

UNSTEADY-STATE UPWARD FLAME SPREADING VELOCITY ALONG VERTICAL COMBUSTIBLE SOLID AND INFLUENCE OF EXTERNAL RADIATION ON THE FLAME SPREADING VELOCITY

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1. INTRODUCTION

Upward flame spread along a vertical combustible solid is a typical process leading to hazardous growth of an enclosure fire. In previous papers^{1,2)} one of the authors (Y.H.) 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. However, while the steady-state flame spreading velocity may be useful as a practical measure to evaluate firesafety performance of lining materials, the concept of steady-state flame spread is still 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 heating of the unburnt surface by the flame.¹⁾

In actual fires, it should be also noted that flame spread along a wall tends to start after it has been preheated from fire source etc. In full scale fire experiments, flame spreading velocity along a vertical solid becomes often several times the spontaneous flame spreading velocity. 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 and conditions of external radiation.

2. AN UNSTEADY-STATE SOLUTION OF UPWARD FLAME SPREADING VELOCITY

Figure 1 describes the concept of upward flame spread based on Refs.1,2. Ignoring the vertical heat conduction and assuming the dependence of incident heat flux on height divided by flame height, surface temperature $T_w(x)$ at the height x can be represented by

$$T_w(x) - T_o = \int_0^t \dot{q}_w(x/Q_g^{2/3} \xi) \phi(t-\tau) d\tau \quad (1)$$

where ξ is the location of pyrolysis front at the time τ , and $Q_g^{2/3} \xi$ is proportional to the flame height. Insignificance of the vertical conduction relative to the horizontal one in a combusting vertical PMMA slab was established by Ito and Kashiwagi³⁾.

The location of the pyrolysis front at time, t , can be calculated by substituting T_{ig} and x_p into T_w and x respectively in equation(1) as

$$T_{ig} - T_o = \int_0^t \dot{q}_w(x_p/Q_g^{2/3} \xi) \phi(t-\tau) d\tau \quad (2)$$

An explicit solution of equation(2) for x_p may be found if there is some functional relation between $x_p/Q_g^{2/3} \xi$ and $t-\tau$; the following is a typical case satisfying this condition.

$$x_p/\xi = f(t - \tau), \quad Q_2^* = \text{const.} \quad (3)$$

The only form of the solution of equation(3) for x_p is

$$x_p = x_{p0} \exp(\alpha t) \quad . \quad V_p = dx_p/dt = \alpha x_p \quad (4)$$

where x_{p0} is the initial location of the pyrolysis front, and $\alpha \equiv f'(0)$ is a constant which is determined by substituting this relation into equation(2).

Equation(4) implies that flame spread satisfying equation(3) starts at an infinitely small source at the bottom of a vertical slab, and 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 works on spontaneous vertical flame spread, e.g. $V_p \propto x_p^{0.864}$ ⁴⁾. It is in contrast with the steady state flame spread, where both pyrolysis length and flame spreading velocity are constant; practically, the steady-state flame spreading velocity is expected to give the upper bound of flame spreading velocity for arbitrary initial conditions while equation(4) may correspond to its lower bound, since larger pyrolysis length must result in stronger preheat of unburnt surface. It may be also noteworthy that, according to equation(3), time necessary for the advancement of pyrolysis front from x_a to x_b depends only on x_b/x_a . In this sense, equation(3) implies a sort of similarity in the process of flame spread.

The central problem in solving equation(2) is the determination of α . Using $\phi(t) = 1/\sqrt{\pi k \rho c t}$, $d\tau = d\xi/\alpha \xi$, and $\alpha t = \ln(x_p/x_{p0})$, equation(2) becomes

$$T_{ig} - T_0 = \lim_{x_{p0} \rightarrow 0} \int_{x_{p0}}^{x_p} \frac{q_w^-(x_p/Q_2^{*2/3} \xi)}{\sqrt{\pi k \rho c \ln(x_p/\xi)}} \frac{d\xi}{\sqrt{\alpha \xi}} \quad (5)$$

Using $\lambda = \ln(x_p/x_{p0})$, and transforming equation(5) to obtain an expression for α

$$\alpha = \frac{1}{\pi k \rho c (T_{ig} - T_0)^2} \left[\int_0^\infty q_w^-(\exp(\lambda)/Q_2^{*2/3}) / \sqrt{\lambda} d\lambda \right]^2 \quad (6)$$

