Burn-out time data analysis on interaction effects among multiple fires in fire arrays

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Abstract

This paper gives an experimental and methodological investigation on the behaviors of square fire arrays which are composed of $3 \times 3$ to $7 \times 7$ n-heptane fires initiated from fuel pans of 5 cm in diameter and 2 cm in height. It is intended to develop a burn-out time (BOT) data analysis method to analyze the interaction effects (which may induce fire merging and fire whirls) among the multiple fires. In 26 fire tests the fire point spacing $D$ varied from 20 to 50 cm for each array size and in several cases shear flow was added from one side of the array. By considering the flame height $L$ a reasonable critical condition for initiation of fire merging was implied to be $D/L = 0.29 \pm 0.34$, which is independent of the fire array size and fire point spacing. By burn-out time data the Interaction index $I(m)$ and Interaction link index $A(m,n)$ were defined to characterize the fire interactions. The assumptions essential to solve the equation system of $I(m) = \sum A(n,m)$ were examined in detail, whereby the equation system was solved. The analysis showed that the burn-out time data analysis realizes a quantitatively reasonable comparison of the fire interaction effects, thus indicating that it is reasonable to regard the burn-out time as a measure for the average burning rate for each specific fire point. An apparent criterion of $\text{BOT}(m)/\text{BOT}(R) = 0.5$ was summarized to identify whether any fire point $m$ will be completely involved in fire merging (where $\text{BOT}(R)$ is the burn-out time of the free burning reference fire point). It was implied that the interaction effect imposed on any fire is mainly ascribed to its adjacent four fires. The effects of shear flow to fire burning and occurrences of fire whirls were also discussed.

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Keywords: Fire array; Fire interaction; Fire merging; Burn-out time data analysis; Fire whirl

1. Introduction

Multiple free burning fires from separate fuel beds may induce significant interactions among the fires, leading to intense burning and different types of dynamical behaviors under different conditions. However, the method to characterize the fire interactions is an old but unsolved problem.

Due to fire interactions the fires may tend to merge and ultimately behave as a single large (or mass) fire when the fires are placed sufficiently close. The major topic for fire merging is the critical condition which determines the transition from multiple fires to one single mass fire. So far, there has been only limited available literature concerning the fire merging behavior. Putman and Speich [1] measured the flame height increase for different arrangement of multiple fires based on effective point sources. Thomas et al. [2] considered the flame merging when two fires were placed...
side by side and obtained a dimensionless equation relating the merged flame height to fire spacing. Baldwin [3] deduced a theoretical scaling law for the condition of flame merging. The scaling law is independent of the number of fires involved, and the flame height and the size and separation of the fuel beds scale geometrically. By tests using \( n \)-heptane as fuels, Satoh and Yang [4,5] examined the fire interactions among \( 3 \times 3 \) and \( 5 \times 5 \) square arrays. A critical fire spacing of 40 cm was indicated as an apparent critical condition for the occurrence of fire merging, however, the relevance of the critical condition with the combustion behavior for the specific fuel was not further analyzed.

Another important behavior due to fire interactions is the initiation of fire whirl, which acting as a destructive fire phenomenon has been evidenced in a number of wildland and urban fire instances [4]. The formation of fire whirls requires a source of ambient vorticity, a concentrating mechanism, and a favorable environment for fire whirl stability and growth. Emmons and Ying wrote the defining paper about the primary mechanism of the fire whirl behavior [6]. Satoh and Yang [7] developed an excellent physical model in which fire whirl is generated naturally by placing a free standing fire in a square enclosure with symmetrical corner gaps. They also presented some observations on the fire whirls in \( 3 \times 3 \) and \( 5 \times 5 \) fire arrays [4,5]. However, so far there is still little experimental information available in literature concerning the induction of fire whirls within free-standing fires.

This paper intends to investigate the method of using the burn-out time data to characterize the interactions among the fires in fire arrays. By the burn-out time analysis, the interactions effects among different fires may be quantitatively compared, the critical condition for fire merging may then be further clarified, and the occurrence behavior of fire whirls may also be examined.

