THE EFFECTS OF BUILDING ELEMENTS AND SMOKE LAYER ON FIRE SPREAD BETWEEN COMBUSTIBLE MATERIALS

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ABSTRACT

Model-scale experiments were conducted on fire spread where the fire sources are placed in an open area, near a wall, under a ceiling, and under a ceiling with a suspended wall. The time required for a fire to spread between five liquid fuel pools arranged linearly is measured by igniting the central pool. The extension of the flames on a wall accelerates the fire spread; however, when the fire sources are placed away from the wall, the rate of fire spread is almost the same or is slightly lower than that in an open area. When the flames impinge continuously or they enter the smoke layer, the rate of fire spread increases significantly. Simple calculation methods are developed and the results are in fair agreement with the results of the experiments under a ceiling with suspended wall.

KEYWORDS: Model experiment, Fire spread, Building elements, Heat release rate

NOTATIONS

A	: total surface area [m^2]	L_m	: mean flame height [m]
c_p	: specific heat of smoke layer gas [kJ/kgK]	L_{mb}	: mean beam length [m]
d	: distance between the edge of pools and the wall [mm]	m	: mass flow rate [kg/s]
D	: diameter of fuel tray [m]	q	: radiation heat flux [kW/m^2]
F	: shape factor [-]	Q^*	: dimensionless heat release rate [-]
h	: the depth of a suspended wall [mm]	Q	: heat release rate [kW]
H	: ceiling height [mm] or opening height [m]	S	: smoke layer height [m]
k	: absorption coefficient [-]	T	: temperature [K]
L_c	: continuous flame height [m]	V	: volume of smoke layer [m^3]

Greek letters

ε	: emissivity [-]	σ	: Stefan-Boltzmann's constant (5.67 x 10^{-11} [kW/m^2/K^4])
ρ	: density [kg/m^3]	$\tau_{i,j}$	: overall transmissivity of the flames between trays i and j

Subscripts

a	: ambient	j	: *j*-th tray
f	: flame	p	: plume
i	: *i*-th tray	s	: smoke layer

INTRODUCTION

Performance-based fire safety design allows for various designs as long as the evacuation safety or prevention of collapse for the design fire source is assured. Nowadays, a *t*-squared fire is widely used as a design fire source in the early stages of fire development. In an area with high fire load density, the fire spreads like a continuous body, and it is rational to assume a *t*-squared fire. However, in an area with low fire load density, the fire spreads discretely by thermal radiation and its speed depends on the arrangement of combustible materials and building elements such as walls and a ceiling near these materials.

Emmons[1] proposed a compartment fire model by combining sub models of each fire phenomena such as pyrolysis, burning, plume, smoke movement, etc. and the experimental results of a simple compartment fire were compared with the calculation results. In this study, one combustible material was placed in a compartment as a target and the fire spread between multiple combustible materials was not considered. The effects of combustible arrangements on the fire spread were studied by Deguchi[2]. The time required for a fire to spread from an ignited crib to other cribs in the vicinity was measured in an open area and was compared with that of the simple model.

In usual buildings, combustibles are arranged near or under building elements such as walls and a ceiling. In these cases, the characteristics of burning such as flame extension and increase in flame temperature due to walls or impinging flame lengths have been studied[3–8]; however, their effects on the fire spread between combustible materials were not obvious. Systematic and simple experiments are thus conducted to investigate such effects by varying the distance between the fire sources and the wall, ceiling height, and the depth of the wall suspended from the edge of the ceiling.

EXPERIMENTAL METHODS

Schematic diagrams of the experimental setups are shown in Fig. 1. The time required for a fire to spread between five liquid fuel pools arranged linearly at intervals of 50 mm is measured by igniting the central pool (No. 3 in Fig. 1). These pools are created at the center of a floor with a length and width of 1200 mm and 1800 mm, respectively. The diameter and depth of each pool are 200 mm and 35 mm, respectively. The floor, walls, ceiling, and suspended walls are made of ceramic fiberboards. The temperatures in the region of the flames and the lower part of the plumes are measured using thermocouples. The fuel surface temperatures are also measured. The radiation heat flux to the floor is also measured. The flame heights are recorded at 60 frames per second using video cameras mounted in front of the pools and in an area to the side of one of the outermost pools.

Experimental conditions and corresponding number of tests are listed in Table 1. In experiments near the wall, the distance between the edge of pools and the wall, denoted as d in Fig. 1a), is in the range of 0 to 400 mm. In experiments under the ceiling, the height, denoted as H in Fig. 1a), is varied in the range of 300 to 700 mm. In experiments in an open area, near the wall and under the ceiling, the fire is produced by using 500 ml of ethanol in stainless steel trays. Experiments under the smoke layers are conducted under the ceiling with the suspended wall, the depth of which, denoted as h in Fig. 1b), is in the range of 0 to 600 mm. In this case, the fire is produced by using 200 ml of kerosene in the same trays. When the ambient air temperature is in the range of 12 to 18°C, ethanol is warmed by the hot water and its temperature is in the range of 23 to 27 °C.

