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Effect of Reduced Pressure on the Burning Dynamics of Fire Whirls

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Abstract: The fire whirl is an intensification of combustion, but its pressure effect is still unknown. In this study, small-scale fire whirls were generated by square enclosures with slits inside a large low-pressure chamber. As the pressure decreases, the fire whirl becomes bluer, and the burning rate decreases linearly at a rate five times faster than the pool fire. Thus, the hazard of fire whirl drops significantly at the reduced pressure. Unlike the flame height of pool fire increasing with pressure, the flame height of fire whirl is almost insensitive to the pressure.

Keywords: *Fire tornado; Reduced pressure; Flame height; Blue flame; Burning rate*

1. Introduction

Fire whirl is an intensification of combustion that has been seen in mass urban fires and wildfires [1], posing significant fire hazards. Besides the sudden formation and dissipation, fire whirls can also move erratically to destroy a vast area and produces massive firebrands [2]. The knowledge of the fire whirls is still limited, and quantitative data are only available in small-scale tests [3,4]. Fire whirls can be generated by the rotating mesh screen [5] and the fixed enclosures with slits [6–9]. Many studies also applied scale laws to couple the small scale fire whirl with the real fire whirls [10].

The low-pressure environment is common at the high-altitude lands and aircraft cabins. Although the effect of pressure on regular pool fire and solid-fuel flames has been studied [11–16], it is unknown if fire whirl can be formed at low pressures due to the change in buoyancy, and if similar phenomena and variation trends of pool fire can be extended to low-pressure fire whirl. In this study, the small-scale fire whirls were investigated inside a low-pressure chamber.

2. Experimental method

The fire whirl generator was a square screen frame consisting of four tempered glasses (1 m high and 0.5 m wide) with four slits open, as shown in Fig. 1. Three slits sizes (z) of 2 cm, 5 cm, and 8 cm were employed. The circular fuel pan with 40 g pure ethanol and 11-cm diameter (D) was placed at the center and embedded into a thermal insulation board at the same level [1,7]. The entire fire whirl generator was assembled and placed inside a low-pressure chamber (3×2×2 m^3) [14].

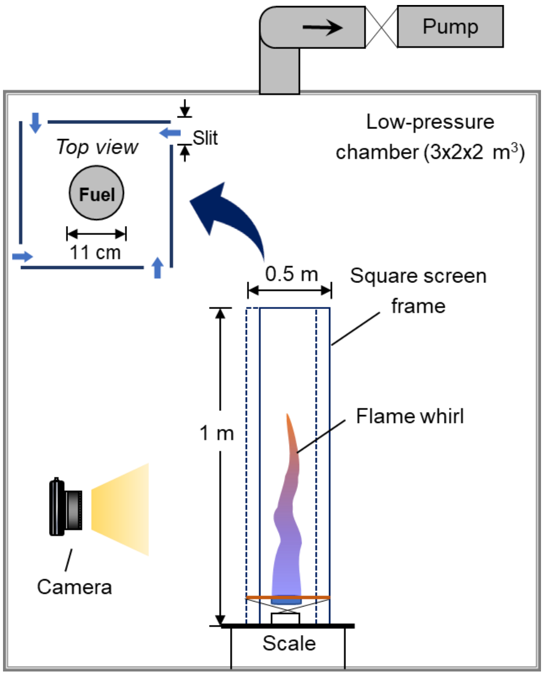

Fig. 1. Setup of fire whirl in the low-pressure chamber.

The chamber pressure varied from 101 kPa to 20 kPa by the vacuum pump. After the pressure was reduced to the target value, the liquid fuel was ignited by the spark to form a pool fire, and then gradually forming a fire whirl. During the burning process, the variation of pressure and oxygen level was small, and the mass loss was measured by the scale. The flaming and burning behaviors were recorded by the digital camera at 25 fps with fixed ISO and aperture and processed in MATLAB. At least 2-3 repeating tests were conducted.

3. Results and discussion

Fig. 2(a-b) show the flame shapes of fire whirl and pool fire under different pressures (see Videos S1 and S2). There was a transition stage for the initial pool fire to develop into a fire whirl, i.e., about 30 s at reduced pressures and <10 s at 1 atm. At 20 kPa (burning limit), the ignition and the formation of fire whirl sometimes became unsuccessful, similar to PE [15] and PMMA [16]. Moreover, the intensity of the ambient circulation also decreased with the pressure, limiting the whirling behavior of flame at lower pressure. All these results indicate that it was more difficult to form a stable fire whirl at a lower pressure.

