Unsteady-State Upward Flame Spreading Velocity along Vertical Combustible Solid and Influence of External Radiation on the Flame Spread

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ABSTRACT

An asymptotic solution of flame spreading velocity along a vertical combustible solid is derived on the basis of previous experimental relations on the heat transfer from the flame to the surface. From the comparison of this with the steady-state solution, it was found that spontaneous flame spreading velocity starting from arbitorary initial conditions falls within relatively narrow range. Measurements of flame spread along vertical PMMA slabs with and without external radiation were conducted to verify the solution, which have revealed considerable acceleration of flame spread due to external radiation. Application of the theory to the evaluation of this influence has resulted in 30～40% overestimate of flame spreading velocity. This error is attributed to the higher pyrolysis temperature in the experiments than reference value and the dripping of molten fuel which was not considered in the model.

Key Words: upward flame spread, unsteady, asymptotic, external radiation.

INTRODUCTION

Upward flame spread along a vertical combustible solid is a typical process leading to hazardous growth of an enclosure fire. One of the authors has proposed an engineering model of steady-state upward flame spread based on the concept of ignition and flame spread as a result of inert heating of the solid to an ignition temperature.1) However, while the steady-state flame spreading velocity may be useful as a practical measure to evaluate fire safety performance of lining materials, the concept of steady-state flame spread is somewhat unusual, since the nature of upward flame spread in unwanted fires is essentially transient. In this paper, an unsteady-state solution of spontaneous upward flame spread is obtained on the basis of the experimental relationship on the preheating of the unburnt surface by the flame.

On the other hand, in actual fires it should be noted that flame spread along a wall tends to start after it has been preheated from fire source. Also it has been often reported in full scale fire experiments that flame spread on interior linings can be accelerated significantly even by weak radiation from fire source. In this paper, measurements of flame spreading velocity are made on vertical PMMA slabs under different levels of external radiation from radiant panels. Exploratory analysis is made to correlate flame spreading velocity with conditions of external radiation.

ASYMPTOTIC SOLUTION OF THE UPWARD FLAME SPREADING VELOCITY

Ignoring the heat conduction in the parallel direction to the wall surface and assuming the dependence of incident heat flux on height divided by flame height, the location of the pyrolysis front at time, t, is given by solving

$$T_{ig} - T_o = \int_0^t \dot{q}''_w (x_p/Q_\ell^{*2/3}\xi)\phi(t-\tau)d\tau \qquad (1)$$

for x_p. In equation(1) ξ is the location of pyrolysis front at the time τ, and $Q_\ell^{*2/3}\xi$ is a quantity proportional to flame height. Insignificance of the vertical heat conduction relative to the horizontal one in burning vertical solid has been established on PMMA.[2)] An explicit solution of equation(1) for x_p may be found only when there is some functional relation between $x_p/Q_\ell^{*2/3}\xi$ and $t-\tau$; the following is a typical case satisfying this condition.

① $x_p/\xi = f(t - \tau)$, ② $Q_\ell^* =$ constant

The only function satisfying the condition① is the exponential function; equation (1) can be solved in the following form.

$$x_p = x_{po}\cdot\exp(\alpha t),\ V_p = dx_p/dt = \alpha x_p \qquad (2)$$

where x_{po} is the initial location of pyrolysis front and α is a constant.

Equation(2) is an asymptotic solution corresponding to the situation that flame spread starts at an infinitely narrow ignited part of a vertical slab, and then the pyrolysis zone advances at a velocity proportional to the height of the pyrolysis front; the proportionality of V_p to x_p is consistent with the results reported in previous experimental work on spontaneous vertical flame spread under a similar condition, e.g. $V_p \propto x_p^{0.964}$.[3)] Such behavior is in contrast with the steady-state flame spread, where both pyrolysis length and flame spreading velocity are constant. Since larger pyrolysis length must result in stronger preheat of unburnt surface, the steady-state flame spreading velocity is expected to give the upper bound of flame spreading velocity for arbitorary initial conditions, while equation(2) may correspond to its lower bound. Conditions① and ② are consistent with empirical relation that time from the arrival of flametips to that of pyrolysis front is practically constant.[3,4)] Weak dependence of Q_ℓ^* on x_p as condition② is found at spontaneous upward flame spread along a PMMA slab.[5)]