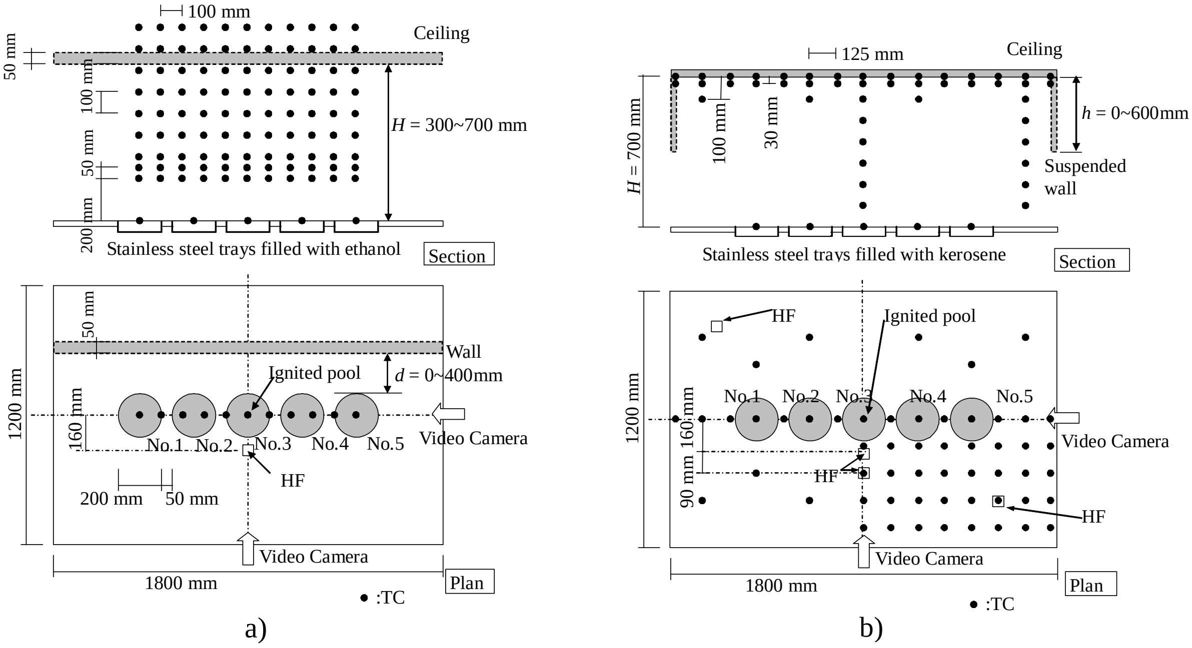


FIGURE 1. Schematic diagrams of the experimental setup: a) in an open area, near a wall, and under a ceiling, b) under a ceiling with a suspended wall

TABLE 1. Experimental conditions

	Parameters [mm]		Fuel[*1]	Number of tests
Open area	-		E	5[*3],3[*4]
Near a wall	Distance from wall *d*	0	E	6[*4]
		100	E	5[*4]
		400	E	5[*4]
Under a ceiling	Ceiling height *H*	700	E	4[*4]
		500	E	5[*4]
		300	E	1[*4]
Under a ceiling with a suspended wall	Depth of a suspended wall[*2] *h*	0	K	3[*5]
		300	K	3[*5]
		400	K	3[*5]
		500	K	2[*5]
		600	K	2[*5]

*1 E: Ethanol 500 ml/tray, K: Kerosene 200 ml/tray
*2 The ceiling is 700 mm high in this case, depth of suspended wall is varied.
*3 Ambient air temperature was in the range of 22–24°C.
*4 Ambient air temperature was in the range of 12–18°C.
*5 Ambient air temperature was in the range of 29–36°C.

EXPERIMENTAL RESULTS

Experiments Conducted in an Open Area

Eight tests were carried out, however, ambient temperature differed between 5 tests and the other 3 tests because of the experimental schedule. Only 5 tests conducted in the temperature range of 22 to 24°C are analyzed here. In the next section, the results of the remaining three tests conducted in the temperature range of 12 to 18°C are compared with those of the experiments conducted near a wall and under a ceiling.

In three of the five tests, the fire spread symmetrically, as shown in Fig. 2. In the remaining two tests, the fire first spread along one direction (to the left in Fig. 3) and then along another direction (to the right in Fig. 3). The first step in these figures indicates that the fire spread from the ignited pool (No. 3 in Fig. 1) to the adjacent pools (No. 2 and No. 4 in Fig. 1), and the second step indicates that the fire spread from these adjacent pools to the outermost pools (No. 1 and No. 5 in Fig. 1).

