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Forman A. Williams
UCSD, faw@ucsd.edu

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Category

Research Article

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Keywords

Fire Whirls, Modeling

Cover Page Footnote

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Forman A. Williams

Department of Mechanical and Aerospace Engineering, University of California at San Diego, La Jolla, CA

E-mails: faw@ucsd.edu

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Abstract

A model is described for the overall structure of intense fire whirls, based on a spatially evolving vortex, with circulation enhancement driven by the axial acceleration of low-density gas in the core through the axial pressure gradient. The axial acceleration increases the entrainment rate into the core which, through mass conservation, increases the circulation if the angle between the tangential and radial velocity components remains fixed. The two-zone model employs general balance equations for regions inside and outside a cylinder of fixed radius, each inviscid, the inside region being presumed to have a constant density small compared with the (constant) value outside. In the outside region the tangential component of velocity is assumed to be large compared with the radial component, which, in turn, is assumed to be large compared with the axial component. The model predicts an exponential increase of the circulation with axial distance for sufficiently long whirls, which persists until the fuel in the core is completely consumed. Predictions of the model appear possibly to be consistent with the experimentally observed scaling of flame lengths of strong fire whirls.

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Introduction

Strong fire whirls that exhibit very long swirling flames have been seen in wildfires and can be reproduced in the laboratory by surrounding a round burning liquid pool with barriers that force the entrained air to enter with a tangential component of velocity [1]. Such fire whirls observationally possess an elongated central yellow region with a radius that is practically independent of the axial distance [1]. Upstream from this intermediate region is the complex boundary layer, affected by the ground, leading to the diffusion flame between the incoming air and the gasified fuel that generates the hot combustion products which support the fire whirl [2], while downstream, where the fuel has been depleted, there is a swirling heated plume, eventually spreading, where buoyant rise of hot gases under the influence of gravity persists [3]. The intermediate section between these end conditions, however, often comprises the major portion of strong fire whirls. This may be seen clearly in the two examples exhibited in Fig. 1, where estimates of the lengths of the intermediate sections are indicated by arrows.

The structure of this intermediate region has not been addressed specifically in theoretical investigations for these very intense whirls. Certain aspect of its structure can, however, be inferred from experimental observations. The existence of tilted fire whirls, with axes that are not vertical [1], for example, precludes buoyant acceleration in gravitational fields from being relevant to the intermediate structure, at least for the tilted whirls. This rules out the application of a detailed theory of vertical fire whirls [4], developed for comparison with rotating-screen experiments, leading to numerical integration of three coupled nonlinear ordinary differential equations that include a buoyant gravitational term inconsistent with tilted whirls. In the present work a simplified model is suggested for this intermediate structure, based on a potential-flow-like vortex, with acceleration produced by an axial pressure gradient. In a fire-phenomenology sense, the model might be classified as a zone model in that the properties in the hot, low-density, accelerating core are

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Fig. 1. Rough illustrations of the lengths of the intermediate section of two fire whirls in the field, one being slightly tilted. The intermediate section comprises most of the length in both of these examples; left length scale about 1/10 of right.

approximated as having radially uniform average values, appeal being made to overall-balance conservation conditions for relating the structure within a core control volume to that within an external control volume experiencing rotation. The resulting predictions are not consistent with a previously proposed [1] Peclet-number scaling of flame lengths for tilted whirls because the physical processes assumed to control the structure differ; mainly there is a different treatment of momentum conservation (based on a Burgers-vortex model) as well as explicit inclusion of molecular transport in [1].

The model

With the radial coordinate denoted by r and the axial coordinate by x, the model considers a cylinder of radius R centered at $r = 0$, the density of the gas inside the cylinder being ε times that outside. The cylinder is considered to encompass the outer edge of the visible core of the fire whirl and to enclose all of the gas heated by combustion, with R independent of x, a reasonable approximation, as suggested by the experiments. More specifically, although the visible radii of the strongest fire whirls in rotating-screen experiments appear to decrease gradually with increasing distance along their intermediate portions [4], and longer tilted whirls seem to be slightly thinner than shorter ones [1], these differences are small and hence not likely to be controlling. The gas densities inside and outside the cylinder are each approximated as remaining, and, given representative extents of the temperature increase in combustion, a rough reasonable density ratio would be $\varepsilon = 0.2$. The intermediate region of the fire whirl addressed is taken to begin at $x = 0$ and to extend to $x = L$. Control volumes are considered separately for the two regions $r < R$ and $r > R$, for a slice of thickness Δx about an axial position x.

In the region $r > R$, the positive axial component of velocity, u, is considered to be negligibly small compared with the positive inward radial component of velocity, v, which, in turn, is considered to be small compared with the positive tangential component of velocity, w. All pressures will be divided by the density of the gas in the ambient atmosphere to become expressible in units of velocity squared. In these units, the ambient atmospheric pressure is denoted by p_∞, which is assumed to be constant, independent of x.

