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Review Article

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Fire whirl, Vortex breakdown, Rotation

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Scaling considerations for fire whirls

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Abstract

This brief report, based on a presentation made at the Eighth International Symposium on Scale Modeling, held in Portland, Oregon, in September of 2017, summarizes and evaluates different methods for classifying fire whirls and their scaling laws. It is indicated that a number of relevant non-dimensional parameters are known for fire whirls, and future scale-modeling experiments could provide useful additional information and insights.

Keywords: Fire whirl; Vortex breakdown; Rotation

Introduction

It is an honor for me to contribute to this inaugural issue of the International Journal of Progress in Scale Modeling. There are so many different fields of scientific and engineering investigation that can benefit from activities in scale modeling that this journal may be expected to experience a lively future. My comments here, however, will be narrow and specific. They pertain only to a subset of my field of combustion, a particular class of fires that involve swirling motion, namely, fire whirls.

Fire whirls have been found to occur over a wide range of conditions, and the different types that have been encountered can be catalogued in different ways. One approach [1] is to define three different classes, that is, fire whirls of type 1, which are centered over burning material, fire whirls of type 2, which move out from burning material then experience extinction in a few seconds, and fire whirls of type 3, which move out into a protected area but remain burning for a much longer time. This classification was developed in scale modeling of the large and devastating fire whirl that occurred in 1923 in the Hifukusho-ato area of Tokyo during the great Kanto earthquake, claiming numerous fatalities, which was an example of type 3. Over the years, however, an increasing variety of fire whirls have been encountered, motivating broadened classifications.

One possible approach to classification is to place fire whirls into five different categories:

1. Whirls generated by fuel distribution in wind.
2. Whirls above fuels in pools or on water.
3. Tilted fire whirls.
4. Moving fire whirls.
5. Whirls modified by vortex breakdown.

Scaling considerations will be addressed first, and then they will be applied to each of these five types separately.

General scaling considerations for fire whirls

Although scale modeling can help to improve understanding even when performed purely intuitively (for example by simply building and testing something small that appears to resemble something of interest which is too large to be studied conveniently), nevertheless quantitative designs of scale models, through the identification and application of relevant non-dimensional parameters, usually will prove to be more reliable and more revealing. Many years ago I identified 28 different types of non-dimensional parameters for combustion, a paper in the present issue by J. Quintiere lists 22 such parameters for fires in general, and 13 parameters have been defined specifically for fire whirls [2]. Yet, even 13 is too large a number, in that it is impossible to arrange a scale model to maintain that many parameters identical to those of the fire whirl of interest. Reasoned judgment therefore is essential for the scale modeling of fire whirls; decisions must be made concerning which parameters are likely to be most important, and non-dimensional parameters deemed to be of lesser importance then

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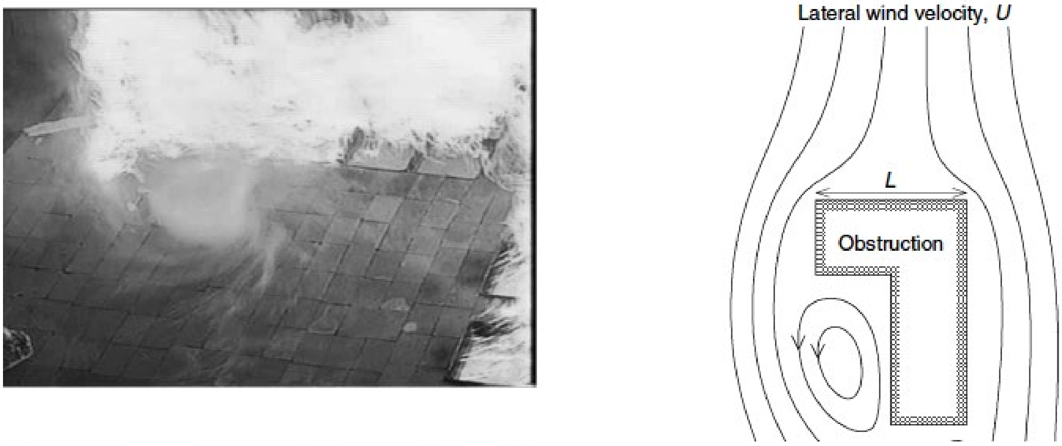

Fig. 1. Illustration of a fire whirl generated by an L-shaped fuel distribution in wind, a photograph of a scale model.

purposely are not forced to be the same in the model as they are at full scale. This is the heart of the art of scale modeling.

