Prediction of Upward Flame Spread over Polymers

Isaac T Leventon
The Fire Problem

• 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
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The Fire Problem

**Controlling Mechanisms of Flame Spread**

Purpose of Study

Flame Heat Feedback Model

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Early analytical models

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

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
Early Flame Spread Models

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• 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

Purpose of Study

• 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

\[
q_{\text{flame}} = \begin{cases} 
q''(y, \frac{dm}{dt}) = \left(\alpha \times q''_{\text{steady}}\right) e^{-\ln(\alpha) \times (y^*)^2}, & y \leq y_f \\
q''_{\text{steady}}, & y > y_f 
\end{cases}
\]
Purpose of Study

• 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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Experiments Conducted

- **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

- 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)
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\[
q_{\text{burner}} \quad \text{(kW m}^{-2}\text{)}
\]

\[
y \quad \text{(cm)}
\]
PMMA
PMMA Mass Loss Rate

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PMMA Mass Loss Rate

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**Graph:**
- $\frac{dm}{dt}$ vs. $t - t_{ign}$ (s)
- Lines for different material lengths: 15 cm, 13 cm, 11 cm, 9 cm, 7 cm, 5 cm, 3 cm

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PMMA Mass Loss Rate

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\[
\frac{dm}{dt} = -5.40 \times 10^{-15} (t-t_{ign})^5 + 4.35 \times 10^{-12} (t-t_{ign})^4 - 8.13 \times 10^{-10} (t-t_{ign})^3 \\
+ 4.75 \times 10^{-9} (t-t_{ign})^2 + 2.79 \times 10^{-5} (t-t_{ign}) + 1.44 \times 10^{-3}
\]

\(\frac{dm}{dt}\) is in g s\(^{-1}\) cm\(^{-1}\) and \(t\) is in s
PMMA Flame Heat Flux

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Prediction of Upward Flame Spread over Polymers

$y = 7.5 \text{ cm}$

$\dot{q}_{HF}\gamma$ (kW m$^{-2}$)

$t$ (s)
PMMA Flame Heat Flux

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Prediction of Upward Flame Spread over Polymers

Graph showing the heat flux $q_H$ over time $t - t_{ign}$ for different thicknesses of PMMA.
PMMA Flame Heat Flux
Effects of Finite Width

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PMMA Flame Heat Flux

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Prediction of Upward Flame Spread over Polymers

$q'_{HFg}$ (kW m$^{-2}$)

$\Delta t = t - t_{ign}$ (s)

- 3 cm
- 4 cm
- 5 cm
- 7.5 cm
- 10 cm
- 12.5 cm
- 15 cm
- 17.5 cm
- 20 cm
Steady State Flame Heat Flux

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y = 17.5 cm
Steady State Flame Heat Flux

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Prediction of Upward Flame Spread over Polymers

Preliminary Burner Configuration
Final Burner Configuration
Weighted Average

\[ q^*_{\text{steady}} (\text{kW m}^{-2}) \]

\[ y (\text{cm}) \]
Normalized Flame Heat Flux

The 7th International Aircraft Fire Cabin Safety Research Conference

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Measured Heat Flux

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Flame Heat Feedback

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$q^* = \frac{q_{\text{fitted}}}{q_{\text{steady}}}$

$t - t_{\text{ign}}$ (s)

$q^*$ vs $t - t_{\text{ign}}$ (s)

- 3 cm
- 4 cm
- 5 cm
- 7.5 cm
- 10 cm
- 12.5 cm
- 15 cm
- 17.5 cm
- 20 cm

0 0.2 0.4 0.6 0.8 1 1.2

0 60 120 180 240 300 360 420 480
Flame Heat Flux Profile

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\[
q_{\text{flame}} = q \left( y, \frac{dm}{dt} \right) = \left\{ \begin{array}{ll}
q_{\text{steady}} & , \quad y \leq y_f \\
(\alpha \times q_{\text{steady}}) e^{-\ln(\alpha) (y^*)^2} & , \quad y > y_f
\end{array} \right.
\]

\[q^* = \frac{q_{\text{fitted}}}{q_{\text{steady}}}\]
Determining Flame Height, $y_f$

