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Can We Predict the Occurrence of Extreme Fire Whirls?

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Introduction

RESULTS of new scale-model experiments are reported for the fire whirls that killed 38,000 people huddled in a large open area adjacent to asymmetric mass fires. A new theoretical scaling model is presented that successfully predicts the wind velocities that are observed to be optimum for the production of intense fire whirls. The importance of the role of the burning rate in determining the fire-whirl circulation by affecting the balance between the buoyant and wind velocities is emphasized in this new understanding.

Around noon on 1 September 1923, a magnitude 7.9 earthquake (known as the great Kanto earthquake, named for the region that includes Tokyo) hit the downtown Tokyo area. Many large fires were quickly ignited in collapsed houses by small lunchtime kitchen fires. These fires quickly spread and created several large mass fires [1]. To escape from the fire threat, evacuees gathered in the Hifukusho-ato area, where an old military-clothing factory had been demolished a few years earlier, leaving an open area of $70,000\ \mathrm{m}^2$ without any structures or trees (see Fig. 1a). Because many evacuees thought that this open space was large enough to be safe from the fire threat, Hifukusho-ato was packed with 40,000 people.

An unexpected disaster, however, struck under fine weather conditions with a south wind of speed $4–5\ \mathrm{m/s}$. Fire whirls suddenly appeared in the crowded Hifukusho-ato space, carrying flame and burning debris as they swept through the area (see Fig. 1b). These fire whirls moved around the Hifukusho-ato area, causing an estimated 38,000 deaths within a period of 15 min [1,2].

Since that time, many studies have been conducted to improve understanding of the interaction between fire and vortices [2–10]. The generation mechanism of fire whirls in open space (such as the Hifukusho-ato fire whirls, HAFW), however, is poorly understood. To our knowledge, only Soma and Saito [2] thoroughly studied HAFW mechanisms. They conducted a $1/100$th scale-model experiment in an open field and a $1/2500$th scale-model experiment in a small wind tunnel. The prototype mass fires caused by the earthquake were simulated by an L-shaped assembly of methanol pool fires. It was found that there was a narrow range of lateral wind velocity that led to the generation of flow circulation (without fire) at a location geometrically similar to that of the prototype HAFW. The range was observed to be different for different scales, and Soma and Saito [2] attempted a scaling analysis based on a Froude number [5,11] to correlate the critical lateral wind velocities between the prototype HAFW and their scale-model experiments. Their analysis, employing the lateral inertial force to obtain a constant Froude number,

$$Fr' = U^2/gL = \mathrm{const} \tag{1}$$

(where U is the wind velocity, L the horizontal dimension, and g the acceleration of gravity) somewhat underestimated the critical lateral wind velocities of the scale models because it did not consider the difference in burning rate between the prototype and the scale models.

The present study has two objectives: 1) to understand the generation mechanism of fire whirls in open space, especially why fire whirls are generated only at certain lateral wind velocities, and 2) to improve the accuracy of scaling laws. To achieve these goals, $1/1000$th scale-model experiments were conducted using heptane pool fires in the large-scale wind tunnel of Japan's Building Research Institute (BRI) [12]. Heptane was chosen because its burning rate is different from that of the prototype HAFW and from that of the scale-model experiments of Soma and Saito [2]; the results for various length scales and burning rates can then be used to test the predictions of the analysis.

Laboratory Reconstruction of Fire Whirls

Figure 2 shows the L-shaped burning area of the experiment conducted at BRI. The scale model consists of a total of 14