Burning rates clearly are important in fire whirls. They generally are determined by the rates of heat transfer from the flames to the condensed fuel. With L a characteristic length scale and g the acceleration of gravity, D denoting a gas-phase thermal diffusivity near the fuel surface and ν the kinematic viscosity there, a relevant scaling parameter for a heat-transfer rate controlled by natural convection is the Rayleigh number, $Ra = (hgL^3)/(\nu D)$, where h is a shorthand notation for an appropriate fractional driving enthalpy difference for the heat-transfer process; the heat-transfer rate, expressed by a Nusselt number, increases with Ra, the variation depending on geometry and size (with turbulent flow tending to dominate at large sizes). In terms of the gas density ρ and the mass burning rate per unit base area of the fuel m'', an effective average normal component of the gas velocity at the surface of the burning fuel can be defined as $V_o = (m''/\rho)$. This is determined by the average rate of fuel gasification per unit area, which (through an energy balance) is the ratio of a heat transfer rate per unit area to the energy per unit mass needed to convert the condensed fuel to gas, and although this burning rate increases with Ra, the specific relationships vary greatly, depending on what fuel is burning, so that V_o scaling with Ra is strongly fuel-dependent. Moreover, the swirl in the flow generally exerts a large influence, as does the fuel orientation, and there are fire whirls in which radiant energy transfer is dominant, further complicating the scaling problem. Burning-rate scaling thus can become the most challenging scaling aspect of fire whirls, to such an extent that, for some purposes, it can be useful to decouple the problem by supplying gaseous fuel at a chosen rate in the scale model, thereby bypassing this complexity, relegating it to later consideration. Fire-whirl burning-rate scaling remains a difficult outstanding problem.

The most eye-catching aspect of fire whirls is their large visible flame lengths. This length will be denoted by H, the flame height for vertical whirls (although the same notation will be retained for tilted fire whirls), its non-dimensional scaling parameter being H/L. For fires in general H/L scales with a fuel Froude number, $Fr_f = V_o/(Lg)^{1/2}$, being approximately proportional to a power of that scaling parameter ranging from $2/3$ at large L to $2/5$ at small L under turbulent conditions. This scaling, however is violated by the swirl in fire whirls. In addition, for a round horizontal fuel source of radius R, under laminar-flow conditions without swirl, taking $L = R$ flame-height correlations for gaseous and liquid fuels often are based on a Peclet number, defined as $Pe = RV_o/D$, according to $H/R = Pe/(4f)$, where f denotes the stoichiometric fuel-to-air mass ratio (typically taking non a small value in this formula). Although this would apply to laminar momentum-controlled gaseous jets, it also has been derived for laminar round buoyancy-controlled fuel jets, both with and without swirl, and it correlates data for small liquid-pool fires, but there are significant departures from this scaling at high swirl. In general, flame-height scaling for fire whirls needs much further investigation, clarifying differences between laminar and turbulent conditions without swirl and explaining combined effects of buoyancy and swirl, which are not yet well understood.

A representative component of velocity along the axis of a fire whirl may be considered to be the velocity V at an axial distance H from the fuel source. For vertical buoyancy-controlled fires, the order of magnitude of V is $(Hg)^{1/2}$, but it may be larger than that at high swirl. Ambient wind can influence fire whirls, and a convenient non-dimensional measure of an average ambient wind velocity U is reasonably defined as U/V. If U is sufficiently large compared with V, then the wind may bend the fire whirl and possibly destroy it, but enhancements may occur when this ratio is of order unity. The most important ambient condition for fire whirls, however, is the circulation Γ about the axis. A swirl number $\Gamma/(VL)$ can be taken to be a critical non-dimensional parameter in determining fire-whirl structures. If buoyancy is important, then a Froude number based on Γ/L instead of V or V_o comes into play. Dependences on such parameters are central to the scaling of fire whirls.