Finally, equation(4) yields

$$V_p = \frac{x_p}{\pi k \rho c (T_{ig} - T_0)^2} \left[\int_0^\infty q_w^-(\exp(\lambda)/Q_2^{*2/3}) / \sqrt{\lambda} d\lambda \right]^2 \quad (7)$$

Interestingly, the form of equation(7) is close to the steady state flame spreading velocity ²⁾, which can be described as

$$(V_p)_{\text{steady state}} = \frac{x_p}{\pi k \rho c (T_{ig} - T_0)^2} \left[\int_0^\infty Q_2^{*1/3} q_w^-(\lambda + 1/Q_2^{*2/3}) / \sqrt{\lambda} d\lambda \right]^2 \quad (8)$$

As discussed in previous papers ^{1,2)}, the unburnt area above the pyrolysis front can be divided into three regions according to the relative location to the flame, i.e. the solid flame(referred to as region I, $x/Q_2^{*2/3} x_p < 2.8$), the intermittent flame(region II, $2.8 < x/Q_2^{*2/3} x_p < 10$), and the plume(region III, $x/Q_2^{*2/3} x_p > 10$)^{*}. In order to compare the contribution of each region to the flame spreading velocity, calculation of the integrals in equations (7) and (8) is made on respective regions(Figures 2 and 3). As seen in Figure 2, value of the

* Height of flametips by visual observation is $5 \sim 6 Q_2^{*2/3} x_p$. This division is based on the distribution of heat flux to the wall surface.

integral for the region I is very close to that for the whole area (integrated from 0 to ∞); this implies that, if equation(3) is satisfied, spontaneous flame spread is governed mostly by the heating by the solid flame. In the steady-state flame spread, contribution of the other regions is more significant.

According to the above discussions, equation(7) divided by equation(8) would give the ratio of the lower bound to the upper bound of the spontaneous flame spreading velocity. This ratio is represented by

$$\Psi = \left[\int_0^{\infty} q_w^* (\exp(\lambda)/Q_c^{*2/3}) / \sqrt{\lambda} d\lambda / \int_0^{\infty} Q_c^{*1/3} q_w^* (\lambda + 1/Q_c^{*2/3}) / \sqrt{\lambda} d\lambda \right]^2 \quad (9)$$

Figure 4 shows this ratio and flame spreading velocity divided by $x_p / \pi k \rho c (T_{ig} - T_o)^2$ as a function of Q_g^* . 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 arbitrary condition must fall within a narrow range between the above two solutions. For usual wall fires in buildings, Q_g^* is considerably less than unity and, therefore, Ψ value is expected to be within the range of 0.5~0.7. It is noteworthy that $\psi = \pi k \rho c (T_{ig} - T_o)^2 \cdot V_p / x_p$ is very sensitive to Q_g^* especially in the relatively low Q_g^* region; this implies that a small change in heat release rate may result in dramatic change in the flame spreading velocity.

3. FLAME SPREAD ALONG VERTICAL COMBUSTIBLE SOLID UNDER EXTERNAL RADIATION

While the above discussion has assumed spontaneous flame spread, preheat of the wall surface by external radiation is often anticipated in actual fires. In order to examine the acceleration of flame spreading velocity by external radiation, flame spreading velocity was observed for vertical slabs of PMMA and oak heated by radiant panels.

The acceleration of upward flame spread by external radiation is related to two processes. One is the acceleration of pyrolysis in the pyrolysis zone; this will result in the increase of flame height and finally the increase of incident heat flux from the flame to the unburnt area. The other is rise of temperature of the unburnt surface. Increase of flame height due to external radiation is reported in Ref.5.

In this experiment, a simplest condition for external radiation is assumed; external radiation is assumed to have continued so that the rise of surface temperature due to the external radiation, ΔT , has become constant by the initiation of the flame spread. In this situation, the first effect of external radiation can be evaluated by substituting T_o by $T_b = T_o + \Delta T$, while the first effect can be estimated by the increase of ψ value as a result of the increase of Q_g^* . The strong dependence of ψ on Q_g^* as shown in Figure 4 implies significance of the first effect.

Figure 5 shows the experimental set-up. The specimen is approximately 1.1m high, 0.7m wide, and 16mm thick. Each specimen was ignited with fuel pills at the bottom after the rate of the surface temperature change had become less than 2K/min. Location of the pyrolysis front is determined from the temperature history at the slab surface; the instance at which a flat plateau starts in the temperature-time curve is defined as the arrival of pyrolysis front at each location of thermocouples. Figures 6~8 show 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.

