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Flame precession of fire whirls: A further experimental study

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ABSTRACT

Following our previous work (Proc. Combust. Inst. 2013, 34: 2607–2615), this work presents a further experimental investigation on the flame precession of quasi-steady fire whirls. Six small to medium-scale fixed-frame facilities and a small-scale rotating screen facility were used for experiments. The fixed-frame facilities were square and hexagon in cross sections, with four and six symmetric corner gaps respectively. It was found that the flame precession frequency was identical to the screen rotating frequency in the rotating screen facility, and close to the characteristic flow revolution frequency in the fixed-frame facilities. The proposed correlation of precession frequency agreed reasonably with the experimental data. It was proved that the flame precession is essentially dominated by aerodynamics. The precession radius increased first and then remained relatively steady when a critical screen rotating frequency was reached, and the critical frequency increased with the heat release rate. For the fixed-frame facilities, the boundary conditions at the base had significant influence on flame precession radius and frequency.

1. Introduction

As compared to a free buoyant fire, a fire whirl is a special swirling diffusion flame with significant increases in burning rate, flame height to diameter ratio, flame temperature, flow velocity and heat radiation to surroundings. Fire whirl can occur in unconfined wildland and urban fires [1], or in confined building and ship fires [2,3]. In view of the severe damages caused by fire whirls in history, some experimental facilities have been designed to examine the burning dynamics of fire whirl. Most of the available experimental works are focused on the quasi-steady behaviors of fire whirls. The experimental facilities are commonly classified into two types, depending on whether the circulation is imposed by a mechanically driven rotating screen (rotating-screen type [4,5]), or induced by the entrained air flows which enter the facility tangentially from spiral gaps (fixed-frame type [2,6–13], fire-wall type [14], air curtain type [15]). An intractable feature of fire whirl is the so-called "flame precession (wander)", which describes that the swirling flame axis deviates and revolves about the vertical central axis of the facility. Obviously, the flame precession would lead to great difficulties in measurements. Moreover, if a fire whirl occurs in a fire, the flame precession could expand the intense burning area and cause more damages. Therefore, for experimental and practical purposes, it is of importance to study the characteristics and mechanism of flame precession of fire whirl.

Available studies on flame precession of fire whirl are very limited. Emmons and Ying [4], by using a rotating screen facility, firstly noticed that fire whirl wandered continuously in a range of several flame diameters with a low frequency. In order to eliminate the background disturbances, the screen was surrounded by a cylindrical grille wall, and the doors and air conditioning system were turned off. These efforts failed to remove the significant flame wander. Then they speculated that the flame precession is related to some inherent instability. Snegirev et al. [10] conducted CFD simulations and experiments on the fire behaviors in a medium-scale compartment with a single corner gap at the front wall and a ceiling vent at the top center. The results showed that the fire whirl was transient and intrinsically unsteady, which were characterized by the periodic formation and destruction of fire whirl and flame precession in the asymmetric enclosure. The formation of fire whirl was related to the interaction of the upward buoyant flow and the externally induced vortex core. The frequency of the unsteady process increased with the burning rate. Similarly, Zou and Chow [2] also observed fire whirl precession in a medium-scale vertical shaft model with a single corner gap and open roof. Note that the central axis of the fire whirl was not vertical in this asymmetric model. Su et al. [3] used FDS software (Fire Dynamics Simulator) for simulation and found that fire whirl would occur in a typical ship engine room. The results showed that the fire whirl precessed roughly in a circular path and the angular speed of flame precession was fitted by a cube polynomial function of the ventilation velocity. However, the FDS code was not modified to incorporate the effect of

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Nomenclature

c	point vortex coordinate (m)
d	burner/pool diameter (m)
D	cross section dimension of the facility (m)
f	frequency (Hz)
H	facility height (m)
H_f	mean flame height (m)
i	imaginary unit ($i^2 = -1$) (−)
p	pressure (Pa)
$\dot{Q}$	heat release rate (kW)
R	radius/distance (m)
t	transverse coordinate across the corner gap (m)
V	velocity (m/s)
w	complex potential ($=\phi + i\psi$)
W	corner gap width (m)
x, y	Cartesian coordinates (m)
z	height above the ground (m)
Z	complex number ($=x + iy$)

Greek symbols

ϕ	velocity potential (m^2/s)
η, ξ	bipolar coordinates (-, rad)
κ	vortex strength (m^2/s)
ρ	density (kg/m^3)
ψ	stream function (m^2/s)
ζ	coaxal coordinate ($=\xi + i\eta$)
Γ	circulation (m^2/s)

