Experimental Observations and Analysis of Square Arrays of Equi-Distant Multiple Fires

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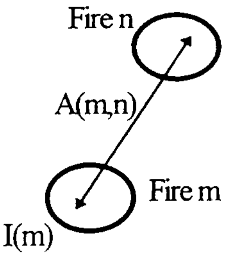
ABSTRACT

Experiments have been carried out to observe fire plume interactions of free-standing equi-distant identical fires in 3x3 and 5x5 square arrays in terms of plume dynamics and fire whirls at various inter-fuel pan distances, and also to measure and record the corresponding burn-out times of individual fires in the arrays from ignition relative to that of a single free-standing fire which is used as a reference. The difference in the burn-out times of any fire in a given array from the reference fire is an indication of how fire plume interaction affects the average burn rate of that fire. It is observed that flame interactions depend strongly on the fuel-pan spacings. An analysis of the empirical data on the burn-out times of individual fires, expressed in terms of an interaction index, shows different extents of interactions at various fire locations in the array and also at different distances between adjacent fuel pans. Similarities and differences in interactions between the 3x3 and 5x5 fire arrays have also been noted.

KEYWORDS: Multiple Fires, Fire Interaction, Fire Whirls, Burn-Out Times

NOMENCLATURE

A(m,n)	dimensionless interaction link between fires m and n
ABOT (m)	average burn-out time, [sec]
BOTR	burn-out time of reference single fire, [sec]
D	inter-fuel pan distance or fuel-pan spacing, [m]
I (m)	Interaction Index of fire m in a given array
m,n	location of fire in array



INTRODUCTION

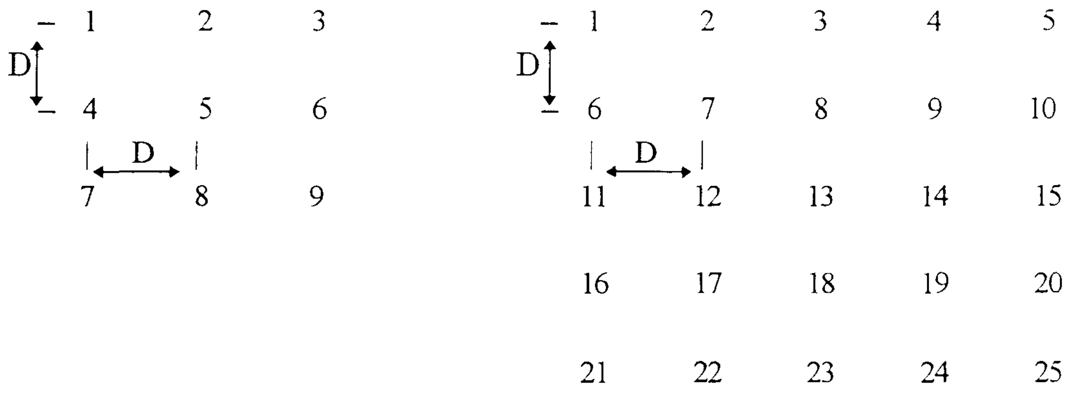
In the infamous 1923 Tokyo Earthquake in Japan, large multiple fires were found to be common occurrences and were often accompanied by destructive fire whirls. In one instance, for example, more than 35,000 lives were lost to the fire at about the same time in a large localized open area in the Tokyo Earthquake. Therefore, the study of the dynamics of such multiple fires is important to enable us to gain insight to the physical conditions under which such destructive phenomena could occur, so that counter measures can perhaps be developed to limit the extent of loss of lives and property damages.

Unfortunately, past studies in either multiple fires or fire whirls are quite limited. In the area of multiple fires, Putman and Speich [1] measured the increase in flame heights for different arrangement of a number of multiple fires based on effective point sources, and only jet flames, however, were considered. Thomas et al. [2] considered the merging of flames when two fires were placed side by side in the range of short flames and obtained a dimensionless correlation equation relating the merged flame height to the fire spacing. It was found that flame interactions of the neighboring fires were responsible for this relationship. Fire whirls, on the other hand, can be generated naturally by placing a free-standing fire in a square enclosure with symmetrical corner gaps, through which the entrainment flow comes into the enclosure tangential to the fire, thus triggering fire whirls [3]. It was shown that this triggering was essentially a hydrodynamic phenomena where the whirl was generated by imparting an angular momentum to the fire plume. This conclusion was more recently substantiated by field-model numerical simulations [4].

