A Framework for Utilizing Fire Property Tests

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ABSTRACT

A complete approximate set of equations is developed to describe fire spread over a surface and its resultant energy release. Wall, floor, and ceiling orientations are considered. The needed model data are couched in terms of available test method results, e.g., Cone Calorimeter and LIFT apparatuses. Several applications are presented to show how energy release rates can be predicted and how well they represent real data from full-scale and model room lining experiments.

KEYWORDS: Energy release, fire property tests, linings, predictions, room fires.

INTRODUCTION

Theories of flame spread and new widely used test apparatuses capable of providing engineering fire property data make it feasible to construct a framework for fire hazard assessment. The test apparatuses include the Cone Calorimeter [1], and the Lateral Ignition and Flame Spread Test (LIFT) [2], both of which have been recently established as ASTM standard methods and are being considered in ISO. We shall formulate a model to compute the energy release rate of the fire as a function of time in terms of the material orientation and properties.

The model to be presented, we emphasize, represents only a framework for a more complete and precise solution to the appropriate characterization of materials through fire test methods. Our results and our model

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should serve as support for other analyses which have used similar property
data to predict the flashover times for actual experiments [3-5]. However,
we believe that our model is less empirical and more physically complete
than these previous analyses [3-5].

**THEORETICAL DEVELOPMENT**

The essential elements of fire growth have been included; namely,
ignition, energy release rate, burning time, and all relevant modes of
flame spread for the surface orientation considered. Also, the effects of
the ignitor and thermal feedback have been parametrically considered.
Detailed transient characteristics and room smoke layering have been
ignored, but their contributions eventually need to be assessed.

Fire Properties

The term "fire properties" will be used to describe the input
material data for the model. Our "fire properties" will not neces­sar­ly be unique, but will depend on environmental conditions.
These are described below:

1. $Q^*$, average peak heat release rate per unit area. This value is
derived from the Cone Calorimeter [1] for which the transient data
have been averaged, and evaluated at a specified irradiance level.
It is illustrated in Figure 1 in which the area under the actual curve is
approximately equal to the area under the rectangle. We have not used a
standardized prescription for determining the average energy release rate
and burn time. This was done in a consistent manner by approximating the
significant burning region of the curve by a square wave. We selected an
average maximum for $Q^*$ and then estimated $t_b$ to maintain the total energy.

2. $t_b$, burn time. This value is the width of the approximating rectangle
in Figure 1. This also corresponds to a given heat flux, and is derivable
from the Cone Calorimeter.

3. $t_{ig}$, ignition time. This value is the time for piloted ignition at a
given heat flux, specifically radiative. The heat flux level should be
selected to correspond to the flame heat flux level appropriate to wind­aided flame spread.

4. $\Phi$, flame heating parameter in opposed flow spread. This "property" is
directly derivable from the LIFT [2,6] standard procedure. It represents
the flame heat transfer and opposed flow velocity effects.

5. $T_{s,min}$, minimum temperature for flame spread. In opposed flow flame
spread it is found that materials require a minimum heating level to
achieve a surface temperature required for spread. Below this temperature
spread is not possible. This temperature is also required but not
available for, wind-aided or upward flame spread. For example, it appears
that a preheated surface temperature in excess of 80°C is necessary to cause sustained upward flame spread on wood particle board [7].

Equations

In developing the governing equations we shall consider all materials to be thermally thick, i.e. no effect of thickness, and laminated materials and substrates are treated as homogeneous, reflective of their bulk properties. The same corresponding equations will apply, without distinction, to horizontal (floor), lateral, and downward wall spread as opposed flow spread; and to upward wall and ceiling spread as wind-aided spread. One might argue with this lack of distinction but the opposed flow case for these different orientations has some support [8] whereas the extension of the upward spread theory to the ceiling is only a convenience for now which needs further study. For all orientations, as illustrated in Figure 2, symmetry is invoked, and the wind-aided coordinate is designated by y and the opposed flow coordinate by x. Spread on the floor (Fig. 2a), and ceiling (Fig. 2b) is radially symmetric, and on the wall (Fig. 2c) is approximated and as a region developed from two (x and y) spreads away from an initially ignited rectilinear zone of area 2x_0y_0. The region between the extended pyrolysis wall fronts (x_p,y_p), and the burnout fronts (x_b,y_b) is formed by straight line approximations (Fig. 2c).