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

\[ y_f = a \left( \frac{dm}{dt} \right)^p + b \]
Flame Heat Flux Beyond $y_f$

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

\[ y^* = \frac{(y + y_0)}{(y_f + y_0)} \]
Flame Heat Flux Model

\[ q_{\text{steady}} = \begin{cases} 
40 \text{ kW m}^{-2} & ; y \leq 5 \text{ cm} \\
34 \text{ kW m}^{-2} & ; y > 5 \text{ cm} 
\end{cases} \]

\[ y_f = 87.734 \left( \frac{dm}{dt} \right)^{0.275} - 11.924 \]

\[ y^* = \frac{(y + 2.2)}{(y_f + 2.2)} \]

\[ q_{\text{flame}} = q'' \left( y, \frac{dm'}{dt} \right) = \begin{cases} 
q_{\text{steady}} & , \quad y \leq y_f \\
1.54 \times q_{\text{steady}} \left( e^{-\ln(1.54) \times (y^*)^2} \right) & , \quad y > y_f 
\end{cases} \]

Units: \( y \) [cm] and \( \frac{dm'}{dt} \) [g s\(^{-1}\) cm\(^{-1}\)]
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Prediction of Upward Flame Spread over Polymers
Condensed phase is represented by a mixture of components that may interact chemically and physically.

2D heat transfer within solid:

\[ q_{\text{conduction}} = -k \frac{\partial T}{\partial x} \text{ or } = -k \frac{\partial T}{\partial y} \]

Material degradation mechanism defined by:

- First order Arrhenius reaction rates:
  \[ r = A \exp \left( -\frac{E}{RT} \right) \xi_{\text{COMP1}} \]

- Temperature dependent material properties \((k, \rho, c_p, \lambda)\):
  \[ \text{property} = p_0 + p_1 T + p_2 T^n \]

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

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

Key predicted quantity

PMMA → PMMA_{th} + PMMA_{h}
Flame Heat Flux Model

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Prediction of Upward Flame Spread over Polymers

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Degradation Mechanism

Milligram Scale Testing

- Thermogravimetric Analyzer (TGA)
  - Kinetics: $A, E$
    $$r = A \exp\left(-\frac{E}{RT}\right)\xi_{\text{COMP1}}$$

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

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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Effect of Dripping on Flame Heat Flux

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Prediction of Upward Flame Spread over Polymers

\[ J_{\text{flow}} = u \exp \left( -\frac{v}{RT_{\text{surf}}} \right) \]
Effect of Dripping on Flame Heat Flux

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

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A Generalized Wall Flame Model

- 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

• **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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Prediction of Upward Flame Spread over Polymers

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Materials Exhibiting Significant Melt Flow: PP and POM
Heavily Sooting Materials: ABS
Heavily Sooting Materials: HIPS
Heavily Sooting Materials: Shielded Heat Flux Tests
Glass-Reinforced Composite Materials: FRP and 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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Acknowledgements: Kevin Korver - University of Maryland
Measured Flame Heat Flux

Acknowledgements: Kevin Korver - University of Maryland

\[ q_{HFg} (\text{Kilowatts m}^{-2}) \]

\[ t - t_{\text{ign}} (\text{seconds}) \]