From these limited studies, it can be readily appreciated that the dynamics of multiple fires in terms of enhanced burning in a given urban locale would depend strongly on the mutual interactions among neighboring fires due to radiation interchange, combustion, and interacting entrainment flows, and the presence of fire whirls triggered by fire-induced entrainment flows through inter-building spaces and other obstacles, which evidently set up sufficient strong shear-flow fields conducive to the generation of whirls. The present study on multiple fires has been motivated by these likely scenarios in large urban fires and the need to study systematically how the fires interact and reinforce one another to generate such large destructive forces. Since the real phenomena are extremely complex, there is a need to simplify the problems that could be studied so that we can build up our knowledge and physical insight to such phenomena in stages until we can finally approach the real fires directly. A series of experiments in the present study have been carried out in the laboratory on the effects of an imposed shear-flow fields and fuel-pan spacings on the burning of arrays of square equi-distant fires to simulate an urban fire scenario. The results of the dynamics and interactions of two free-standing arrays of such fires without the imposed shear-flow fields, one 3x3 fire array and the other, a 5x5 fire array, will be presented in this paper, while the effects of the imposed shear-flow fields on the same fire arrays will be given in a subsequent paper. Emphasis will be placed on experimental observations of the group and individual fire dynamics and on an empirical analysis of the burn-out data of individual fires in the arrays to gain insight as to the relative extent of the interactions between pairs of the fires within the arrays.

EXPERIMENTAL OBSERVATIONS OF MULTIPLE-FIRE ARRAYS

As pointed out above, this paper presents, among others, experimental observations of the dynamics of free-standing 3x3 and 5x5 square fire arrays without any imposed shear-flow fields from ignition to the final burn-out of all the fires. For simplifying the test conditions, all fires originated from identical steel circular fuel pans, 7.5 cm in diameter and 5 cm in height, and 26 grams in weight. Each pan was filled with 82 grams of the same liquid fuel n-heptane to the full depth. All experiments on both arrays were carried out in a high-ceiling open laboratory building with ceiling exhaust vents, which is very large compared to the area of the largest array tested, and all doors to the building were closed during the tests. As a point of reference, a corresponding single free-standing fire of the same configuration with the same fuel burns very closely to 25 minutes from ignition to burn-out at a burning rate of about 3.4 grams/min, except at the very beginning with a burning rate of 3.0 grams/min and in the final minute at a rate of 2.0 grams/min. The essential parameter in the tests was the inter-fuel pan distance D, which is known to be a significant parameter in the phenomena of merging fires [1,2] and varied between 0.1 m to 1.5 m for both test arrays. Each test was video-taped is its entirety from ignition to complete burn-out with a continuous record of elapsing times, so that the burn-out time for each individual fire could be accurately determined. It is clear that this burn-out time is directly related to an average burning rate for that individual fire. Another advantage of the video-tape recording is that any specific passing event, however brief, was also recorded. A good example is the occurrence of fire whirls. It may also be mentioned that for a great majority of the tests, the fuel in a separate and remotely placed fuel pan was also ignited at the same time and continued to burn along with those in the array, so that it was possible to note any deviation of the burn-out time from the average of 1,500 sec (25 minutes) in a given test. The simple geometries of the two fire arrays are schematically shown in Figure 1, in which each fire in a given array is labeled by a numeral for purposes of identification in the discussions.