The objectives of our analysis is to compute the energy release rate, \( \dot{Q}(t) \), as a function of time for the orientation shown in Figure 2 or their combination. For energy release we write the following approximation based on Figure 1.

\[
\dot{Q}(t) = \iint \, \dot{Q}^* \, dx \, dy = \dot{Q}^* \, A_p
\]

where \( A_p \) is the pyrolysis or volatilizing area.

For the floor or ceiling cases it can easily be shown that

\[
A_p = \pi \left( x_p^2 - x_b^2 \right) \text{ or } \pi \left( y_p^2 - y_b^2 \right)
\]

For the wall case,

\[
A_p = 2 \left[ y_p x_0 + (x_p - x_0) y_0 + 1/2 (y_p - y_0)(x_p - x_0) \right] \text{ for } t \leq t_b
\]

or
\[ A_p = 2 \left[ y_p x_o + x_p y_o + \frac{1}{2} (y_p - y_o) (x_p - x_o) \right] - 2 \left[ y_b x_o + x_b y_o + \frac{1}{2} (y_b - y_o) (x_b - x_o) \right] \] for \( t > t_b \) \hfill (3b)

In order to formulate the rest of the analysis we write out and solve the equations for the pyrolysis and burnout fronts.

**Wind-aided Solution**

The upward or wind-aided solution is developed \([9]\) from the equation

\[
\frac{dy_p}{dt} = \frac{y_f - y_p}{t_{ig}} \] \hfill (4)

where \( y_f \) is the position of the flame tip with \( y_f - y_p \) defining the forward heat transfer region of the flame identified with heat flux, \( q_f \). Equation (4) is a quasi-steady model which uses the steady-state flame spread result successively over time as the forward heat transfer region changes. Mathematically, this solution is continuous. This flame heat flux will be taken as 30 kW/m² in our analysis for all materials.

The ignition time is given as

\[
t_{ig} = \frac{\pi kpc (T_{ig} - T_s)^2}{4 (q_f)^2} \] \hfill (5)

where \( T_{ig} \) is the ignition temperature, \( kpc \) is the thermal inertia, and \( T_s \) is the surface temperature of the region \( y \geq y_f \). As can be seen, the "property" \( t_{ig} \) can be related to more valid engineering materials properties (\( kpc \) and \( T_{ig} \)) and other factors.

Finally, the flame length can be estimated by a linear approximation to wall fire data \([9]\) as

\[
y_f - y_b = k_f \left[ \hat{Q}_o + \hat{Q} (y_p - y_b) \right] \] \hfill (6)

where \( y_b \) is taken as identically zero for \( t \leq t_b \), and \( \hat{Q}_o \) is the energy release rate per unit width of the ignitor flame needed to start the process. This ignitor flame is assumed to provide a uniform heat flux \( (q_f^*) \) of 30 kW/m² over the region \((x_0, y_0)\) which is taken to ignite at \( t = t_{ig} \) in Eqn.(5), or corresponding to \( t_{ig} \) in Fig. 1. The value for \( k_f \) is approximately 0.01 m²/kW. In Eqn.(6), the term \( \hat{Q}_o \) is set to zero when \( t > t_b \). This is done after \( t = t_b \) since the initial region as determined by the flame extent due to \( \hat{Q}_o \) is no longer burning, and subsequently the ignitor flame would become discontinuous from the material flame ahead of this region. This ignitor energy is continuously included in the overall heat release.

The burnout front can be approximated as

\[
\frac{dy_b}{dt} = \frac{y_p - y_b}{t_b} \] for \( t > t_b \) \hfill (7)

The initial conditions are given as:

\[
t = 0 \; , \; y_p = y_0 \] \hfill (8a)
\[
t = t_b \; , \; y_p = y_p(t_b) \; , \; y_b = y_0 \] \hfill (8b)
The solutions to the above are given below:

\[ \eta = \left( \frac{a+1}{a} \right) e^{ar} - 1/a \]  

(9)

for \( 0 \leq r \leq t_b/t_{ig} \) where \( r = \frac{t}{t_{ig}}, \eta = \frac{y_f}{y_o}, \quad a = k_r \dot{Q}'' - 1, \) and \( y_o = k_r \dot{Q}'' \). This assumes that the initial pyrolysis length, \( y_o \), is determined by the height of the ignition flame. For \( r > (t_b/t_{ig}) = r_b \), Eqns. (4) and (7) are subtracted and solved to yield

\[ \psi = \frac{y_f - y_o}{y_o} = c e^{b(r - r_b)} \]  