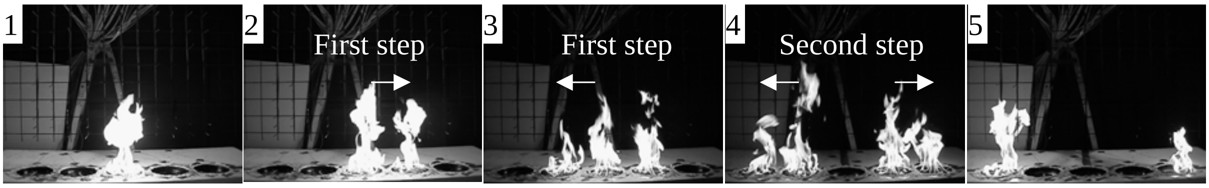


FIGURE 2. Burning behavior when fire spreads symmetrically

FIGURE 3. Burning behavior when fire spreads asymmetrically

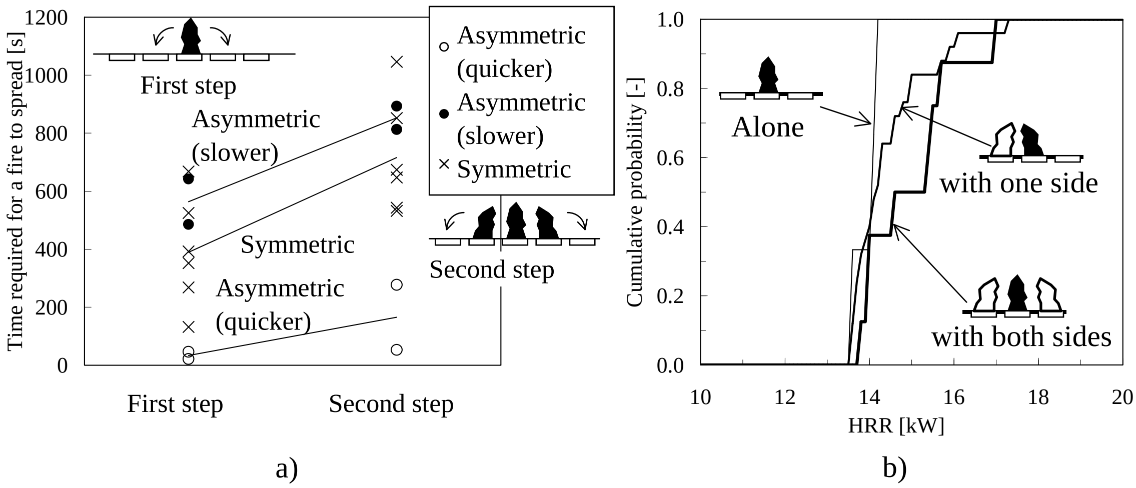


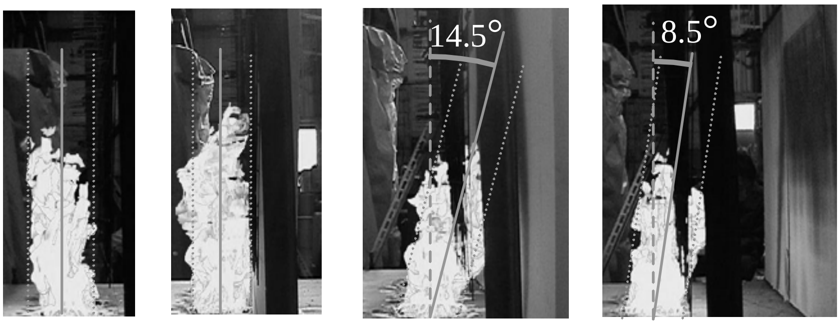
FIGURE 4. a) The time required for the fire to spread in an open area (solid line represents the average times, b) HRR of a pool fire in an open area

The measurements of the time required for a fire to spread and the average times (solid lines) are shown in Fig. 4a). In the case of a symmetrical fire spread, the time required for the fire to spread to the adjacent pools is in the range of 132 to 668 s (median value: 372 s) and the time required for it to spread to the outermost pools is in the range of 546 to 1064 s (median value: 661 s). The median value of the time required for a fire to spread from the adjacent pools to the outermost pools (second step) is 321 s and approximately 15% shorter than the median value of the first step because the outermost pool is heated by the flames on the ignited pool before the flames on the adjacent pool begin heating it. For asymmetric fire spread, the direction along which the fire spreads quickly and that along which the fire spreads slowly are considered separately, as shown in Fig. 4a). For the direction along which the fire spreads quickly, the time required for the fire to spread to the adjacent pool (first step) is in the range of 21 to 46 s and that to the outermost pool (second step) is in the range of 28 to 302 s. In the latter case, the time required for the fire to spread to the adjacent pool is in the range of 485 to 642 s and that to the outermost pool is in the range of 814 to 892 s. The time required for the fire to spread in the latter case is greater than that in the case of the symmetrical spread. The flames on the ignited pool lean in the direction of spread, which results in the decrease in the thermal radiation in the other direction and delays the fire spread to the other direction.

Fig. 4b) shows cumulative probability distribution of the heat release rate calculated from total heat release (500 ml × 0.8 g/ml × 26.8 kJ/g = 10,720 kJ) divided by the burning duration of each pool. The three situations – when a pool burns alone, along with one side pool, and along with a pool on each side – are summarized separately. The heat release rate of a pool that burns alone is approximately 14 kW. In the case where a pool burns along with a pool on each side, the heat release rate is greatest at 17 kW and approximately 20% higher than that when the pool burns alone.

Experiments Conducted Near a Wall

Fig. 5 shows the side profiles of the flame shapes obtained by superposing 20 frames (1/3 s) recorded by a video camera. These figures show the intermittent flame regions. The flame heights on a wall are slightly higher than those in an open area. Flames that are 100 mm or 400 mm from the wall lean toward the wall at around 14.5° and 8.5°, respectively. Such changes result in the different fire spread behavior as follows.



Open area   *d* = 0 mm   *d* = 100 mm   *d* = 400 mm

FIGURE 5. Flame shapes superposed by 20 frame video pictures when the fire sources are placed near a wall

The measurements of the times required for a fire to spread from the ignited pool to each pool are shown in Fig. 6. Some pools did not ignite because of the low ambient air temperature, as indicated in the upper margin of the figure. The median values of the time required for the fire to spread in the first step are 227 s (*d* = 0 mm), 363 s (*d* = 100 mm), 411 s (*d* = 400 mm), and 324 s in an open area in the temperature range of 12 to 18°C. When *d* is 0 mm, the rate of fire spread is slightly higher than that in an open area because the extension of the flames and the heated wall increase the thermal radiation to the adjacent pools. On the other hand, the time required for a fire to spread when *d* is 100 mm and 400 mm is almost the same as or slightly longer than that in an open area due to the fact that a slight extension and leaning of the flames decrease the shape factor and the thermal radiation to the adjacent pools. The fire spread in the second step exhibits the same tendency.