- Measured
- Shielded
- Shielded Interpolation

\[ y = 7 \text{ cm} \]

\[ y = 15 \text{ cm} \]
Measured Flame Heat Flux
Heat of Combustion

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**Prediction of Upward Flame Spread over Polymers**

\[
T_{PMMA} = \begin{cases} 
T_{fl, adiab}^{PMMA} & \forall y_{eff} \leq 5.5 \text{cm} \\
0.87 \times T_{fl, adiab}^{PMMA} & \forall y_{eff} > 5.5 \text{cm}
\end{cases}
\]

\[
y_{eff} = y - y_b \\
y_f = a \left( \frac{dm'}{dt} \right) + b \\
y^* = \frac{y_{eff} + y_0 y_0}{y_{ff} + y_0}
\]

\[
q''_{flame} = q' \left( y, \frac{dm'}{dt}, T_{surf} \right) = \begin{cases} 
h_{flame} \left( T_{fl,max}^{PMMA} - T_{surf} \right) & \forall y \leq y_f \\
h_{flame} \left( \alpha_f \left( T_{fl,max}^{PMMA} - T_{Hfg} \right) e^{-\ln(\alpha_f) \times (y')}^2 + T_{Hfg} - T_{surf} \right) & \forall y > y_f
\end{cases}
\]
Flame Height

- Flame height, $y_f$, can be defined as the highest position, $y_{eff}$, where measured flame heat flux reaches 97.5% of $q^{\text{steady}}$. 

\[ y_{eff} = y - y_b \]
Flame Model Predictions
Extruded PMMA

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Prediction of Upward Flame Spread over Polymers

\[ y_{eff} = y - y_b \]
\[ y_f = \alpha \left( \frac{\Delta H_{dM}}{\Delta H_{cM}} \right) \frac{dm}{dt} + b \]
\[ y^* = \frac{y_{eff}}{y_f + y_0} \]

\[ q_{flame} = q_f \left( y_{bfs}, \frac{dm}{dt}, T_{surf} \right) = \left\{ \begin{array}{ll}
    h_{flame} \left( T_{fl,max} - T_{surf} \right) & \forall y_f \leq y_f^\prime \\
    h_{flame} \left( \alpha_f \left( T_{fl,max} - T_{HF8} \right) - \frac{\Delta H_{fM}}{\Delta H_{cO}} \right) e^{-\frac{y_f}{T_{HF8} - T_{HF8}}} + T_{HF8} - T_{HF8} \right) & \forall y_f > y_f^\prime
\end{array} \right. \]
# Model Accuracy

## Prediction of Upward Flame Spread over Polymers

<table>
<thead>
<tr>
<th>Material</th>
<th>Method 1 ( y_f \sim \Delta H_{c\text{ total}} )</th>
<th>Method 2 ( y_f \sim \Delta H_{c\text{ heat H}} )</th>
<th>Method 3 ( y_f \sim \Delta H_{c\text{ 0 V}} )</th>
<th>Method 4 ( y_f \sim (1-X_p) \Delta H_{c\text{ heat H}} )</th>
<th>Method 5 ( y_f \sim (1-X_p) \Delta H_{c\text{ heat H}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>5.4</td>
<td>6.6</td>
<td>5.9</td>
<td>10.8</td>
<td>6.6</td>
</tr>
<tr>
<td>FRP</td>
<td>1.6</td>
<td>4.0</td>
<td>12.4</td>
<td>5.1</td>
<td>4.0</td>
</tr>
<tr>
<td>HIPS</td>
<td>3.7</td>
<td>9.2</td>
<td>2.4</td>
<td>14.9</td>
<td>9.2</td>
</tr>
<tr>
<td>PBT</td>
<td>5.2</td>
<td>5.1</td>
<td>6.3</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>PMMA&lt;sub&gt;CAST&lt;/sub&gt;</td>
<td>2.1</td>
<td>2.0</td>
<td>2.1</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>POM</td>
<td>9.3</td>
<td>7.8</td>
<td>8.7</td>
<td>7.0</td>
<td>7.8</td>
</tr>
<tr>
<td>PP</td>
<td>1.7</td>
<td>2.1</td>
<td>2.2</td>
<td>6.1</td>
<td>2.1</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>4.2</strong></td>
<td><strong>5.2</strong></td>
<td><strong>5.7</strong></td>
<td><strong>7.3</strong></td>
<td><strong>5.2</strong></td>
</tr>
</tbody>
</table>