2. Experimental

All fire array experiments were conducted in a large experimental hall at SKLFS with ceiling exhaust vents. The doors and windows were closed during tests, and all fires were originated from identical steel circular fuel pans, 6 cm in diameter and 2 cm in height. The fuel of \( n \)-heptane with percentage of 98% was filled into each pan to the full depth. The fire point spacing \( D \) was varied within 20–50 cm (Table 1). Each test was videotaped from ignition to burn-out with a continuous record of elapsed time, and so the phenomena such as fire merging and fire whirls can be fully monitored. In some cases the imposed shear flow was generated by a fan through a vertical slit, and the wind direction at the slit exit was parallel to one side of the array (Fig. 1). A DV camera was located on one side with a measuring scale just against the camera on the other side, and thus the flame height could be determined from the images. For each test, a single free-standing fire located far away from the array was simultaneously ignited as a reference fire. All the reference fires had an average burn-out time of 627 s. Taking \( 3 \times 3 \) fire array as an example, the numbering method is shown in Fig. 1.

In the work of Baldwin [3], town gas burners were used whereby the flame height could be adjusted by varying the gas flow. Wood and city

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**Table 1**

Experimental contents list

<table>
<thead>
<tr>
<th>Fire array</th>
<th>( D = 20 ) cm</th>
<th>( D = 30 ) cm</th>
<th>( D = 40 ) cm</th>
<th>( D = 50 ) cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 3 \times 3 )</td>
<td>No wind</td>
<td>No wind</td>
<td>No wind</td>
<td>No wind</td>
</tr>
<tr>
<td>( 4 \times 4 )</td>
<td>No wind</td>
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<td>No wind</td>
<td>No wind/wind</td>
</tr>
<tr>
<td>( 5 \times 5 )</td>
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<td>No wind/wind</td>
<td>No wind</td>
<td>No wind/wind</td>
</tr>
<tr>
<td>( 6 \times 6 )</td>
<td>No wind</td>
<td>No wind</td>
<td>No wind</td>
<td>No wind/wind</td>
</tr>
<tr>
<td>( 7 \times 7 )</td>
<td>No wind</td>
<td>No wind</td>
<td>No wind</td>
<td>No wind/wind</td>
</tr>
</tbody>
</table>

![Fig. 1. Schematic for fire array experiments: 3 \( \times \) 3 fire array.](image-url)
gas were also used to observe the fire merging [8–11]. Comparatively, the present work used the liquid \( n \)-heptane in stead. Compared with city gas whose flow rate is manually controlled, the present fire evolution of \( n \)-heptane from ignition until burn-out may be more close to practical scenarios. Additionally, by using \( n \)-heptane it is easy to realize the experiments with fairly small fuel pan sizes and so experiments of high numbers of fires can be easily realized, while for woody fuel it is difficult to form stable flames for small fuel pan sizes.

3. Results and discussions

3.1. Definition of interaction index \( I(m) \) and interaction link index \( A(m,n) \)

In ideal case, by geometric symmetry, each equi-distant square array possesses inherent symmetries in fire behaviors. For instance, all the corner fires 1, 3, 7 and 9 in a 3 \( \times \) 3 array fall into one symmetrical group and should behave similarly. For a \( n \times n \) fire array, the number of symmetrical groups can be derived as:

\[
G_n = \begin{cases} 
\frac{(n+1)(n+3)}{8} & \text{n is an odd number} \\
\frac{n(n+2)}{8} & \text{n is an even number}
\end{cases}
\]  

(1)

By substituting \( n = 2m - 1 \) (\( n \) is an odd number) and \( n = 2m \) (\( n \) is an even number) into (1) we obtain

\[
G_{2m} = m(m + 1)/2 \\
G_{2m-1} = m(m + 1)/2 \quad m = 1, 2, 3, \ldots
\]

(2)

This suggests that the adjacent odd and even arrays have the same number of symmetrical groups.

However, in practice the symmetries may be destroyed due to a variety of factors. First, the fire plumes are inherently unstable and are sensitive to local disturbances. Second, some air infiltration from outside may affect the individual fires with different degrees. Third, the symmetry is also affected by the difference of ignition periods for different fuel pans. Nevertheless, for simplification, it is assumed that all the fires in a symmetrical group have the same burn-out time value which is approximated as the average burn-out time values of the fires in the group. We define the dimensionless interaction index \( I(m) \) for any fire \( m \):

\[
I(m) = 1 - \frac{\text{BOT}(m)}{\text{BOTR}}
\]

where \( \text{BOT}(m) \) is the average burn-out time, and \( \text{BOTR} \) is the burn-out time of the reference fire. This index characterizes the total interaction effect received by fire \( m \) and varies between 0 and 1 when \( \text{BOT}(m) < \text{BOTR} \) (in the case that the fire is not the reference fire).

