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The wall-free non-stationary fire whirls generation by axisymmetric burning of solid fuel pellets

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ABSTRACT

This paper is aimed to demonstrate an opportunity of the generation of wall-free non-stationary fire whirls under laboratory conditions without using mechanical swirling devices and estimation of their integral parameters. A simple experimental facility making possible the generation of concentrated fire vortex structures by means of combustion of solid fuel (urotropine) arranged symmetrically on a metallic underlying surface is described. With the use of photography, some data on the generation conditions and integral parameters (lifetime, height, and diameter) of fire whirls have been determined.

1. Introduction

Fire whirls are possible and potentially catastrophic forms of fire. These swirling fire plumes are known to increase the danger of naturally occurring or post-disaster fires. Although fire whirls linger for a few seconds or minutes only, they may cause great damage and human fatalities.

Several extremely large fire whirls (fire tornadoes) have been described in urban fires that demonstrate their potentially destructive force [1–5]. Here the some historical facts from [1–5] collected and taken from review [6]. In 1871, the Great Chicago Fire generated whirlwinds that lifted and transported burning planks 600 m ahead from main fire. On the same day, a fire in Peshtigo, Wisconsin produced a whirl that was strong enough to lift a house off its foundations. It was described a whirl which was one of many formed during a large oil storage facility fire and too strong to move a house. This whirl separated from the fire and moved 1000 m downwind, lifted the small house, and replaced it 45 m killing 2 persons inside. A much more devastating whirl formed in 1923, when a earthquake with a magnitude ca. 8 on the Richter scale hit the area of Tokyo, causing a mass urban fire. This fire spawned an extremely large fire whirl that killed 38,000 people within less than 15 min. Last, the World War II city bombings of Dresden, Hamburg, and Hiroshima were reported to have caused extremely large and destructive fire whirls.

Fire whirls, as compared to general fires, are characterized by significant enhancement in burning rates, flame temperature and flame heights, in addition to a strong swirling motion of the flame itself (for example, [7–10]). These peculiarities of them allow to intensify the processes of heat and mass transfer in different engineering devices.

In a fire whirl, the hot gases generated by the fire itself serve as a fluid sink which entrains the ambient air with angular momentum from the eddy to the vortex core (flame). Fire whirls simulation in a laboratory environment is not a new concept. Various types of facilities can be used to produce single steady fire whirls at laboratory conditions. They are based on the concepts of generating eddy and a fluid sink. These facilities may be generally classified into two types, depending on whether the generating eddy is imposed mechanically by a rotating screen (Emmons-type or rotating screen type [11–14]) or induced by the entrained air flowing through well-arranged spiral path (fixed-frame type [15–19]). Being similar in many aspects, since both produce a fire swirl, they differ in details.

With the rotating screen method, a spinning cylindrical screen concentric with the round pool of liquid fuel ideally imposes a specified tangential velocity at the screen location while allowing radial inflow of air there at the velocity required by the fire, as it was made in pioneer experiments by Emmons and Ying [7]. This facility has an advantage consisting in permitting an easily adjustable circulation, at the expense of the complex moving screen construction and operation.

An experimental unit similar to that applied in [7] was used in [14]. A gas (propane) burner with a diameter of 5 cm was installed

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at the centre of a stationary table. A rotating mesh screen (with a diameter of 50 cm) and a height of 1 m) was made of stainless steel. The rotation velocity could vary from 0 to 120 rad min^{-1}. The following conclusions resulted from the experiments: (1) if the initial angular speed was not higher than a certain critical value, an initial vertical freely convective flame deviated by a certain angle as a result of the action of the Coriolis force; (2) the angle of the flame deviation from the vertical axis increased with increasing screen rotation velocity and reached 60°; (3) the deviated flame revolved relative to the device central axis at a velocity coincident with the screen rotation velocity; (4) when the screen rotation critical velocity was reached, the inclined flame became vertical again and a fire whirl was finally formed; (5) the fluctuation frequency of the deviated flame was higher than that of the typical flame without screen rotation.

In the fixed-frame experiments [15–19], a number of solid, usually transparent walls are placed symmetrically at a fixed distance from the fire and arranged overlapping each other for the air to enter tangentially only, via the slots created by overlapping parts of the surfaces. Generally, the walls are half-cylinders, but planar walls also may be used because the flow quickly becomes nearly axisymmetric inside. In the fixed-frame facility, the radial component of velocity at the entry locations is almost absent, and the circulation is determined by the inflow requirements of the fire. The circulation may be modified only by varying the dimensions of the fixed frame (for example, by using frames with different diameters), what is not made generally. Thus, the outer boundary conditions for the fire whirl are different for the two main types of experiments, the former of which involves non-zero radial velocity and the latter excludes it. In the most scale-model fire whirl experiments [15–19] is used a fixed-frame facility due to its simpler design.

