Generation of Fire Whirls over a Line Fire in a Crossflow: An Experimental Study on the Role of Near-ground Flow

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1 Introduction

Fire whirls often occur during urban and wildland fires [e.g., 1-5]; they tend to increase the burning rates and make sudden and unpredictable changes of fire-spread direction. It is therefore crucial to understand their generation mechanism.

Fire whirls in urban and wildland fires are usually generated by interaction between fires and crosswinds [1-3]. It is known that there is a narrow range of wind speed that can generate intense fire whirls. The critical wind speed depends on the burning rate as well as the scale of fire, and Froude-number scaling has been proposed [1, 3].

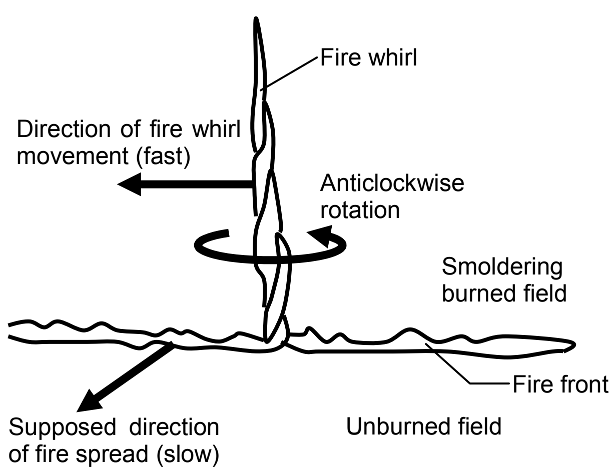

Figure 1. Schematic diagram of a moving fire whirl over a line fire that was observed in Brazil in 2010

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The topic of this study is moving fire whirls over line fires, which were previously discussed in [6, 7]. A fire whirl observed during a wildland fire in Brazil in 2010 is a typical example, which is depicted in Fig. 1; movie files of this fire whirl can be found at vide-sharing websites. The fire whirl suddenly appeared (presumably under a certain critical wind velocity) over a narrow but long fire front in a flatland bush. It then started moving at a nearly constant speed, which was much faster than the fire spread velocity.

Refs. [6, 7] reported that fire whirls were generated over a straight line fire when the angle between the line fire and a crosswind is within a certain range. The generation mechanism of fire whirls over line fires, however, remains largely unknown. On the other hand, recent studies on fire whirls of different configurations [8-11] concluded that the presence of a near-ground flow toward the fire is a necessary condition for an intense fire whirl to be formed. As a first step to understand the generation mechanism of fire whirls over line fires, experiments have been conducted to study the role of near-ground flow, and results are reported herein.

2 Experimental Setup

Fig. 2 shows a schematic diagram of the present experimental setup. Ethanol was poured to a container of 1 cm wide × 1 cm deep × 43 cm long, which was embedded into the floor of the test section such that its top rim was flush with the floor surface. The distance between its upstream edge and the wind-tunnel exit was 20 cm. A crossflow of velocity U was provided by a wind tunnel whose exit size was 60 cm × 60 cm. The angle between the line fire and the crossflow was fixed at 45° based on the results of previous studies [6, 7].

In this study, a blocking board was attached to the wind-tunnel exit to vary its opening height, h. Three different values of h, i.e., 3, 5, and 10 cm, were tested to examine the effect of near-ground flow. The value of U was measured by a hot-wire anemometer placed immediately after the blocking board. The evolution of flame was recorded from the downstream side by a digital camera at a time interval of 1/3 s. An image-processing technique similar to that described in Ref. [11] was used to measure the instantaneous flame height.

