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Scaling of a small scale burner fire whirl

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ABSTRACT

The behavior of a fire whirl generated using a burner is examined using Particle Image Velocimetry. Swirl is generated using two staggered cylinder halves that surround the burner. The unsteadiness of the whirl is characterized, and the ensemble-averaged mean velocity profiles are obtained based on the instantaneous whirl position. The non-dimensional circulation and whirl height, and the Froude number based on the centerline velocity and height above the burner, are shown to follow simple scaling laws. In particular, we show that the non-dimensional whirl height depends only on the non-dimensional circulation.

1. Introduction

Fire whirls are standing vortex structures that often form in forest fires. Qualitatively, we know that fire whirls form in the presence of ambient swirl and heat. As the fire on the ground burns, an updraft forms as the hot air rises. This creates a pressure minimum on the ground, which pulls in the surrounding air. The ambient vorticity is amplified by the conservation of angular momentum as the flow moves inward, and it is further intensified along the fire whirl by vortex stretching in the presence of the strain field created by the rising air. This forms the upright and concentrated vortex core typical of a fire whirl. Because of their intensity and unpredictable movement, they can present great danger to firefighters, civilian and animal populations, and property.

To help quantify the formation and characteristic features of fire whirls, many laboratory studies have been conducted, starting with the seminal work of Emmons and Ying [1]. For laboratory purposes, fire whirls are usually generated using either a burner or a pool fire. Also, the swirl is imposed external to the fire by using either a rotating screen surrounding the fire source, or a fixed frame device that introduces swirl into the air as it is drawn into the fire. In a pool fire [2–7], the swirl increases the burning rate because the flame sheet is drawn closer to the surface of the pool when the rotation is established. This provides more heat to the fuel surface, which increases the fuel evaporation rate, which burns more fuel and draws in more air. This surface heating is difficult to control since the fire whirl base can move around the pool fire, unevenly heating the surface, which results in a non-constant heat release rate. In addition, the whirl diameter is typically considerably smaller than the dimensions of the pool and its position is not stationary, which makes it difficult to characterize accurately.

To avoid these difficulties, and to understand better how the flame height responds to the ambient swirl and level of heat release, a burner fire can be used instead of a pool fire. With a burner, the fuel flow rate is kept constant, and can be varied over a wide range. Studies of burner fires are not numerous, but important investigations include [8–11]. Beér et al. [9] demonstrated a 1.7-times increase in whirl aspect ratio of a small-scale burner flame subjected to external rotation, and Lei et al. [11] found that the entrainment coefficient of a medium-scale burner fire whirl is one to two orders of magnitude lower than the entrainment coefficient of a pool fire.

Here, we expand on this work, and describe an experimental investigation of a laboratory-scale fire whirl generated using a burner and a fixed frame swirl generator. The principal aims of this study are to investigate the whirl velocity distributions, and scaling laws for the average whirl height and centerline velocity. To this end, we use Stereo Particle Image Velocimetry (SPIV) to measure the velocity field inside the whirl, as well as in the surrounding flow. Previous studies of fire whirls using PIV include [10,12,13], but only [10] examined a burner fire, and reported some limited velocity distribution data. Here we use SPIV to examine all three velocity components, examine the flow steadiness, and develop scaling laws for burner fire whirls.

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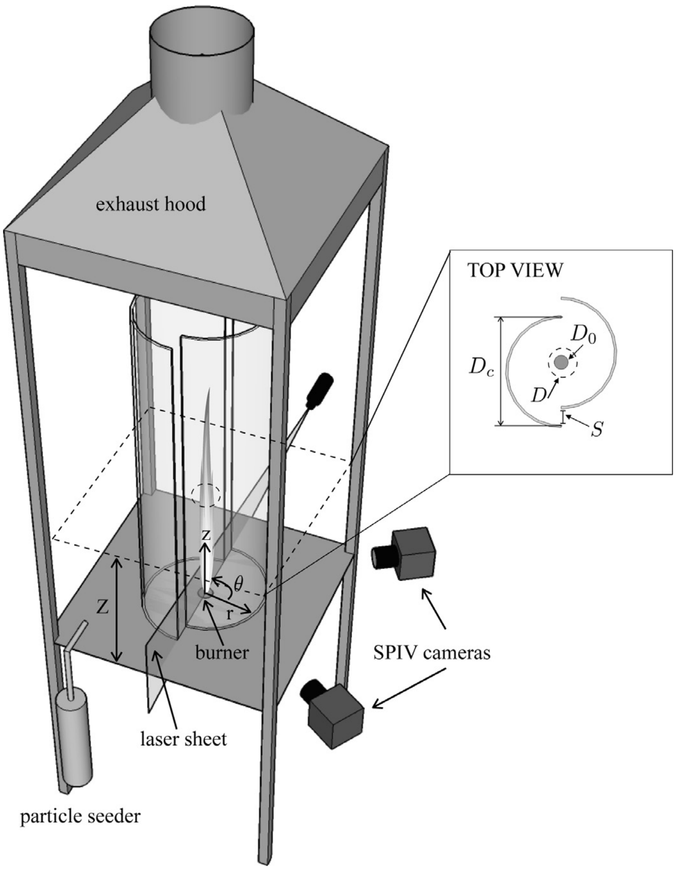

Fig. 1. Experimental setup.