The central problem in solving equation(1) is the determination of α. Using $\phi(t) = 1/\sqrt{\pi k \rho c t}$, $d\tau = d\xi / \alpha \xi$, and $\alpha t = \ln(x_p/x_{po})$, equation(1) becomes

$$T_{ig} - T_o = \lim_{x_{po} \to 0} \int_{x_{po}}^{x_p} \frac{\dot{q}''_w(x_p/Q_\ell^{*2/3}\xi)}{\sqrt{\pi k \rho c \ \ln(x_p/\xi)}} \frac{d\xi}{\sqrt{\alpha}\ \xi} \tag{3}$$

Using $\lambda = \ln(x_p/x_{po})$, and transforming equation(3) to obtain an expression for α

$$\alpha = \frac{1}{\pi k \rho c (T_{ig} - T_o)^2} [\int_0^\infty \dot{q}''_w\{\exp(\lambda)/Q_\ell^{*2/3}\}/\sqrt{\lambda} d\lambda]^2 \tag{4}$$

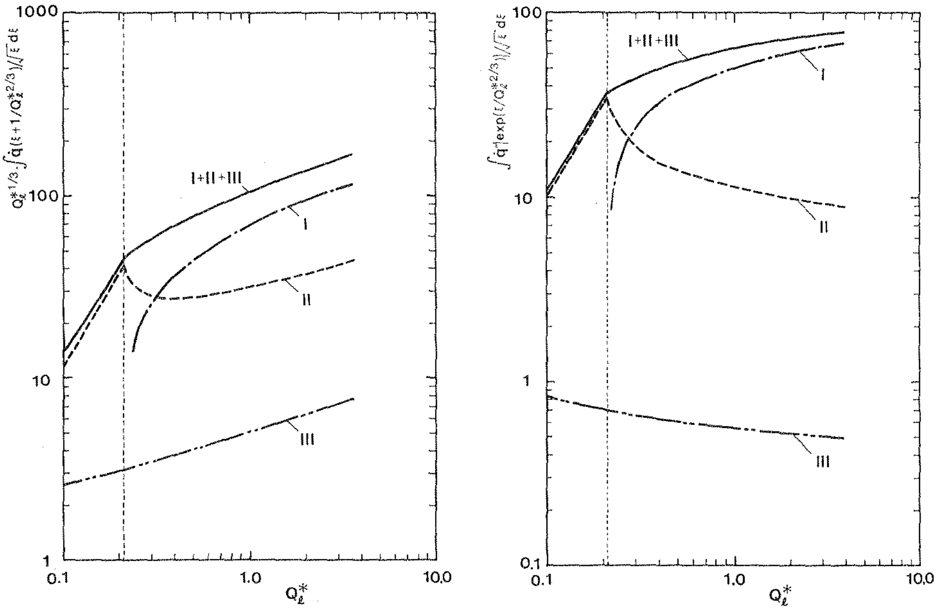
Finally, equation(2) yields

$$V_p = \frac{x_p}{\pi k \rho c (T_{ig} - T_o)^2} [\int_0^\infty \dot{q}''_w\{\exp(\lambda)/Q_\ell^{*2/3}\}/\sqrt{\lambda} d\lambda]^2 \tag{5}$$

Interestingly, the form of equation(5) is close to the steady-state flame spreading velocity[1], which can be written in a form comparable to equation(5) as

$$V_{p,\,steady\ state} = \frac{x_p}{\pi k \rho c (T_{ig} - T_o)^2} [\int_0^\infty Q_\ell^{*1/3} \dot{q}''_w(\lambda + 1/Q_\ell^{*2/3})/\sqrt{\lambda} d\lambda]^2 \tag{6}$$

From the heat flux distribution characteristics, the unburnt area above the pyrolysis front can be divided into three regions according to the relative location to the flame, i.e. solid flame(region Ⅰ), intermittent flame(region Ⅱ), and plume (region Ⅲ)[1]. Contribution of each region to the flame spreading velocity can be



(a)steady state solution (b)asymptotic solution

Fig.1 Contribution of solid flame, intermittent flame and plume to the preheat in the flame spreading process as a function of Q_ℓ^*

evaluated by calculating the integrals in equations(5) and (6)(Figure 1(a),(b)). For $Q_\ell^* > 1$, the partial integral for the region I is close to that for the whole area(integrated from 0 to ∞), while the integral is mostly governed by the region II for $Q_\ell^* < 2.8^{-3/2}$ where solid flame does not reach the unburnt area. This tendency is especially pronounced for the asymptotic solution; contribution of the other regions is less negligible for the steady-state solution.#