(a) 3x3 Fire Array (b) 5x5 Fire Array

Figure 1 Schematic Test Fire Arrays with Numerals Identifying Individual Fires

Before observations of the fire tests in both square fire arrays are described, it is instructive to note several anomalies that occurred in the tests. The most important is that theoretically each array in Figure 1 possesses several inherent symmetries in the fire behaviors, provided that nothing in the laboratory space or in the test procedure would disrupt such symmetries. For instance, all the corner fires 1, 3, 7 and 9 and 1, 5, 21 and 25 in the 3x3 and 5x5 arrays, respectively, should behave similarly. Other symmetrical cases include the groups of fires 2, 4, 6, 8 in the 3x3 array and fires 2, 4, 6, 10, 16, 20, 22, 24, fires 3,11,15, 23, fires 7, 9, 17, 19, and fires 8, 12, 14, 18 in the 5x5 array. Also, the orientation and location of either test array on the floor of the laboratory should not be relevant. Unfortunately, such symmetries were not exactly observed as well as could be hoped for in all the tests, for a variety of reasons. For one, fire plumes are inherently very unstable, and are sensitive to local disturbances. Secondly, despite all careful precautions, the very size of the laboratory space and infiltration from outside easily induced stray air currents that affected the individual fires differently. Thirdly, the laboratory space did have several large furnitures that were in the farther-away vicinity from the test array and uneven disturbances were also likely to occur from moving research personnel in that same vicinity. Finally, it should be noted that all the fuel pans in a given test could only be ignited sequentially, thus providing uneven ignition times for different fires in the array. This last factor, however, was not considered significant, since all fires in the array were ignited within just seconds, which were very short compared to the variability of the burn-out times at supposedly symmetrical fires. The maximum variability in the burn-out times usually occurred at the corner fires and was found to be about 15% of the averaged value. This is somewhat expected as the corner fires are most affected by disturbances in the laboratory.

Similar to the burning of a single free-standing fire, any fire in a given array behaves similarly in that it achieves a steady burning soon after ignition and in the last seconds before burning out, its flame oscillation frequency reduces and then quickly extinguishes itself out. However, it is noted that the flame heights of the fires in the array in the steady burning period are always larger than that of the reference single fire, evidently due to the flame interaction noted previously. The flame dynamics is also quite different, and the extent of this difference depends strongly on the fuel-pan spacing D. For small D's lower than 0.4 m, the fires in either array only retain their individual presence at very close to the pan level, and the flames in the entire array start to merge just above the pan and burn vigorously as a single fire. Consequently, the entire fire from the array appears very much like an area fire. A further evidence is that the flames on the array boundaries show a strong leaning toward the combined flame, undoubtedly because of the strong entrainment flow coming in

Figure 2 Merged Flames for the 3x3 Array at D=0.2 m

Figure 3 Merged Flames for the 5x5 Array at at D=0.2 m

from outside the array, similar to what is expected in an area fire. This result is compatible with the merging-fire correlation discussed by Thomas et al. [2]. The above behaviors are clearly shown in Figures 2 and 3 for the two arrays with D=0.2. As D increases to 0.4 and beyond, the flames start to behave more and more like individual fires with their own separate flames, along with reduced leaning toward the array center from the boundary fires, even though they still maintain their dynamic vigor as compared to the reference fire, indicating somewhat reduced flame interactions. These are shown in Figures 4 and 5 for the two arrays at D=0.6 m. The flame interaction often causes s a swirling flame, particularly in the 5 x 5 array., as shown in Figure 6-(A) and the burn-out time of the pan decreases as shown in Figure 6-(B).

Figure 4 Flames for the 3x3 Array at D=0.6 m

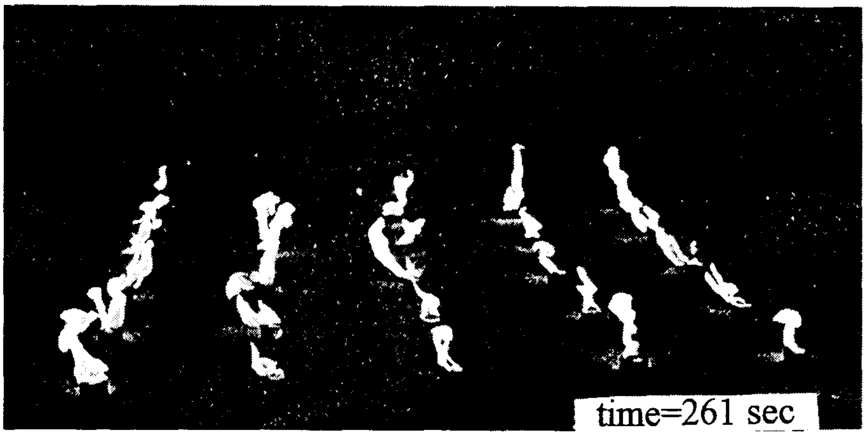


Figure 5 Flames for the 5x5 Array at D=0.6 m

From what could be observed at D=1.5 m in both cases, all flames appear to be very close to that of the reference flame, even though some residual interactions can still be discerned from the burn-out data even at this value of the pan separation, as will be shown later in the analysis of the data.