(10)

where \( b = a - 1/r_b \) and \( c = \left( \frac{a+1}{a} \right) [e^{ar_b} - 1] \). From Eqn. (7) it follows that

\[ \eta_b = \frac{y_f}{y_o} \quad \text{is given by} \]

\[ \eta_b = 1 + \frac{c}{b r_b} \left( e^{b(r-r_b)} - 1 \right) \]  

(11)

The parameters \( a \) and \( b \) must be greater than zero in order for the upward fire spread to accelerate. For values less than zero, the spread will eventually stop. This bimodal behavior is a distinct characteristic of upward flame spread which is conditional on the form of Eqn. (6). This clearly shows the role of the energy release rate per unit area and its duration in time, i.e., \( \dot{Q}'' \) and \( t_b \).

Opposed flow solution

From the LIFT procedure [2,6] the governing equation for the pyrolysis position is

\[ \frac{dx_p}{dt} = \frac{\dot{Q}}{k_r c (T_{ig} - T_s)^2} \quad \text{for} \quad T_s \geq T_{s,\text{min}}. \]  

(12)

This can be rewritten as

\[ \frac{dx_p}{dt} = \frac{\pi \dot{Q}}{4 (\dot{Q}_s')^2} \quad \frac{t}{t_{ig}} \]  

(13)

The dimensionless solution \( \xi = x_p/x_o \) follows as

\[ \xi = \beta r + 1 \quad \text{where} \quad \beta = \frac{\pi \dot{Q}}{4 (\dot{Q}_s')^2} x_o \]  

(14)

The burnout solution analogously follows from Eqn. (7), i.e.

\[ \frac{dx_b}{dt} = \frac{x_p - x_b}{t_b} \]  

(15)

and it can be shown that \( \xi_b = x_b/x_o \) is given by

\[ \xi_b = \beta (r - r_b) + 1, \quad r \geq r_b. \]  

(16)
This completes the solution. These equations will now be applied to specific applications. For each case we shall appropriately apply the equations by accounting for the effects of geometry and thermal feedback as a parameter. For example, a corner wall and ceiling fire will be considered as an extended vertical wall representative of the actual corner wall and ceiling jet region plus a quadrant of a circular ceiling. To review, the procedure for implementing this solution is as follows:

1. Assemble material data namely, $Q_n$, $t_{ig}$, $t_b$, $\phi$ and $T_{s,min}$.
2. Prescribe the ignition source, $Q_c$.
3. Since no room fire model is coupled to this analysis, one must set $T_s$ at a value representative of the particular room configuration.
4. Compute the pyrolysis area $A_p$ for the surface configuration using the formulas for $x_p$ and $y_p$.
5. Compute the fire product output rate, e.g. rate of any energy release, by multiplying $A_p$ by $Q_n$.

APPLICATIONS

Several applications of the analysis will be presented for cases where scenario results for total energy release exist along with a complete set of fire property data.

Full Scale Room - Corner Tests

A series of full scale room lining fire tests were performed at the Swedish National Testing Institute, Borås, Sweden [10]. The test scenario consisted of lining the walls and ceiling of the room (2.43 m by 3.66 m by 2.43 m in height with an opening 2 m by 0.9 m) with a given material. A 0.17 m by 0.17 m propane sand burner was placed in the corner of the room. Initially a 100 kW fire was allowed to burn in the corner. If this fire did not cause flashover in 10 minutes, then the burner output was increased to 300 kW.

Small scale fire test data were obtained by other researchers for the materials used in the Borås study [5,11,12] and were used to develop Table 1. These values are used for the model inputs. In the calculations, ceiling fire spread is accounted for by having the ceiling ignite when the pyrolysis front reaches the ceiling. The ceiling spread follows the wind-aided spread along the wall ceiling interface. Thus, the pyrolyzing ceiling area is given as the quadrant of the ceiling with a radius equal to the distance from the corner to the wall ceiling interface pyrolyzing front. Lateral spread was