According to the above discussions, equation(5) divided by equation(6) is expected to give the ratio of the lower bound to the upper bound of the spontaneous flame spreading velocity. This ratio is represented by

$$\Psi = [\int_0^\infty \dot{q}_w''\{\exp(\lambda)/Q_\ell^{*2/3}\}/\sqrt{\lambda}\,d\lambda / \int_0^\infty Q_\ell^{*1/3} q_w''(\lambda+1/Q_\ell^{*2/3})/\sqrt{\lambda}\,d\lambda]^2 \qquad (7)$$

Figure 2 shows this ratio along with flame spreading velocity divided by $x_p/\pi k \rho c (T_{ig}-T_o)^2$ as a function of Q_ℓ^*. Ψ is expected to be a measure of predictability of flame spreading velocity in the sense that, if Ψ value is close to unity, flame spreading velocity under arbitorary initial condition must fall within a narrow range between the above two solutions. For usual wall fires, Q_ℓ^* is considerably smaller than unity and therefore, from Figure 2, Ψ should be within the

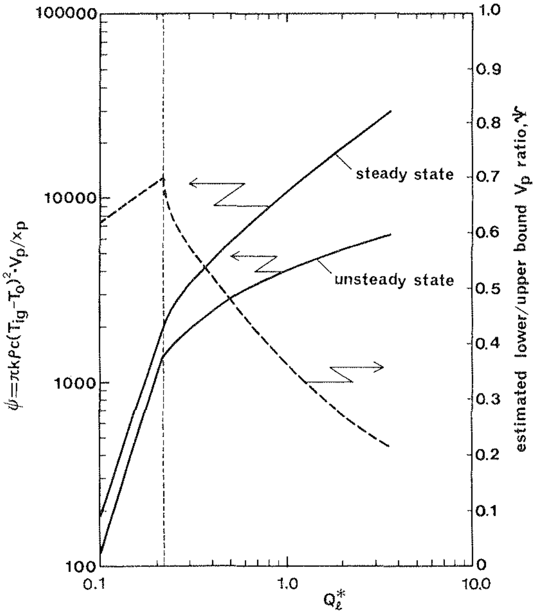


Fig.2 $\pi k \rho c(T_{ig}-T_o)^2 \cdot V_p/x_p$ and estimated lower/upper bound V_p ratio, Ψ, as functions of Q_ℓ^*

The division of the regions is based on the heat flux distribution. It should be noted that height of flametips based on visual observation is considerably lower than the upper limit of the region II by the present definition.[1)]

range of 0.5~0.7. It is also noteworthy that $\phi = \pi k \rho c(T_{ig} - T_o)^2 \cdot V_p/x_p$ is very sensitive to Q_ℓ^* especially in the relatively low Q_ℓ^* region; this implies that even a small change in heat release rate may result in dramatic change in the flame spreading velocity in actual fires.

FLAME SPREAD ALONG VERTICAL COMBUSTIBLE SOLID UNDER EXTERNAL RADIATION

While the above discussion assumes spontaneous flame spread, preheat of the wall surface by external radiation is often anticipated in actual fires. Influence of external radiation on upward flame spread is related to two processes.6) One is the acceleration of pyrolysis; this will result in the increase of flame height and finally the increase of incident heat flux from the flame to the unburnt surface(effect Ⅰ). The other is the rise of temperature of the unburnt surface (effect Ⅱ).

In order to examine the acceleration of flame spreadingvelocity by external radiation, flame spread was observed for vertical slabs of PMMA heated by radiant panels. In this experiment, a simplest condition is assumed on the external radiation; the heating was continued until the rise of surface temperature due to the external radiation, ΔT, becomes constant. In this situation, the effect Ⅱ can be evaluated by substituting $T_b = T_0 + \Delta T$ into T_0 in equation(6), while the effect Ⅰ can be estimated from the increase of ϕ value as a result of the increase of Q_ℓ^*. The strong dependence of ϕ on Q_ℓ^* as shown in Figure 2 suggests the general significance of effect Ⅰ.

