series (Exolit) Mass Loss Rate



PBT 220 Series (Exolit) Flame Heat Flux