Fires at normal pressure usually have yellow flame due to the radiation of soot particles. As the pressure was reduced, the flame color gradually became bluer, as pressure would affect chemical kinetics of soot formation and the oxygen supply to the flame sheet, like other fires [12–16]. Based on the RGB color model, we defined the *blue intensity of flame* by the total blue value of all flame pixels divided the total RGB value. In addition, the *blue flame area ratio* was quantified by converting the color image into a binary image with a threshold value of 0.2.

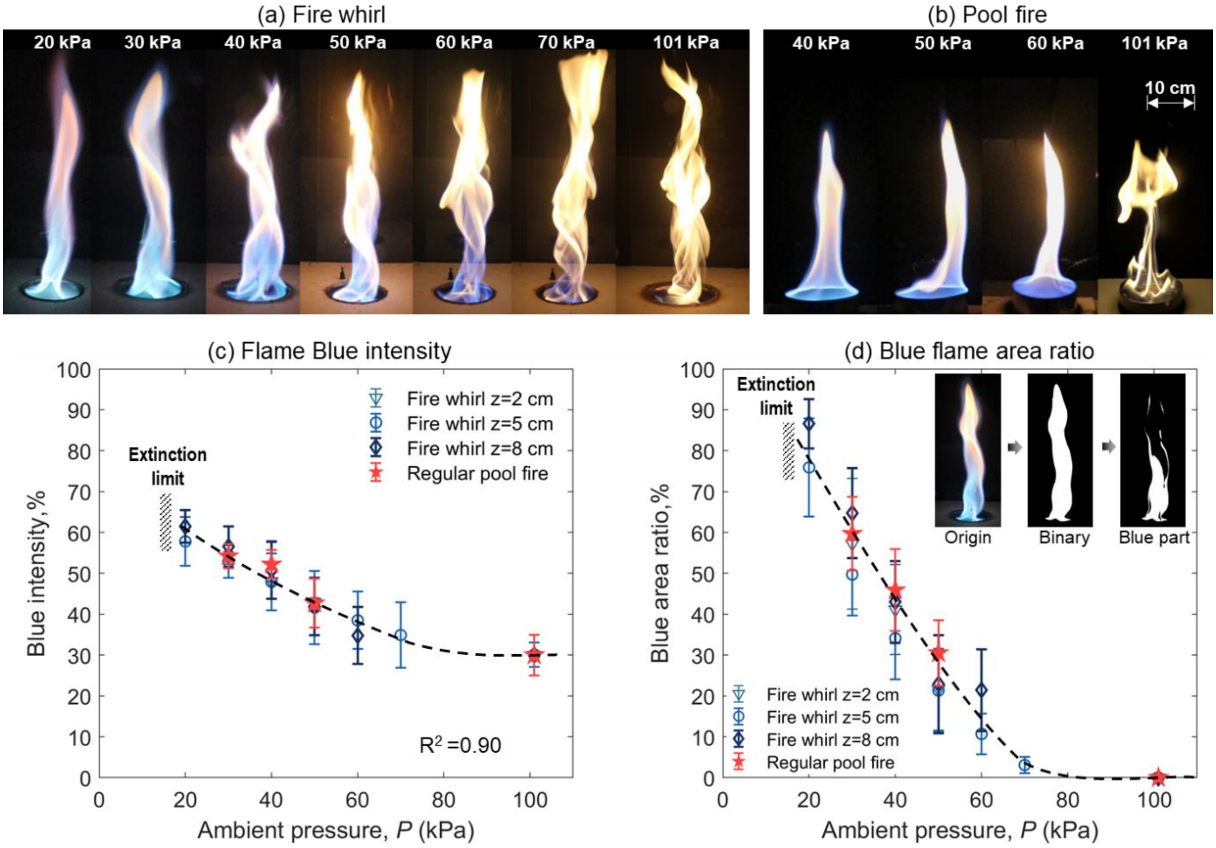

Fig. 2. Snapshots of (a) fire whirls, and (b) pool fires; (c) the blue intensity of flame, and (d) blue flame area ratio under different pressures.

Fig. 2(c-d) shows the trendlines of the flame blue intensity and blue flame area ratio for the pool fire and fire whirl, both of which increase as the pressure decreases. When the pressure decreased from 101 kPa to 20 kPa, the blue flame area ratio of fire whirl increased from 0% (yellow) to 90% (almost blue). Under the same ambient pressure, blue-flame characteristics were almost the same between the fire whirl and pool fire. The slit size also has a negligible influence on the flame color, indicating that the oxygen supply to fire whirl is always sufficient. As the pressure decreases, the flame temperature may decrease, which is one of the primary factors responsible for suppressing soot inception and agglomeration and the blue color of flame (to be further verified in future measurements).