All the above-mentioned experimental facilities belong to the solid-wall enclosure type, and, therefore, the steady fire whirl scenario (generation and evolution) realized in experiments differs from that one in open (wall-free) real fire whirls generated during urban and wildland fires.

There are some investigations [20–26] where the authors tried to simulate the fire whirls in an open area (without solid walls around the flame).

One of the formation mechanism of fire whirls, which often occur in a cross flow downward of a fire was studied experimentally by Shinohara and Matsushima [20] in a wind tunnel using a flow visualization techniques.

Emory and Saito [21] and Kuwana et al. [22,23] conducted small-scale experiments in a wind tunnel to explore the generation mechanism and to study the dynamics and scaling laws of fire whirls. So Kuwana et al. [23] used L-shaped heat source subjected to a cross-flow wind. The whirls formed in the inside bend of the L-shaped heat source. It was found, that the critical cross-flow wind velocity is very important. If the velocity is above or below the critical value, whirls are less likely to form.

Zhou and Wu [24] and Zhou [25] experimentally simulated the scenario with a central flame surrounded by several other ones, and proved the fire whirl to be generated by the interaction among multiply fires. They discussed configurations under which whirls are able or unable to form. They also showed the whirls to be formed under randomly oriented plume locations.

Liu et al. [26] gives the experimental investigations on the behaviors of square fire arrays which are composed of 3 × 3 to 7 × 7 n-heptane fires initiated from fuel pans (5 cm in diameter, 2 cm in height). A method for analysis the interaction effects (which may induce fire merging and fire whirls) among the multiply fires has been developed. It should be noted that for used square fire arrays the generation of separated flows can take place in the corner areas promoting the generation of fire whirls. The effects of shear flow to fire burning and occurrences of fire whirls were also discussed.

In all these studies [20–26], the fire whirls could be maintained stable over a very short period only, due to the instability of the generating eddy. The study of wall-free non-stationary concentrated (the vorticity is localized in space) fire whirls is complicated due to a number of reasons such as spontaneity of formation, space-time instability and practical impossibility to control the characteristics. The difficulties identified above account for the probable absence of experimental studies producing results on generation and dynamics of wall-free non-stationary concentrated fire whirls.

This study continues the previous authors investigations [27–30], where was demonstrated a principal opportunity to generate and study wall-free non-stationary air vortices under laboratory conditions without using of mechanical swirling devices. There have been determined thermal modes of heating of underlying surface, in which vortices are formed, and their integral parameters (geometric dimensions, lifetime, velocity of travel, and others) have been found [27–29]. In [30] we studied the effect of different net structures on the non-stationary air vortices behaviour.

This paper is aimed to demonstrate an opportunity of the generation of wall-free non-stationary fire whirls under laboratory conditions caused by the axisymmetric flames instability.

2. Experimental setup and measurement procedure

The generation of wall-free non-stationary fire whirls was carried out with the use of a very simple facility, schematic diagram of which is shown in Fig. 1. The experimental setup is mounted in a room with the floor area of 6 × 6 m^2 and ceiling height of 3.3 m, at a distance of 0.5 m from one of walls. The experimental facility includes a table with a height 0.35 m supported by three legs. An aluminium alloy (grade D16AM) plate 1100 mm in diameter and 1.5 mm of thickness was used as the horizontal surface of the table. The upper (underlying) surface of the aluminium sheet was blackened with a heat-resistant paint. Before the experiments, urotropine pellets (hexamethylenetetramine $C_6H_{12}N_4$) were mounted in the central part of the underlying surface. Each pellet has a mass 21 g and is 40 mm of diameter. The combustion heat of urotropine is 30 MJ/kg.

Experiments were carried out with different amounts of the combustible pellets and different arrangements of them on the underlying surface (see Fig. 2). The first, second, and third modes corresponded to combustion of 1, 7, and 19 pellets, respectively.

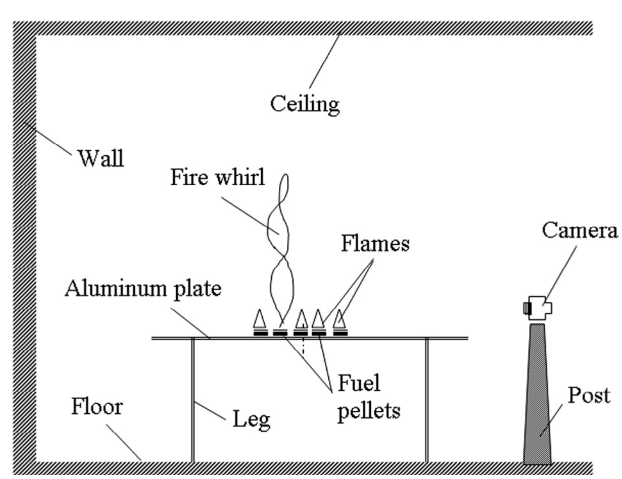

Fig. 1. Schematic diagram of the experimental facility.