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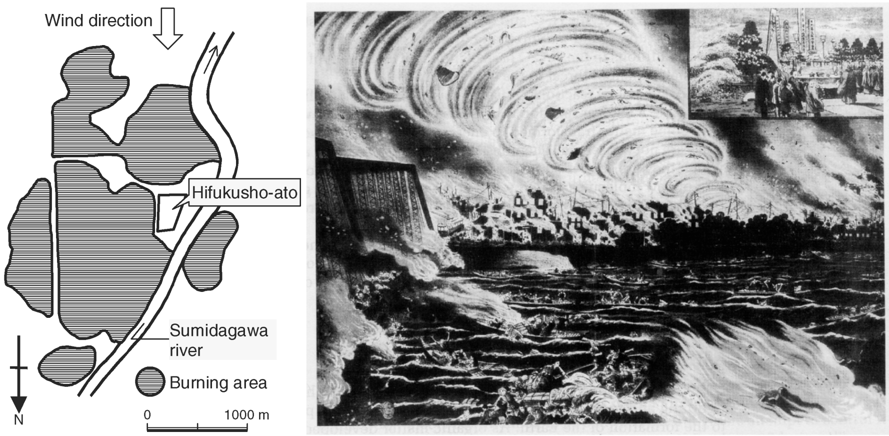


a) b)

Fig. 1 Hifukusho-ato fire whirls: a) geometrical map of Hifukusho-ato from [2], and b) Japanese painting of Hifukusho-ato fire whirls from [18].

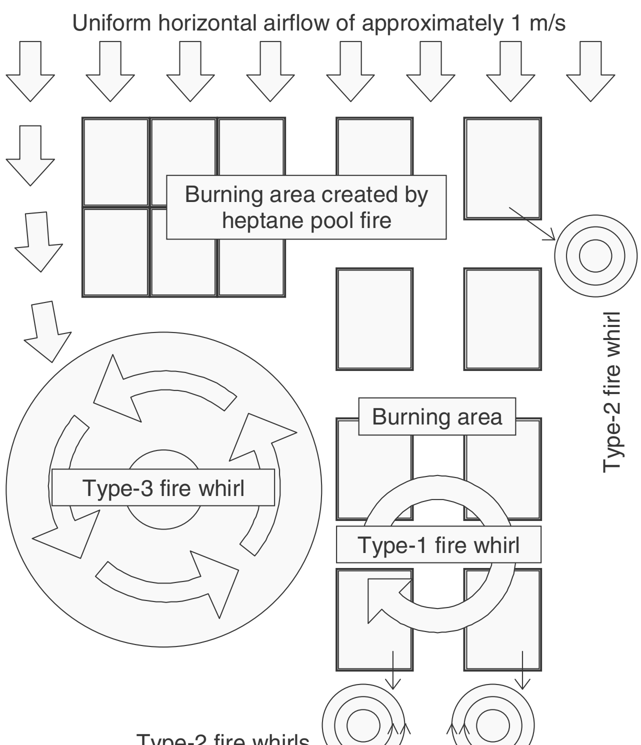


Fig. 2 Schematic of the 1/1000th scale-model experiment conducted at BRI and of the five different fire whirls that were observed.

rectangular-shaped open-top pans which are surrounded by a layer of bricks to make the burning liquid surfaces of the pans at the same level as the solid surface surrounding them. The lateral wind velocity in the wind tunnel was varied from 0.5 to 2 m/s to study its effect on fire-whirl generation. A total of seven different movie cameras, including two stationary charge-coupled device (CCD) cameras, were used to record the motion of fire whirls from both the top and the side. Smoke generators were used to visualize the flowfield near the pool fires.

Figure 2 also shows schematically five different fire whirls that were identified from the movie film recorded and from direct observation during the experiments. These fire whirls can be categorized into three different types: 1) the fire whirl spinning over the downstream-side burning area creating a tall fire column, 2) the fire whirl periodically spinning off from the burning area and traveling to the downstream unburned area, and 3) the relatively stable spinning of air initially without fire in the unburned area but then attracting fires into its spinning motion from the burning area. The type-3 fire whirl is generated at a location geometrically similar to that of the HAFW disaster, and its observed behavior matches the description that was given of the HAFW and the results of the scale-model experiments of Soma and Saito [2]. Figure 3 shows color images of the type-3 fire whirl, where the spinning air (visualized by smoke from a smoke generator) initially is attracting the flame from the left side of the burning area in Fig. 3a. Two top-view images are shown in Figs. 3b and 3c, taken approximately 1 s apart, documenting the initiation stage (Fig. 3b) and the fully developed stage (Fig. 3c) of the fire whirl.