It also seems that the flame interactions due to the interacting radiation exchange, combustion, and entrainment flows under dynamic conditions are very complex and are seen to generate rather small scale air

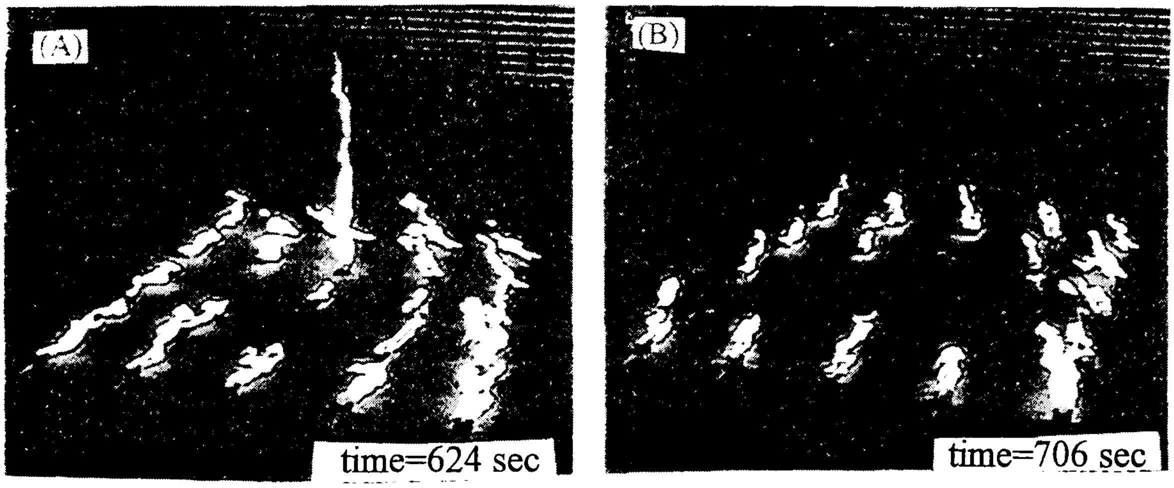


Figure 6 Swirling and Burning-out Flames for the 5 x 5 Array at D=0.5 m.

circulations within the confines of the array, indicated by the frequent leaning of adjacent flames in quite different directions, especially for flames away from the boundaries in the 5x5 array. The presence of such internal air circulations is intriguing in the following sense. If indeed we do have symmetries of the fires in either of the two arrays as mentioned before, it would be difficult to generate shear-flow fields, which are responsible for the triggering of fire whirls. However, any deviation from such symmetry conditions could conceivably induce a shear-flow field that may lead to fire whirls. If, furthermore, the deviations are small, then the resulting fire whirls would also be expected to be few and short lasting. Interestingly enough, this is exactly what was observed in the tests for both arrays. Fire whirls were observed in the 3x3 array tests only once for D=0.3 m at fire 5 before fires merged, twice for D=0.4 m also at fire 5, once for D=0.5 m also at fire 5, 7 times for D=0.6 m at fires 5 and 6, 4 times for D=0.7 m at fire 6, and no more appearance of fire whirl for D>0.7 m. All observed whirls were somewhat weak and did not last long at all. For the 5x5 array tests, whirls were observed at fire 13 for D=0.4 m several times, at fires 13 and 14 for D=0.5 m, several times at fires 7 and 8 for D=0.6 m, once each at fire 8 and fire 14 for D=0.7 m, and no more whirls for D>0.7m. These observed whirls were also weak and short lasting. It is very conceivable that the small scale air circulations within the arrays are responsible for these whirl occurrences, and that the weak whirls are due to small deviations from the symmetry conditions. The small unsteady internal air circulations are likely also responsible for the short duration of the whirls. It is therefore clear that the maintenance of strong whirls must depend on the presence of much stronger shear-flow fields than those available in the free-standing fire arrays studied here.