Note: The values represent model accuracy scores.
Model Accuracy

<table>
<thead>
<tr>
<th>Material</th>
<th>Method 1</th>
<th>Method 2</th>
<th>Method 3</th>
<th>Method 4</th>
<th>Method 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$y_f \sim \Delta H_{c\text{ total}}$</td>
<td>$T_{fl} \sim \Delta H_{c\text{ total}}$</td>
<td>$y_f \sim \Delta H_{c \text{ heat } H}$</td>
<td>$T_{fl} \sim \Delta H_{c \text{ heat } H}$</td>
<td>$y_f \sim (1-X_r) \Delta H_{c \text{ heat } H}$</td>
</tr>
<tr>
<td>ABS</td>
<td>5.4</td>
<td>6.6</td>
<td>5.9</td>
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<td>3.7</td>
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<td>5.1</td>
<td>6.3</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>PMMA_{CAST}</td>
<td>2.1</td>
<td>2.0</td>
<td>2.1</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>POM</td>
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<tr>
<td>Average</td>
<td>4.2</td>
<td>5.2</td>
<td>5.7</td>
<td>7.3</td>
<td>5.2</td>
</tr>
</tbody>
</table>
Model-Predicted Flame Heat Flux

Prediction of Upward Flame Spread over Polymers
Generalized Flame Model

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Acknowledgements: Chad Lannon - University of Maryland
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Prediction of Upward Flame Spread over Polymers

11/24/2015
Mechanisms of Action of Flame Retardants During Flame Spread

- Effect of flame retardants on:
  - Flame height, \( y_f \)
  - Peak flame heat flux \( (q_{\text{steady}}') \) at \( y < y_f \)
  - Flame stability
Mechanisms of Action of Flame Retardants During Flame Spread

• **Effect of flame retardants on:**
  - Flame height, $y_f$
  - Peak flame heat flux ($q_{\text{steady}}$) at $y < y_f$
  - Flame stability
Mechanisms of Action of Flame Retardants During Flame Spread

- Effect of flame retardants on:
  - Flame height, $y_f$
  - Peak flame heat flux, $q''_{steady}$ at $y < y_f$
  - Flame stability

![Graph showing effect of flame retardants on flame height and peak flame heat flux](image)
Mechanisms of Action of Flame Retardants During Flame Spread

- **Effect of flame retardants on:**
  - Flame height, \( y_f \)
  - Peak flame heat flux, \( q_{steady}^{''} \) at \( y < y_f \)
  - Flame stability
Mechanisms of Action of Flame Retardants During Flame Spread

- Effect of flame retardants on:
  - Flame height, $y_f$
  - Peak flame heat flux, $q_{\text{steady}}$, at $y < y_f$
  - Flame stability

Prediction of Upward Flame Spread over Polymers
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.
Conclusions

• 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
Conclusions

- 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
Conclusions

- 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

• 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
Publications


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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)
Determine radiative fraction of total flame to surface heat flux

\[ q_{\text{net}} = h(T_{\text{flame}} - T_{\text{surf}}) + \varepsilon q_{\text{flame}}^\text{rad} - \varepsilon \sigma T_{\text{surf}}^4 \]

- The heat flux gauge is recessed, determine radiation view factor:
  \[ q_{\text{HF}g} = \frac{0.77 \pm 0.05}{q_{\text{rad}} + q_{\text{conv}}} \]

- 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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$q_{rad}^{\%} = 100 \times \left( \frac{q_{rad}}{q_{steady}} \right)$
Recessed Heat Flux Gauge Measurements

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![Graph showing the equations for recessed heat flux and their applications]
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
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ABS

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

- August 2015 Pre-mixed Methane Burner
- August 2014 Non-premixed Propane Burner

- Height above base of Burner (cm)
- $q_{\text{HFg}}$ (kW m$^{-2}$)
# 221 Series (Pure Polymer + 12, 16, or 24% Bromiertes Acrylat FR)