Strong fire whirls were observed when the lateral wind velocity U was about 1 m/s in this experiment. Whirls were very weak for $U = 0.5$ m/s, whereas for $U = 2$ m/s the pool fires were tilted downstream, not fully engulfing the open area, and few fire whirls were observed. There thus seems to be a critical lateral wind velocity U_c that generates the strongest fire whirls, in agreement with observations made by Soma and Saito [2]. Each case has a different U_c, as summarized in Table 1. The difference can be understood as follows.

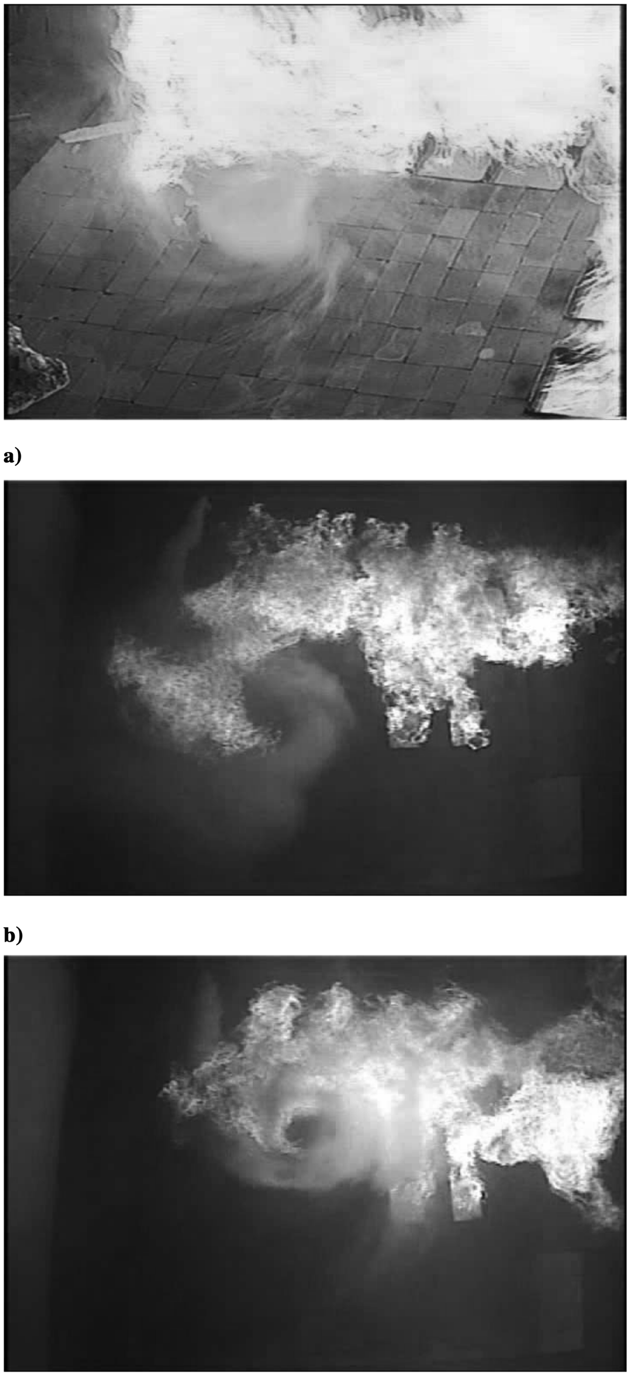
Prediction of the Occurrence of Fire Whirls

The fire whirls are generated by the interaction between the buoyant upward flow and the lateral wind. This interaction between vertical and horizontal flows is similar to that between a jet and a crossflow [15,16]. The flow structure of the near wake of a circular jet exhibits strong similarity to that of a cylinder, although their detailed structures are different [16]. Similarly, the burning area may be regarded as an obstruction to estimate its near-wake flow structure [11]. Figure 4 shows a schematic diagram of the flow around an L-shaped obstruction. The vortices on the leeward side of the obstruction in Fig. 4 well represent the flow patterns observed in the type-2 and type-3 fire whirls of our experiments (Fig. 2), supporting the use of the obstruction model to predict the locations of fire-whirl generation in open spaces. The circulation (Γ) of the whirls may be estimated from this model as [11]

$$\Gamma \sim UL \tag{2}$$

where L is the horizontal length scale of the obstruction, and so Γ increases linearly with U.