Figures 9~11 show 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/m², were chosen such that q_o^- would become considerably lower than the incident heat flux from the flame to the slab surface. These levels are still comparable with the usual critical radiation intensity for evacuation in fire, 2.0~2.5kW/m².

The result shows that the flame spreading velocity is still approximately proportional to the height of pyrolysis front when the pyrolysis zone has become enough greater than the ignition source, and that flame spreading velocity can be accelerated even by such weak radiation. Time from the arrival of flametips to the arrival of pyrolysis front is approximately constant for each situation. These imply that the similarity anticipated for the process of spontaneous flame spread is still generally effective for weakly heated surface.

It is noteworthy that the surface temperature at the arrival of flametips is considerably higher than T_o . This implies a significant role of heat flux from the upper region of the turbulent flame in the preheat for the flame spread.

Finally, Table 1 shows a summary of the relation between $\alpha = V_p/x_p$ and $\pi k \rho c (T_{ig} - T_o)^2$. In this correlation, $k \rho c$ and T_{ig} are taken as 0.66kW²/m⁴K²s and 373K respectively. The obvious increase of the ratio of the two properties, ψ , with q_o^- seems to reflect the increase of Q_2^* , or pyrolysis rate by the external radiation. ψ values estimated from Figure 4 using usual values of the combustion properties of PMMA are also compared; ψ values predicted from only material properties are found to be 30~40% lower than the present experiment. This difference seems to be due to either overestimate of heat release rate or underestimate of $k \rho c$.

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TERMINOLOGY

- D characteristic fuel size(pyrolysis front)
- Q_2 heat release rate by combustion per unit width
- Q_2^* dimensionless heat release rate per unit width defined as $Q_2 / \rho_o C_p T_o \sqrt{gD^3}$
- T_{ig} ignition temperature
- T_o ambient temperature
- T_w temperature of wall surface
- V_p flame spreading velocity
- c specific heat of wall material
- k thermal conductivity of wall material
- g gravitational acceleration
- q_o^- external radiation
- q_w^- incident heat flux to wall surface
- q_{rr}^- surface reradiation
- t, τ time

- x height from the bottom of fuel
 V_p location of pyrolysis front
 α constant, defined as V_p/x_p
 ρ density of wall material
 ρ_o density of ambient air
 ξ location of pyrolysis front at the time τ
 ψ $\pi k \rho c (T_{ig} - T_b)^2 V_p / x_p$

Table 1 Comparison of experimental and theoretical flame spread properties

\bar{q}_e (kW/m ²)	experiment				calculation		
	T_b (°C)	$\pi k \rho c (T_{ig} - T_b)^2$ (kW ² /m ⁴ s) x 10 ⁵	V_p/x_p (1/s)	ψ (kW ² /m ⁴ s ²)	Q_2 (kW/m)	Q_2^* (-)	ψ (kW ² /m ⁴ s ²)
0.0	23	2.54	0.0031	787	77	0.20	1100
2.3	70	1.90	0.0048	912	92	0.24	1550
4.7	92	1.64	0.0063	1033	107	0.28	1770

