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A PRACTICAL MODEL ON FLAME SPREADING OVER MATERIALS

C. W. LEUNG
Department of Building Services Engineering,
The Hong Kong Polytechnic University
Hong Kong, China
E-mail: vicky.leung@polyu.edu.hk

W. W. YUEN
Department of Mechanical and Environmental Engineering, University of California, Santa Barbara,
Santa Barbara, CA. 93106, USA
E-mail: yuen@engineering.ucsb.edu

W. K. CHOW
Department of Building Services Engineering,
The Hong Kong Polytechnic University
Hong Kong, China
E-mail: bewkchow@polyu.edu.hk

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ABSTRACT

Flame spreading is a very important phenomenon in the hazard assessment for fire, which is a key element in providing fire safety in buildings with engineering performance-based fire codes. A mathematical model is presented in this paper to predict the flame spreading of materials using the experimental data from cone calorimeter. Numerical prediction of the flame front position and flame spreading velocity of the ASTM LIFT test are generated The heat flux from the external radiation panel, irradiance from the burning part of the sample and convective heat loss to the ambient air were included to model the total net heat flux incident on the specimen. A two dimensional radiation model, together with a simplified model of luminous flame emissivity, are used to characterize the radiative transfer from the flame to the sample.

Simulation results agree well with the experimental data, giving confidence that the model is reliable. Radiation is identified as an important mechanism affecting the flame spread behavior. This model can be taken as the first step for modeling flame spreading over materials for implementing engineering performance-based fire codes.

NOMENCLATURE

a	Absorption coefficient
b	Width of the specimen
c	Specific heat capacity of specimen (J/kgK)
C_2	Second radiation constant
D	Flame thickness (m)
dA	The area receiving the radiative feedback from the flame
f_v	particulates volume fraction
$F_{dx\text{-}f}$	Configuration factor between the top of the flame to a differential area element, dx, at x (Eq. (8))
$F_{dx\text{-}L}$	Configuration factor between a horizontal plane of length L to a differential area element, dx, at x (Fig. 2)
$F_{dx,g}$	Exchange factor between the flame at a differential area element, dx, at x
F(x)	Distribution factor of external radiative heat flux on specimen
h	Total heat loss coefficient (W/m^2K)
h_c	Convective heat transfer coefficient (W/m^2K)
k	Conductivity of specimen (W/mK)
$\dot{q}_{av}''$	Average value of heat release rate of material under 25 kW/m^2 within time period, t_d (W/m^2)
$\dot{q}_c''$	Convective heat loss along specimen surface (W/m^2)
$\dot{q}_{cr}''$	Critical irradiance for ignition (W/m^2)
$\dot{q}_e''(x)$	External irradiance on x mm position of speciman from radiation panel (W/m^2)
$\dot{q}_f''$	Radiative feedback from burning part of the specimen (W/m^2)
$\dot{q}_{\max}''$	Maximum heat release rate of specimen (W/m^2)
$\dot{q}_t''$	Total net heat flux on the specimen (W/m^2)
$S_2(x)$	2-dimensional radiation function
t	Time (s)
t_0	Preheat time measured in LIFT tests
t_{ig}	Ignition time (s)
t_d	Time period within which the heat release rate is greater than 60% $\dot{q}_{\max}''$ of the material in the cone calorimeter (s)
$t_{d,c}$	Flame duration from cone calorimeter data (s)
t_{ph}	Preheat time (s)
$t_{ph,\,min}$	Minimum preheat time (s)
T_s	Surface temperature of specimen (K)
T_∞	Initial / ambient temperature (K)
T_f	Flame temperature (K)
T_{ig}	Critical surface temperature for ignition (K)
x_H	Flame front position, (m)
x_L	Flame end position, (m)
y	Coordinate in the span wise direction of the sample
z	Coordinate in the direction perpendicular to the sample
ρ	Density of the material (kg/m^3)
kρc	Thermal inertia of the material (W^2s/m^4K)
ε	Emissivity of surface of the material
ε_f	Emissivity of the radiating plane used in ref. [12]
σ	Stefan-Boltzmann constant
α	Absorptivity of fuel surface
κ	empirical constant used in Eq. (11)