| Table 2 Interaction index \( I(m) \) for the symmetrical group in fire arrays |
|-------------------|-------------------|
| \( D (\text{cm}) \) | \( 3 \times 3 \text{ fire array} \) | \( 4 \times 4 \text{ fire array} \) | \( 5 \times 5 \text{ fire array} \) |
| \( 20 \) | 0.345 | 0.483 | 0.581 |
| \( 30 \) | 0.338 | 0.462 | 0.559 |
| \( 40 \) | 0.331 | 0.454 | 0.554 |
combustion of fire $m$ is enhanced by the interaction effect it receives) (Table 2).

Further, we introduce a dimensionless interaction link index $A(m, n)$ which measures the relative extent of interactions between the fires $m$ and $n$. The essential notion is that $I(m)$ can be broken down into the parts representing the contributions due to neighboring fires. So

$$I(m) = \sum A(m, n)$$

Since the interaction effect is always mutual, it is expected that $A(m, n) = A(n, m)$.

### 3.2. Critical condition for the initiation of fire merging in fire arrays

In all the experiments it was naturally observed that each fire has remarkable burning intensity increase with higher flame height, when compared with a single free-standing fire. This fact implied that generally the fire interactions received by any specific fire have a significant combustion enhancement effect, and so the burn-out time would decrease. The flames of boundary fires showed a strong leaning toward the centre, indicating strong entrainment in-flows at the boundaries. When fire merging occurred, the square fire array with small fire point spacing burned similarly to an area fire. Additionally, the transition to fire whirl was usually foretold by the frequent leaning of adjacent flames in different directions.

The fire point spacing $D$ is one critical parameter for fire merging. It was observed that for any array size, the critical fire point spacing $D$ remains to be 40 cm. For $D < 40$ cm, fire merging will occur for all the fire arrays, while as $D$ increases to 40 cm and beyond, the flames start to behave more and more like individual fires until burn-out, even though they still maintain their dynamic vigor as compared to the reference fire, evidenced by leaning toward the array center from the boundary fires. As shown in Fig. 2, for $7 \times 7$ fire array, when $D = 20$ cm, fully merged fire can be observed at 126 s from ignition, while for $D = 40$ cm, merging did not occur until burn-out. The critical spacing of 40 cm is consistent with the results of Satoh et al. [4,5]. However, the spacing $D$ is only one of the parameters essential for fire merging, since it does not reflect the feature of fuel combustion. A reasonable parameter to reflect the effect of fuel type is the flame height $L$, since in principle $L$ is determined by the rate of fuel burning. We refer back to the work of Baldwin [3], in which the critical condition when the flames are just merging was derived by the total air flow balance and the assumption that the thrust on the flame is balanced by a buoyancy force:

$$S/W = f(L/W)$$

where $S$ is the width of the channel between neighboring fires, little different from $D$, $W$ is the size of fuel pan. Baldwin formulated a critical condition involving the fire point spacing $D$ and the flame height $L$ for $1 < L/W < 10$:

$$S/W = 0.14(L/W)^{0.96}$$

The coefficient 0.14 was determined by linear regression from the data due to a number of authors, using wood and gas as fuels. In the present work, the flame height at the onset of merging for flames (in which the deflection from the vertical was not very great) remained within 20–40 cm, while the flame heights for fully merged fires remained at nearly 1–1.2 m. Thus the quantity $L/W$ remained within 20–24, which is different from that for expression (6), maybe due to different fuels used in this work. In view of this, substituting the obtained values of $S$, $W$, and $L$ into the formula

$$S/W = a \cdot (L/W)^{0.96}$$

we obtained $a = 0.33–0.39$. Since the power index of $L/W$ is not significantly different from unity, the critical condition can be reorganized as (using $D$)

$$D/L = 0.29–0.34$$

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Fig. 2. Typical fire behaviors of fire arrays. Left: $7 \times 7$, $D = 20$ cm, time from ignition = 126 s, fully merged; right: $7 \times 7$, $D = 40$ cm, time from ignition = 126 s.
This is the critical condition correlating the onset of fire merging to the fire spacing and the merged flame height under the present fire array scenario.