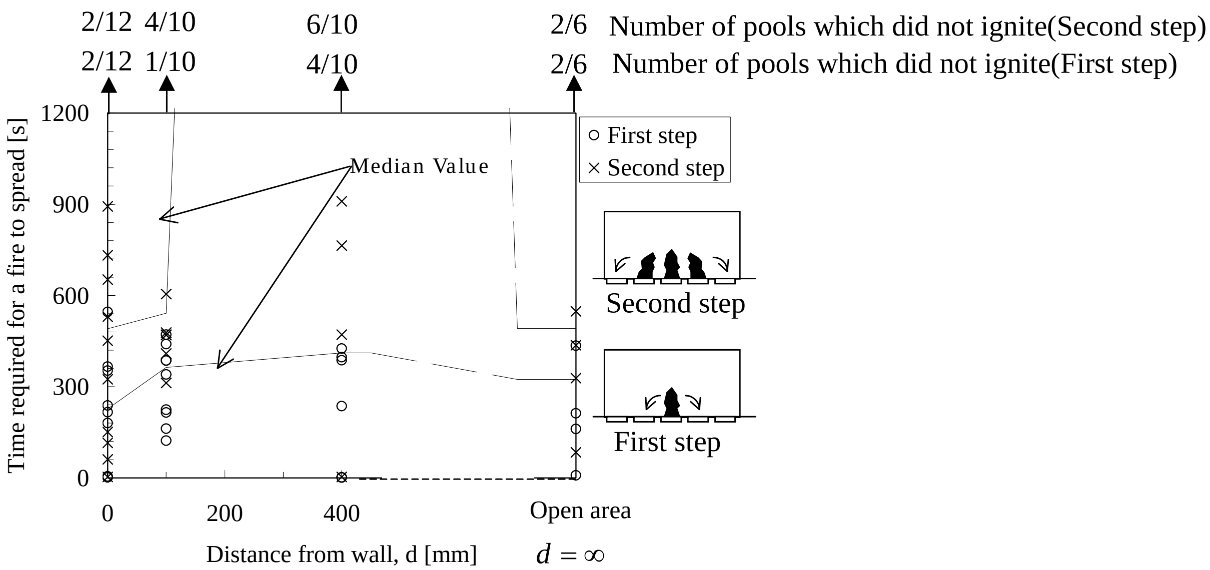


FIGURE 6. The time required for a fire to spread in near-wall experiments

The HRR of each pool is calculated from the burning duration and the total fuel mass of each pool and it is shown in Fig. 7a). When the fire sources are placed in contact with wall, d = 0 mm, the average of HRR is approximately 25% higher than that in an open area because of thermal feedback from the heated wall and increase in the flame temperature. On the other hand, when d is 100 mm and 400 mm, the HRR is almost the same as that in an open area.

The HRR curves, which are the averages of each experiment, are shown in Fig. 7b). When trays are in contact with the wall, the peak HRR value is approximately 20% higher and the peak occurs earlier than that in an open area, which indicates the significant effect of a wall on the HRR.

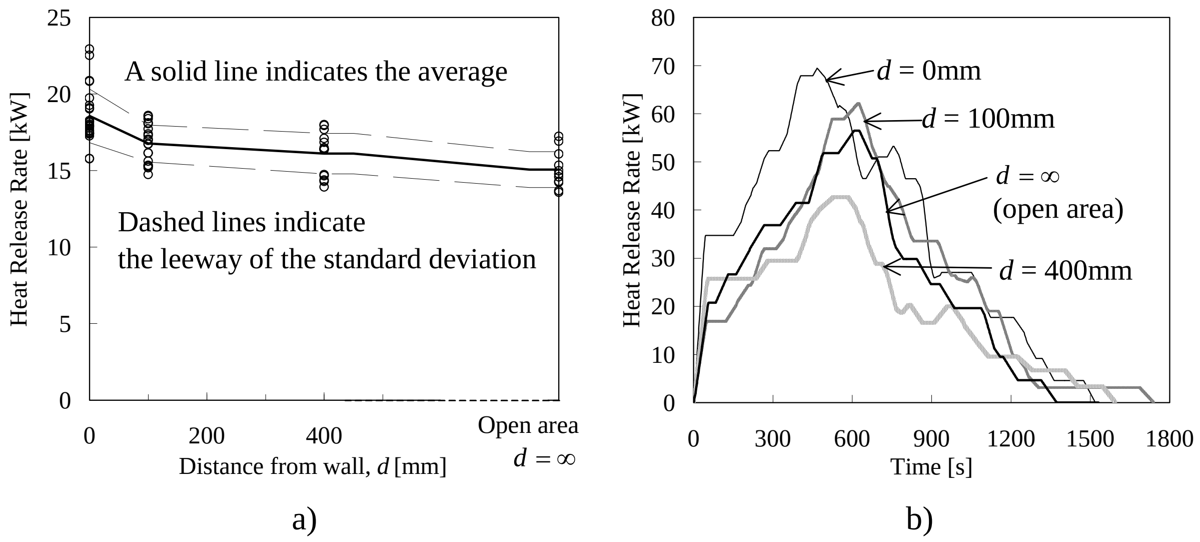
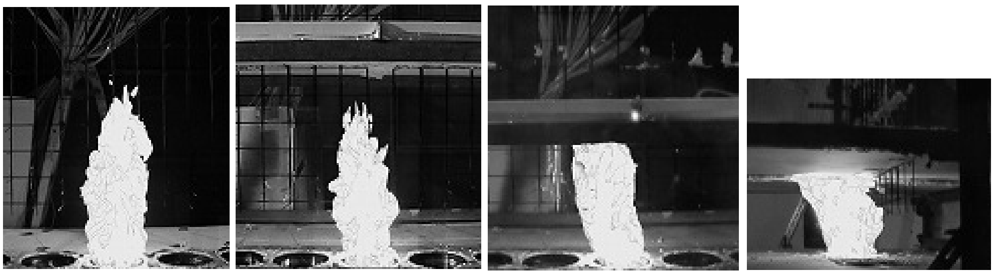


FIGURE 7. a) HRR of a pool fire in the experiments near the wall, b) Average of HRR curves (sum total of each HRR) in the experiments near the wall

Experiments Conducted under a Ceiling

The flame shapes obtained by superposing 20 frames (1/3 s) recorded by a video camera (in the figure, *H* = 300 mm is recorded from the side) are shown in Fig. 8. When the ceiling height is 700 mm, the maximum flame height is almost same as those in open area. When *H* = 300 mm, the flame continuously impinges the ceiling.



Open Area H = 700 mm H = 500 mm H = 300 mm

FIGURE 8. Flame shapes obtained by superposing 20 frame video pictures in the experiments under a ceiling.

The measurements of time required for a fire to spread are shown in Fig. 9. The median value of the measurements (solid line) in the first step is 348 s when *H* is 700 mm. This is almost the same as that in an open area because the flame tip does not touch the ceiling, as shown in Fig. 7, and the temperature of the ceiling jet is low (100 to 200°C). The time required for the fire to spread increases with the ceiling height when the height is lower than the maximum flame height. The medians of the measurements are 147 s and 52 s when the ceiling heights are 500 mm and 300 mm, respectively. When the height is 300 mm, the time required for a fire to spread in both steps is very short because the flames continuously impinge the ceiling and they spread concentrically, thereby increasing the thermal radiation to the other pools significantly.