INTRODUCTION

For providing adequate fire safety in buildings, partition walls for compartmentation must be designed to withstand an accidental fire over a finite time period. A good understanding on flame spreading over wall materials including paint coatings is important for the design development. Flame spreading also plays an important role in the understanding of other fire assessment parameters such as heat release rate of the room, time to flashover in the compartment and the available safe egress time for occupants. This is very important when implementing engineering performance-based fire codes [1]. As reviewed [2,3], only the old bench-scale test [4] was specified in the Hong Kong fire codes [5-7] for assessing the flame spreading behavior of materials. This approach is not adequate for assessing wall structures made of more than one material such as sandwich panels in actual fires. Full-scale room corner fire test [8], on the other hand, is too expensive to be a practical assessment tool. The development of a mathematical model based on bench-scale test results to assess the flame spreading of materials is thus an important task to the industry.

There are many models for various aspects of fire available in the industry such as zone models, field models and airflow network models, etc. However, very few [9,10] of them include a good prediction for flame spreading [11]. Many of the existing models still require further experimental verification and thus have uncertain accuracy. There is a need for developing a suitable model for flame spreading.

Reviews of models reported in the literature had identified an approach of using bench-scale testing data to predict the flame spreading results [12] such as those generated by the ASTM Lateral flame spread and ignition test (LIFT) [13]. Cone calorimeter [14] results including ignition time, critical surface temperature for ignition, heat release rate, and flame duration are used as input data to predict the test results. Assumptions were made for particular flame configuration, flame duration and emissivity. The heat flux from the external radiation panel, irradiance from the burning part of the sample and convective heat loss to the ambient air were included to model the total net heat flux incident on the specimen. The transient surface temperature of the sample was calculated and data from cone calorimeter were used to define flame ignition and extinction. The flame front position and the flame spreading velocity were computed.

One of the difficulties of this existing modelling approach [12] is its radiation model. Specifically, this approach treats the flame as a planar surface at a given flame height radiating to the unburned material with an emissivity ε_f. Since flame radiation is a volumetric effect, it is extremely difficult, if not impossible to relate ε_f to physical properties of the flame. The use of this model as a practical tool for fire safety assessment is thus limited.

In this work, this existing modeling approach [12] is improved by implementing a more realistic radiation model. A two-dimensional radiative transfer model and a simplified model of the luminous flame emissivity are used to simulate the radiative heat transfer from the flame to the unburned surface. To demonstrate the capability of the model, a sensitivity study is performed to assess the effect of the absorption coefficient, flame thickness and preheating period on the prediction of the flame spreading data. The current model, together with bench-scale test data, can be used as a material assessment and selection tool for fire safety.

ANALYSIS

Basic Principles Of The Model

The existing model on flame spreading [12] will be used as framework in the current model. The basic principle of the model is to use the data from the cone calorimeter tests and to simulate the flame spreading results including flame front distances and velocities in the standard LIFT test. A schematic of the model is shown in Fig. 1. Mathematically, assuming that at each location x, the heat transfer into the solid can be considered as one-dimensional conduction in the z direction, the conservation equation can be written as [12,15]

$$\frac{\partial T}{\partial t}=\frac{k}{\rho c}\frac{\partial^2 T}{\partial z^2} \qquad (1)$$

with boundary conditions of

at $t=0$, $\quad T = T_\infty$

at $z=0$,

$$k\frac{\partial T}{\partial z}\equiv \dot{q}_t''$$

where $\dot{q}_t''=\dot{q}_e''+\dot{q}_c''+\dot{q}_f''$

In the above expression, $\dot{q}_e''$ is the external irradiance from the radiation panel, $\dot{q}_f''$ is the radiative feedback from the burning part of the specimen and $\dot{q}_c''$ is the convective and radiative heat loss from the specimen given by

$$\begin{aligned}\dot{q}_c''&=-h_c(T_s-T_\infty)-\varepsilon\sigma(T_s^{\,4}-T_\infty^{\,4})\\&=-h(T_s-T_\infty)\end{aligned} \qquad (2)$$

where, in the second part of Eq. (2), h is the total heat loss coefficient, including both radiative and convective heat transfer.

