Effect of Wind on Fire Whirl Over a Line Fire

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Abstract. Fire whirls are often reported to occur in wildland and urban fires due to the effect of ambient wind. This paper presents an experimental study on the fire whirls over a line fire with cross wind, focusing on the occurrence frequency of fire whirls. The experimental observations indicated that the fire whirls induced by a line fire may spread beyond the line fire region with the effect of wind. For the effect of cross wind, it is indicated that the cross wind basically increases the occurrence frequency, while the velocity components parallel or perpendicular to the line fire have competitive effects. A scaling law is presented for the critical wind speed inducing fire whirls based on the experimental data in this work and literature. A method is proposed to estimate the magnitude of the fire whirl height under the critical wind speed.

Keywords: Fire whirl, Wind speed, Line fire, Occurrence frequency, Scaling analysis

1. Introduction

Fire whirls are frequently observed in urban and wildland fires, and wind has been considered to be an essential condition for fire whirls. As examined by small-scale experiments [1, 2], medium-scale experiments [3, 4], large outdoor experiments [5] and upslope fire spread experiments [6, 7], the interaction between air flow and fire plume produces the concentrated vortex necessary for the formation of fire whirl. The leeward slope due to the mountain-blocking effect on wind provides eddy source for fire whirl formation [8]. The L-shaped fire with the imposed cross wind is easy to generate fire whirls that move in a tortuous path [1, 9]. Fire whirls can also be easily induced by the interaction of multiple fires with the imposed shear flow [10], or by the interaction between cross wind and line fire [11–13]. In particular, the wind speed necessary for fire whirl formation was correlated with the dimensionless heat release rate [9, 12]. However, all the above cited

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works only qualitatively examined whether or not a fire whirl may form under different wind conditions, and the effect of wind on the occurrence frequency of fire whirls has not been studied.

This work attempted to investigate the occurrence frequency of fire whirls over a line fire by experiments under a considerable range of cross wind speeds. The occurrence frequency of fire whirls for different levels of flame height and different wind speeds was examined by statistical method. A scaling law regarding the critical wind speed inducing fire whirls was developed. A method was also proposed to estimate the flame height of fire whirl under the critical wind speed.

2. Experimental

2.1. Experimental Setup

The experiments of line fire under the effect of wind were conducted by a facility which consisted of a mechanical wind wall and a line burner located inside a sand bed (Figure 1). The wind wall provided a uniform wind speed at the outlet section (100 cm in width and 200 cm in height). The wind speed U was calibrated to fit the formula $U = 0.102n - 0.53$, where n is the fan output frequency. For using this formula, the output frequency should be over 5.2 Hz, otherwise the wind speed is regarded to be zero. The wind wall has no sidewalls, which is different from that of Kuwana et al. [11, 12]. For the detailed description of the wind wall used in this work, refer to Ref. [13]. The center of the line burner was 500 cm away from the outlet of the wind wall. Two video cameras were used to monitor the experimental process.

Two different-sized burners, 300 cm × 5 cm × 5 cm and 200 cm × 5 cm × 5 cm, were used in experiments. Attack angles of 25° and 30° were used respectively for the 300 cm and 200 cm long burners. The fan output frequencies of 0–20 Hz were adopted to produce wind speeds within 0–1.51 m/s. Heptane was used as the fuel. In comparison with our previous work [13], the burner rim was flush with the ground surface during all tests. All the experimental conditions are pre-

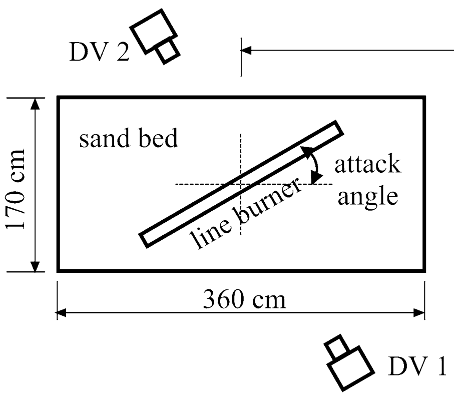

Figure 1. Schematic for experimental setup.