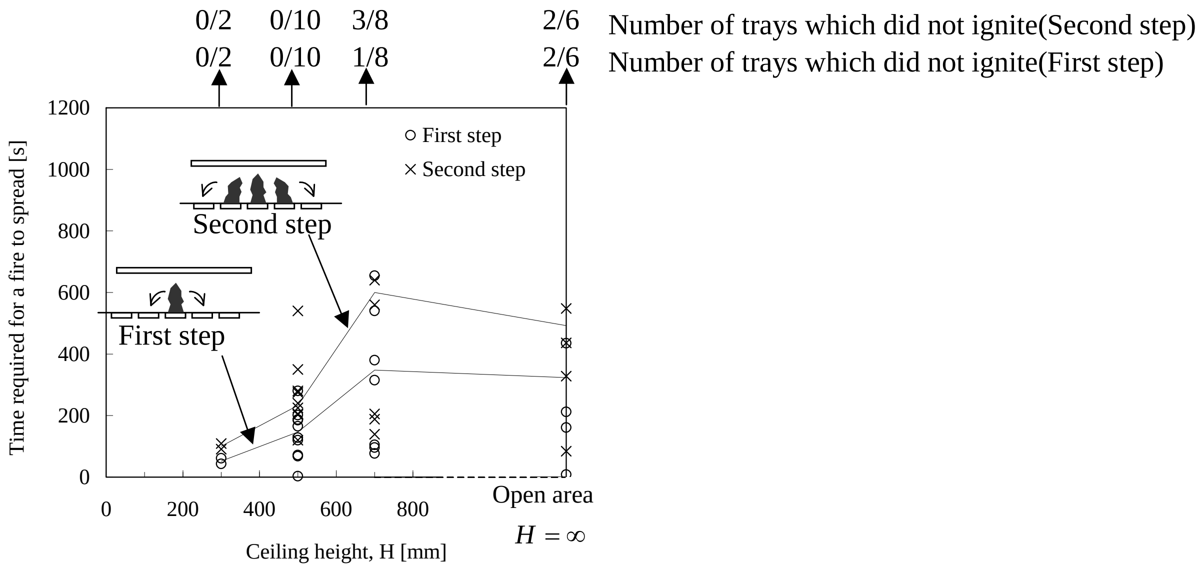


FIGURE 9. The time required for a fire to spread in the experiments conducted under the ceiling

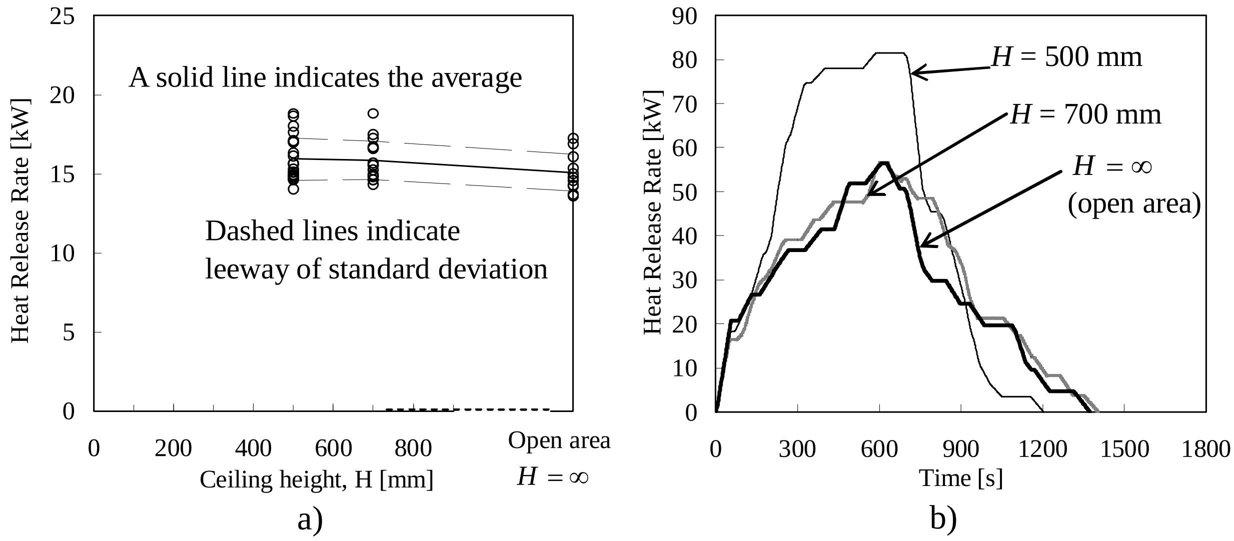


FIGURE 10. a) HRR of a pool fire in experiments under ceiling, b) Average of HRR curves (sum total of each HRR) in experiments conducted under a ceiling

HRR of each pool fire is shown in Fig. 10a). When ceiling height is 700 mm or 500 mm, heat release rate is only 10 % higher than in an open area. When *H* is 300 mm, burning was too intense to continue experiment until burnout. Thus the burning duration was not measured.

Shown in Fig. 10b) are the HRR curves of 5 pool fires. Because some pool did not burn when *H* is 700 mm and in an open area, the total heat release is less than that for H = 500 mm. When *H* is 700 mm, the HRR is almost the same as the results in an open area. When *H* is 500 mm, peak HRR is about 150 % of that in an open area and time to peak burning is earlier.

Experiments Conducted under a Ceiling with a Suspended Wall

The burning behavior under a smoke layer is very complicated since the smoke layer interferes with the combustion. When the depth of the suspended wall is small, the burning behavior is only slightly affected because a shallow smoke layer builds up over the flames. In contrast, when the smoke layer descends to the continuous flame region, we observe a penetration of the flame into the smoke layer, as shown in Fig. 11, and the burning behavior changes significantly.