The total heat flux irradiating on the sample, $\dot{q}_e''$, is derived by the external heat flux from the radiative panel, the radiative heat flux from the flame and the natural convective heat loss to the ambient air. During the preheating period, t $<$ t_{ph}, there is no flame and $\dot{q}_f''$ is set to be zero. The surface temperature at every position along the specimen is calculated according to the impressed net heat flux. It is assumed that pilot ignition occurs when the surface temperature reaches the ignition temperature which is assumed to be constant for a particular material and is independent of the way of heating nor the heat flux level [16,17]. In this way, the flame front distance and thus the velocity of flame spreading can be computed.

Detail Discussion Of The Model

The irradiance impressing on the sample comes from two sources, i.e. the radiative heat flux from the external furnace, and the radiation from the flame after ignition. Since the objective of the model is to simulate the LIFT test, the profile of the external radiative heat flux is taken to be that used by the test. Specifically, the heat flux is calibrated according to the heat flux on the 50 mm position from the hot end of the specimen, which should be of 5 kW/m^2 higher than the minimum irradiance as determined in the ignition protocol of the LIFT test, and the distribution factors

$$F(x)=\frac{q''_e(x)}{q''_e(50)} \qquad (3)$$

as stated in the ASTM E1321-97a [13]. Hence,

$$\dot{q}''_e(x)=F(x)\cdot\dot{q}''_e(50) \qquad (4)$$

The solution to Eq. (1) is generated in two stages. First, ignition determined for a specified preheating time, t_{ph}. For t < t_{ph}, $\dot{q}_f''$ is assumed to be zero and the surface temperature at a location x is calculated by a Duhamel integral as follow

$$\begin{aligned}&T_s(x,t)=T_\infty+2\dot{q}_e''(x)\sqrt{\frac{t}{\pi k\rho c}}\\&+\int_0^t 2\left\{\frac{\partial}{\partial\zeta}\left[\dot{q}_c''(x,\xi)\right]\right\}\sqrt{\frac{t-\xi}{\pi k\rho c}}d\xi\end{aligned} \qquad (5)$$

Note that the second term in Eq. (5) represents the contribution from the convective heat loss. $\dot{q}_c''$ is a function of both x and t since it is a function of the surface temperature.

Equation (5) is evaluated for different value of x starting with x = 0 at the time $t = t_{ph}$. If the surface temperature at a position x reaches the ignition temperature (which is assumed to be constant and is specified for a particular material), the surface temperature for the next value of x is calculated. This procedure continues until the calculated surface temperature at a position x_{ig} is below the ignition temperature. The flame is assumed to cover the entire area from x = 0 to $x = x_{ig}$ at time $t = t_{ph}$.

In the second stage of the calculation, the propagation of the flame front is determined. For a location x ahead of the flame, the Duhamel integral used in the calculation of surface temperature becomes

$$
\begin{aligned}
T_s(x,t) &= T_\infty + 2\dot{q}_e''(x)\sqrt{\frac{t}{\pi k\rho c}} \\
&+\int_0^t 2\left\{\frac{\partial}{\partial\zeta}[\dot{q}_c''(x,\xi)]\right\}\sqrt{\frac{t-\xi}{\pi k\rho c}}d\xi \\
&+2\dot{q}_f''(x,t_{ph})\sqrt{\frac{t-t_{ph}}{\pi k\rho c}} \\
&+\int_{t_{ph}}^t 2\left\{\frac{\partial}{\partial\zeta}\left[\dot{q}_f''(x,\xi)\right]\right\}\sqrt{\frac{t-\xi}{\pi k\rho c}}d\xi
\end{aligned} \tag{6}
$$

The last two terms in Eq. (6) corresponds to the radiative heating from the flame. It is a function of the location of the flame end, $x_L(t)$ and flame front, $x_H(t)$ at time t.