Another important result of the present study is the recorded data on the burn-out times of individual fires in the test arrays. As mentioned previously, these data are directly related to the average burning rates of n-heptane at the fire locations. Typical such data in seconds for the fire locations given in Figure 1 are shown in Table 1 for both arrays, as compared to the reference value of 1,500 seconds for the single standing fire. The lack of good symmetry at the fire locations where symmetry should prevail may be noted and was discussed before. The shortest burn-out times are located at the central fires, as expected, since they interact with most neighboring fires at short distances. On the other hand, the higher burn-out time occurs at the

Table 1 Typical Burn-Out Data in Seconds from Ignition (Reference 1500 Seconds)

3x3 Array at D=0.4 m

1113	940	1019
916	820	877
1112	982	1021

5x5 Array at D=0.6 m

1106	980	946	1000	1127
990	831	871	655	1047
832	755	584	551	841
858	744	695	767	788
1191	895	908	936	1007

array boundaries. Since the corner fires interact with the least neighboring fires at close proximities, they command the highest burn-out times among all the boundary fires. It is thus seen that the extinction of fires migrate from the center of the array toward the boundaries, and this scenario is also compatible with what has been observed in large urban fires. For either array, as the pan spacing D increases from a small value, say 0.1 m, the burn-out times, according to the present data, increases monotonically at any given fire location due to reduced interactions. It is thus expected that as D approaches infinity, all the burn-out times will approach 1,500 seconds as a limit, where the interactions are reduced to zero. The following section presents an empirical analysis of the burn-out time data to determine the relative extent of interactions at different pairs of neighboring fires at various fuel-pan spacings.

EMPIRICAL ANALYSIS OF BURN-OUT TIME DATA

According to data typically shown in Table 1, it is instructive to note that the values of burn-out times in all cases are consistently lower than that for a single free-standing fire, indicating that each individual fire in the array has a higher average burning rate due to effects from the neighboring fires, or the interaction effects. At the same time, the degree of such increased burning rate at each fire is seen to depend on the specific location of that fire in the array. For instance, the average burning rate of a fire increases as the fire location moves toward the array center. Physically it is not difficult to surmise that, in view of the consideration of the interaction effects of radiation, which always improves the burning rate, and convection due to entrainment flows, which may not necessarily increase the burning rate depending on the upstream temperature conditions of the entrainment, the average burning rate or the burn-out time at each fire depends on interactions from each neighboring fire. At the same time, radiation interaction is expected to become more important as we consider the inner fires as compared to those around the array boundaries. Based on these interaction effects, it is possible to carry out an empirical analysis on the data obtained in the present study. The idea here is to attempt to determine the relative levels of such interaction for every pair of interacting fires. This exercise is considered to be worthwhile as it is closely related to the physical phenomena found in multiple fires in large urban-fire scenarios.

Because of the general complexity of the fire phenomena in the array due to the unsteadiness in both the individual fires and the fires affected by others in the array, simplifying assumptions are needed so that more of the global features of the interacting fires can be discerned. First of all, on a time averaged basis, we would like to invoke all symmetries noted previously. In the analysis, the burn-out time of each fire in a symmetry group is taken to be the same, and will assume the average of the burn-out times of all the fires in the group. In addition, a dimensionless Interaction Index I(m) is introduced as follows:

$$I(m) = 1 - [ABOT(m) / BOTR] \qquad (1)$$

where m signifies a given fire in the array, ABOT(m) is the average burn-out time of fire m in the symmetry group in seconds, and BOTR is the reference burn-out time of the reference fire, which is taken to be 1500 seconds from our tests. The significance of this definition is that this index is a true measure of the interaction effects received by fire m and has a value between 0 and 1. Zero value signifies no interaction, and represents the limit for large values of D, in which case each fire in the array behaves like a single free-standing fire without the effect of neighboring fires. A value of unity indicates maximum, where the fire is instantaneously burned out after ignition. Now since the analysis of the 5x5 fire array is somewhat more complex than that for the 3x3 array, the analysis for the 3x3 array will be presented first.