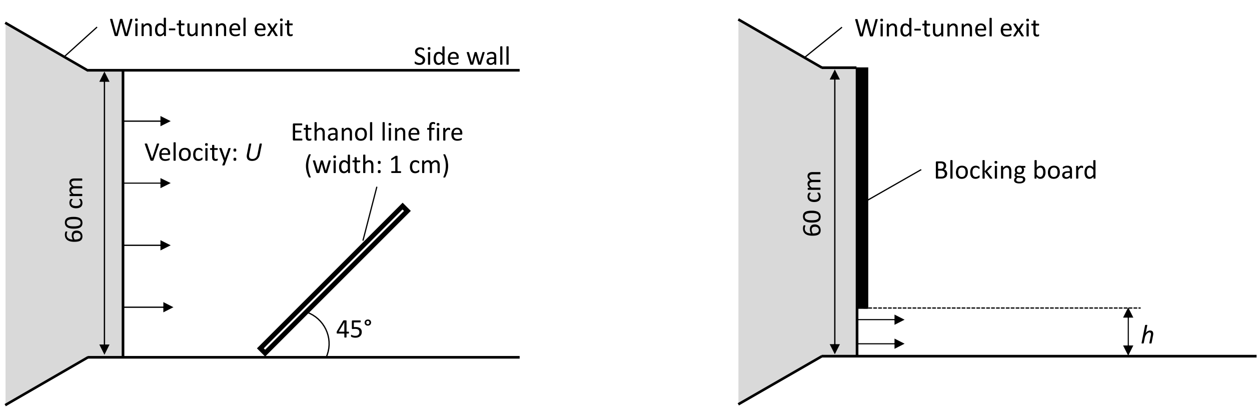
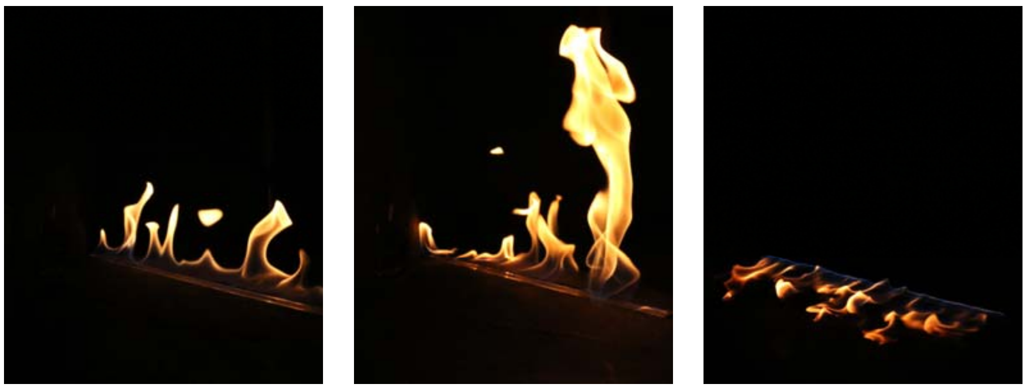


Figure 2. Schematic diagram of the experimental configuration. Left: a top view; right: a side view

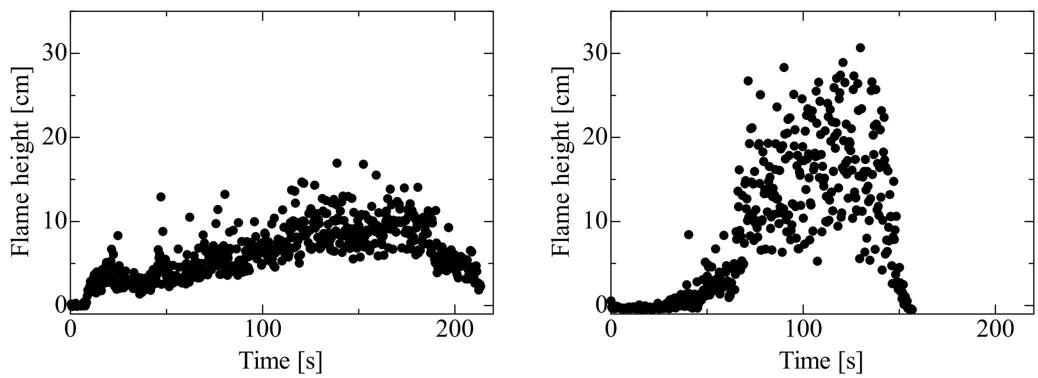
3 Results and Discussion

Fig. 3 shows images of typical flames for three different crossflow velocities at the fixed height of wind-tunnel exit of h = 5 cm. When U was small at 0.5 m/s, the crossflow was so weak that its influence on the line fire was negligible (Fig. 3a). When U was increased to 1.0 m/s, formation of fire whirls were

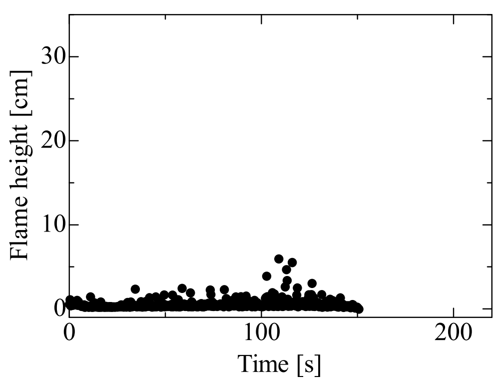


(a) U = 0.5 m/s (b) U = 1.0 m/s (c) U = 1.2 m/s

Figure 3. Images of line fires at h = 5 cm



(a) U = 0.5 m/s (b) U = 1.0 m/s



(c) U = 1.2 m/s

Figure 4. Flame height evolution at h = 5 cm

frequently observed (Fig. 3b). Fire whirls were generated typically near the center of the line fire and moved toward its downstream edge. When U was further increased to 1.2 m/s, however, the crossflow was too strong to generate fire whirls, and the flame is tilted downstream (Fig. 3c). There is clearly a critical crossflow velocity, agreeing with previous observations [6, 7].