![Figure 3 Energy release predictions for the Swedish data ($T_s = 80^\circ C$, irradiance level = 25 kW/m$^2$).](image)
allowed to occur only if the wall surface temperature is at the material's $T_{s,\text{min}}$ or greater. The model was run with $T_s$ at 25°C and 80°C. While at the start of the test the surface temperature is uniform (about 25°C), allowing $T_s$ to be an input parameter shows the sensitivity to feedback and the effects which increased lateral spread has on the results. This is justified because, while early on in the test $T_s$ of 25°C is more representative of the room conditions, the upper layer temperature is always increasing and radiative feedback is raising wall and ceiling temperatures. We selected burner flame heights ($y_o$) of 1.3 m and 2.1 m for the 100 and 300 kW settings. We determined $y_o$ values from an axisymmetric fire plume correlation realizing that corner flames would be taller and could interact with the ceiling. For cases that stopped propagating before 10 minutes, the analysis was restarted at $t=600$ s from a new origin at $y_o(600 \text{ s})$. If $y_o(600 \text{ s})$ is greater than 2.1 m, the ignitor flame height, we arbitrarily selected 0.3 m as a new $y_o$ in order to initiate spread again. Also for $t > 600$ s, we selected $T_s = 250$°C based on the maximum gas temperatures measured [10]. Model predictions and experimental results for the time to a 1 MW fire are given in Table 2. Figures 3 and 4 show the experimental rate of heat release as a function of time (solid curves) and model calculations (dashed curves) with $T_s = 80$°C for six of the materials. The results are comparable to the calculations of Karlsson [5], but appear to be distinctly better than the results of Wickström and Göransson [3].

Table 1 Fire Properties of Swedish Fire Test Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_{15}$ (°C)</th>
<th>$kpc$ (kW/m²K)</th>
<th>$\Phi$ (s)</th>
<th>$T_{s,\text{min}}$ (°C)</th>
<th>$Q_{b}$ (kW/m²)</th>
<th>$t_b$ (s)</th>
<th>$Q_{w}$ (kW/m²/s)</th>
<th>$t_w$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Board</td>
<td>405</td>
<td>0.626</td>
<td>8</td>
<td>140</td>
<td>&gt;500</td>
<td>200</td>
<td>&gt;500</td>
<td></td>
</tr>
<tr>
<td>Insulating Fiberboard</td>
<td>381</td>
<td>0.229</td>
<td>14</td>
<td>90</td>
<td>120</td>
<td>&gt;500</td>
<td>150</td>
<td>&gt;300</td>
</tr>
<tr>
<td>Medium Density Fiberboard</td>
<td>361</td>
<td>0.732</td>
<td>11</td>
<td>80</td>
<td>140</td>
<td>170</td>
<td>&gt;600</td>
<td></td>
</tr>
<tr>
<td>Wood Panel (Spruce)</td>
<td>389</td>
<td>0.569</td>
<td>24</td>
<td>155</td>
<td>140</td>
<td>&gt;200</td>
<td>160</td>
<td>&gt;400</td>
</tr>
<tr>
<td>Melamine on Particle Board</td>
<td>483</td>
<td>0.804</td>
<td>&lt;1</td>
<td>435</td>
<td>-</td>
<td>-</td>
<td>115</td>
<td>&gt;400</td>
</tr>
<tr>
<td>Wall Paper on Gypsum Board</td>
<td>388</td>
<td>0.593</td>
<td>0.5</td>
<td>300</td>
<td>100</td>
<td>40</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>PVC on Gypsum Board</td>
<td>410</td>
<td>0.208</td>
<td>25</td>
<td>300</td>
<td>105</td>
<td>20</td>
<td>160</td>
<td>20</td>
</tr>
<tr>
<td>Textile on Gypsum Board</td>
<td>406</td>
<td>0.570</td>
<td>9</td>
<td>270</td>
<td>200</td>
<td>30</td>
<td>300</td>
<td>20</td>
</tr>
<tr>
<td>Textile on Mineral Wool</td>
<td>391</td>
<td>0.183</td>
<td>6</td>
<td>174</td>
<td>250</td>
<td>30</td>
<td>375</td>
<td>20</td>
</tr>
<tr>
<td>Paper on Particle Board</td>
<td>426</td>
<td>0.680</td>
<td>13</td>
<td>250</td>
<td>140</td>
<td>&gt;500</td>
<td>150</td>
<td>&gt;500</td>
</tr>
<tr>
<td>Rigid Polyurethane Foam</td>
<td>393</td>
<td>0.031</td>
<td>3</td>
<td>105</td>
<td>110</td>
<td>60</td>
<td>180</td>
<td>60</td>
</tr>
<tr>
<td>Expanded Polystyrene Foam</td>
<td>482</td>
<td>0.464</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td>Gypsum Board</td>
<td>469</td>
<td>0.515</td>
<td>14</td>
<td>380</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>20</td>
</tr>
</tbody>
</table>