Subscripts

a	amplitude
c	centerline of the corner gap
f	flame
in	inflow of air from the gap
p	precession
s	screen
w	wall

turbulence suppression due to imposed rotation. In addition, the simulation results were not compared with experiments. Lei et al. [16] studied the flame precession of fire whirls in a medium-scale shaft model with four symmetric corner gaps. The n-heptane fuel pans (diameters: 10–55 cm) were placed centrally in a round hole (diameter: 60 cm) that located in the center of a wood base table. The annular trench between the pan wall and the hole sidewall was not filled. Quasi-steady vertical fire whirls were generated in the facility. The precession frequency was extracted from the quasi-periodic radial temperature data. It was found that the flame precession frequency was proportional to the air inflow velocity.

The main aim of this work was to further experimentally quantify the effects of facility type, facility scale, imposed circulation and heat release rate on flame precession of quasi-steady fire whirls. A series of experiments were carried out in six fixed-frame facilities ranging from small to medium-scales and a small-scale rotating screen facility. The air inflow velocity profile across the corner gap was measured. The flame precession frequencies were extracted from the time-sequence DV images in the fixed-frame facilities and the synchronous fluctuations of tangential dynamic pressure data in the rotating screen facility. The relationship between the flame precession frequency and the revolution frequency of fluid adjacent to the enclosed walls and screen was revealed. The flame precession radius and velocity in the rotating screen facility were obtained by image processing. The effects of the heat release rate and bottom boundary conditions on flame precession were discussed.

2. Experimental

Two kinds of fixed-frame facilities (FFF), with cross sections of square and regular hexagon respectively, were designed for

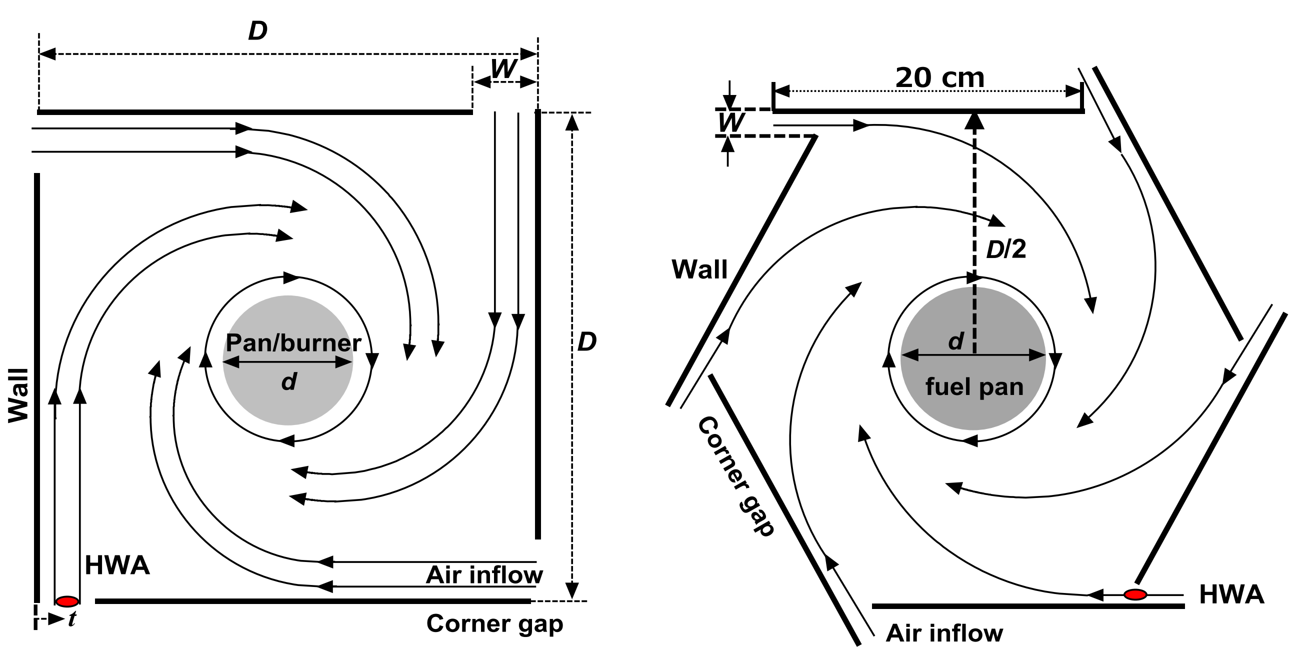

Fig. 1. Schematic of the cross sections in the fixed-frame facilities (left: four sidewalls; right: six sidewalls).