After averaging the burn-out times for fires in a given symmetry group, the Interaction Index I(m) can be readily calculated according to Equation (1). With reference to Figure 1(a) for the 3x3 array, there are only three independent symmetry groups which can be represented by the indices I(1), (2) and I(5). It is obvious that the central fire 5 is the only member of that group. Values of these Interaction Indices for different fuel-pan spacings D, calculated directly from the experimental burn-out time data, are given in Table 2. It is seen that the indices are quite consistent, and each index decreases essentially monotonically to zero as D increases toward infinity. The essential step in this empirical analysis is to introduce a notion that each index I(m) for m=1, 2 and 5 can be broken down into parts which represent the contributions of the neighboring fires toward that index. Here we define a dimensionless interaction link A(m,n) for the interaction between the fire m and the fire n, and since the interaction is always mutual, we expect that A(m,n)=A(n,m). The physical meaning of this interaction link is that it is a measure of that part of the interaction which is contributed by a specific pair of fires, normalized by the Interaction Index I(n).

Table 2 Interaction Index and Interaction Link Results for the 3x3 Fire Array

D (m)	I(1)	I(2)	I(5)	A(1,2)	A(1,5)	A(1,6)	A(2,4)	A(2,5)
0.1	0.750	0.806	0.827	0.187	0.208	0.084	0.132	0.264
0.2	0.636	0.740	0.789	0.204	0.162	0.091	0.116	0.266
0.3	0.400	0.507	0.622	0.104	0.098	0.047	0.074	0.205
0.4	0.289	0.381	0.455	0.096	0.066	0.043	0.055	0.158
0.5	0.256	0.300	0.325	0.066	0.065	0.030	0.047	0.109
0.6	0.204	0.244	0.279	0.053	0.052	0.024	0.037	0.092
0.7	0.158	0.182	0.199	0.040	0.041	0.018	0.029	0.065
1.0	0.120	0.119	0.140	0.028	0.038	0.013	0.020	0.037
1.5	0.045	0.049	0.101	0.010	0.017	0.004	0.007	0.021
oo	0	0	0	0	0	0	0	0

As a result, we may write, with reference to Figure 1-(a),

$$A(5,1) + 2A(6,1) + 2A(2,1) = I(1) \tag{2}$$

$$2A(1,2) + 2A(4,2) + A(5,2) + 2A(7,2) = I(2) \tag{3}$$

$$4A(1,5) + 4A(2,5) = I(5) \tag{4}$$

where 2A(6,1) in Equation (2) is really the sum of A(6,1) and A(8,1), but A(6,1) = A(8,1) because of symmetry. Similarly, it is noted that A(2,1) =A(4,1). Also, we have taken A(3,1) =A(9,1) =A(7,1) =A(8,2) =A(7,3) =0, since for example fire 1 cannot see fire 3 due to radiation blockage by fire 2. This is of course only an approximation to the real phenomena. Because of symmetry, the above equations can now be written respectively as

$$A(1,5) + 2A(1,6) + 2A(1,2) = I(1) \tag{5}$$

$$2A(1,2) + A(2,5) + 2A(1,6) = I(2) \tag{6}$$

$$4A(1,5) + 4A(2,5) = I(5) \tag{7}$$

which can also be written as

$$A(1,5) - A(2,4) = [I(1) - I(2)]/2 + I(5)/8 \tag{8}$$

$$A(1,2) + A(1,6) + A(2,4)/2 = [I(1) + I(2)]/4 - I(5)/16 \tag{9}$$

$$A(2,5) - A(2,4) = [I(2) - I(1)]/2 + I(5)/8 \tag{10}$$

Here we have five unknowns A(1,2), A(1,5), A(1,6), A(2,4), and A(2,5). In order to make estimates for all these link quantities, we choose to introduce the following two relations based on the intuitive idea that the strength of the link is inversely proportional to the distance between the linked fires:

$$A(1,2) / A(1,6) = 1/\sqrt{5} = 0.236 \tag{11}$$

$$[A(1,2) + A(1,6)] / A(2,4) = [1 + 1/\sqrt{5}] / [1/\sqrt{2}] = 2.0467 \tag{12}$$