At a specific time t with a known value of $x_L(t)$ and $x_H(t)$ and a time step Δt, Eq. (6) is evaluated for $x > x_H(t)$. The first value of x at which the surface temperature is below the ignition temperature is defined to be the location of the flame front at $t+\Delta t$, i.e., $x_H(t+\Delta t)$. To determine the location of the "tail" of the flame, $x_L(t+\Delta t)$, the concept of flame duration is utilized.

Experimentally, flame duration is a parameter determined in the cone calorimeter test and is taken as the period within which the heat release rate of the material to be greater than 60% of the maximum heat release rate. However, the testing nature of the cone calorimeter tests and the LIFT tests are different. A more complete burning of the sample is expected in the former. To include such difference and the incompleteness burning of the specimen in the LIFT test, the following empirical relation was introduced [12]

$$
t_d = t_{d,c} - \sum_i\left(\sqrt{\frac{q_{cr}''-q_{e,i}''}{q_{cr}''}}\sqrt{\frac{400-q_{av}''}{400}}\cdot\Delta t_i\right) \tag{7}
$$

where t_d is the flame duration of the burning strip and $t_{d,c}$ is the flame duration from Cone Calorimeter data. $\dot{q}_{cr}''$ is the critical ignition irradiance for the material. $\dot{q}_{av}''$ is the heat release rate of the material under 25 kW/m^2 from the cone calorimeter tests. 400 kW/m^2 is the reference data taken as the PMMA data under 25 kW/m^2 from Cone tests. $\dot{q}_{e,i}''$ is the external irradiance at the position x. Δt_i is the difference of arrival time of the flame front between two adjacent burning strips (i.e., x and x + Δx). Since the ignition time for each burning strip at x is known from the solution to the Duhamel integral, Eq. (7) can be used to determine the location of the tail of the flame, $x_L(t)$. Together with a radiation model for $\dot{q}_f''$ which will be described in the next section, Eqs. (3) to (7) constitute a complete mathematical description of the flame spread problem. For a given material and a known set of data from the cone calorimeter test, the flame spread behavior under the LIFT test conditions can be determined. Extinction is defined as the time at which $x_L(t) = x_H(t)$.

The Previous Radiation Model

For the evaluation of $\dot{q}_f''$, the radiative heat transfer between the propagating flame and the unburned surface needs to be determined. In the previous work [12], the flame radiation is assumed to be emitted entirely from a surface at the top of the flame ($z = D$, $x_L(t) < x < x_H(t)$ in Fig. 1) to a differntial area dx at $x > x_H(t)$. The view factor can be obtained from standard reference [18] to be

$$
F_{dx-f} = F_{dx,x_L} - F_{dx,x_H} \tag{8}
$$

where $F_{dx,L}$ is the view factor between a plane surface and a differential strip as shown in Fig. 2. It is given by

$$
F_{dx-L} = \frac{1}{\pi Y}\left(\begin{array}{l}\sqrt{1+Y^2}\tan^{-1}\frac{X}{\sqrt{1+Y^2}} \\ -\tan^{-1}X \\ +\frac{XY}{\sqrt{1+X^2}}\tan^{-1}\frac{Y}{\sqrt{1+Y^2}}\end{array}\right) \tag{9}
$$

where

$$
X = \frac{L}{D},\quad Y = \frac{b}{D}
$$

with D being the flame thickness, b the width of the specimen under consideration.

The flame thickness, D, is difficult to be measured and thus it is assumed to be related to the average heat release rate of the material under the irradiance level of 25 kW/m^2, $\dot{q}_{av}''$ in the cone calorimeter test, with the data of PMMA as reference. The correlation for flame thickness of different materials is given by

$$D = 0.01\sqrt{\frac{\dot{q}_{av}''}{\dot{q}_{av}''_{PMMA}}} \tag{9}$$

where 0.01 m is the flame thickness for 25 mm PMMA. The range of flame thickness for the materials considered in this paper is 6.1 mm to 10 mm. Based on Eq. (8), $\dot{q}_f''$ is expressed as

$$\dot{q}_f'' = \varepsilon_f \sigma T_f^4 F_{dx,f} \tag{10}$$

where ε_f is the emissivity of the radiating surface.

