Upward Flame Spread: The Width Effect

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ABSTRACT

Previous work has demonstrated upward flame spread on vertical surfaces to be one of the most hazardous fire scenarios. To assess the risk of this scenario, several models have been developed to predict the flame spread rate, relying on empirical correlations of flame height and heat feedback to unburned surface ahead of pyrolysis region. However, the width effect was not regarded particularly in those models but to influence flame thickness, causing the variation of radiation. Therefore, experiment has been designed to access the width effect. Samples used were 6 and 20 mm thick clear PMMA with height of 1000 mm and widths of 100, 300, 500, 700 and 900 mm. Our data showed that the width effect was significant for samples less than 300 mm wide and not significant for 300 to 900 mm wide samples. In addition, the width effect was slight in total heat flux distribution and not obvious in flame height correlation. As to the radiant heat flux distribution, our measurements were much lower than recognized in previous studies.

KEYWORDS: upward flame spread, width effect, flame height, heat feedback

NOMENCLATURE

K	effective emission coefficient（m^{-1}）
L	mean beam length（m）
$\dot{Q}'$	heat release rate per unit width（kW/m）
$\dot{Q}_{rad}$	radiant heat flux（kW/m^2）
$\dot{q}''$	total heat flux （kW/m^2）
T	temperature（K）
X	vertical distance from the bottom of wall（m）
X_b	burnout front height（m）
X_f	flame height（m）
X_p	pyrolysis height（m）
ε	emissivity (-)
σ	Stefan-Boltzmann constant （5.67×10^{-8} $W/m^2.K^4$）

INTRODUCTION

Previous work has demonstrated upward flame spread on vertical surfaces to be one of the most hazardous fire scenarios due to concurrent direction of flame propagation and air flow. The process is illustrated in Fig. 1. The surface in the region $(X_f\text{-}X_p)$ is heated progressively and when the surface achieves its ignition temperature, the flame propagates. Clearly, flame height and heat transfer in the region $(X_f\text{-}X_p)$ play crucial roles.

FIRE SAFETY SCIENCE–PROCEEDINGS OF THE EIGHTH INTERNATIONAL SYMPOSIUM, pp. 409-419

To assess the risk, several models [1-12] have been developed. Most of these models relied on empirical correlations of flame height and heat feedback to unburned surface ahead of pyrolysis region and the effect of the width of burning area is not considered in those correlations. Their predictions have been compared with experiments and reasonable agreements were showed.

However, the width of burning area is regarded to influence flame thickness [13], causing the variation of radiation. (The "thickness" is orthogonal to the PMMA surface.) This has been shown to affect the flame height correlations [14] and heat flux to the unburned surface [13]. In addition, the previous models (see Table 1) used different heat flux representatives in their modeling work. One interesting point is that the representative heat fluxes used were larger while the burning areas in their experiments were wider (see Fig. 2) besides one study which underestimated flame spread rate [8]. Therefore, the existence of width effect was implies. In our study, the width effect is focused on furthermore and experiments have been designed to access its effect.

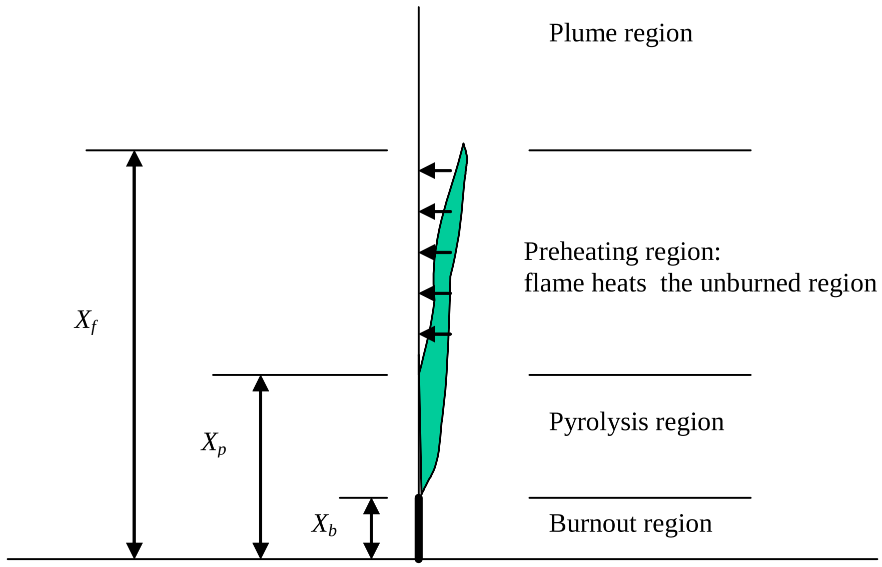

Fig. 1. Upward flame spreading.