Fig. 3(a) shows the evolution of flame height (H_f) of both fire whirl and pool fire under 50 kPa, where the flame height of fire whirl is always larger. For the fire whirl, the averaged flame height gradually increases with time until a sudden drop near burnout. Differently, the flame height of regular pool fires only has a small variation. Fig. 3(b) further compares the peak flame heights between fire whirl and regular pool fire under different ambient pressures, where the flame height of fire whirl is larger, except for near-extinction conditions below 30 kPa. Generally, the influence of the slit size on fire-whirl flame height is not prominent and smaller than the variation induced by flame puffing.

For the regular pool fire, the flame height increased with the decreasing pressure. A similar trend was also observed for other liquid fuels [11,17], although some other studies showed different trends

[13]. However, except for near extinction, the flame height of the fire whirl was almost insensitive to the ambient pressure. Furthermore, this trend is also different from many other solid-fuel flames [15,16] and gas-jet flame [12], where the flame height decreases significantly at lower pressure. By reducing the pressure, both the convective and radiative flame heat fluxes to the solid fuel surface decrease, so the mass burning (pyrolysis) rate is decreased to lower the flame height [16].

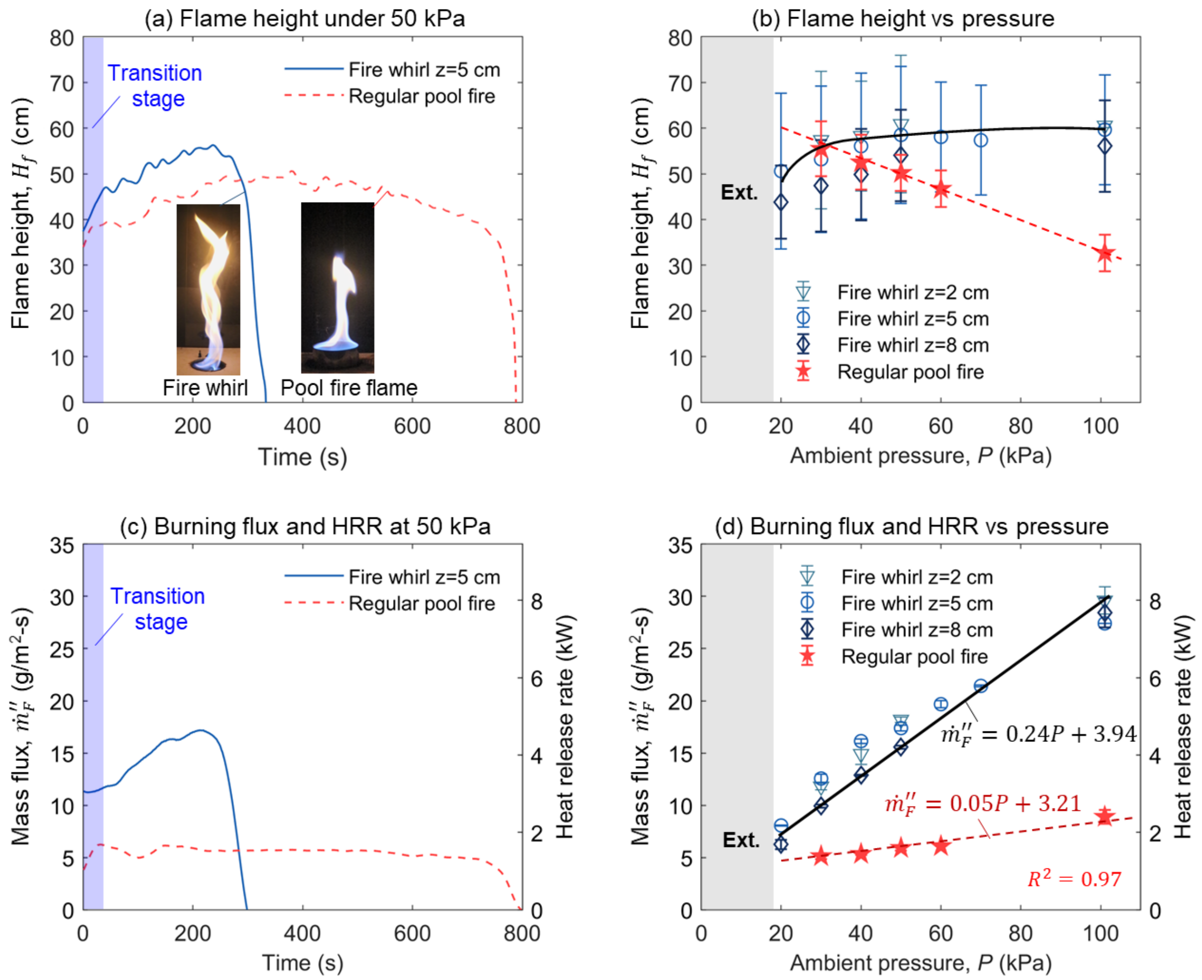

Fig. 3. Fire whirl vs. pool fire, (a) flame height at 50 kPa, (b) peak flame height vs. pressure, where the error bar also includes the influence of flame puffing, (c) burning flux and HRR at 50 kPa, and (d) peak burning flux and HRR vs. pressure.

Fig. 3(c) compares the evolution of the mass flux ($\dot{m}''_F$) and the heat release rate (HRR or $\dot{Q}$). The flame HRR was proportional to the burning rate as

$$\dot{Q} = \frac{\pi}{4} D^2 \dot{m}''_F \Delta H \propto \dot{m}''_F \quad (1)$$

where ΔH is the heat of combustion (27 MJ/kg for ethanol). Like flame height in Fig. 3(a), the mass flux of fire whirl increases with time, while for the pool fire, it is almost constant at 5 g/m^2-s.

Fig. 3(d) compares peak mass flux (or burning rate) and HRR between fire whirl and regular pool fire vs. pressure, where the fire whirl is always larger. For example, the burning rate of fire whirl at normal pressure is 4 times that of pool fire. On the other hand, as the pressure decreases, both burning rates decrease almost linearly as

$$\dot{m}_F'' \propto \dot{Q} \propto P \tag{2}$$