The determination of ε_f as a function of measurable physical parameters is the fundamental difficulty of this radiation model. It is important to note that ε_f is not the flame emissivity. While some attempts [12] have been made to correlate ε_f with the soot volume fraction in the flame, the effort has been only speculative. Indeed, in the existing work [12] which utilizes this radiation model, ε_f is essentially an adjustable parameter used to fit the flame spread model with experimental data. This difficulty limits severely the applicability of the existing model [12] for actual application.

The Current Radiation Model

In this model, the radiative exchange between the flame and the unburned surface is evaluated exactly assuming that the flame is a two-dimensional homogeneous gas/particulates medium with temperature T_f and particulates volume fraction f_v. Assuming that the size of soot particulates is sufficiently small so that the Rayleigh's limit of particle absorption is valid, the absorption coefficient is given by [19]

$$a = \frac{3.6\kappa f_v T_f}{C_2} \tag{11}$$

where κ is an empirical constant in the range of 3.5 to 7.5 (depending on the fuel) and C_2 is the second radiation constant.

At a specific time t when the flame location is specified by x_L and x_H as shown in Fig. 1, an exchange factor between the flame and a differential area dx at a location x can be written as [18]

$$F_{dx,g} = \int_0^D \int_{-\infty}^{\infty} \int_{x_L}^{x_H} \frac{a e^{-ar\left(\frac{x_H - x'}{x - x'}\right)} z' dx' dy' dz'}{\pi r^3} \tag{12}$$

with

$$r = \sqrt{(x - x')^2 + y'^2 + z'^2}$$

The integration in the y' direction can be readily performed to yield

$$F_{dx,g} = \int_0^D \int_{x_L}^{x_H} \frac{a z' S_2\left[a s \left(\frac{x_H - x'}{x - x'} \right) \right] dx' dz'}{s^2} \tag{13}$$

with

$$s = \sqrt{(x - x')^2 + z'^2}$$

where $S_2(x)$ is a function given by

$$S_2(x) = \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} e^{-\frac{x}{\cos\theta}} \cos\theta d\theta \tag{14}$$

The property of the function $S_2(x)$ has been studied extensively and its numerical value is available from standard references [19,20]. Numerical evaluation of the exchange factor $F_{dx,g}$ from Eq. (13) is straight forward. Introducing the following dimensionless variables

$$\eta = \frac{x'}{D}, \quad \zeta = \frac{z'}{D}$$

Eq. (13) becomes

$$\begin{aligned} F_{dx,g} &= \int_0^1 \int_{x_L/D}^{x_H/D} \frac{aD\zeta S_2\left[aD\overline{s}\left(\frac{x_H/D - \eta}{x/D - \eta} \right) \right] d\eta d\zeta}{\overline{s}^2} \\ &= F_{dx,g}\left(aD, \frac{x_H}{D}, \frac{x_L}{D}, \frac{x}{D} \right) \end{aligned} \tag{15}$$

and $\dot{q}_f''$ becomes

$$\dot{q}_f'' = \alpha \sigma T_f^4 F_{dx,g}\left(aD, \frac{x_L}{D}, \frac{x_H}{D}, \frac{x}{D} \right) \tag{16}$$

with α being the absorptivity of the fuel surface. Equation (16) illustrates that the important flame parameter which affect the radiative flux is the optical thickness aD and the dimensionless parameters x_L/D, x_H/D and x/D.

RESULTS AND DISCUSSION

Four materials, which were materials for ISO round robin for LIFT method in 1989 [20], are taken as basis of comparison for the current model. Thermal properties of the materials and input data necessary for the calculation are shown in Table 1.