Table 1
Test Conditions

Fan frequency (Hz)	Wind speed (m/s)	Water + heptane (mL) for 3 m-long-burner	Water + heptane (mL) for 2 m-long-burner
0	0	3000 + 2000	2700 + 2000
7.5	0.24	3000 + 2000	2700 + 2000
10	0.49[a]	3000 + 2000	2700 + 2000
12.5	0.75	3000 + 2000	2700 + 1800
15	1.00	3000 + 2000	2700 + 2000
17.5	1.26	–	2700 + 2000
20	1.51	3000 + 2000	2700 + 2000

[a] All the tests were conducted for once, except that the tests under 0.49 m/s were repeated for three times to testify the repeatability of the experiments

sented in Table 1. Note for both burners experiments under the wind speed of 0.49 m/s were repeated for three times to check the repeatability of the tests.

2.2. Experimental Observation

All fire whirls rotated clockwise during tests. Figure 2 shows the video images of two typical fire whirls. The fire whirl in Figure 2a moved downwind along the burner, and when it reached the end of the burner, the whirling flame fled from the burner (Figure 2b). This suggests that the fire whirl induced by a line fire could spread beyond the line fire region with the effect of wind. This seems to be consistent with the tragic disaster after Great Kanto earthquake in 1923, in which large-scale fire whirls also fled from an L-shaped warehouse fire mainly responsible for approximately 38,000 deaths [1, 9]. The flame diameter of fire whirl was nearly equal to the width of line burner, similarly as the observed results in small-scale experiments [12].

2.3. Data Pretreatment

Our previous work [13] mainly focused on the initial conditions of the fire whirl formation. In comparison, this study addressed the occurrence frequency of fire whirls, mainly by using statistical method. Test images were obtained from the video record by a signal sampling frequency of 10 Hz. Then the flame images with apparent whirling motion and those with flame heights over 1 m and over 1.5 m were respectively extracted. The burner length was used as the ruler for measuring the flame heights of fire whirls. The occurrence frequency of fire whirls with different levels of flame height was characterized by the proportion of images of whirling flames (for different levels of flame height) in all images.

3. Results and Discussion

3.1. Occurrence Frequency of Fire Whirls: Wind Speed Effect

Figure 3 presents the fire whirl occurrence frequencies under different wind speeds for both line burners. As shown, the occurrence frequency of fire whirls reaches as large as 0.8. Note for the repeated tests under the wind speed of 0.49 m/s, the standard deviation is small as compared to the occurrence frequency itself. It seems that a line fire is easy to induce fire whirls with well repeatability, especially when the cross wind is present.

As shown, with increasing wind speed the occurrence frequency of fire whirls firstly increased and then decreased. Recall that fire whirls can be produced by multiple fires interaction, and in general the imposed shear flow helps increase the occurrence frequency of fire whirls [10]. During our tests, jagged flames were observed over the line fire in still air that essentially created a multiple-fire system, and the cross wind can be decomposed as sum of two component velocity vectors, respectively parallel and perpendicular to the line fire. The parallel velocity vector