The five unknown interaction links can then be determined as shown in Table 2, along with the interaction indices, as functions of D. As expected, these interaction links decrease essentially monotonically toward zero as D increases, as the interactions become increasingly weaker. Also, from these results, it is of particular interest to note that the strongest interaction is between fires 2 and 5. This is not surprising, since fire 5 is the strongest among all the fires in the array, as it receives the most interactions. Furthermore, in the order of decreasing link strengths, links between fires 1,2 and 1,5 are somewhat comparable, and these are then followed by A(2,4) with the link A(1,6) the lowest. This is somewhat expected, since the distance between fires 1 and 6 are the largest among all the fire pairs. It is also seen that the interactions are particularly strong at small D values which correspond to those of merged fires. They decrease, as already pointed out, as D increases, and at just D=1.5 m, the fires already behave almost like free-standing fires with extremely small interactions among the fires in the array.

A similar analysis has been carried out for the 5x5 array with the experimental data on the burn-out times, and the averaged I(m) of the various symmetry groups at different inter-fuel pan distances D are shown in Table 3. Because of the increased complexity and the large number of interaction links, additional simplifying assumptions need to be introduced. First of all, any interaction link between pair of fires that has a distance between the two fires larger than D times $\sqrt{5}$ will be neglected, since they are expected to be small. Secondly, all internal links away from any boundary with distances of D and D times $\sqrt{2}$ will be treated the same, respectively. For instance, A(7,8)=A(8,13) and A(7,13)=A(8,12), and so on. Thirdly, we will again take advantage of all the symmetries in the array. As a result, we may write, similar to those for the 3x3 array case already presented,

$$2A(1,2) + A(1,7) + 2A(1,8) = I(1) \tag{13}$$

$$2A(1,2) + A(1,7) + 3A(1,8) + A(2,6) + A(2,7) = I(2) \tag{14}$$

$$2A(1,2) + 2A(1,7) + 4A(1,8) + A(2,7) = I(3) \tag{15}$$

$$3A(1,7) + 4A(1,8) + 2A(2,7) + 2A(7,8) + A(7,13) = I(7) \tag{16}$$

$$2A(1,7) + 6A(1,8) + 2A(2,7) + 3A(7,8) + 2A(7,13) = I(8) \tag{17}$$

$$8A(1,8) + 4A(7,8) + 4A(7,13) = I(13) \tag{18}$$

Since we only have six equations for the seven unknowns, we will need an additional condition to enable us to solve the above algebraic equations. One reasonable ad hoc condition is to let A(1,7) =A(7,13), signifying that the boundary effects are of less importance in the determination of the link quantities. This condition leads to the following

$$A(1,8) = 0.5\,[\,-I(1) + I(3) - 0.5\,I(7) + 0.25\,I(13)\,] \tag{19}$$

Based on this additional condition, all the seven link quantities can be determined and the results are also shown in Table 3. It is interesting to note that this condition is almost equivalent to letting A(1,8) be zero, which is physically reasonable, as this link quantity involves the largest distance among all the fire pairs included in the analysis.

It is seen here that similar to the 3x3 array results, all I(m) and A(m,n) quantities, except those with very small and insignificant values, decrease monotonically as D increases, indicating that the interactions between any pair of fires become weaker as the inter-fuel pan distance increases, as expected. In general the values of I(m) for the 5x5 array are larger than those for the smaller array, since here we have many more

Table 3 Interaction Index and Interaction Link Results for the 5x5 Fire Array

D (m)	I(1)	I(2)	I(3)	I(7)	I(8)	I(13)
0.2	0.613	0.735	0.829	0.879	0.886	0.894
0.3	0.495	0.615	0.705	0.781	0.800	0.823
0.4	0.437	0.525	0.610	0.680	0.717	0.749
0.5	0.352	0.413	0.480	0.545	0.583	0.579
0.6	0.261	0.375	0.430	0.485	0.521	0.530
0.8	0.200	0.275	0.315	0.340	0.357	0.365
1.0	0.200	0.258	0.268	0.291	0.300	0.315
oo	0	0	0	0	0	0