Figure 3 shows the experimental set-up. The specimen is approximately 1.1m high, 0.7m wide and 16mm thick. Temperature was measured with 0.2mm diameter C-A thermocouples. The radiant panels are essentially propane premixed burners. Each specimen was ignited with fuel pills at its bottom after the rate of the surface temperature change had become less than 2K/min. Flame from the pills was laminar and approximately 5cm high. Location of the pyrolysis front was determined from the temperature history at the slab surface; the start of the temperature plateau was defined as the arrival of pyrolysis front at each location of thermocouples.

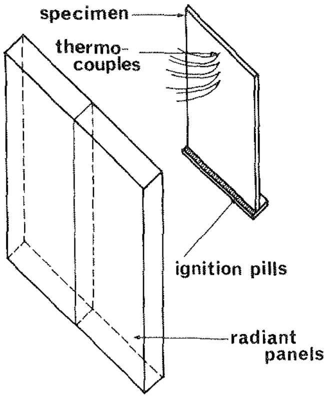
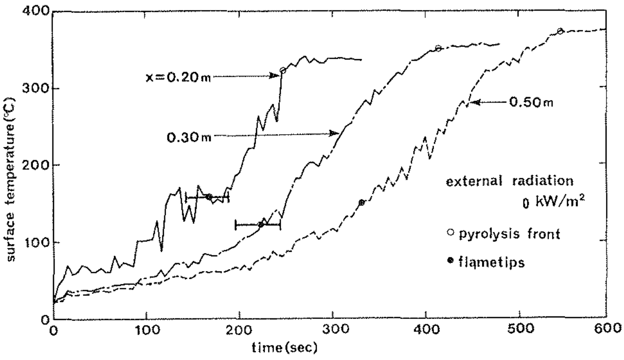
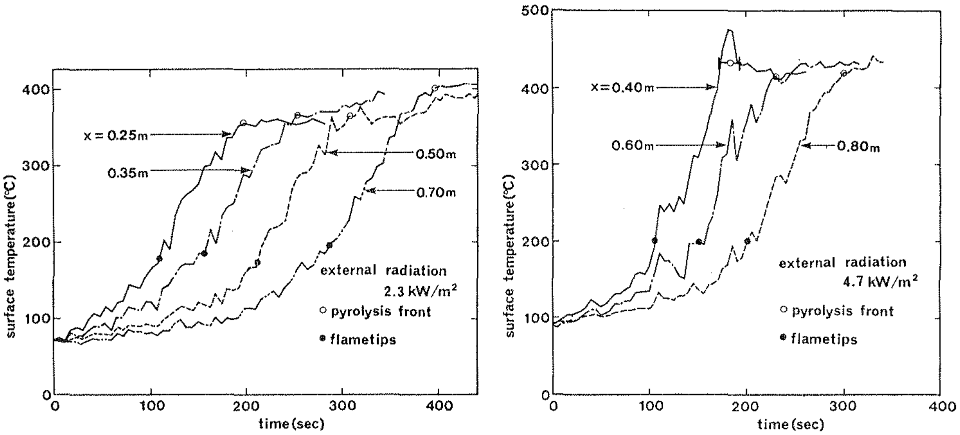


Fig.3 Schematic view of the experimental set-up

Figure 4 shows examples of the measured histories of surface temperature. Flame over the slab surface was recorded by the video camera; height of flametips were measured for reference from the videotapes. Figure 5 shows a summary of the histories of the location of pyrolysis front thus obtained and the height of flametips. The levels of external radiation, 0.0, 2.3, and 4.7kW/㎡, were chosen such that $\dot{q}_e''$ would become enough lower than heat flux from the flame. These levels are still comparable with the usual critical radiation intensity for evacuation in fire, 2.0～2.5kW/㎡.7) The result shows that the flame spreading velocity is still approximately proportional to the height of pyrolysis front after the pyrolysis zone has become enough greater than the height of flames from the igni-