Effect of The Preheating Time

It is important to note that in addition to parameters which are needed as input parameters to the model, ($q''_{cr}, q''_{av}, t_{d,c}, k\rho c, T_{ig}, q''_e(50)$), the LIFT test data also include a measured value of the preheating time, t_0. Experimentally, it was stated in the literature [21] that a preheating time is generally set in LIFT tests, which may cause unwanted pyrolysis of material in the absence of a pilot, and hence poor ignition which can affect the flame spread characteristics. Since pyrolysis and the presence of a pilot is not included in the current modeling effort, the concept of the preheating time , t_{ph}, is physically different from that of t_0. In the model, the preheating time is simply the time required to maintain the incident flux from the radiation panel so that ignition occurs. Indeed, a minimum preheating time, $t_{ph,min}$, at which only the leading edge of the sample is ignited can be computed for each material and results for the four selected materials are shown in Table 2. It is interesting to note the relative large value for the minimum preheating time predicted by the model and the preheating time from the LIFT test for 40mm expanded polystyrene. This can be attributed to the large value of the heat capacity factor, kρc. There is, however, a large discrepancy between the minimum preheating time and the LIFT's preheating time for PMMA. This is probably due to the pyrolysis effect.

Numerical experiments show that while the selection of a preheating time higher than the minimum ignition time can have some effect on the flame spread (since the radiation from the flame to the sample is ignored for $t < t_{ph}$), the effect on the general flame spread behavior for $t > t_0$ is insignificant. This effect is illustrated for 40mm expanded polystyrene in Fig. 3.

Interpretation of LIFT Data

While the effect of the assumed preheating time on the overall thermal behavior is insignificant, it has an effect on the quantitative interpretation of the experimental data. A detailed investigation into this effect, however, would require a further refinement and extension of the model which will be the basis of future works. For the present work, the LIFT data will be interpreted with the preheating time observed in the test, i.e, $t_{ph} = t_0$.

The variation on the prediction of the flame front (x_H) for different value of the optical thickness (aD) for the four materials is shown in Figs. 4a to 4d. It is apparent that radiative emission from the flame has an important effect on the flame propagation behavior. As the optical thickness of the flame increases, the flame spreads further and propagates with a higher speed. The model is quite effective in simulating not only the magnitude of the flame spread, but also the spreading rate. Values of aD, together with the values of D, a and f_v which give the "best fit" of the LIFT data for the four materials are shown in Table 3.

CONCLUDING REMARKS

The specification on the testing of the flame spreading properties of materials in Hong Kong is inadequate. The ISO 9705 [8] was considered as the suitable testing method for local use [2,3]. However, the costs of the large-scale fire tests, tight budget and fast track of design and construction of local projects might not allow assessing materials with such tests. Bench-scale tests include uncertainties in giving confident results of behaviors of materials, especially composite materials like sandwich panels in actual fires. Using mathematical models for prediction of flame spreading with experimental results for verification is a cost-effective and scientific method.

An existing model was reviewed and modified to include a more realistic radiation model using the two-dimensional flame geometry. Data from cone calorimeter tests were used as input data for prediction of LIFT test results. Results showed that the new model gives a good correlation with experimental data and mitigates some uncertainties in the previous model. It is also demonstrated that the absorption coefficient, assumptions on the flame thickness and the designated preheating time have direct impact on the flame spreading results. In-depth analysis on those parameters and using more experimental data for verification of the new program will be published in upcoming papers.

This model is the first step for modeling the flame spreading of materials in large-scale tests. Literature showed that results from cone calorimeter provide a good correlation with the data from the ISO full-scale burning tests. It also provides important information on the oxygen consumption and heat release rate which are relevant for prediction of the time to flashover. Using those cone calorimeter results as input data demonstrates a high confidence in using the up-graded model for prediction of more realistic data in full-scale experiments.

Material	$\dot{q}_{cr}''$ (kW/m^2)	$\dot{q}_{av}''$ (kW/m^2)	$t_{d,c}$ (s)	kρc (kW^{2}s/m^{4}K^2)	T_{ig} (K)	t_0 (s)	$\dot{q}_e''(50)$ (kW/m^2)
4mm expanded polystyrene	20	240	120	2.471	707	645	29.9
3mm PMMA	10	400	150	0.8616	575	533	22.0
9mm birch faced plywood	14	170	320	0.8106	636	383	24.2
4mm FR plywood	16	150	120	0.5718	662	239	26.4

Table 1: Input data for the calculation

Material	t_0(s)	$t_{ph,min}$(s)
4mm expanded polystyrene	645	537
3mm PMMA	533	156
9mm birch faced plywood	383	187
4mm FR plywood	239	127

Table 2: The computed minimum preheating time, $t_{ph,min}$ and the LIFT preheating time, t_0 for the four materials.