<table>
<thead>
<tr>
<th>Sample Preheat Duration ( (q_{\text{preheat}} = 10 \text{ kW m}^{-2}) )</th>
<th>Burner Application ( (\text{Methane, premixed}) )</th>
<th>External Heat Flux ( (q_{\text{ext}} = 20 \text{ kW m}^{-2}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBT 221_1</td>
<td>5 minutes</td>
<td>30 s</td>
</tr>
<tr>
<td>PBT 221_2</td>
<td>10 minutes</td>
<td>20 s</td>
</tr>
<tr>
<td>PBT 221_3</td>
<td>12 minutes</td>
<td>Propane Hand Torch (~8 s)</td>
</tr>
</tbody>
</table>

- Typical burning & extinction behavior, see: PBT 221_1 7x5 cm 20150820 1110am
221 Series (Pure Polymer + 12, 16, or 24% Bromiertes Acrylat FR)

Note: All samples exposed to q''ext = 20 kW m\(^{-2}\) during burning BUT preheated by q"=10 kW m\(^{-2}\) for different lengths of time:
- 221_1 = 5 min,
- 221_2 = 10 min,
- 221_3 = 12 min
221 Series (Pure Polymer + 12, 16, or 24% Bromiertes Acrylat FR)

Measurements shown here are not corrected for applied external heat flux of 20 kW m\(^{-2}\). First drop is flame extinction, second is heater removal.
221 Series (Pure Polymer + 12, 16, or 24% Bromiertes Acrylat FR)

**Graph 1:**
- **X-axis:** Time After Sample Ignition (s)
- **Y-axis:** $dm/dt$ (g/s)
- **Legend:**
  - PBT 221_1
  - PBT 221_2
  - PBT 221_3

**Graph 2:**
- **X-axis:** Time after sample ignition (s)
- **Y-axis:** $q'_{HNG}$ (kW m$^{-2}$)
- **Legend:**
  - PBT 221_1
  - PBT 221_2
  - PBT 221_3
220 Series (Pure Polymer + 8, 12, 16, or 20 % Exolit OP 1230)

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample Preheat Duration ( (q''_{preheat} = 10 \text{ kW m}^{-2}) )</th>
<th>Burner Application (Methane, premixed)</th>
<th>External Heat Flux ( (q''_{ext} = 20 \text{ kW m}^{-2}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBT 220_1</td>
<td>7 minutes</td>
<td>20 s</td>
<td>Apply immediately after sample ignition</td>
</tr>
<tr>
<td>PBT 220_2</td>
<td>7 minutes</td>
<td>40 s</td>
<td>Apply immediately after sample ignition</td>
</tr>
<tr>
<td>PBT 220_3</td>
<td>10 minutes</td>
<td>55 s</td>
<td>Apply immediately after sample ignition</td>
</tr>
<tr>
<td>PBT 220_4</td>
<td>10 minutes</td>
<td>70 s</td>
<td>Apply immediately after sample ignition</td>
</tr>
<tr>
<td>PBT 220_5</td>
<td>10 minutes</td>
<td>70 s</td>
<td>Apply immediately after sample ignition</td>
</tr>
</tbody>
</table>
PBT 220_2 (8 % Exolit)
Mass Loss Rate

![Graph showing mass loss rate over time after sample ignition. The graph has multiple data points representing different conditions, such as Aug 7th 1:45, 3:09pm, Aug 8, 3:09pm, and avg dm/dt (q_{ext} = 20).]
PBT 220_2 (8 % Exolit)
Flame Heat Flux

![Graph showing flame heat flux over time after sample ignition.](image)

- Black line: 7 cm 20150810 515 pm
  - $q^{\text{ex}}=20\text{ kW/m}^2$
- Red line: 7 cm 20150810 610 pm
  - $q^{\text{ex}}=20\text{ kW/m}^2$
- Green line: 10 cm 20150812 1230 pm
  - $q^{\text{ex}}=20\text{ kW/m}^2$
- Purple line: Avg 10, 7 cm (clean tests)
PBT 220_2 (8 % Exolit)