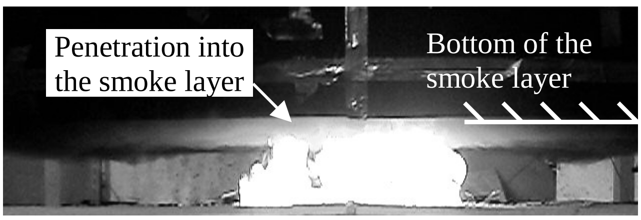


FIGURE 11. Penetration of the flame into the smoke layer (*h* = 400)

Fig. 12a) shows the measurements of the time required for a fire to spread. The fuel surface temperature was about 90°C before the fire spread. The depths of the suspended wall, which are almost equal to the depth of the smoke layer, significantly influence the time required for a fire to spread. In the case where the suspended wall has the smallest height (*h* = 300 mm), the time required for the fire to spread in the first step is approximately 30% less than that when *h* = 0 mm; however, it is not significantly greater than the other cases (*h* = 400 ~ 600 mm). In other words, the time required in the first step is considered to be dependent on the existence of the suspended wall and to be independent of the depth. In contrast, the effects of the depth on that in the second step are prominent, since the smoke layer temperature is significantly high when the suspended wall is deep. Fig. 12b) shows the temperature transitions in all tests. The smoke layer temperature rapidly increases when h = 500 mm and 600 mm, and the maximum temperatures are approximately 700°C. The smoke layer temperatures are significantly dependent on the fire spread.

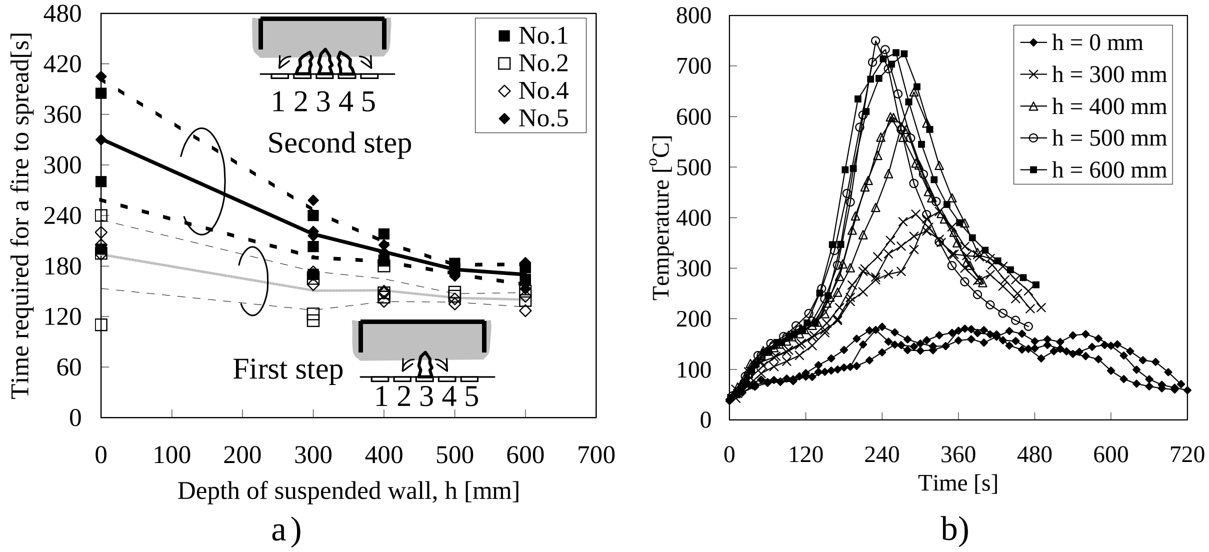


FIGURE 12. a) The time required for a fire to spread under the smoke layer (Dashed lines indicate the leeway of the standard deviation), b) The temperature transitions of the smoke layer

The HRR for each pool of fire calculated from the burning duration and total heat release are plotted against the depth of the suspended wall in Fig. 13a). The HRR of the ignited pools are independent of the depth, while those of the other pools depend on the depth because the thermal radiation from the hot smoke layer increases significantly. The HRR of the outermost pools for the case h = 600 mm is smaller than that when h = 500 mm. In the former case, the flame temperature is believed to be lower than the other case since the height of smoke layer is too low to entrain sufficient air for combustion. This leads the decrease in the burning rate.

The average HRR curves for each case are shown in Fig. 13b). The existence of the suspended wall accelerates the fire spread. When h = 500 mm and 600 mm, the HRR increases rapidly because the fire spread accelerates once the fire spreads to the adjacent pools from the ignited pool.

ANALYSIS

A simple model was developed to examine the effect of smoke layer on fire spread. The results obtained by using this model were compared with the results of experiments conducted under a ceiling with a suspended wall.

Method of Calculation

<u>Schematics of calculation method</u>

To simulate the overall fire spread phenomena, the thermal radiation from the flames and the smoke layer is calculated as shown in Fig. 14a). In the beginning, only the central tray (tray No. 3) is burning. The flame on tray 3 emits thermal radiation toward the other trays – No. 1, No. 2, No. 4, and No. 5. Simultaneously, the radiation from the smoke layer reaches the fuel surface. Both these radiation fluxes raise the fuel surface temperature. When the surface temperatures reach the ignition temperature, the adjacent trays (trays No. 2 and No. 4) are ignited; consequently, the thermal radiation from the flame on trays No. 2, No. 3, and No. 4 heats up the trays No. 1 and No. 5.