2. Dimensional analysis

In an effort to gain more fundamental insight into the behavior of fire whirls, dimensional analysis has been used in the past, primarily to find scaling laws for the critical lateral wind velocity at which a pool fire produces the strongest fire whirl (see, in particular [14]). Here we consider the case of a burner fire, in the absence of a lateral wind, where the parameters of particular interest are the flame height, H, and the variation of the centerline velocity, U_{CL}.

The experimental arrangement is shown in Fig. 1. Two plexiglass tube cylinder halves were centered and staggered around the burner. As the fuel burns and hot gases rise, air is drawn to the burner through the gap created by the staggered cylinders, establishing a rotating flow that surrounds the fire whirl. The flow circulation can be controlled by changing the gap size, S, and the rate of heat generation, q.

Following the literature that focuses on the effects of combustion, generally with respect to pool fires, we start with

$$U_{CL} = f_1(z, D, D_0, D_c, S, q, C_{p0}, \rho_0, \Delta\rho, T_0, \Delta T, g) \tag{1}$$

$$\Gamma = f_2(z, D, D_0, D_c, S, q, C_{p0}, \rho_0, \Delta\rho, T_0, \Delta T, g) \tag{2}$$

$$H = f_3(D, D_0, D_c, S, q, C_{p0}, \rho_0, \Delta\rho, T_0, \Delta T, g) \tag{3}$$

where z is the vertical distance from the whirl base, D is the diameter of the fire whirl core at height z, D_0 is the burner diameter, D_c is the cylinder diameter, Γ is the ambient circulation level at height z, C_{p0} is the specific heat of air at ambient temperature, ρ_0 and T_0 are the ambient air density and temperature, $\Delta\rho$ and ΔT are the changes in density and temperature at the flame front, and g is the gravitational acceleration.

Dimensional analysis yields

$$Fr = f_1'\left(S^*, q^*, \frac{z}{D_0}, \frac{\Delta\rho}{\rho_0}, \frac{\Delta T}{T_0}, \frac{gD_0}{C_{p0}\Delta T}, \frac{D}{D_0}\frac{D_0}{D_c}\right) \tag{4}$$

where $Fr = U_{CL}/\sqrt{gz}$, $S^* = S/D_c$, and $q^* = q/(C_{p0}\rho_0\Delta T D_0^2\sqrt{gD_0})$. Following Kuwana et al. [14], it is assumed that $\Delta\rho/\rho_0$ and $\Delta T/T_0$ are nearly constant in ordinary fires, and D/D_0 is a parameter of order unity, so that D is assumed to be independent of height. Also, $gD_0/C_{p0}\Delta T$ represents a ratio of potential energy to thermal energy which will be small ($\mathcal{O}(10^{-4})$) D_0/D_c. We use ΔT in these dimensionless quantities instead of T_0 because buoyancy is expected to be significant in this flow. Finally, we assume that the Froude number and circulation are independent of height (this will be verified by experiment). Hence,

$$Fr = f_1'(S^*, q^*) \tag{5}$$

Similarly, we obtain

$$\Gamma^* = f_2'(S^*, q^*) \tag{6}$$

where $\Gamma^* = \Gamma/D_0\sqrt{gD_0}$, and

$$H^* = f_3'(S^*, q^*) \tag{7}$$

where $H^* = H/D_0$.

3. Experimental methods

To explore these scaling relationships, experiments were conducted on the laboratory fire whirl shown in Fig. 1. The burner was a Fisher Scientific 1201 Meker type burner, with an exit diameter of 38.1 mm, and a grid 10 mm thick made of holes 2 mm square. The burner base was sealed with epoxy to create a diffusion flame, and the base was filled with glass beads 3 mm in diameter. The purpose of both the grid and the beads was to evenly distribute the flame across the burner surface. The burner was centered inside the staggered plexiglass cylinders which have an approximate diameter of 305 mm and a height of 890 mm. The fire whirl base and plexiglass cylinder halves rested on a flat, 0.6 m square surface, 0.6 m above the ground, seated inside an enclosure. The burner surface was flush with the raised surface. To prevent warping the cylinder walls due to the heat release, the duration of a single experiment was limited to 1 min, with a 10 min cool down between each experiment. The fire whirl never extended beyond the top of the cylinder walls, with the highest fire whirl achieved being 635 mm in height. The fire whirl was considered established when the base of the whirl remained stationary, although the height fluctuated in time and the whirl precessed around its nominal centerline position.

The flow rate of fuel, dimethyl ether (DME), was controlled with a needle valve, and the flow rate for each valve position was determined using a DryCal 2, with the flow rate determined by the average of 10 measurements. The pressure in the fuel line to the burner was held at 207 kPa. An exhaust, connected to a fume hood and situated 1.5 m above the base of the whirl, drew combustion products and seeding particles out of the enclosure, but only after each data set was taken. For the duration of an experiment, the exhaust was turned off.

The height of the fire whirl was extracted from video of the fire whirl using a modified version of Otsu's method for determining a threshold level for a grey-level image [15]. The fire whirl length was recorded at 60 fps, at a resolution of 1280 × 720 pixels, for 60 s. Otsu's method calculates the separation deviation for each possible intensity value, using a grey-level histogram, and then uses the intensity with the maximum separation deviation as the threshold value. For our images (large amounts of black space with a small flame area, as shown in Fig. 2), using the histogram of the maximum intensity for each row of the image was a more reliable approach.