which is similar to solid-fuel flame [16]. Although the boiling point is lowered in the reduced pressure, the reduction of flame convective heating (i.e., weak buoyancy) and radiation (i.e., no-soot blue flame) dominates the decrease of burning rate. Moreover, the burning rate of fire whirl varies with the pressure at a rate five times larger than the regular pool fire. Specifically, the HRR of fire whirl drops 75% from 8 kW to 2 kW at 20 kPa; thus, the hazard of fire whirl drops significantly at reduced pressures. Visually, the flame whirling intensity also decreases prominently, which is close to regular pool fire at 20 kPa.

Because the fast linear increase of fire-whirl burning rate with pressure is different from the constant flame height in Fig. 3(b), the flame height of fire whirl is not controlled by the burning rate, different from the solid-fuel flame. If the fire-whirl flame is controlled by the buoyancy-induced air entrainment, the HRR may be correlated to the flame height (H_f), based on the Froude modeling [17] as

$$\dot{Q} = \rho_0 c_p T_0 \sqrt{g H_f} H_f^2 \propto P H_f^{5/2} \tag{3}$$

Combining Eqs. (2) and (3) derives the pressure-independent flame height of fire whirl, as

$$H_f \propto \left(\frac{\dot{Q}}{P}\right)^{\frac{2}{5}} \propto P^0 = \text{const.} \quad \text{(Fire whirl)} \tag{4}$$

which suggests that the flame height for the fire whirl should not change with the pressure, agreeing with experimental observation in Fig. 3(b). On the one hand, lowering the pressure also reduce the fuel burning rate, which reduces the flame height. On the other hand, for these low-pressure fire whirls, they are in the laminar or laminar-turbulent transition regime, and likely to be under-rotated. The rotating airflow around the flame comes from four tangential slits and is driven by the buoyancy flow [1], which reduces as the pressure decreases. Then, the reduced whirling effect helps the laminar flame to expand vertically and increases the flame height, due to increased residence time and reduced flame temperature. Thus, such a competition helps maintain a constant flame height vs. pressure.

In contrast, for regular pool fires, the HRR releases changes very little with the pressure, so that the flame height decreases with the raising pressure ($H_f \propto P^{-2/5}$) in Fig. 3(b). The drop of pressure decreases the oxygen concentration, so the flame sheet needs to expand in height to consume all gaseous fuels. Note that more future studies are needed to determine whether these observed trends for fire whirl can be extended to other fuels and the larger scales.

CRediT author statement

Peiyi Sun: Methodology, Writing - Original Draft, Formal analysis. **Xiaoning Zhang:** Investigation, Resources. **Chao Ding:** Investigation, Resources, Funding acquisition. **Xinyan Huang:** Methodology, Conceptualization, Formal analysis, Supervision; Writing-Review & Editing.

Conflicts of interest

The authors declare that they do not have any conflicts of interest.

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