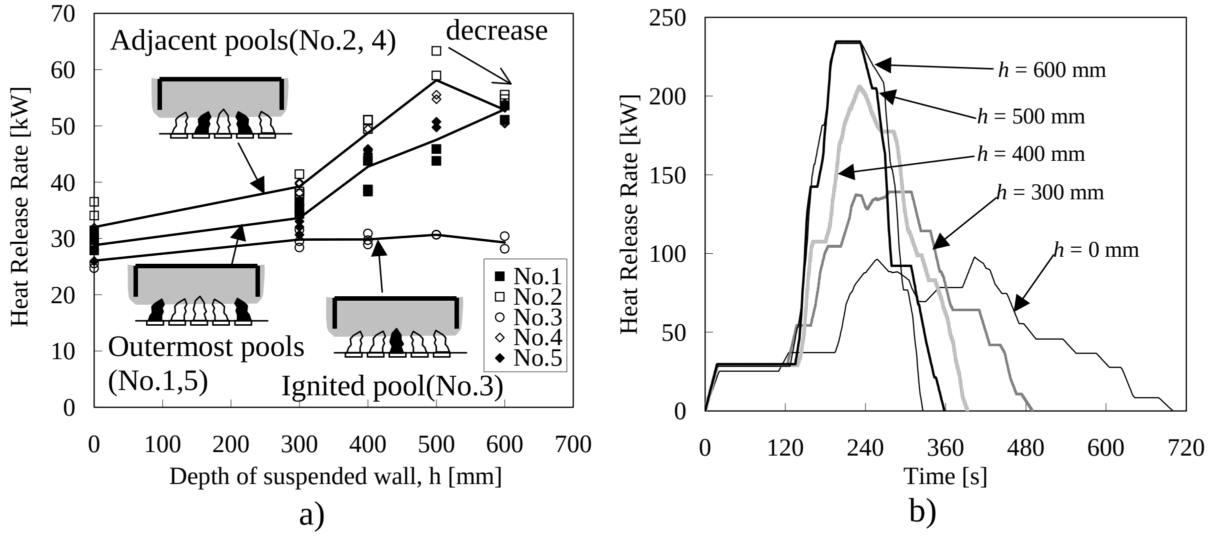


FIGURE 13. a) HRR for each pool of fire in the experiments under a smoke layer, b) HRR curves (sum total of each HRR) in the experiments conducted under a smoke layer

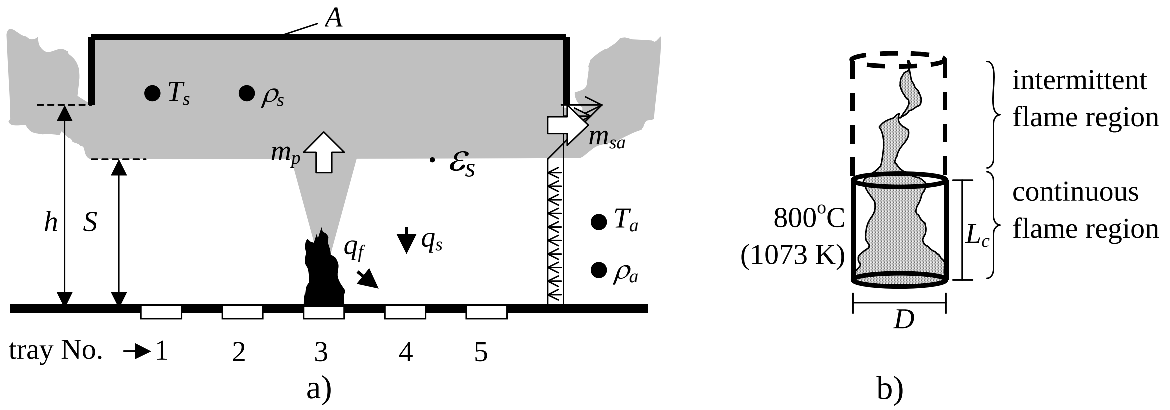


FIGURE 14. a) Schematics of the calculation method, b) Shape and temperature profile of a flame

<u>Thermal radiation from flames</u>

The flame shape is approximated by a cylinder with a diameter equal to that of the fuel tray, D, as shown in Fig. 14b). The thermal radiation is emitted by the continuous flame region (T_f = 800ºC). Given the heat release rate (Q = 24 kW) and tray diameter (D = 0.2 m), the continuous flame height, the emissivity of the flame, and the shape factors between the flame and the fuel surface are calculated as follows.

The mean flame height L_m is calculated by:

$$L_m / D = 3.3Q^{*n} \qquad [1]$$

$$Q^* = Q/1116D^{5/2} \qquad [2]$$

where n = 2/3 for 0.3 < Q^* < 1.0, n = 2/5 for 1.0 < Q^*

The continuous flame height is assumed to be the height of the flame at a temperature greater than 800ºC. Using McCaffrey's experimental correlation[9],

$$L_c = 0.61 L_m \qquad [3]$$

is assumed. The radiation from the intermittent flame region is neglected.

The thermal radiation to the fuel surface *i* is calculated by the sum of the radiation flux emitted by the flames on the other trays (j = 1, 2, …, 5):

$$q_{fi} = \sum_{j=1}^{5} \sigma \varepsilon_j T_f^{\,4} F_{i,j} \tau_{i,j}\,, \qquad [4]$$

where the emissivity of the flame, the mean beam length, and the overall transmissivity of the flames are calculated by:

$$\varepsilon_j = 1 - e^{-k_j L_{mbj}} \qquad [5]$$

$$L_{mbj} = 0.81(1 - e^{-2.2 L_{cj}/D})D \qquad [6]$$

$$\tau_{i,j} = (1-\varepsilon_{j-1})(1-\varepsilon_{j-2})\cdots(1-\varepsilon_{i+1}) \qquad [7]$$

From the thermal heat flux measurements, the absorption coefficient *k* is estimated as 2.69 m^{-1} for a kerosene flame. Equation [6] is an approximate expression led from the relation between mean beam length of cylinder and the ratio of the height to the diameter[10]. Using these values, the thermal radiation to the fuel surface is calculated.

<u>Thermal radiation from smoke layer</u>

The thermal radiation from the smoke layer is calculated in a straightforward manner. The smoke layer height and temperature were calculated in accordance with Annex B of ISO DIS 16735[11]. When multiple trays are burning, the mass flow rate and the energy input to the smoke layer were simply summarized over the burning trays. The thermal radiation from the smoke layer to the surface of tray *i* is calculated from the smoke layer temperature, the emissivity of the smoke layer, and the coefficient of the smoke layer as follows.

$$q_{si} = F_{s\,i} \varepsilon_s \sigma T_s^{\,4} \qquad [8]$$

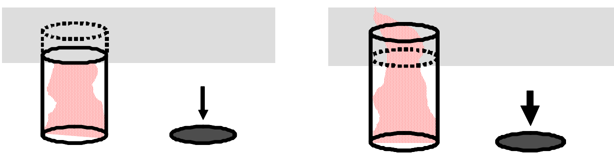
$$\varepsilon_s = 1 - e^{-k_s L_{mbs}} \qquad [9]$$

$$L_{mbs} = 4V_s / A_s \qquad [10]$$

Here, the absorption coefficient of smoke layer k_s was put equal to that of flame *k*.