<table>
<thead>
<tr>
<th>t = 0 s (ignition)</th>
<th>t = 60 s</th>
<th>t = 180 s (vertical flickering)</th>
<th>t = 300 s (attempted reignition of vapors)</th>
<th>t = 390 s</th>
</tr>
</thead>
</table>

PBT 220_2 10 x 5 cm 20150812 325pm
PBT 220_3 (12 % Exolit)  
Mass Loss Rate

Sample Mass Loss Rate (g s$^{-1}$) vs. Time after sample ignition (s)
PBT 220_3 (12 % Exolit)
Flame Heat Flux

$q_{HFg}$ (kW m$^{-2}$) vs. Time after sample ignition (s)

- 6.8 cm 20150813 1157am $q^{ex}=20$kW/m$^2$
- 6.8 cm 20150813 1230pm $q^{ex}=20$kW/m$^2$
- 9 cm 20150806 508pm $q^{ex}=20$kW/m$^2$
PBT 220_3 (12 % Exolit)

- PBT 220_3 6.8x5 cm 20150813 1230pm
PBT 220_4 (16 % Exolit)
Mass Loss Rate

Time after sample ignition (s)

- 7 cm Aug11 300pm q"ext = 20
- 7 cm Aug11 330pm q"ext = 20
- 4 cm Aug11 5pm q"ext = 20
PBT 220_4 (16 % Exolit)
Flame Heat Flux

![Graph showing heat flux over time after sample ignition with data points at 0, 120, 240, 360, 480, 600, 720 seconds. The graph compares two sets of data, one marked "6.8 cm 20150818 407 pm q''ex=20kW/m^2" and another marked "6.8 cm 20150818 504 pm q''ex=20kW/m^2".](image-url)
PBT 220_4
(16 % Exolit)
PBT 220_5 (20 % Exolit)
Mass Loss Rate

$\frac{dm}{dt} (\text{g s}^{-1})$

Time after sample Ignition (s)

- Blue diamonds: 7 cm Aug11 530pm $q^{ext} = 20$
- Red squares: 7 cm Aug11 640pm $q^{ext} = 20$
PBT 220_5 (20 % Exolit)
Flame Heat Flux

$q_{HF,2}$ (kW m$^{-2}$)

Time after sample ignition (s)

6.8 cm 20150813 512 pm $q^{ex}=20\text{kW/m}^2$

PBT 220_5 6.8 cm 20150813 540 pm $q^{ex}=20\text{kW/m}^2$
PBT 220_5 (20 % Exolit)

- PBT 220_5 7x5cm 20150811 533 pm

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Image Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>t = 0 s</td>
<td>Image 1</td>
</tr>
<tr>
<td>t = 160 s</td>
<td>Image 2</td>
</tr>
<tr>
<td>t = 390 s</td>
<td>Image 3</td>
</tr>
<tr>
<td>t = 190 s</td>
<td>Image 4</td>
</tr>
<tr>
<td></td>
<td>Image 5 (side view)</td>
</tr>
</tbody>
</table>
PBT 220 Series (Exolit)
Mass Loss Rate

Time after sample ignition (s)

\[ \frac{dm}{dt} (\text{g s}^{-1}) \]
PBT 220 Series (Exolit)
Mass Loss Rate

![Graph showing mass loss rate over time for different samples labeled as Fitted 220_2, Fitted 220_3, Fitted 220_4 (7 cm), Fitted 220_4 (4 cm), Fitted 220_5, and 220_1 15 cm. The x-axis represents time after sample ignition in seconds (0 to 1200), and the y-axis represents mass loss rate (0 to 0.05 g s⁻¹).]
PBT 220 Series (Exolit)
Flame Heat Flux

Measurements shown here are not corrected for applied external heat flux of 20 kW m$^{-2}$.