With a further increase in U, however, the fire plume will be deflected in the downstream direction, causing the obstruction model and Eq. (2) to become invalid. There is a critical velocity ratio U/U_b (where U_b denotes the upward buoyant velocity at the flame tips), above which vortices are not formed on the leeward side of the fire plume. Wu et al. [15] studied asymmetric jets in a crossflow and found that wake vortices were formed only when $U/U_j < 1/3$ (where U_j is the jet exit velocity); they obtained this result only for asymmetric jets but did not find any wake vortices for symmetric jets



a)

b)

c)

Fig. 3 Color images of type-3 fire whirl generated on the leeward side of the pool fires: a) side view; b) top view, initiation stage; and c) top view, fully developed stage.

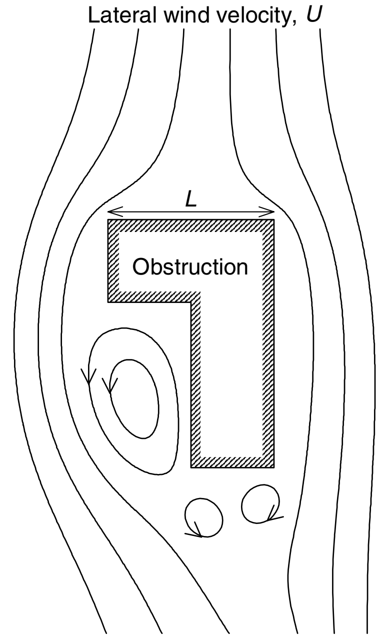


Fig. 4 Schematic of flow around an L-shaped obstruction.

in a crossflow over the range $1/9 < U/U_j < 1$ tested. This supports the idea that the asymmetry of the L-shaped mass fire favors the formation of type-3 fire whirls. From these experimental results, we can roughly estimate the critical lateral wind velocity (at which the strongest fire whirls are generated) as

$$U_c \approx U_b/3 \tag{3}$$

Given Eq. (3), estimation of U_b is needed to complete the analysis.

The buoyant velocity depends on height H of the fire plume as [17]

$$U_b \sim gt \sim (Hg)^{1/2} \tag{4}$$

It is well established experimentally, with some theoretical understanding, that in terms of the burning rate m (the mass of fuel consumed per unit ground area per unit time)

$$H/L \sim Fr^n, \qquad Fr \equiv m^2/(\rho^2 gL) \tag{5}$$

where $1/5 < n < 1/3$ and ρ represents the air density in the definition of the Froude number Fr based on the upward inertial force [11]. Combining Eqs. (3–5) results in

$$U_c \sim L^{3/8} m^{1/4} \tag{6}$$

where we have set $n = 1/4$, an intermediate value, in Eq. (5). Table 1 shows that the U_c predicted by Eq. (6) agrees better with the fire-whirl experiments than the U_c from Eq. (1), emphasizing the importance of accounting for differences in the burning rates.

Table 1 Critical lateral wind velocities for four different scale-model experiments

Type of fire whirl	L_i/L_1	m_i/m_1[a]	Measured U_c, m/s	Predicted U_c, m/s: Fr'-based model	Predicted U_c, m/s: Present model
1. Prototype HAFW	1	1	4	——	——
2. Soma & Saito [2]	1/100	2	1.3	0.4	0.9
3. Soma & Saito [2]	1/2500	10	0.3	0.08	0.4
4. Present work	1/1000	100	1.0	0.1	1.0

[a]Estimated from [2,13,14].

Conclusion

The explanation of the 1923 great Kanto earthquake fire whirls, reported here, offers a new theoretical scaling model to predict the occurrence of intense fire whirls and is validated against scale-model experiments.

Acknowledgment

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