### 3.3. Identification of the fire points completely involved in fire merging

When a fire merging occurs, generally not all the fires would be fully involved in the merging. Some fires on the boundary and corner of the array may not fully join in merging due to lower interaction effects. Since in principle the burn-out time data are a measure of the average burning rate for any specific fire, it is possible to relate the burn-out time to the fires fully involved in merging. By extensive comparison between the interaction indices and the recorded video images, it was found that for all the fire arrays except $3 \times 3$, the $I(m)$ values for all the fires not fully involved into merging remained lower than nearly 0.5. This is an apparent criterion independent of the array size, and it can be expressed by $I(m)$ or the burn-out time as follows:

$$I(m) = 0.5$$ \hspace{1cm} (9a)

$$\frac{BOT(m)}{BOTR} = 0.5$$ \hspace{1cm} (9b)

### Table 3
Example of interaction indices for fires involved in merging behavior

<table>
<thead>
<tr>
<th>$5 \times 5$, $D=20\text{cm}$</th>
<th>$5 \times 5$, $D=30\text{cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.461 0.574 0.575 0.574 0.461</td>
<td>0.421 0.468 0.475 0.468 0.421</td>
</tr>
<tr>
<td>0.574 0.667 0.667 0.667 0.574</td>
<td>0.468 0.560 0.589 0.560 0.468</td>
</tr>
<tr>
<td>0.575 0.677 0.699 0.677 0.575</td>
<td>0.475 0.589 0.609 0.589 0.475</td>
</tr>
<tr>
<td>0.574 0.667 0.677 0.667 0.574</td>
<td>0.468 0.560 0.589 0.560 0.468</td>
</tr>
<tr>
<td>0.461 0.574 0.575 0.574 0.461</td>
<td>0.421 0.468 0.475 0.468 0.421</td>
</tr>
</tbody>
</table>

An instance is given in Table 3 (in which the merged fire points are shaded in) combined with Fig. 3. For the $5 \times 5$ fire array, when $D = 20\text{cm}$, the corner point 1 kept separate from the merged fire and $I(1) = 0.461$, while when $D = 30\text{cm}$, the corner and boundary points 1, 2 and 3 all kept separate from the merged fire and respectively $I(1) = 0.421$, 0.468, 0.475 for $m = 1, 2, 3$. In mechanism, the interactions received by fire $m$ are in essence due to the composite effects of chemical reaction (combustion) and physical transportation behaviors (thermal convection and radiation). The dynamical details of such composite effects cannot be elucidated at present. However, Expressions (9a) and (9b) suggest that there is a definite critical value to measure the total composite effects, and most importantly this critical value seems to be nearly independent on the fire array size, fire location, and fire point spacing. An exception is the $3 \times 3$ fire array, for which fire merging did not occur. We can clarify the reason by the critical condition (8). From test for the $3 \times 3$ fire array the flame height $L$ kept within $0.1–0.3\text{m}$, which does not support the condition (8) and so the interactions among the fires are not intense enough to induce fire merging.

### 3.4. Fire interaction analysis by burn-out time data

This section intends to analyze the relative extent of interactions for different pairs of neighboring fires. The essential step is to solve the equation system (4) correlating the interaction index $I(m)$ and the interaction link index $A(m,n)$. In mathematics, the indices $A(m,n)$ act as unknowns, and only the data of $I(m)$ can be used for solutions. Therefore, assumptions should be introduced to produce supplementary expressions to close the equation system. By extensive examination we propose the following assumptions for solutions:

![Fig. 3. Fires involved in merging behavior. Left: $5 \times 5$, $D = 20\text{cm}$, $time = 161\text{s}$, fully merged. The fire point 1 was not fully involved in merging; right: $5 \times 5$, $D = 30\text{cm}$, $time = 180\text{s}$, fully merged. The fire points 1, 2 and 3 were not fully involved in merging.](image-url)
1. Symmetry approximation. Any two interaction links at symmetrical locations have the same values of $A(m,n)$.

2. Inverse proportion hypothesis. The strength of the link is inversely proportional to the square of the distance between the links. This hypothesis comes from the fact that the interaction effect between any two fires is largely due to the heat radiation between them. It differs from the assumption used by Sato in which it was assumed the strength of the link is inversely proportional to the distance between the linked fires.

3. No interaction between two fires with blockages. For example, for $5 \times 5$ fire array, we take $A(1,3) = 0$ since fire 1 cannot see fire 3 due to radiation blockage by fire 2.