- Data were not taken.
Table 2  Time to Achieve a 1 MW Fire for the Swedish Room Tests

<table>
<thead>
<tr>
<th>Material</th>
<th>Experimental Time (s)</th>
<th>Model Calculations (25 kW/m²) (Ts = 25°C) (s)</th>
<th>Model Calculations (50 kW/m²) (Ts = 25°C) (s)</th>
<th>Model Calculations (25 kW/m²) (Ts = 80°C) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Board</td>
<td>157</td>
<td>198</td>
<td>143</td>
<td>145</td>
</tr>
<tr>
<td>Insulating Fiberboard</td>
<td>59</td>
<td>77</td>
<td>58</td>
<td>55</td>
</tr>
<tr>
<td>Medium Density Fiberboard</td>
<td>131</td>
<td>180</td>
<td>148</td>
<td>125</td>
</tr>
<tr>
<td>Wood Panel (Spruce)</td>
<td>131</td>
<td>165</td>
<td>143</td>
<td>117</td>
</tr>
<tr>
<td>Melamine on Particle Board</td>
<td>465</td>
<td>-</td>
<td>402</td>
<td>-</td>
</tr>
<tr>
<td>Wall Paper on Gypsum Board</td>
<td>640</td>
<td>622</td>
<td>616</td>
<td>641</td>
</tr>
<tr>
<td>PVC on Gypsum Board</td>
<td>611</td>
<td>619</td>
<td>606</td>
<td>622</td>
</tr>
<tr>
<td>Textile on Gypsum Board</td>
<td>639</td>
<td>615</td>
<td>613</td>
<td>615</td>
</tr>
<tr>
<td>Textile on Mineral Wool</td>
<td>43</td>
<td>33</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>Paper on Particle Board</td>
<td>143</td>
<td>237</td>
<td>220</td>
<td>177</td>
</tr>
<tr>
<td>Rigid Polyurethane Foam</td>
<td>6</td>
<td>11</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Expanded Polystyrene Foam</td>
<td>115</td>
<td>-</td>
<td>122</td>
<td>-</td>
</tr>
<tr>
<td>Gypsum Board</td>
<td>*</td>
<td>-</td>
<td>*</td>
<td>-</td>
</tr>
</tbody>
</table>

- Data were not taken
* Did not reach 1 MW

Textile Wall Covering Room Tests

A series of textile wall fire tests was performed by the U.C., Berkeley for the American Textile Manufactures Institute [13]. In these tests, 0.31 m (1 ft) and 0.62 m (2 ft) wide strips of different textile wall covering materials were applied to a corner section and the wall portion of the wall-ceiling interface of a room with roughly the same dimensions of the room described above. A 0.31 m by 0.31 m propane sand burner was placed in the material lined corner approximately 10 cm from the walls. A small 40 kW fire was allowed to burn in the corner for 5 minutes, then the burner output was increased to 150 kW. The position of the burner and the size of the small 40 kW fire was such that in most cases it did not cause the textile material to ignite, but shortly after the burner output was increased to 150 kW, all wall lining materials ignited. The rate of heat release was obtained during each test. The data for input into the model is given by Harkleroad [14]. Here lateral spread was not included in the calculations since lateral spread is not expected with the 0.31 m wide strips anyway. It appears from the experimental results that the 40 kW fire only served to preheat the room, therefore we picked an initial surface temperature of 100°C based on the maximum gas temperatures measured during this preheating time. Table 3 shows the experimental and calculated results. By examining the 0.31 m and 0.62 m wide strip results, it appears in some cases lateral spread is significant. The model calculations were performed for the 0.31 m wide strip cases using Cone Calorimeter data at external irradiances of 30 and 50 kW/m². Ignition delay times for each of the materials were calculated from Eq. (5). For this calculation, we assumed Ts = 100°C and 60 kW/m² to represent the heat flux of the ignitor [15], and added the calculated ignition time to the model calculated time to reach the peak rate of heat release. The peak rate of heat release and the time interval from the start of the 150 kW fire for the 0.31 m strips are in fair agreement with the calculations. After the peak heat release
was obtained a rapid decay was observed experimentally for most cases, this was predicted well by the model.