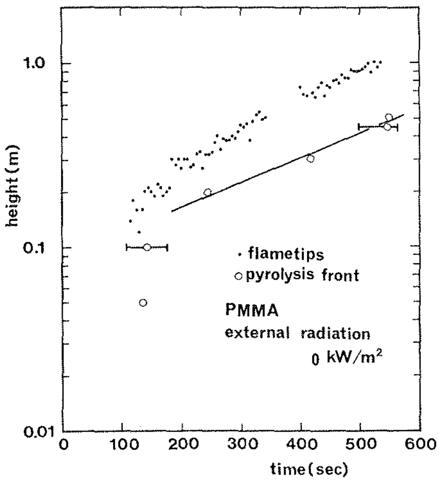
(a) without external radiation



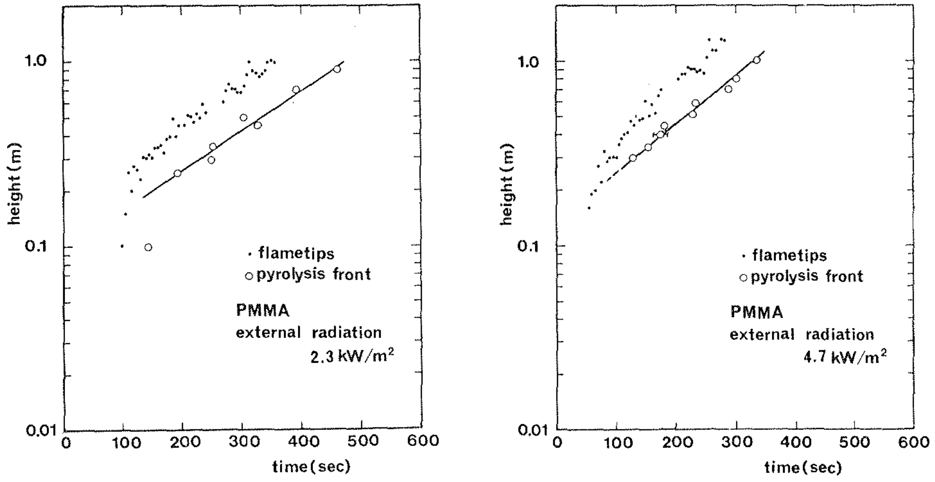
(b) $\dot{q}_e''$=2.3kW/㎡

(c) $\dot{q}_e''$=4.7kW/㎡

Fig.4 Time history of surface temperature tion source, and that flame spread can be accelerated by even such weak radiation. V_p/x_p ratio for $\dot{q}_e''$=4.7kW/m² is approximately twice the value without external radiation. Time from the arrival of flametips to that of pyrolysis front was approximately constant at each test. It is also noteworthy that the surface temperature at the arrival of flametips is approximately 110K higher than T_b. This shows the significance of the preheat from the hot current above the visible flame. Since the preheat by the plume($x/Q_\ell^{*2/3}\xi > 10$) is negligible(Figure 1), this temperature rise is attributed to the heating by the upper invisible part of the intermittent flame($6 < x/Q_\ell^{*2/3}\xi < 10$). Finally, Table 1 shows a summary of the relation between $\alpha = V_p/x_p$ and $\pi k \rho c(T_{ig} - T_b)^2$. In this correlation, $k\rho c$ and T_{ig}



(a) without external radiation



(b) $\dot{q}_e''$=2.3kW/m²　　(c) $\dot{q}_e''$=4.7kW/m²

Fig.5 Location of flametips and pyrolysis front

Table 1 Experimental and theoretical flame spread properties($x_p=0.5$m)

	experiment					calculation			
$\dot{q}_e''$ $\left(\frac{kW}{m^2}\right)$	T_b (℃)	$\pi k\rho c\cdot(T_{ig}-T_b)^2$ $\left(\frac{kW^2}{m^4 s}\right)$	V_p/x_p (1/s)	ψ $\left(\frac{kW^2}{m^4 s^2}\right)$	L_f/x_p (−)	Q_ℓ $\left(\frac{kW}{m}\right)$	Q_ℓ^* (−)	ψ $\left(\frac{kW^2}{m^4 s^2}\right)$	L_f/x_p (−)
		x 10^5							
0.0	23	2.54	0.0031	787	1.7～2.1	77	0.20	1100	2.1
2.3	70	1.90	0.0048	912	1.6～1.9	92	0.24	1550	2.3
4.7	92	1.64	0.0063	1033	1.6～1.8	107	0.28	1770	2.6
Orloff et al(Ref.3)#									
0.0			0.0037	940	1.9～2.2			1100	2.1

calculated using $T_b=$ 23℃.