Material	aD	D (m)	a (1/m)	f_v
4mm expanded polystyrene	1.2	0.77e-2	0.15e+3	0.14e-3
3mm PMMA	0.475	0.01	0.48e+2	0.42e-4
9mm birch faced plywood	1.6	0.65e-2	0.25e+3	0.22e-3
4mm FR plywood	2.0	0.61e-2	0.33e+3	0.29e-3

Table 3: Parameters which yield the "best fit" of the LIFT flame spread data of the four materials.

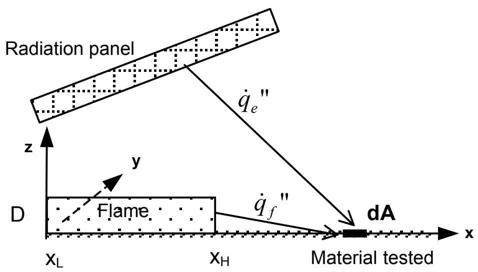

Figure 1. Basic geometry and coordinate system of the flame spreading model.

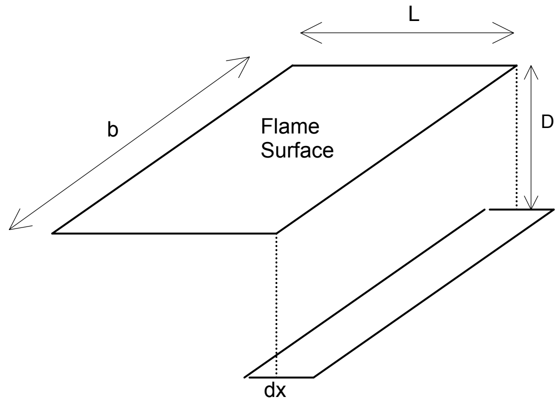

Figure 2: Geometry used in the determination of the view factor $F_{dx,L}$.

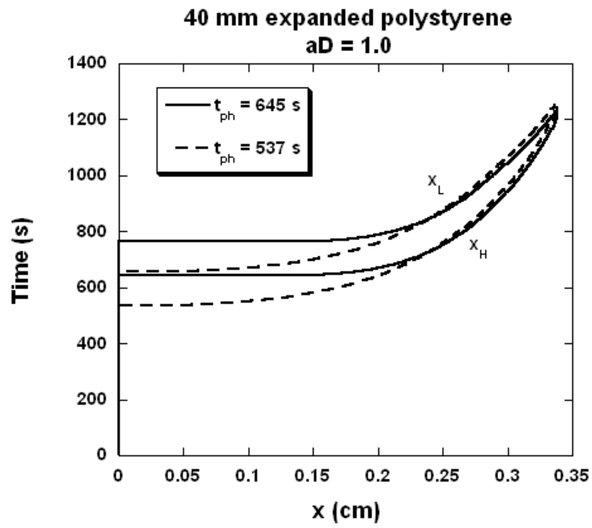

Figure 3: Effect of the preheating time on the prediction of flame spread for 40 mm expanded polystyrene with aD = 1.0.