4. No interaction between two fires of great distance. Any interaction link index of pair of fires which have a spacing larger than $\sqrt{5D}$ will be neglected. In addition, all interaction link indices between pair of fires that have a spacing of $\sqrt{5D}$ are regarded as equal.

5. Two pairs of fires whose locations have the same mode have equal interaction. This assumption is used for fire arrays with sizes higher than $4 \times 4$. The so called “same mode” means, taking $5 \times 5$ fire array for instance, $A(2,7) = A(3,8)$, $A(1,7) = A(3,7)$, $A(1,8) = A(2,11)$ and so on. Especially, $A(1,2) = A(2,3)$ is also assumed.

By these assumptions, we found the equation systems for up to $7 \times 7$ fire array can be closed. Taking $5 \times 5$ fire array as an example (similar numbering method to $3 \times 3$ fire array), we obtain

$$I(1) = 2A(1,2) + A(1,7) + 2A(1,8)$$
$$I(2) = 2A(1,2) + 2A(1,7) + 3A(1,8) + A(3,8)$$
$$I(3) = 2A(1,2) + 2A(1,7) + 4A(1,8) + 2A(3,8)$$
$$I(7) = 3A(1,7) + 7A(1,8) + 2A(3,8) + 2A(8,13)$$
$$I(8) = 2A(1,7) + 6A(1,8) + 4A(3,8) + 3A(8,13) + 2A(7,13)$$

The interaction link indices $A(m,n)$ are shown in Table 4. As expected, these indices decrease essentially monotonically toward zero as $D$ increases. It is interesting to note that $A(1,8)$ is almost zero, which is physically reasonable, since this link has the largest distance among all the fire pairs. $A(1,7)$ and $A(7,13)$ are also nearly zero, which means the interaction between fires with spacing larger than $D$ is fairly weak. The interaction link indices between fires with spacing of $D$, namely $A(1,2), A(3,8)$ and $A(8,13)$, have large values, implying that the interaction effect imposed on any fire comes mainly from its adjacent four fires.

An important fact is that any odd fire array (size $n = 2m - 1$) and the adjacent even fire array (size $= 2m$) have the same equation systems of (4). This can be proved by the following considerations. Firstly, it is obvious that the fire points to be dealt with lie at the same locations, i.e. the upper triangular matrix. Secondly, by the above fourth assumption, the fire points to be dealt with can be further limited in the sub-array of $(n + 5)/2 \times (n + 5)/2$. In view of (2), the two fire arrays correspond to the same equation systems.

The assumptions can be verified in some degree by the reasonability of the resulted interaction link indices, which seems to be a “Round Robin Test.” In fact, with unreasonable assumptions, the results are easy to lose its reasonability even in qualitative sense. For example, if we replace the above second assumption by that used by Sato, that is, the strength of the link is inversely proportional to the distance between the links, we find for most fire spacings $A(1,6) > A(2,3)$, which is obviously unreasonable.

### 3.5. Effect of shear wind on the interactions

With shear wind added, the symmetries of square array are destroyed significantly and the symmetrical approximation cannot be used. Therefore, a modified index $IS(m)$ is defined as follows:

$$IS(m) = \frac{BOTS(m) - BOTS(m)}{BOTR}$$

where $BOTS(m)$ is the burn-out time of the fire $m$ with the shear-flow field. Due to loss of symmetries, all the fires must be dealt with separately, and also the individual fire burn-out time values in the absence of the shear-flow field must be used for calculations. Here, the $7 \times 7$ array is used for instance (Table 5). Higher positive $IS(m)$ values refer to higher shear-flow effects which accelerate the burning of the fire, while minus $IS(m)$ values imply that the shear-flow suppresses the fire burning.

To make such data more qualitatively meaningful, we partition the $IS(m)$ values into five ranges (Table 6), by which we clearly identify

<table>
<thead>
<tr>
<th>$D$ (cm)</th>
<th>$A(1,2)$</th>
<th>$A(1,7)$</th>
<th>$A(1,8)$</th>
<th>$A(3,8)$</th>
<th>$A(7,13)$</th>
<th>$A(8,13)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.236</td>
<td>0</td>
<td>0.001</td>
<td>0.124</td>
<td>0</td>
<td>0.226</td>
</tr>
<tr>
<td>30</td>
<td>0.199</td>
<td>0.009</td>
<td>0.007</td>
<td>0.031</td>
<td>0</td>
<td>0.222</td>
</tr>
<tr>
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<td>0.174</td>
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<td>0</td>
<td>0.101</td>
<td>0</td>
<td>0.128</td>
</tr>
</tbody>
</table>
three regions, i.e. strong, intermediate and low effect regions by the following judgment (Fig. 4):