**Table 3 Textile Wall Coverings Room Fire Tests**

<table>
<thead>
<tr>
<th>Material</th>
<th>Full Scale Screening Tests</th>
<th>Model Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(0.31 m width) (0.62 m width)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\dot{Q}_p$ ($kW$) $t_p^*$ (s)</td>
<td>$\dot{Q}_p$ ($kW$) $t_p^*$ (s)</td>
</tr>
<tr>
<td></td>
<td>(30 kW/m²) (50 kW/m²)</td>
<td>(30 kW/m²) (50 kW/m²)</td>
</tr>
<tr>
<td>(H) 85% wool 15% cotton</td>
<td>46 30 160 40</td>
<td>- 146 46</td>
</tr>
<tr>
<td>(C) 55% cotton 45% rayon</td>
<td>62 30 119 60</td>
<td>137 40 139 37</td>
</tr>
<tr>
<td>(G) 100% polyester</td>
<td>83 30</td>
<td>64 39 56 44</td>
</tr>
<tr>
<td>(B) 100% polyester</td>
<td>207 45 298 60</td>
<td>121 46 270 46</td>
</tr>
<tr>
<td>(Q) 100% polyester</td>
<td>207 40 480 40</td>
<td>145 50 293 55</td>
</tr>
<tr>
<td>(QFy) 100% polyester</td>
<td>310 40</td>
<td>- 157 43 292 59</td>
</tr>
<tr>
<td>(R) 100% nylon</td>
<td>587 70 590 70</td>
<td>46 46 416 51</td>
</tr>
<tr>
<td>(AA) 70% acrylic 30% wool</td>
<td>684 30</td>
<td>- 725 109 744 106</td>
</tr>
<tr>
<td>(PPPF) polypropylene</td>
<td>- 337 50</td>
<td>271 45 450 48</td>
</tr>
</tbody>
</table>

- Data were not taken

$\dot{Q}_p = $ peak energy release rate

$t_p^* = $ time interval from start of 150 kW burner to peak energy release rate

**CONCLUDING REMARKS**

We have presented evidence that an engineering approach utilizing "fire property" data from test methods can satisfactorily predict full scale energy release of room lining fires. The choice of the fire properties used is somewhat arbitrary until the fire heat transfer conditions can be related to the test method irradiance levels. The framework presented should serve as a basis for further analysis, but it could be used now to estimate the fire growth hazard of lining materials.

**Acknowledgement**

We are grateful to Mr. Richard Gottwald and the Society of Plastics Industries for partial support in developing this study.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Subscripts:</th>
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<tr>
<td>$A$</td>
<td>area</td>
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<tr>
<td>$a$</td>
<td>dimensionless parameter, Eq. (9)</td>
<td>b burnout</td>
</tr>
<tr>
<td>$b$</td>
<td>dimensionless parameter, Eq. (10)</td>
<td>f flame</td>
</tr>
<tr>
<td>$c$</td>
<td>dimensionless parameter, Eq. (10)</td>
<td>g ignition</td>
</tr>
<tr>
<td>$k_{pc}$</td>
<td>thermal inertia</td>
<td>i initial</td>
</tr>
<tr>
<td>$k_f$</td>
<td>constant, 0.01 m²/kW, Eq. (6)</td>
<td>o initial</td>
</tr>
<tr>
<td>$q$</td>
<td>heat transfer</td>
<td>p pyrolysis</td>
</tr>
<tr>
<td>$Q$</td>
<td>energy</td>
<td></td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
<td></td>
</tr>
<tr>
<td>$T$</td>
<td>temperature</td>
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</tr>
<tr>
<td>$x$</td>
<td>opposed flow coordinate direction</td>
<td>655</td>
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Nomenclature (continued)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>y</td>
<td>wind-aided coordinate direction</td>
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<td>$\beta$</td>
<td>dimensionless parameter, Eq. (14)</td>
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<tr>
<td>$r$</td>
<td>dimensionless time, $t/t_o$</td>
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<td>$\xi$</td>
<td>dimensionless pyrolysis position, $x_p/x_o$</td>
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<td>$\xi_b$</td>
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<td>$\eta_b$</td>
<td>dimensionless burnout position, $y_b/y_o$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>flame heating parameter, Eq. (12)</td>
</tr>
</tbody>
</table>

Superscripts:

- (') average
- (\per unit time)
- (\per unit area)
- (\per unit width)

REFERENCES

15. Mowrer, F., Private Communications, Univ. of Maryland, July 1990.