are taken as $0.66kW^2/m^4K^2s$ and 373℃ respectively from reference.[8)] Q_ℓ^* was estimated from the heat balance at the surface of the pyrolysis zone as

$$Q_\ell^*=Q_\ell/\rho_0 CpT_0 g^{1/2}x_p^{3/2}=\int_0^{x_p}(\dot{q}_w''+\dot{q}_e''-\dot{q}_{rr}'')dx\cdot\Delta H_c/\Delta H_G\,\rho_0 CpT_0 g^{1/2}x_p^{3/2} \tag{8}$$

The calculation was made on x_p=0.5m as a representative condition during the process of flame spread. The obvious increase of ψ with $\dot{q}_e''$ seems to reflect the increase of Q_ℓ^* by the external radiation. ψ values estimated from Figure 2 using usual values of the combustion properties of PMMA are also compared; ψ values predicted with only the material properties are found to be 30～40% larger than result of the present experiment. Assuming the adequacy of equation(5), this discrepancy is attributed to the underestimate of $k\rho c$ or T_{ig}, or overestimate of Q_ℓ^* in the calculation. Underestimate of T_{ig} and overestimate of Q_ℓ^* are actually suspected. Figure 4 obviously shows the higher pyrolysis temperature for stronger external radiation; especially the measured T_{ig} with external radiation is considerably higher than the assumed value, 373℃. Overestimate of Q_ℓ^* is suspected from the flame height observations; as compared in Table 1, the height of visible flame calculated from $L_f=6.0Q_\ell^{*2/3}x_p$[1)] was always larger than the measured flame height. Since L_f/x_p ratio is a function of only Q_ℓ^*, this difference suggests the overestimate of Q_ℓ^* in the calculation. This overestimate may be due to the dripping of molten PMMA within the pyrolysis zone; this phenomenon must lead to the decrease of the fuel gas generation and finally the decrease of heat release rate. Greater difference with theory in the results with external radiation is consistent with the observation that dripping is enhanced by external radiation. The reported value on PMMA without external radiation by Orloff et al[3)] is compared in Table 1 for reference; their result is somewhat closer to the calculation.

Significance of the two effects of external radiation on the flame spread can be compared from ψ (for effect Ⅰ) and $1/\pi k\rho c(T_{ig}-T_b)^2$ (for effect Ⅱ) in Table 1; ψ value and $1/\pi k\rho c(T_{ig}-T_b)^2$ for $\dot{q}_e''$=4.7kW/m² are 1.3 times and 1.5

times the results without external radiation respectively. This suggests slight superiority of the effect II in the present experiment. However, it should be noted that the effect I depends only on the incident heat flux while the effect II depends essentially on the surface temperature;ignition after the wall surface has reached steady temperature as in this experiment must have resulted in the most significant appearence of the effect II. For shorter preheat of the wall surface by external radiation would result in less significance of the effect II.

CONCLUSIONS

From the comparison of the present asymptotic solution of flame spreading velocity with the steady-state one along with the experiment on vertical PMMA slabs, following conclusions can be drawn.

1)The present solution gives the lower bound of spontaneous upward flame spreading velocity for arbitorary initial coniditions. For wall fires of usual lining materials, the ratio of the lower bound of spontaneous flame spreading velocity to its upper bound is 0.5～0.7.

2)Upward flame spreading velocity in usual preflashover conditions of a room fire is quite sensitive to Q_ℓ^*. Both the theory and the experiment suggest the significant influence of external radiation on the acceleration of flame spread.

3)The present solution agrees with experiment within the error of 30～40%. This error is attributed to such phenomena ignored in the model as the rise of pyrolysis temperature by external radiation and dripping of molten fuel.

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TERMINOLOGY

C_p	specific heat of air
ΔH_C	heat of combustion
ΔH_G	heat of gasification
L_f	flame height
Q_ℓ	heat release rate per unit width
Q_ℓ^*	dimensionless heat release rate per unit width, defined by equation(8)
T	temperature
ΔT	temperature rise
V_p	flame spreading velocity
c	specific heat of wall material
k	thermal conductivity of wall material
g	gravitational acceleration
$\dot{q}_e''$	external radiation
$\dot{q}_{rr}''$	surface reradiation
t, τ	time
x	height from the bottom of fuel
x_p	location of pyrolysis front
ρ	density of wall material
ϕ	preheat index defined as $\pi k \rho c(T_{ig}-T_b)^2 \cdot V_p/x_p$

suffix

b	base, or beginning of flame spread
ig	ignition or pyrolysis
o	ambient or initial condition
w	wall or wall flame