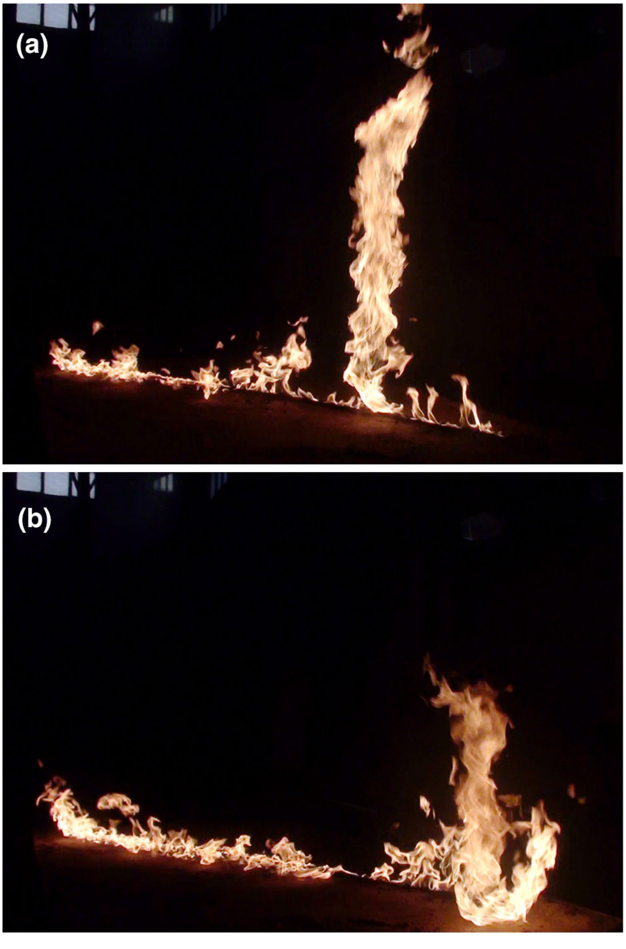

Figure 2. Fire whirls observed during test: (a) over and (b) away from the line burner. The burner was 300 cm × 5 cm × 5 cm in size, with wind speed and attack angle being 1.00 m/s and 25°, respectively.

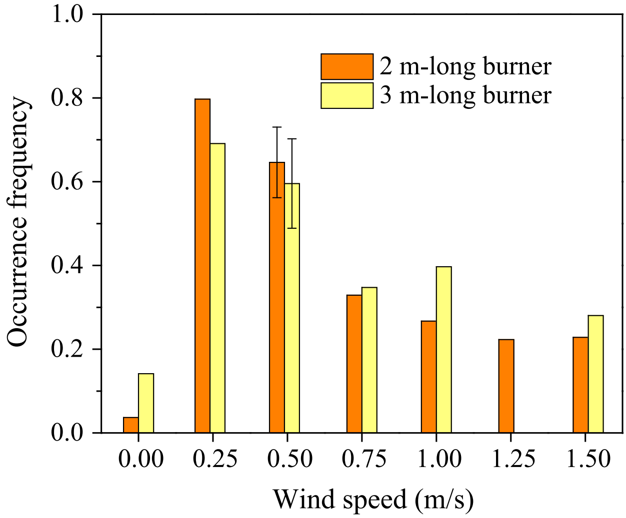

Figure 3. Effect of wind speed on the occurrence frequency of fire whirls.

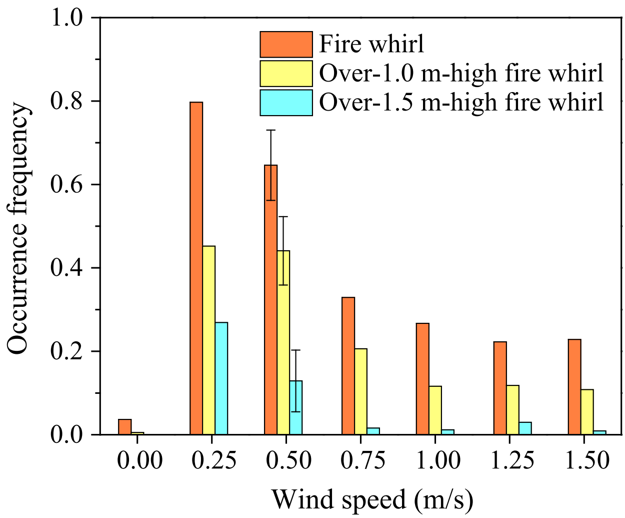

Figure 4. Effect of wind speed on the occurrence frequency of fire whirls with different flame heights (2 m-long burner).

plays a role as the shear flow that increases the occurrence frequency of fire whirls, while the perpendicular velocity vector imposes a pressure force on the flame surface that destroys the multiple-fire system. Therefore the first increase and then decrease of the occurrence frequency of fire whirls is inferred to be