<u>Interaction between flames and smoke layer</u>

If the smoke layer descends close to the floor, the top of the flame penetrates the smoke layer. In such a situation, it would be difficult to calculate the thermal radiation incident on the fuel surfaces based on the information available currently. In this study, two approximate methods are adopted as shown in Fig. 15. In method A, the penetration of the flame into the smoke layer is simply neglected. In method B, the radiations from the flame and the smoke layer are calculated independently. The resulting heat fluxes are then simply added.



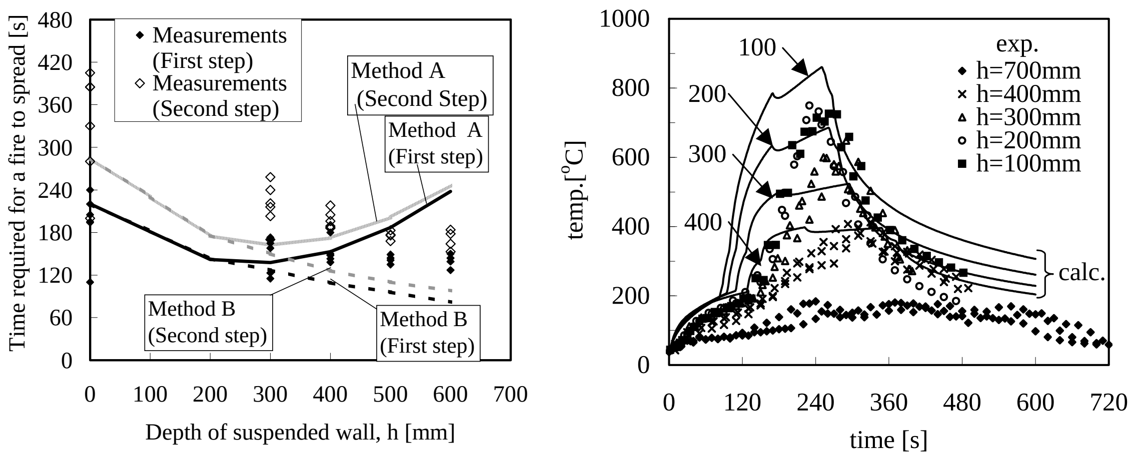
Method A Method B

FIGURE 15. Calculation of thermal radiation from a flame that penetrates the smoke layer

Fuel surface temperature
The temperature of fuel surface is calculated until the fuel surface reaches the ignition temperature. The ignition temperature is assumed as 90ºC.

Calculation Results

Calculations are carried out for each case of experiments under smoke layer. The calculated results are shown in Fig. 16. In the experiments, the time to spread gradually decreases as the depth of the suspended walls increases. As shown in Fig. 16a), this tendency is reproduced well by method B. However, the calculated spread time is shorter than the experiments. This is because the method B would overestimate the radiation heat flux. In contrast, method A results in too long spread time as the depth of the suspended walls. As shown in Fig. 16b), smoke layer temperature is calculated excessively, because the fire spread takes place simultaneously in calculation, while in experiments symmetrical spread is not so often.



a) time to spread b) smoke layer temperature (method B)

FIGURE 16. Comparison of the calculation results with experimental results

CONCLUSION

In the present study, the time required for a fire to spread between five liquid fuel pools is measured in an open area, near a wall, under a ceiling, and under a ceiling with a suspended wall. A model was developed to predict the fire spread between the fuel trays and compared them experimentally.

In an open area, an asymmetrical fire spread is observed in some cases because the merging and leaning of the flame along the direction of the fire spread delays the fire spread along other directions. This necessitates the estimation of the merged flame height and the leaning of the flame. An empirical model for estimating the flame height from multiple fire sources has been proposed by Sugawa *et al.*[6]. In contrast, the leaning of the flame is unclear and requires further study.

When the fire sources are placed on the wall, the extension of the flames increases the thermal radiation to the vicinity and accelerates the fire spread. The flames enlarge along planar walls and the thermal radiation along the orthogonal direction is larger than that in the other cases, which is believed to affect the fire spread. In contrast, when the fire sources are placed away from the wall, the leaning of the flame decreases the thermal radiation along some direction and delays the fire spread process. The effects of the distance between the fire sources and the wall on the flame height and the leaning of the flame are unclear and require further study.

When the ceiling height is higher than the maximum flame height, the rate of fire spread and the HRR are almost the same as those in an open area because of the low temperature of the ceiling surface and the ceiling jets. In contrast, when the flames touch the ceiling, the rate of fire spread increases as the ceiling height decreases. In particular, when the flames continuously impinge the ceiling, the flames spread concentrically under the ceiling and the rate of fire spread increases significantly; further, the HRR for each pool increases rapidly. The ceiling jets of strong fire plumes significantly affect the fire spread and increase the HRR of the original fire source that produces the fire plume. The temperature distribution model has been proposed by Heskedstad *et al*[7]. Therefore, a method that predicts the thermal radiation to the floor by using this model should be developed.

In the initial stage of fire development in the experiments conducted under a ceiling with a suspended wall, the effects of the thermal radiation from flames on the fire spread are dominant, while those of the smoke layer are marginal. Subsequently, the smoke layer temperature increases and the thermal radiation from the smoke layer becomes dominant. The calculated results of the fire spread are in fair agreement well with the measurements; however, the calculated fire-spread time is too small if the radiation from the smoke layer and the flame are independently calculated and added. In the case where the flames enter the smoke layer, the interaction between the flame and the smoke layer would have to be calculated correctly. This issue is currently being studied.

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