Table 1. The heat flux to unburned surface and the width of burning area in experiments in some upward flame spread models.

Modeling work of upward flame spread	**The heat flux to unburned surface used in modeling work (kW/m^2)**	**The width of burning area in experiments (m)**
Saito *et al.* [1]	25	0.3
Mowrer and Williamson [2]	30	Nil
Delichatsios *et al.*[3]	30	0.41
Delichatsios and Delichatsios [4]	25	0.2
Delichatsios and Chen [5]	25	Nil
Grant and Drysdale [6]	20	Nil
Anderson *et al.* [7]	35	0.6
Kokkala *et al.* [8]	25	1.2
Qian and Saito [9]	25	Nil
Quintiere and Lee [10]	25	Nil
Tsai and Drysdale [11,12]	15	0.08

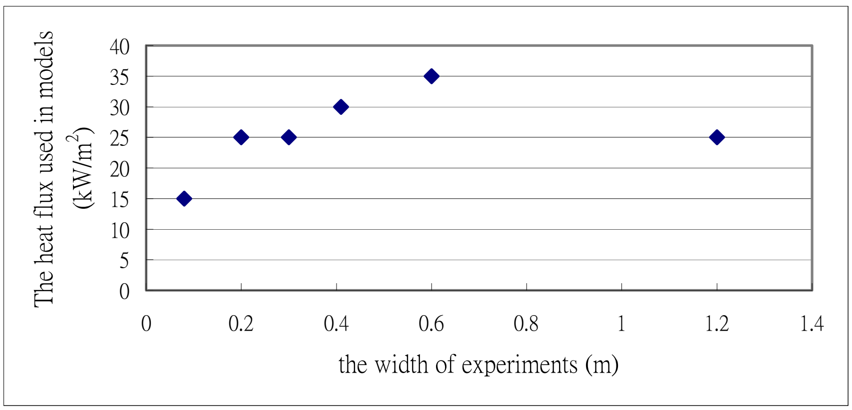

Fig. 2. The relationship of heat flux used in models and widths of burning area in experiments.

EXPERIMENTAL

A schematic of the experimental set-up is shown in Fig. 3. The samples used were 6 and 20 mm thick clear PMMA, 1000 mm tall and with width of 100, 300, 500, 700, and 900 mm. The samples were held against a 3 mm thick steel plates to prevent flame spreading up the back of the sample, distortion and slumping. Two 50 mm wide sidewalls made of marinite were used to produce uniform flame height. A hand-held butane-fueled blowtorch was used to ignite the bottom 100 mm of the sample and removed out after ignition. One Gargon-gage total heat flux meter was set up at position of 850 mm height along the central line of the sample and one Schmidt-Boelter radiant heat flux meter 8 mm above the total heat flux meter. In addition, the visual flame thickness at the top of the samples was recorded by eye for further radiation estimation. The height of flames was recorded by a camcorder and the rate of upward flame spread was determined by analyzing infra-red video recordings of each experiment. The accompanying software allowed the pyrolysis front to be tracked as the 350ºC contour as it advanced upwards. This experimental arrangement measured flame height, total/radiant heat transfer and flame spread rate simultaneously.

RESULTS AND DISCUSSION

The experiments were designed to provide data on the early stages of fire growth on a vertical surface. Figure 4 shows typical measurements of the pyrolysis front and flame height on a 100 mm wide and 1000 mm high PMMA sample.

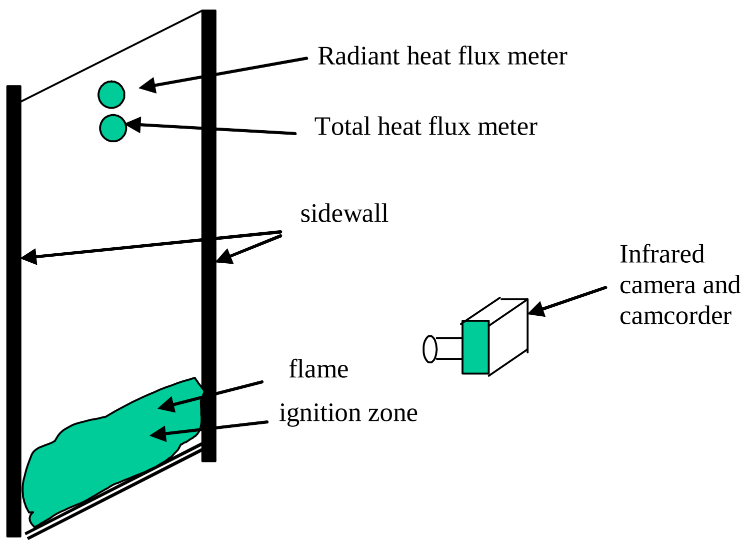

Fig. 3. The experimental rig.