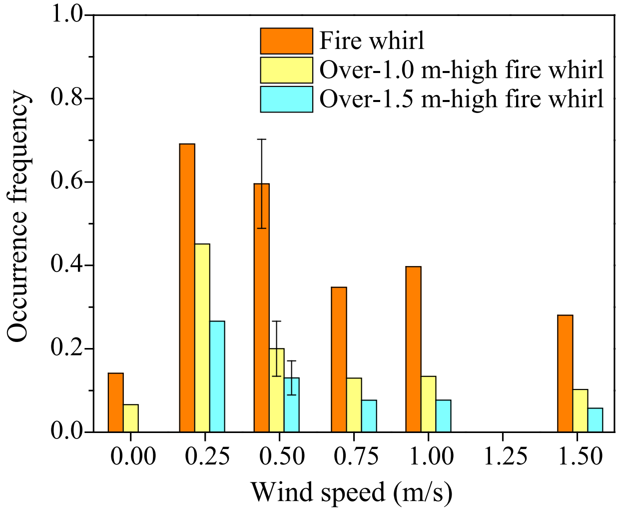

Figure 5. Effect of wind speed on the occurrence frequency of fire whirls with different flame heights (3 m-long burner).

caused by the competition of the effects of the two velocity vectors. In addition, note that even with no wind, fire whirls could also be induced occasionally with lower frequencies, which is inferred to be caused by the small ambient air fluctuation. This suggests that for a line fire, fire whirls can be induced under very low air flow velocities.

Figures 4 and 5 show the occurrence frequency versus wind speed for fire whirls with different flame heights over both line fires, respectively. As shown, the cross wind plays an important role in the flame height of fire whirl. For all wind speeds, the occurrence frequency of over-1.5 m-high fire whirls was much lower than that of over-1.0 m-high fire whirls. Especially, the occurrence frequency of over-1.5 m-high fire whirls approached zero for tests without wind speed, regardless of the line fire length. For the 2 m-long burner, the occurrence frequency of over-1.5 m-high fire whirls almost approached zero under all the wind speeds except the 0.24 and 0.49 m/s, and the 0.24 m/s wind speed held the highest occurrence frequency of fire whirls. For the 3 m-long burner, fire whirls occurred most frequently also at 0.24 m/s wind speed, and then the occurrence frequency decreased as the wind speed increased.

The role of the cross wind in the flame height of fire whirl can be interpreted by the generation and transportation of vorticity due to the interactions among the wind speed, the ground surface and the upward fire plume. As shown in Figure 6, the horizontal vortex line (namely vorticity) near the ground surface can be generated by the viscous shear as the wind blows over the ground surface, and then is transported downwind under wind pressure force, and finally is transformed to a vertical one as it meets the upward buoyant fire plume. Moreover, the strength of the vertical vortex line can be enhanced due to the stretching effect of the upward buoyant plume. Thus the horizontal vortex line resulted from the interaction

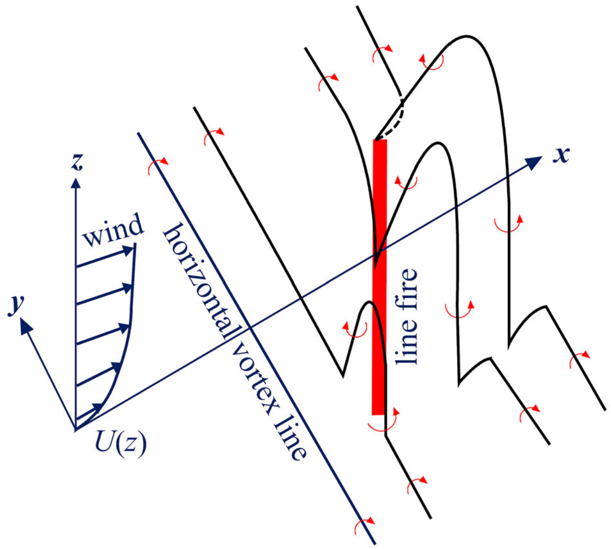

Figure 6. Interactions among the wind speed, the ground surface and the upward fire plume.

between the wind and the ground surface provides the eddy source for the increase of the flame height of fire whirl. However, the upward line fire plume would gradually incline to the horizontal style with increase in the cross wind. The horizontal vortex line never turns into the vertical one as it meets the horizontal fire plume. Note that in physics the above analysis is invalid after the formation of fire whirl, since the fire whirl could impose a significant effect on the local flow field.