D (m)	A(1,2)	A(1,7)	A(1,8)	A(2,6)	A(2,7)	A(7,8)	A(7,13)
0.2	0.198	0.217	0	0.123	0	0.007	0.217
0.3	0.142	0.187	0.013	0.097	0	0	0.187
0.4	0.133	0.150	0.010	0.065	0.003	0.017	0.150
0.5	0.123	0.107	0	0.040	0.021	0.038	0.107
0.6	0.079	0.097	0.003	0.036	0.067	0	0.097
0.8	0.065	0.074	0	0.032	0.045	0	0.074
1.0	0.064	0.070	0.001	0.010	0	0.008	0.070

fires that can interact with each other. For the same reason, the link quantities are somewhat smaller, since they deal with the contributions of only two individual fires. Another contributing factor is that the many more fires in the array tend to act as barriers for the interaction phenomena. In the 3x3 array, the interaction index is the highest at the center, and this is the same as that in the larger array. However, the fire 8 in the 5x5 array is perhaps equally important, since it interacts with the boundary fires more, where we expect better entrainment to promote the combustion process. The interaction links are the strongest at small D values, with the strongest occurring between fires 1 and 7, and also between fires 7 and 13, which are then followed by fires 1 and 2. However, the link A(1,2) tends to become more prominent in the middle range of D values, which is the essential behavior for the 3x3 array. Consequently, it seems that as the array becomes larger (more fires), the cross interaction links become more important. The reason could be that the interference due to more fires in the array tend to favor the cross fires because of the freer entrainment flows.

CONCLUDING REMARKS

In the present study, tests have been carried out to experimentally observe the group fire dynamics of 3x3 and 5x5 square equi-distant fire arrays at various fuel-pan spacings, and an empirical analysis has been made to identify and estimate the relative interactions among fire pairs in the array. The following conclusions can be drawn:

1. In either array, the interactions among fires for pan spacing less than 0.4 m are sufficiently strong to

merge the individual flames into a single area fire with a single plume and very strong entrainment in-flows at the boundaries have been observed. As the pan spacing increases, interactions reduce accordingly, and the flames begin to behave like individual free-standing fires. In either array, interactions seem to be almost insignificant when the fuel-pan spacing is only at D=1.5 m, and will tend to zero asymptotically as D increases without limit. Such behaviors are compatible with the idea that interactions are caused by interplay of radiation exchange, entrainment flows, and combustion.

2. In either array, only weak fire whirls lasting only momentarily between D= 0.4 m and 0.7 m have been observed. It is likely that such weak whirls are caused by weak shear-flow fields generated by dynamic flame movements of the fires in the array, and would not be expected to have material effects on flame interactions.
3. In great majority of cases, the central fire burns out first and is then followed by outer fires. The corner fires usually burn out last. This scenario is compatible with what is generally known for isolated areas in large urban fires. Theoretically, some fires, because of symmetry, should behave similarly . This, however, has not been found to be the case because of unavoidable non-symmetrical disturbances in the laboratory. Fortunately, the deviations have not been found to be excessive to nullify all the test results.
4. Empirical analyses based on dimensionless Interaction Indices and interaction links have been carried out to estimate the relative interaction levels among fire pairs in the array. It has been found that for the 3x3 array the strongest interaction occurs between the corner fire and the fire just next to it along the boundary, followed by the interaction between the central fire on the boundary and the fire next to it on the interior side. Interestingly, the interaction between the corner fire and the adjacent fire along a diagonal becomes more significant in the 5x5 array. This difference is attributed to the larger flow resistance in the 5x5 array case.

Further insight to the dynamic behavior of fires in the square equi-distant array is not possible until detailed measurements on the radiation exchange and entrainment flows are made. Simulations using field models similar to those on enclosed fire whirls carried out by the present authors [4] will also be useful to the advancement of our understanding of the phenomena as related to large urban fires.

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