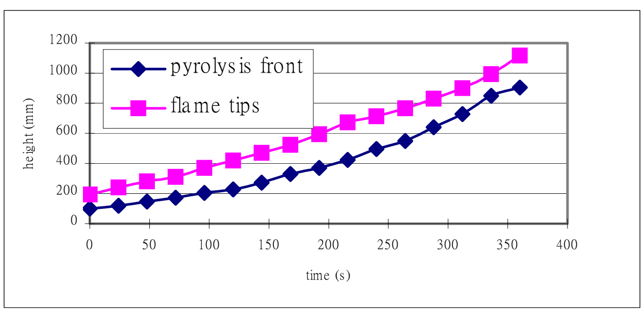

Fig. 4. A typical flame height and pyrolysis front measurement on a 100 mm wide PMMA sample as a function of time.

Flame Height Correlation

Figure 5 and Fig. 6 show the flame height measurements (average of 3 tests) against pyrolysis height of these 100, 300, 500, 700 and 900 mm wide samples. The results shown in Fig. 5 were for 6 mm thick samples while in Fig. 6 were 20 mm thick samples. These measurements were compared with the correlation produced from data of Hasemi [15] and Tu and Quintiere [16], giving $X_f = 0.032\dot{Q}'^{0.76}$. Very good agreement was shown. In addition, it can be seen that the width effect was not obvious.

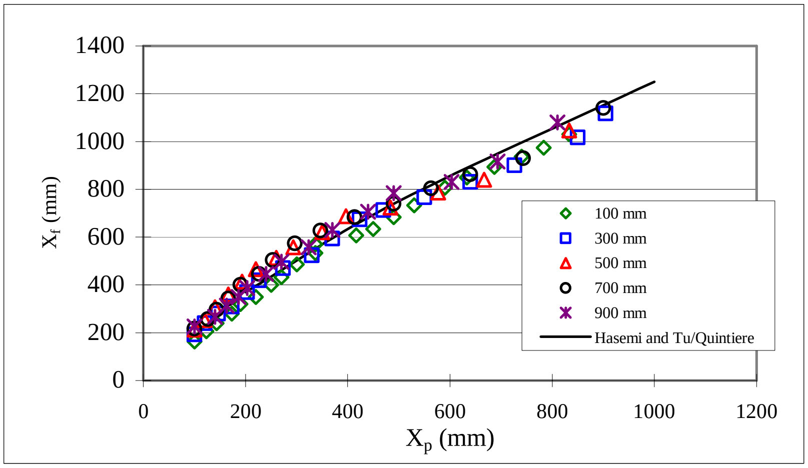

Fig. 5. The flame height correlation (against pyrolysis height) of 100, 300, 500, 700, 900 mm wide and 6 mm thick samples.

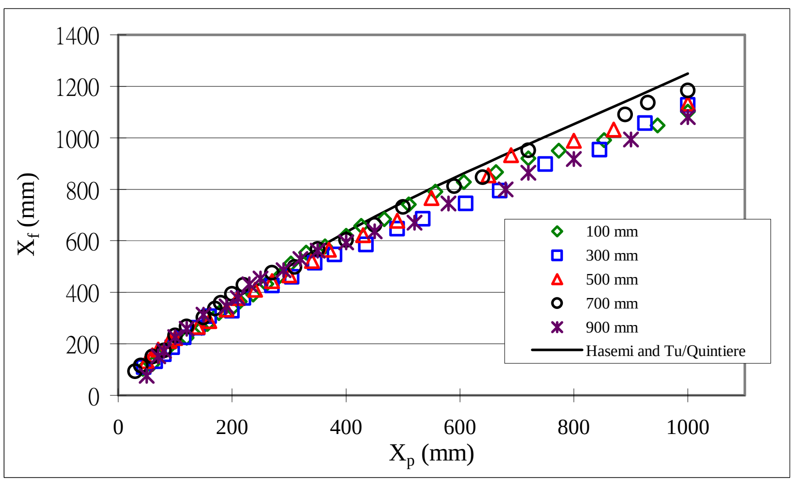

Fig. 6. The flame height correlation (against pyrolysis height) of 100, 300, 500, 700, 900 mm wide and 20 mm thick samples.