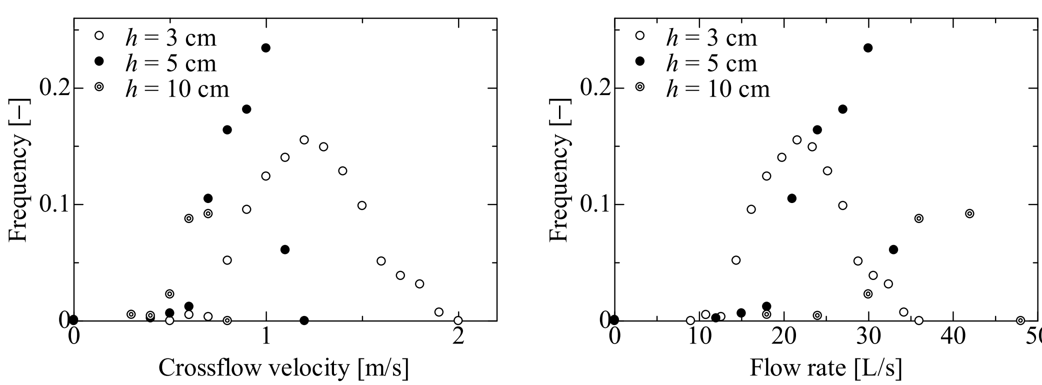
Fig. 4 shows evolution of instantaneous flame height under the same conditions as Fig. 3. When U = 0.5 m/s, the flame height gradually increased after ignition, achieved a quasi-steady state at about 120 s, and then sharply decreased when the fuel was burned out. The burn-out time was about 210 s, and the flame height was mostly less than 15 cm.

When U = 1.0 m/s, on the other hand, fire whirls were frequently generated, and the flame height increased to as high as 30 cm. After the formation of a fire whirl, the flame height locally increased, and then it moved along the line fire. The fire whirl dissapeared when it reached the downstream edge of the line fire; the local flame height then decreased to about 10 cm. This process was repeated, and fire whirls were formed rather periodically. The generation of fire whirls resulted in an increase in the burning rate; the burn-out time was reduced to about 150 s.

At U = 1.2 m/s, the flame was tilted, and the flame height rarely reached 5 cm. The burning rate was nevertheless as large as that at U = 1.0 m/s. This is because the crossflow pushed down the flame toward the liquid surface, enhancing its evaporation. A small flame height is not always associated with a small burning rate.

Based on the observations discussed above, the frequency of fire-whirl formation can be quantified by measuring that of flame height exceeding a threshold value. Because the flame height was mostly less than 15 cm when U = 0.5 m/s, the threshold value was chosen to be 15 cm. Note that the choice of the threshold value does not alter the major conclusions of discussion below; see also Ref. [7] for the definition of the frequency of fire-whirl formation. Fig. 5 shows the frequency of fire-whirl formation for three different values of the opening height h of the wind-tunnel exit. Fig. 5a plots the data as a function of crossflow velocity, whereas they are plotted as a function of volumetric flow rate in Fig. 5b. At any value of h, the frequency first increased with crossflow velocity and then decreased, demonstrating the presence of a critical wind velocity. The critical crossflow velocity tends to decrease with the increase in h. On the contrary, the critical flow rate increases with h.

The maximum frequency for h = 5 cm was greater than that for h = 10 cm; multiple fire whirls were often observed simultaneously when h = 5 cm and U = 1 m/s. This suggests that the near-ground flow is indeed important to generate fire whirls over line fires, while a strong crossflow far above the ground tends to



(a) Frequency and crossflow velocity (b) Frequency and volumetric flow rate

Figure 5. Frequency of fire-whirl formation at three different values of opening-height h of wind-tunnel exit

weaken them. Note that experiments without attaching a blocking board to the wind-tunnel exit (i.e., h = 60 cm) resulted in similar results to h = 10 cm. When h was decreased to 3 cm, strong enough near-ground flow could not be maintained, leading to the least frequency among the three cases tested. Fig. 5b suggests that the total flow rate is not an important parameter. Rather, the opening height, h, determines the frequency of fire whirl formation.

The importance of near-ground flow suggests possible control of fire-whirl formation by blocking the flow near the floor. A simple idea is to place a square-rod of 1 cm high × 1cm wide × 43 cm long on the immediately upstream side of the line fire. It was found that this simple device effectively prevented the occurrence of intense fire whirls.

4 Conclusions

The generation mechanism of fire whirls over a line fire in a crossflow has been studied with a particular focus on the influence of near-ground flow. A wind tunnel was used to provide a crossflow of velocity U, and a blocking board was placed to cover the wind-tunnel exit and adjust its opening height, h. Evolution of flame height was measured for various values of h and U, from which the frequency of fire-whirl formation was obtained.

The frequency of fire-whirl formation for h = 5 cm was found to be greater than that for h = 10 cm. A near-ground flow is necessary to generate fire whirls, but strong crossflow far above the ground tends to weaken their intensity. When h was too small at 3 cm, strong enough near-ground flows could not be maintained, resulting in a small frequency. Finally, it was demonstrated that formation of fire whirls could be prevented by blocking near-ground flow.

Acknowledgments

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