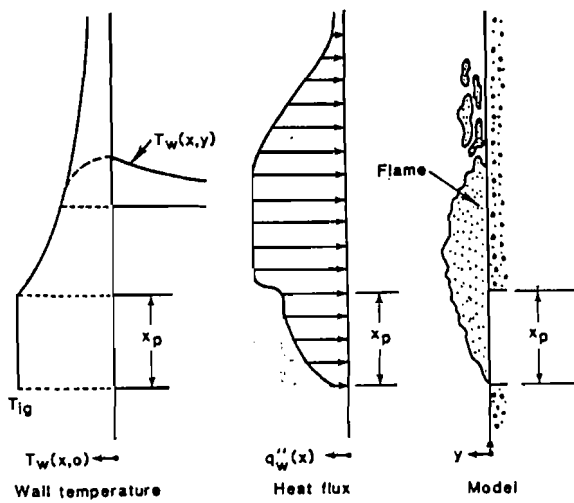


Figure 1 Concept of Upward Flame Spread along Vertical Combustible Solid

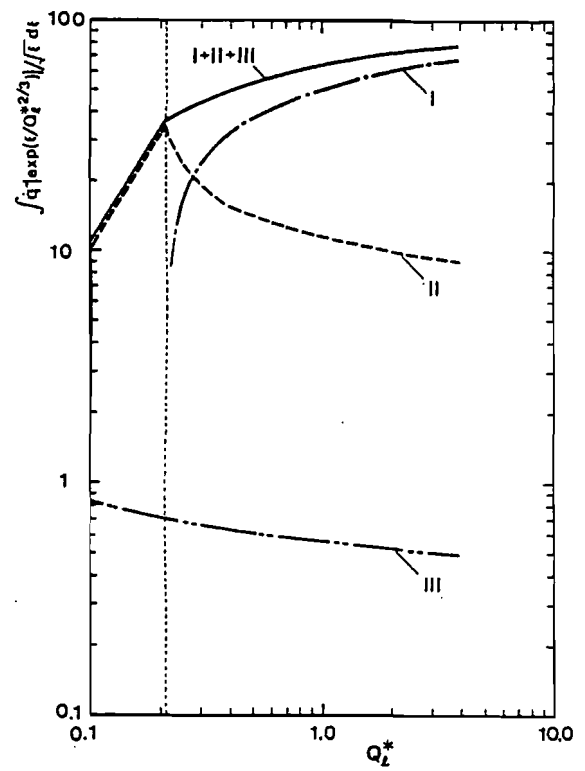


Figure 2 $\int q'' \exp(\xi/Q_2^{*2/3}) / \sqrt{\xi} d\xi$ vs. Q_2^*

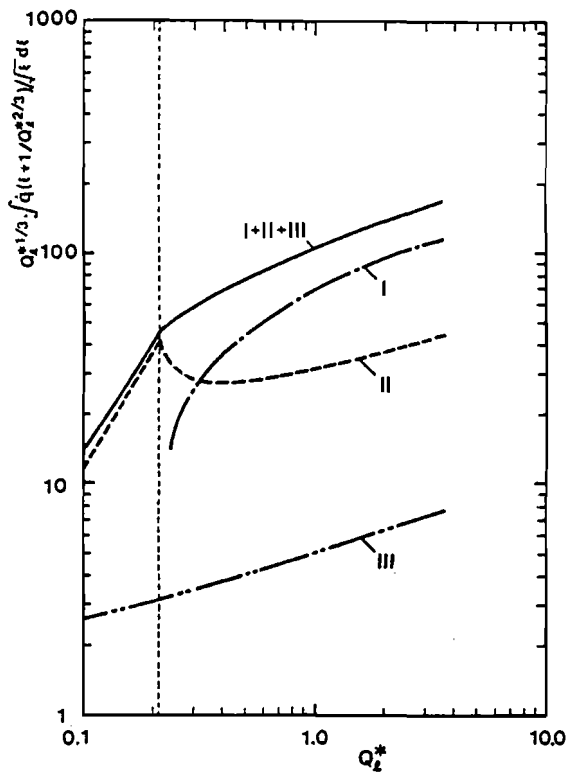


Figure 3 $Q_2^{*1/3} \int q'' (\xi+1/Q_2^{*2/3}) / \sqrt{\xi} d\xi$ vs. Q_2^*

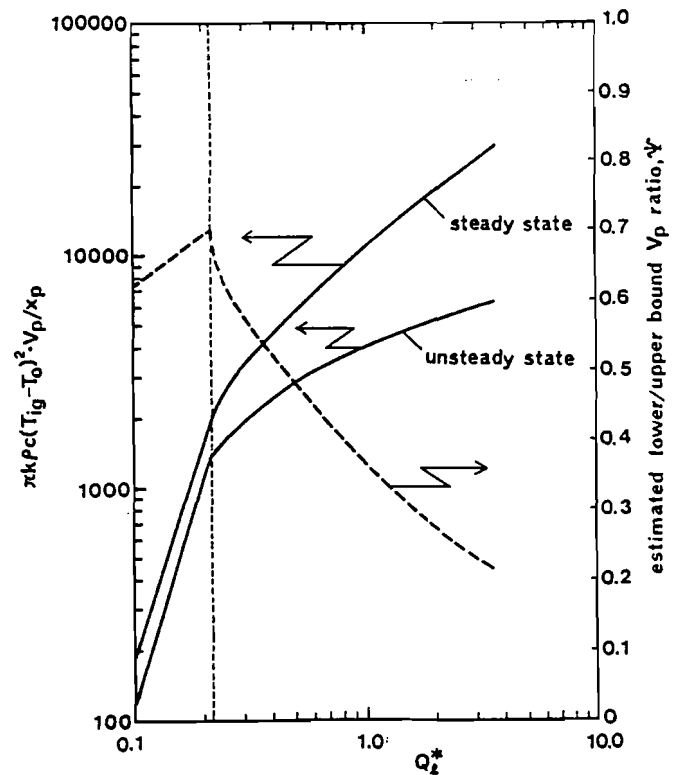