Heat Flux Correlation

Figure 7 and Fig. 8 present the total and radiant heat flux distributions (average of 3 tests) of the spreading PMMA wall fires plotted as a function of height (*X*) normalised against the flame height (X_f). Only the data for 20 mm thick and 100, 300, 500 and 700 mm wide samples were showed here. For 6 mm thick and 900 mm wide samples, the thermal expansion of mild backing steel during the flame spreading especially for wider flames occurred and caused deformation which led to a change of positions of heat flux meters and influenced heat flux measurements.

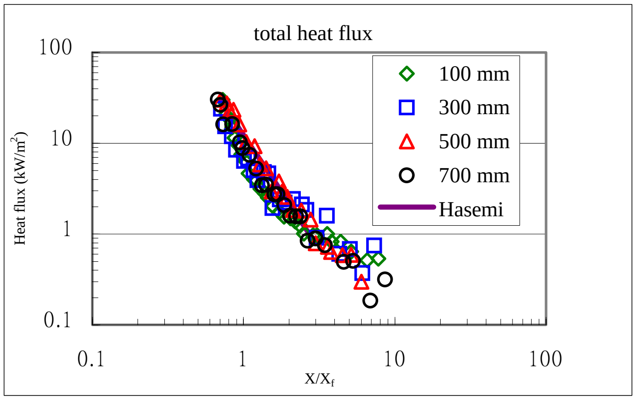

Fig. 7. The total heat flux distributions of the spreading PMMA wall fires plotted as a function of height (X) normalised against the flame height. The samples were 20 mm thick.

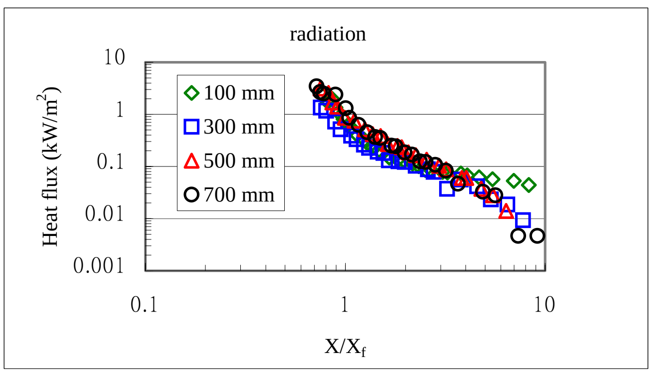

Fig. 8. The radiation distributions of the spreading PMMA wall fires plotted as a function of height (X) normalised against the flame height. The samples were 20 mm thick.

The total and radiant heat fluxes for PMMA samples of different widths while flame tips reached the heat flux meters and pyrolysis fronts did were listed in Table 2. The total heat fluxes were between 8-10 kW/m^2 and 25-30 kW/m^2. This indicates the total heat flux distribution of the preheating region (see Fig. 1). Hasemi's correlation [15], giving

$\dot{q}'' = 12.3\left(X/X_f\right)^{-2.5}$ (for X/X_f >0.7), was additionally put in Fig. 7 for comparison. Very good agreement was shown. Furthermore, it can generally be seen that for wider flames, the total heat fluxes were higher. However, the effect was not significant. As to the radiant heat flux, the measurements were about 0.3-3.5 kW/m^2. These values were very low and the width effect was not obvious.

Table 2. The total and radiant heat fluxes for PMMA samples of different widths while flame tips reached the heat flux meters and pyrolysis fronts did.

Width of sample (mm)	Total heat flux		Radiant heat flux	
	flame tips reached the heat flux meter (kW/m^2)	pyrolysis fronts reached the heat flux meter (kW/m^2)	flame tips reached the heat flux meter (kW/m^2)	pyrolysis fronts reached the heat flux meter (kW/m^2)
100	9.49	23.58	0.61	2.31
300	8.45	23.95	0.38	1.35
500	10.28	30.04	0.85	3.15
700	10.21	30.21	1.30	3.47

Radiation at Pyrolysis Front Estimated by Visual Flame Thickness

The radition measured in this study was very low compared with data from previous studies [13] noticing that radiation plays a primary role in wall fires. Therefore, the radiation measurements were checked with estimations by visual flame thickness. Although this estimation method is of approximation, it should give some information. The radiation from luminous flames can be calculated by equation 1.

$$\dot{Q}_{rad} = \varepsilon\sigma T^4 \qquad (1)$$

where σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^{2}K^4), ε is the emissivity and T is the temperature (K). The emissivity can be estimated by Kirchhoff's law (equation 2)

$$\varepsilon = 1 - \exp(-KL) \qquad (2)$$

where K is an effective emission coefficient and L is the flame thickness (or mean beam length). The value of K for PMMA is taken to be 1.3 [13], and flame temperature to be 850^{o}℃ (1125 K). The flame thickness at pyrolysis front for samples of different widths is presented in Table 3. The radiation is calculated and shown in Table 3 to be among c.5 to 9 kW/m^2. These values were higher than our measurements (Table 2), less than the experimental result by Zhang *et al*. [17] to be c. 12 kW/m^2 and much less than the recognised radiation of wall fires to be 25~30 kW/m^2 (see Table 1). Inconsistency exists.