Momentum conservation in the radial direction for $r > R$ in the slice shows, given the assumptions concerning the ordering of the velocity components, that throughout this region the pressure in this inviscid flow can be approximated well as $p = p_\infty - \Gamma^2/(2r^2)$, where $\Gamma = rw$ denotes the circulation divided by 2π, which depends only on x according to the differential equation. In addition, the differential equation for mass conservation in this region shows that $v = VR/r$, where V, which denotes the value of v at $r = R$, also may depend on x. The small value of the ratio

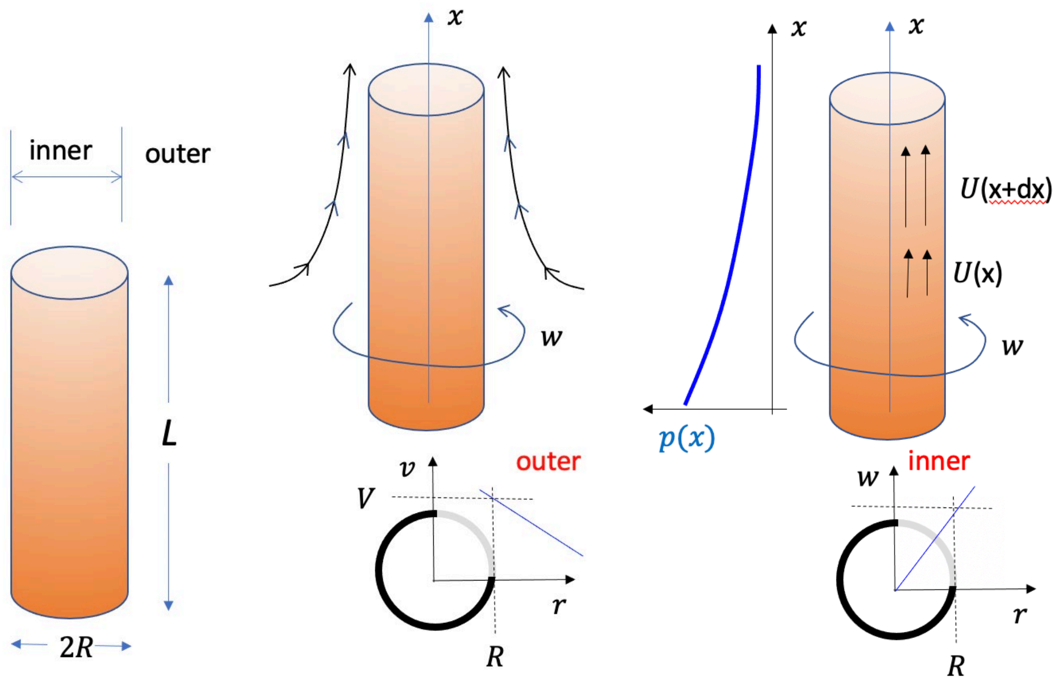

Fig. 2. Schematic illustration of the two-zone model, the control volume being indicated on the left, aspects of the structure of the outer zone in the center, and aspects of the structure of the inner zones on the right.

$(vr)/(wr)$, denoted by δ, probably may be expected to lie between 0.01 and 0.10 in typical fire whirls, this being the smallest of the small parameters in the model. The approximate radial-momentum and mass-conservation equations are essential to determining the structure of this region, with other components of momentum conservation not playing significant roles there.

In this external region, basically, the core-related variation of pressure with x at the cylinder surface, $r = R$, imposes a variation of Γ with x (under these approximations), which is then seen to affect the radial pressure gradient and therefore the inflow rate, there thus being a variation with x of the rate of entrainment of fluid at the boundary $r = R$, reflected in an x variation of the inflow velocity component. These axial changes of the radial velocity component occur along with the tangential-velocity-component variations associated with the x dependence of Γ for $r > R$. In the zero-Mach-number approximation, accurate for fire whirls, the effect of the x variation of pressure at $r = R$ is felt immediately throughout the region $r > R$, producing these axial changes of the velocity components in the plane.

In the region $r < R$, the radial pressure gradient, radial velocity, and radial variation of the axial velocity are neglected, with only averages over the radial direction being considered, so that, according to the differential equation for conservation of axial momentum in this region with negligible axial viscous forces, $dp/dx = -\varepsilon U\, dU/dx$, where U denotes the axial component of velocity in this core. Overall mass conservation for this region requires that the inflow air velocity at $r = R$ be $V = (\varepsilon/2)R\, dU/x$, which must remain small compared with Γ/R (the ratio being δ) for the model to apply, as it should if ε is small enough. The radial component of momentum conservation across the interface at $r = R$ is not addressed, it being assumed that radial pressure and velocity variations within the core can be adjusted to satisfy that conservation. Moreover, the radial variation of the tangential component of velocity within the core does not play a role in the model and so does not need to be addressed.