Figure 4 $\pi k \rho c (T_{ig} - T_0)^2 \cdot V_p / x_p$ and estimated lower/upper bound V_p ratio, Ψ vs. Q_2^*

Figure 5 Experimental Set-up.

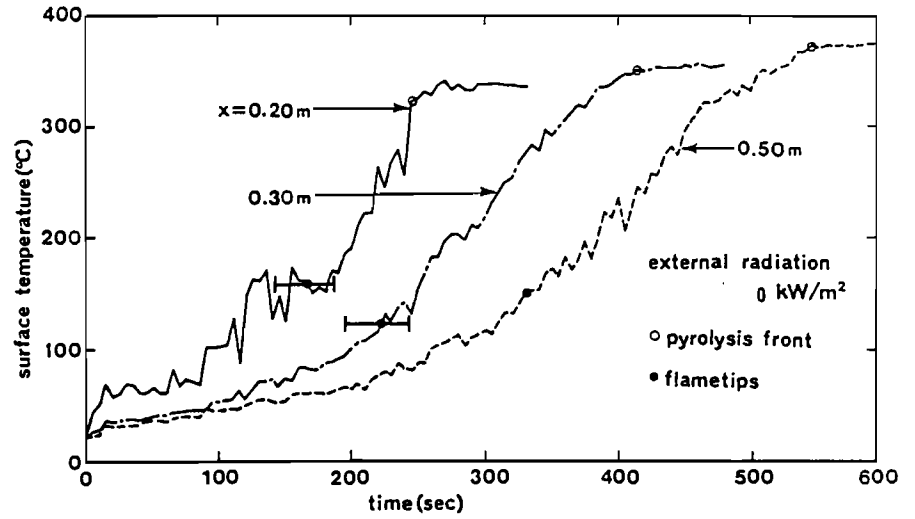
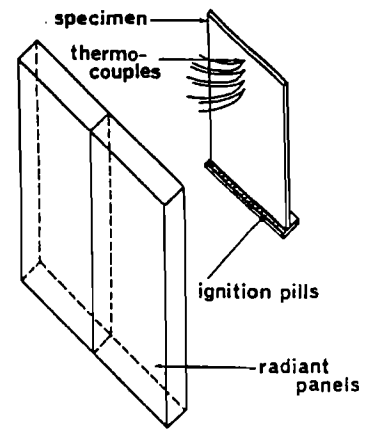


Figure 6 Time History of Surface Temperature ($q_e^- = 0.0 \text{ kW/m}^2$)

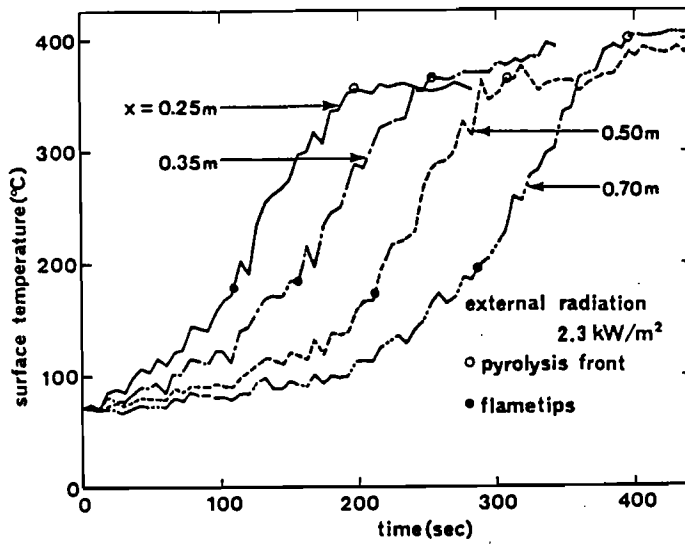


Figure 7 Time History of Surface Temperature ($q_e^- = 2.3 \text{ kW/m}^2$)