Figure 7 shows the proportion of over-1.5 m-high fire whirls, which is defined as the ratio of the occurrence frequency of 1.5 m-high fire whirls to that of all the fire whirls. This proportion was zero without wind for both line fires, while the 0.25 m/s wind speed held the largest proportion. As the wind speed increased, the proportion of over-1.5 m-high fire whirls for the 2 m-long burner quickly decreased and then remained to be nearly constant, while the 3 m-long burner involved almost a constant proportion. Note that the 3 m-long burner has much higher proportion of over-1.5 m-high fire whirls than the 2 m-long burner, especially for higher wind speeds. The results suggest that the wind speed over the upper limit holds little influence on the flame height of fire whirl. It seems that the line-fire length and/or attack angle have little effect on the flame height within the critical wind speeds, but have a significant effect for wind speeds over the upper limit. The future work should focus on the effect of line-fire length and attack angle on the occurrence frequency of fire whirls.

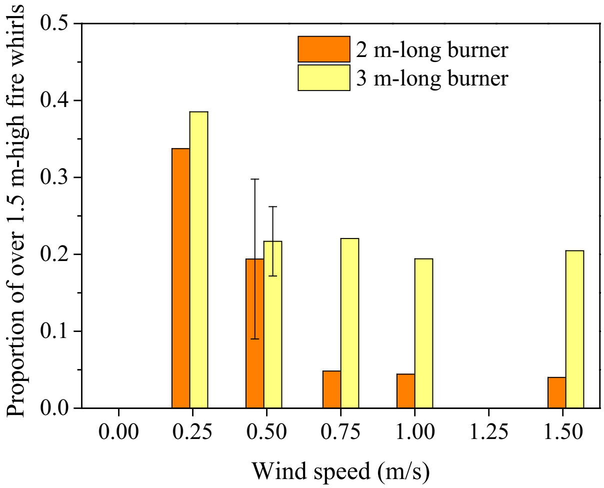

Figure 7. Effect of wind speed on the proportion of over 1.5 m-high fire whirls.

3.2. Scaling Analysis on the Critical Wind Speed

The critical wind speeds generating different types of fire whirls have been determined for different fuel arrays in scaled experiments [1, 2, 8–13]. According to the analysis of occurrence frequency versus wind speed in Section 3.1, the 0.24–0.49 m/s is suggested to be the critical wind speeds for both burners in this paper. In Ref. [11], the linear fuel arrays simulated by the ethanol line fire and the heated nickel–chromium wire were used to determine such critical wind speeds. In detail, one end of the ethanol line fire was connected to the sidewall of the wind tunnel, while for the experiments of the heated nickel–chromium wire, both ends of the wire were far away from the sidewall, which was similar to the experimental condition of the current work. Therefore, the experimental data for the nickel–chromium wire are used to conduct the scaling analysis in this work. All the used data are listed in Table 2.

The critical wind speed (denoted by U_c) is suggested to correlate with the characteristic upward speed expressed by $\sqrt{gH_p}$ where g is the acceleration of gravity and H_p the line fire flame height [9, 11–13]. Note that the mean flame height of line fire was used in still air [13]. However as discussed in Section 3.1, the component velocity vector of wind perpendicular to the line fire plays a negative effect on the fire whirl frequency, and the attack angle (denoted by θ) is also another important parameter for fire whirl frequency [12, 13]. Thus we propose a critical wind speed correlation inducing fire whirl over a line fire, expressed as

$$U_c \sin\theta \big/ \sqrt{gH_p} = \text{constant} \tag{1}$$

The mean flame height of line fire in still air can be formulated by [14]

$$H_p \big/ w = 3.64 \dot{Q}_l^{*2/3} \tag{2}$$

Table 2
Verification of Scaling Law of Equation (3) by the Experimental Data in Ref. [11]

Variable	Nickel–chromium wire [11]	Heptane line fire		Heptane line fire	
l (cm)	50	200		300	
w (cm)	5	5		5	
θ (°)	20	30		25	
$\dot{Q}_l$ (kW/m)	2.4	40		37	
U_c (m/s)	0.15	Predicted	Measured	Predicted	Measured
		0.26	0.24–0.49	0.30	0.24–0.49

[a] The density of heptane is 686 g/L. The heat release rates were calculated by assuming unity of combustion efficiency with the complete combustion heat for heptane, i.e. 44.6 kJ/g