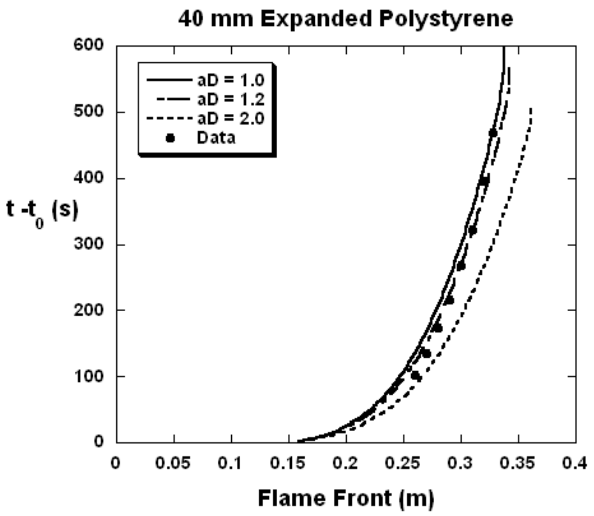

Figure 4a: Comparison between the predicted flame front location with measurements for 40 mm expanded polystyrene.

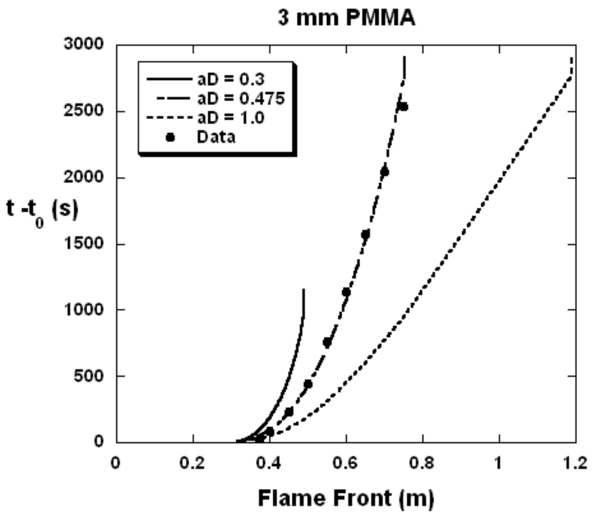

Figure 4b: Comparison between the predicted flame front location with measurements for 3 mm PMMA.

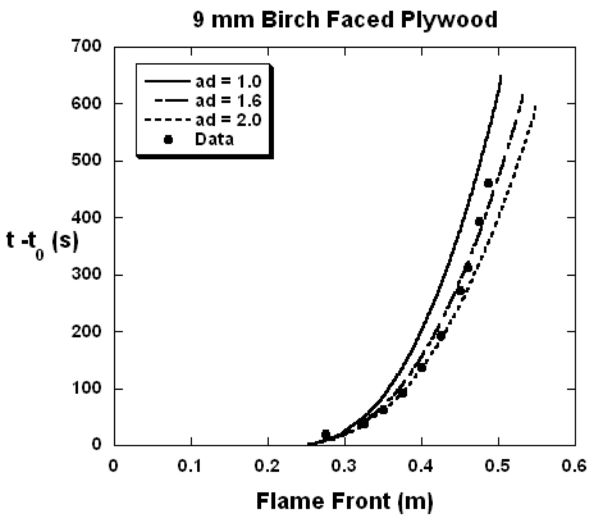

Figure 4c: Comparison between the predicted flame front location with measurements for 9 mm birch face plywood.

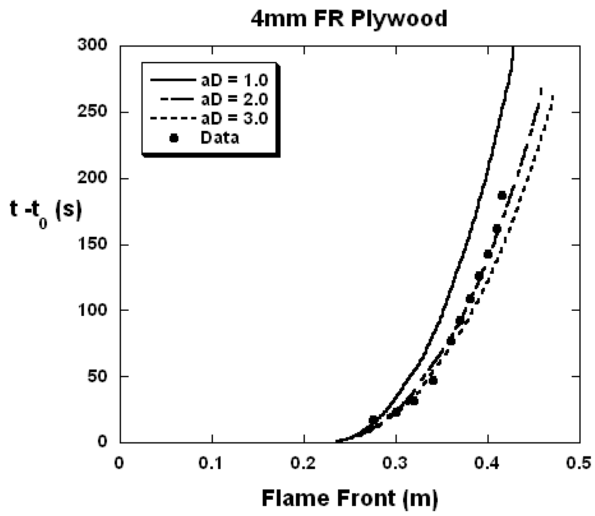

Figure 4d: Comparison between the predicted flame front location with measurements for 4 mm FR plywood.

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