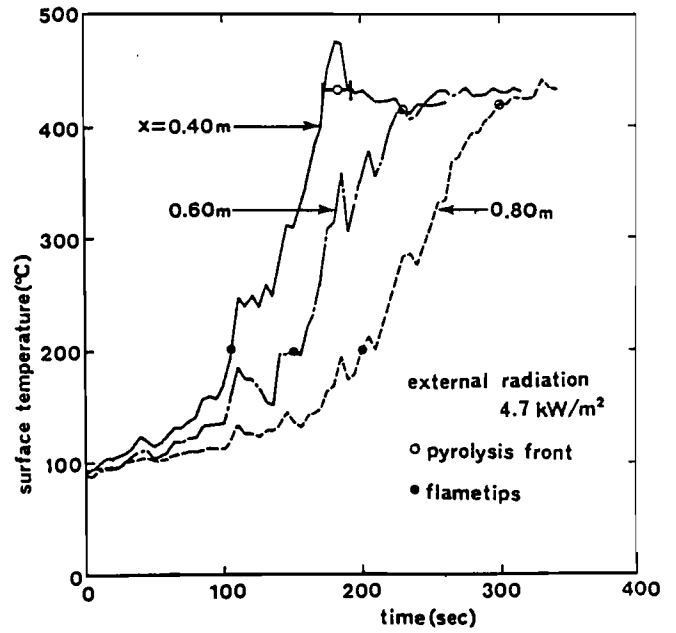


Figure 8 Time History of Surface Temperature ($q_e^- = 4.7 \text{ kW/m}^2$)

Figure 9 Location of Flametips and Pyrolysis Front
 ($q_e = 0.0 \text{ kW/m}^2$)

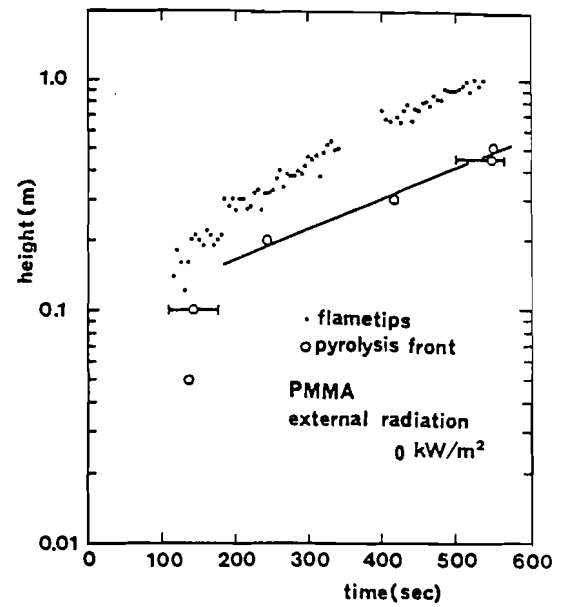


Figure 10 Location of Flametips and Pyrolysis Front
 ($q_e = 2.3 \text{ kW/m}^2$)

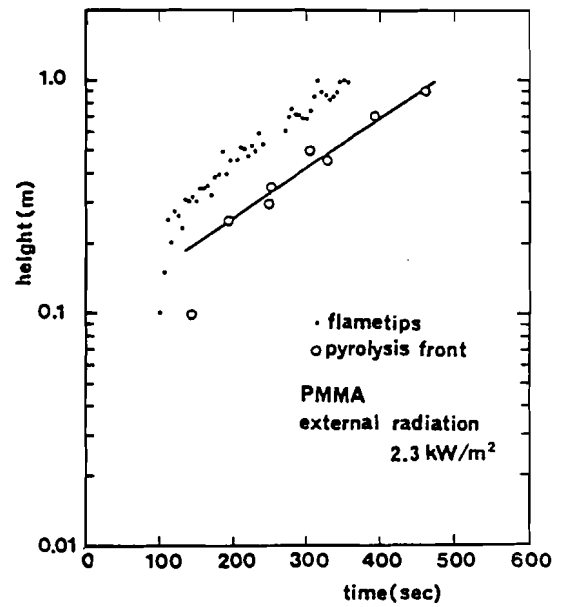


Figure 11 Location of Flametips and Pyrolysis Front
 ($q_e = 4.7 \text{ kW/m}^2$)