Flame Spread Rate

Figures 9 and 10 show the flame spread rates (average of 3 tests) of the wall fires. Figure 9 is for 6 mm thick samples while Fig. 10 for 20 mm thick samples. It can be seen that the width effect existed. For both sets of experiments, the difference is not significant among the flames of 300, 500, 700 and 900 mm wide and the 100 mm wide flames spread much slower than those cases.

Table 3. The flame thickness and calculated radiation to the unburned surface of samples measured while the pyrolysis front reached the position of heat flux meters.

Width of flame (mm)	**Thickness of flame (mm)**	**Radiation (kW/m^2)**
100	45	5.12
300	50	5.68
500	80	8.91
700	80	8.91
900	80	8.91

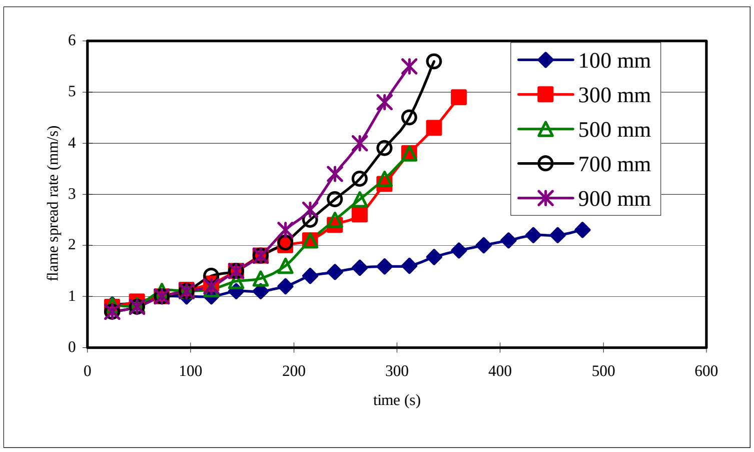

Fig. 9. The flame spread rates of the wall fires.
The samples were 6 mm thick.

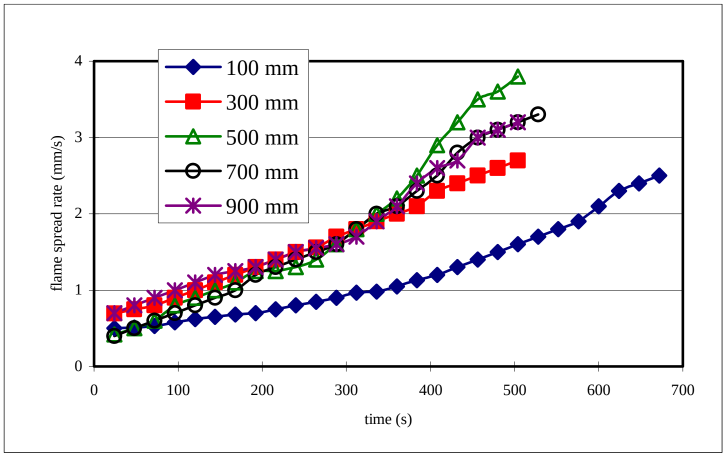

Fig. 10. The flame spread rates of the wall fires.
The samples were 20 mm thick.

Sample Thickness Effect

The samples used were 6 and 20 mm thick PMMA. Comparing the data for samples of different thicknesses, the flame height correlation and heat flux distribution did not varied with thickness. However, the flames spreading on thicker samples propagated slower. This is consistent with the studies reported by Drysdale [13].

Further Modeling Work

In upward flame spread models, it is important to use as input data the best available representations of flame height and heat transfer to the preheating region. Previous models did not consider the width effect. Therefore, their flame height correlation and heat flux distribution were identical. However, from our data, the width effect was significant in flame spread rate, which clearly shows that one-dimensional simplification is not proper for samples wider than 300 mm.

CONCLUSION

Experiments were designed to study the width effect in upward flame spread. Our data showed that the width effect does exist for samples less than 300 mm wide and not significant from 300 to 900 mm wide. In addition, the width effect is slight in total heat flux distribution and not obvious in flame height correlation. As to the radiant heat flux distribution, our measurements were much lower than recognized in previous studies.

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