The inflowing air is assumed to react stoichiometrically with the fuel remaining in the core, to release the heat needed to maintain ε constant, thereby depleting the fuel, reducing the fuel volume at a rate f/ε times the volume rate of entrainment of air, where f denoted the stoichiometric ratio of fuel mass to air mass. The value $f = 0.1$ is roughly typical of hydrocarbon combustion processes. The strong intermediate fire-whirl structure can persist only so long as some fuel remains in this core region to be burnt. From the equation for conservation of fuel, if Y_0 denoted that mass fraction, Y, of fuel in the core region at $x = 0$, then fuel is found to disappear completely when an integral over x of a function involving U reaches $\varepsilon^{1/2}R\ln(1+Y_0)/(2f\delta)$, which determines the flame length, L. Fig. 2 provides schematic illustrations of the model.

The structure

At $r = R$, the axial pressure gradient in the external region must match that in the core. Therefore, by integration, the circulation is related to the velocity in the core through the requirement that

$$\Gamma^2 = \Gamma_0^2 + \varepsilon R^2 (U^2 - U_0^2), \tag{1}$$

where the subscript 0 identifies conditions at $x = 0$. Use of the outer-region relationship between Γ and V in the inflow condition then shows that $(dU/dx) = \{(4\delta^2/\varepsilon)[(U^2 - U_0^2)/R^2 + \Gamma_0^2/(\varepsilon R^4)]\}^{1/2}$, the integral of which,

$$U = U_0 \cosh\left(\frac{2\delta}{\varepsilon^{1/2}}\frac{x}{R}\right) + \frac{\Gamma_0}{\varepsilon^{1/2} R} \sinh\left(\frac{2\delta}{\varepsilon^{1/2}}\frac{x}{R}\right), \tag{2}$$

determines the variation of U with x, which shows that U becomes proportional to $\exp\left[\left(2\delta/\varepsilon^{1/2}\right)x/R\right]$ when x becomes large enough. The resulting structure then exhibits an exponential increase in both the core velocity U and the circulation (measured by Γ) with increasing axial distance x in this intermediate section of strong fire whirls, there also being a corresponding exponential increase of the entrainment velocity.

Flame length

The conservation equation for fuel in the core can be reduced to $\varepsilon R\, d(YU)/dx = -2fV$, which, with $V = \delta\Gamma/R$ and Eq. (1), yields

$$\int_0^L \sqrt{1 + \frac{\Gamma_0^2/(\varepsilon R^2) - U_0^2}{U^2}}\, dx = \sqrt{\varepsilon} R \ln(1 + Y_0)/(2f\delta) \tag{3}$$

as the equation determining the flame length, L, the left-hand side of which approaches simply L in the large-x limit. It is seen from this equation that L will be appreciably larger than R, consistent with the assumed model, if δ and f are small enough. The scaling of L with the diameter D of the fuel source then depends mainly on how R and δ scale with D. Unfortunately no good systematic data are available on the dependence of L on D to test previous predictions [1], since experiments have been performed only at one fixed value of D. Mass-loss rates of fuel were, however, measured experimentally, enabling values of U_0 to be estimated, and the experimental results [1] indicate that, if Eq. (3) is applicable, then the observed variation of L in those experiments must be associated with variations of δ, which then would be the source of the mass-loss-rate variations, but unfortunately δ could not be measured in those experiments. In the rotating-screen experiments [4] the variations of δ are better determined, but the strong fire whirls in those experiments extended well above the top of the apparatus, and so L could not be measured. There thus seems to be no way to test the prediction (3) against any available experimental data. It could be of interest to seek data on the dependence of L on R and δ, to test this prediction, which differs from predictions [1] involving a Peclet number.

Conclusions

The simplified model suggested herein may or may not provide a reasonable description of the intermediate structure of strong fire whirls. The model, moreover, is incomplete in that it does not predict the value of the fire-whirl radius R. If the model is to be employed, then the simplest choice would be to set R equal to half the fuel-source diameter D, but that might introduce appreciable inaccuracy. Future experiments could test how well the model may perform. In general, the development of simplified descriptions of long, strong fire whirls is a challenging task that may not be achievable even if they could provide results that are useful in field evaluations.

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Appendix. A Comment on Scale Modeling of the Intermediate Structure of Strong Fire Whirls

Rotating-screen approaches to scale modeling may be expected to tend to have a circulation Γ determined by the product of the screen radius and the rotational velocity, both of which are independent of the axial distance x. In the model suggested here, however, this circulation increases with x. To the extent that the present model is applicable, therefore, rotating-screen modeling would appear to be inappropriate. On the other hand, scale models in which the rotation is generated by fixed surfaces that induce tangential velocity components of the air drawn into the fire are likely to enforce more nearly a constant angle of flow in the plane normal to the axis, so that the circulation will increase with axial distance if the entrainment rate increases, favoring a value of the parameter δ that remains independent of x. That would be more consistent with the present model. In the field, the atmospheric boundary layer may lead to an ambient circulation that also increases with the axial distance along the fire whirl. Fixed-barrier scale models therefore may produce better modeling of the intermediate structures of real-world strong fire whirls than rotating-screen scale models.