I Strong effect region: mainly H and partly M
II Intermediate effect region: mainly L
III Low effect region: partly L, O and N

The three regions expand or dwindle with variation of test conditions such as fire spacing, the intensity of shear wind and the fire array size. In dynamics, as the imposed shear wind encounters a fire in the array, it tends to seek to move through the locally available free area with the lowest resistance. This is the mechanism for the shear flow to lose its jet-flow feature and to penetrate into the array, thus affecting other fires in the array through interacting with the prevalent local entrainment into fires.

As $D$ increases, the locally available free area becomes larger, leading to ease of penetration, while at the same time the affecting distance reduces. Correspondingly, Regions I and III expand, while Region II dwindles. As wind speed $V$ increases, the imposed shear field naturally has higher effect on the fires, and so Regions I and II expand, while Region III dwindles. When the fire array size increases, more fires keep far away from the imposed shear wind, and so Region I and II dwindle, while Region III gradually occupies the major part of fire array.

### 3.6. Fire whirls

Vertical fire whirls occurred frequently in fire arrays, and when the shear wind is imposed, horizontal fire whirls were also observed (Fig. 5). The occurrence behaviors of fire whirls are summarized in Table 7. Without shear flow, generally the induced fire whirls only last for 2–3 s, 0.5–0.7 in height. The lasting period, location and time of occurrence seem to be random. Fire whirls occur a bit frequently in either array at about $D = 30$ cm. Shear flow enlarges the deviations from symmetry, so the frequency of fire whirls increases greatly, and the fire whirls mainly occur on the border region between the Strong effect region and the Intermediate effect region.
4. Conclusions

This paper presents a systematic experimental study for the fire dynamics of square fire arrays. A critical condition reflecting the feature of fuel combustion for the initiation of fire merging is implied, i.e. \( D/L = 0.29 - 0.34 \). An apparent critical value of \( I(m) = 0.5 \) or \( BOT(m)/BOTR = 0.5 \) is found which act as a criterion (independent of size of fire array, fire location and fire point spacing) to determine whether one specific fire would be completely involved in merging. To estimate the relative interaction levels among fires, the essential point is on the assumptions which help close the equation system correlating the interaction index \( I(m) \) and the interaction link index \( A(m,n) \). The assumptions used can be verified by the reasonability of the resulted interaction link indices. It is shown that the interaction effect imposed on any fire comes mainly from its adjacent four fires.

With increasing shear flow, the array can be divided into three regions which expand or dwindle with fire point spacing, wind velocity and size of fire array, and the frequency of fire whirls increases greatly, which mainly occur on the border region between the Strong effect region and the Intermediate effect region.

### Acknowledgments

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### References


### Comments

*Dieter Pawel, Physikalisch-Tech Bundesanstalt, Germany.* The experiments have been made with heptane. What about other liquids, as e.g. pentane or an opposite—decane?

*Reply.* The authors want to address that the present work was conducted as a continuation of work of Satoh and Yang who have published many relevant papers on fire arrays consisting of fuel pans with heptane. Therefore,

### Table 7

Occurrence of fire whirls

<table>
<thead>
<tr>
<th>Without imposed shear flow</th>
<th>With imposed shear flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D ) (cm)</td>
<td>Times</td>
</tr>
<tr>
<td>4 \times 4</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>50</td>
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<td>7 \times 7</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
</tbody>
</table>
in order to quantitatively compare the experimental results of our work with the previous work by Satoh and Yang, we mainly conducted the experiments using heptane.

Kazunori Kuwana, University of Kentucky, USA.

Soma and Saito showed that the Froude-number-based model can correlate fire whirls of different scales. Does the Fr-based model work for your experiment?

Reply: The authors agree that the fuel arrangement considered in the work of Soma and Saito [1] is similar to that used in our work. However, the major aim of the present study was on the method of using the burn-out time data to analyze the interactions among the multiple fires. In fact the fire whirls have been only examined by experimental observations in our present work. We plan to correlate the experimental results with the scale models proposed by Soma and Saito in our following work.

Reference