[b] The temperature, density and specific heat of ambient air are 298 K, 1.1707 kg/m^3 and 1.007 kJ/(kg K), respectively

where $\dot{Q}_l^* = \dot{Q}_l / \left(\rho_\infty c_{p,\infty} T_\infty g^{0.5} w^{1.5}\right)$ is the dimensionless heat release rate, in which $\dot{Q}_l = \dot{Q}/l$ is the heat release rate per unit length, $\dot{Q}$ the heat release rate, l the burner length, w the line burner width, ρ_∞, $c_{p,\infty}$ and T_∞ are the density, specific heat and temperature of ambient air, respectively. With equation (2), the scaling law of the critical wind speed can be rewritten as

$$U_c \sin\theta / \sqrt{gw} \sim \dot{Q}_l^{1/3} \Big/ \left(\rho_\infty c_{p,\infty} T_\infty g^{0.5} w^{1.5}\right)^{1/3} \tag{3}$$

Table 2 presents the critical wind speeds of this study predicted from equation (3), by using the small-sale experimental data of the nickel–chromium wire. As shown, the predicted results agree well with the experimental data, which verifies the above scaling law.

3.3. Estimation of Flame Height of Fire Whirl Under the Critical Wind Speed

For a constant pool size, the flame height of a fire whirl is much higher than that of a general pool fire. The increase of flame height is caused by two mechanisms: mass burning rate increase due to the positive effect of flow circulation on the air entrainment in the flame root, and the oxygen-fuel mixing reduction due to the pure aerodynamic effect of flow circulation in the upper flame. Therefore, the flame height of fire whirl can be correlated with the mass burning rate (or heat release rate) and flow circulation (or angular velocity). A correlation developed for a medium fire whirl with flame height within 1–10 m was [15]:

$$H/H_p = 0.36\left(\Gamma \Big/ \sqrt{gD^3}\right)^{1.11} \tag{4}$$

where H is the flame height of the fire whirl, H_p the flame height of general pool fire in still air, Γ the flow circulation and D the pool diameter. Equation (4) could fit the

Table 3
Physical Parameters of Line Fires in Still Air

l (cm)	w (cm)	Mass (g)	Time (s)	$\dot{Q}_l$ (kW/m)	$\dot{Q}_l^*$	H_p (m)
200	5	1372	760	40	0.104	0.40
300	5	1372	544	37	0.096	0.38

[a] In calculation, the temperature, density and specific heat of ambient air are the same as those in Table 2

line fire induced fire whirl, for which H_p denotes the line fire flame height instead, and D is replaced by the line burner width. Equation (2) can be used to calculate the flame heights of both line fires in still air, as listed in Table 3. Note that the heat release rate per unit length is required to be over 30 kW/m in equation (2). According to Kelvin's theorem (i.e. the conservation of vorticity as it moves with the fluid), the intensity of the eddy source for fire whirl formation should equal to that of another one behind the line fire before the fire whirl formation, as shown in Figure 6. The flow circulation of eddy source behind the line fire could be expressed by $\Gamma \sim U_c l \sin\theta$, thus the flow circulations are estimated to be approximately 0.24 m^2/s and 0.30 m^2/s for 2 m and 3 m-long line fires under 0.24 m/s wind speed, respectively. With equation (4), the flame heights for fire whirls induced by both line fires are calculated respectively to be approximately 1.22 m and 1.49 m, which are consistent with the observed flame heights in this work.

4. Conclusions

This paper presents an experimental study on fire whirls over a line fire. The focus of this work was to examine the occurrence frequency of fire whirls. The experimental results showed that wind had a significant effect on the occurrence frequency of fire whirls over a line fire, and especially it was found that the occurrence frequency of fire whirls firstly increased and then decreased with increasing wind speed. This was inferred to be caused by the competition of the effects of the two velocity vectors: the velocity vector parallel to the line fire mainly plays a positive role as the shear flow to increase the occurrence frequency of fire whirls, while the perpendicular velocity vector plays a negative role. We also proposed a scaling law to characterize the critical wind speed inducing fire whirls, which was validated by the experimental data in this work and literature. A method was proposed to estimate the magnitude of flame height of fire whirl induced by the line fire under the critical wind speed. This method was roughly verified by the comparison between the calculated and observed flame heights.

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