Scaling for different types of fire whirls

Fire whirls can be generated by L-shaped fuel distributions in wind [3], as illustrated in Fig. 1. In this situation, the deflection of the wind by the fire plume generated the swirl, and the fire and wind effectively determine the order of magnitude of the circulation as $\Gamma = UL$, Froude and Rayleigh numbers being relevant parameters for flame heights and burning rates, respectively. A continuous L-shaped fuel distribution, however, actually has four independent horizontal lengths; besides L, the illustrated length normal to the wind direction, there is the width w of that leg, the length l of the other leg, and the width t of that other leg. As t approaches L and w approaches l, the fuel distribution approaches a rectangle; as l/L approaches zero the distribution approaches that of a line fire perpendicular to the wind for small values of w/L, and as L/l approaches zero for small values of t/l the distribution approaches that of a line fire parallel to the wind. These limits emphasize the wide variety of possible geometrical configurations, a variety that clearly is extremely broad, in view of the fact that this reasoning is restricted to continuous fuels, does not consider topography variations, and neglects possible regularly or irregularly placed fuel clumps or barriers, etc. These different configurations produce different fire-whirl patterns, in general, thereby emphasizing complications that arise in attempts to generalize classifications.

Fire-whirl generation different from that shown in Fig. 1 can occur for fires in which liquid fuel burns while floating on water in lakes or rivers if surrounding obstacles or vegetation happen to be arranged in an asymmetric pattern sufficient to produce swirling circulation of the air being drawn into the fire. For scale models in the laboratory, such circulation similarly can be generated by placement of obstacles that force tangential motion of the entrained air [2], or swirl may be forced by moving screens [4]. Tilted fire whirls have been observed in wildfires (possibly associated with topographical features on hillsides) and have been subjected to scale modeling in the laboratory [5]; Froude numbers cannot be fully responsible for the flame lengths of these tilted whirls, and a complete proper physical explanation of these flame lengths remains a difficult outstanding challenge. Fire whirls have been observed to travel at approximately constant velocities along line fires, both in the direction of the wind and, in certain cases, upwind, opposite to the expected downwind direction [6]; the mechanism by which upwind fire-whirl motion can occur is a mystery in need of further study (some ideas having been put forward recently).

It is well known that, as swirl numbers increase, at some point vortex breakdown often occurs—an abrupt bifurcation in which separation of the axial flow produces a bubble-like toroidal vortex encircling the original axis of rotation. Laboratory fire-whirl experiments, with round liquid-fuel pools, surprisingly exhibited this type of vortex breakdown at a critical swirl number [7]. Post-breakdown fire-whirl structures are dramatically different; instead of the usual tall, yellow swirling flames, visible through soot radiation, there are short, fat, blue flames from chemiluminescence (residence times being insufficient for soot production), revealing a triple flame with a bright ring at its outermost location, having a fuel-rich branch extending inward and downward below it and a fuel-lean branch extending inward above. Froude numbers likely have small effects on the flame heights of these blue whirls, and Rayleigh numbers also become relatively irrelevant, the air drawn in over the surface of the liquid pool being cool, so that the convective heat transfer at the surface is directed from the fuel to the air, radiant energy transfer from the flames to the liquid causing the vaporization needed to provide fuel to the fire whirl. Extensive further scale-modeling investigations of these blue whirls are needed if they are to be fully understood.

Conclusions

From these observations it may be concluded that significant unknowns remain concerning scaling of fire whirls. Although some of the relevant non-dimensional scaling parameters are known, for some types of fire whirls these known parameters are not very important, and the dominant parameters remain to be discovered. In general, clearly more fire-whirl scale-modeling research is needed.

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