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Effect of flow circulation on combustion dynamics of fire whirl

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Abstract

In this paper, the effect of flow circulation on the combustion dynamics of fire whirl is systematically investigated by experiments. New correlations for the burning rate, flame height, radial temperature and mass flow rate are established for fire whirl. It is clarified that flow circulation helps increase both the fuel-flame contact area and the actual fuel surface area, which in turn increases both the heat feedback to the fuel surface and the radial velocity in the ground boundary layer, leading to increase of burning rate. A novel idea for correlation of fire whirl flame height is proposed by assuming that the ratio of the fire whirl flame height to the flame height without circulation solely characterizes the effect of circulation. This idea is fully verified, thereby a new formulation for flame height is established, which successfully decouples the burning rate and the circulation. It is indicated that the fuel-rich core in the flame body of fire whirl significantly affects the radial temperature distribution in the continuous flame region, and the flame body can be described by the combination of a cylinder and a cone. The flow circulation significantly suppresses fire plume radius and thus decreases its increasing rate with vertical distance. It is also demonstrated that the fire whirl flame involves laminarized regions in its lower section, coexisting with turbulent regions in the upper portion. The flow circulation enhances the air entrainment in the ground layer by altering the radial velocity profile and increasing the radial velocity. In the low section of flaming region, the significant decrease of mixture between the combustion products and surrounding air dominates the pure aerodynamic effect of flow circulation on the flame height. Finally, it is clarified that fire whirls maintain higher centerline excess temperature than general pool fires due to the effect of less air entrainment.

Keywords: Fire whirl; Flow circulation; Mass burning rate; Flame height and temperature; Air entrainment

1. Introduction

In wildland and urban fires, fire whirls were frequently reported to occur in the lee side of obstructions (structures or fires) where flow circulation may be induced [1,2]. As evidenced by experimental investigations [2–9], fire whirls generally involve sharp increases in burning rate, flame height, upward velocity and flame radiation as compared to general pool fires. Ambient flow circulation is obviously the essential condition

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for transition from a general pool fire to fire whirl. However, there is still very limited literature on the experimental study on the role of flow circulation in fire whirl dynamics. Instead, many researchers used numerical simulations to analyze the flow structure of fire whirl, with verifications by simple experimental observations [5–7] or comparisons with the experimental data of Emmons and Ying [4] (*e.g.* [10]). Some researchers (*e.g.* [2,11]) used scaling laws to explore the onset condition of fire whirl.

There is lack of experimental studies upon the flow circulation effect on the velocity and air entrainment of fire whirls. Emmons and Ying [4] examined the circulation effect on buoyant plume by assuming similar radial profiles of vertical velocity and temperature. Soma and Saito [2] correlated the tangential velocity as functions of radius by the Rankine vortex theory, while Hayashi et al. [12] argued that the tangential and radial velocities satisfy Burgers vortex theory.

In view of the limitations of previous researches, in this paper we present a systematical investigation upon the flow circulation effect on the fire whirl combustion dynamics, by experiments of medium-scale fire whirls. We aim at developing definite correlations for the burning rate, flame height, radial temperature and air entrainment of fire whirl. The burning characteristics of fire whirl are extensively discussed and physically interpreted by addressing the dynamical differences between fire whirls and general pool fires.

2. Experimental

2.1. Experimental apparatus

The medium-scale fire whirl apparatus consisted of a square enclosure made of tempered glass, with horizontal dimensions of 2×2 m and a vertical height of 15 m. The channel was open at the top. Each corner contained a uniform 20 cm width vertical gap which ensured that the entrained air induced by the burning flame could enter the channel, thus imparting the rotational flow necessary for fire whirl formation. The base table (2×2 m) was made of pine wood with a round hole (60 cm in diameter and 10 cm in depth) in the center. Steel circular fuel pans with diameters of 20–55 cm (with step of 5 cm) and depth of 10 cm, were placed into the hole for experimentation, using *n*-heptane (97%) as the fuel. A water layer was used to maintain the initial fuel surface height constant in all tests.

Figure 1 shows a diagram depicting the location of the various sensors used to measure tangential and vertical velocities. The tangential and vertical velocities (respectively used for calculations of circulation and mass flow rates) were measured by calibrated temperature-compensated bi-directional pitot tubes (series 160S pitot tubes produced by Dwyer Instruments, Inc.) and Type-K (chromel–alumel) thermocouples with a bead diameter of 0.4 mm. The radial velocities of the 40 cm-diameter pan at five different altitudes (1, 3, 6, 9 and 11 cm) at a radial position of 30 cm from centerline were measured to calculate air entrainment at the ground layer. The fuel mass versus time was recorded by an electronic balance with a precision of 0.1 g. A video camera was installed on an elevator which could be lifted to a certain height to catch the whole intermittent zone of flame and the nearby vertical ruler. The entire apparatus was placed in a large test hall and all the doors and windows were closed during each experiment.

Besides the data obtained in this work, data from our previous work (refer to [8] for detailed experimental conditions) was also used to investigate the flame structure. The used data covered the radial temperatures at four different altitudes (0.5, 1.5, 2.5 and 3.5 m) and radial positions ranging from 0 to 30 cm with spacing of 2.5 cm, for three pool diameters of 30, 40 and 50 cm. The vertical velocities and temperatures at six different altitudes (0.17, 0.91, 2, 3, 4, 5 m), at radial positions of 0–25 cm (with step of 5 cm) (not reported previously) were also used to calculate the mass flow rates for pool diameters of 40 and 50 cm.

2.2. Data pretreatment

The quasi-steady burning rates were determined by averaging the data of repeated tests

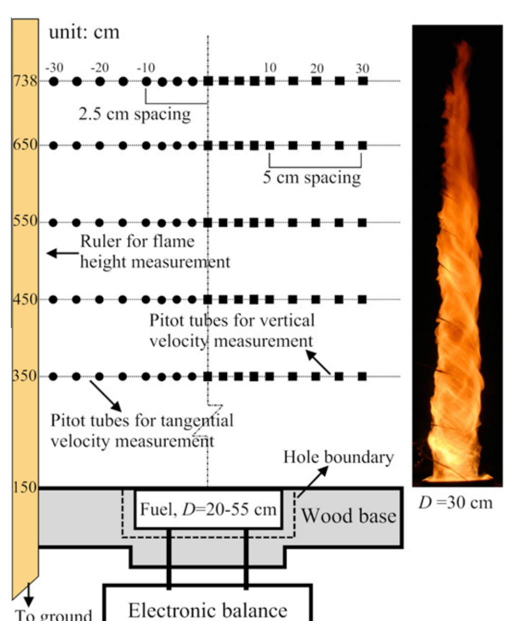

Fig. 1. Schematic of fire whirl experiments.