Combustion and Flame 162 (2015) 745–758

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Temperature, velocity and air entrainment of fire whirl plume: A comprehensive experimental investigation

Jiao Lei, Naian Liu *, Linhe Zhang, Kohyu Satoh

State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, PR China

ARTICLE INFO

Article history:
Received 9 April 2014
Received in revised form 2 August 2014
Accepted 21 August 2014
Available online 26 September 2014

Keywords:
Fire whirl plume
Temperature
Axial velocity
Tangential velocity
Mass flow rate
Entrainment coefficient

ABSTRACT

Comprehensive measurements were performed to examine the temperature, velocity (in axial and tangential directions) and air entrainment of propane fire whirl plume in a medium-scale fixed-frame facility. It is found that the radial profile of excess temperature varies consistently with the continuous flame shape and the radial decay rate of excess temperature decreases in the intermittent flame and plume. The centerline axial velocity depends on both the buoyancy and the axial pressure gradient related to the tangential velocity. A weak annular reverse flow is found outside the upward core at $z/D \leqslant 1.0$, while the absolute axial velocity slightly increases with fire size. The growth of axial velocity core is found to be constrained by the reverse flow. The mean axial velocity radius is confirmed to be greater than the mean excess temperature radius in the continuous flame. The radial profile of tangential velocity varies steadily with height, and is little affected by heat release rate. The radial swirl flow consists of the vortex core, the quasi-free vortex and the near wall region, and the active reaction occurs in the vortex core. The plume growth rate increases with decreasing Ri_B (Richardson number) and three distinct regions are identified in different Ri_B ranges. The air entrainment is strong at the bottom inflow boundary layer, while the mass flow rate increases slowly with height as compared to buoyant pool fires. The suppression of air entrainment may be attributable to the radial force balance and stable stratification in the centrifugal acceleration filed. The entrainment coefficient in the continuous flame is about one to two orders of magnitude lower than that in a buoyant pool fire, and it generally increases with height in the plume of fire whirl, approaching the value for pure buoyant plume. The mean entrainment coefficient depends on the mean Ri_B by -1 power law for $z \leqslant H_f$.

1. Introduction

Fire whirl, an intense tornado-like vortex with diffusion combustion, is often observed in urban and wildland fires. Fire whirl may have a size up to over 1 km in diameter, and so it is a great threat to life and property. Besides, fire whirl is an important cause for inducing spotting fire, which accelerates the fire spread substantially. The earliest quantitative experiment of fire whirl was traced to 1967 conducted by Emmons and Ying [1], who produced fire whirls using an acetone pool (d = 10 cm) surrounded by a rotating cylindrical screen (diameter of 2.25 m, height of 3.05 m) which generated a wide range of ambient circulations (Γ_s = 0.60–3.38 m^2/s). The conventional turbulent plume theory was extended to integrate the comprehensive effects of combustion and rotation. However, their fire plume model failed to describe the dependence of fire plume growth on height. As compared to general pool fires, the entrainment coefficient (E) was found to decrease by about an order of magnitude. Note that E was only nominal, because it was obtained by matching the temperature data rather than by using the data of mass flow rate. In the work by Beér et al. [2], both air and helium jet in the non-rotating and rotating coaxial air stream (isothermal model, to simulate the methane flame at temperature of 1400 °C) were used for experiments, and the turbulent shear stress was measured by a hot wire anemometer. They found that the rotation alone caused marked decrease in the shear stresses within a coaxial air stream, while the combined density and rotation will drastically reduce the shear stresses for helium jet. Soma and Saito [3] categorized the historical fire whirls in open field into three different types, for which reduced-scale experiments were conducted. Satoh and Yang [4] designed a fixed-frame fire whirl facility and made a few axial velocity measurements on the centerline. Hassan et al. [5] presented some experimental data on the velocity distributions of a fixed-frame type fire whirl (d = 5 cm, 1-propanol) by 2-D particle image velocimetry (PIV). They found that both the tangential velocity and the absolute radial velocity

* Corresponding author.

http://dx.doi.org/10.1016/j.combustflame.2014.08.017

Nomenclature

a	centrifugal acceleration (m/s^2)
b	plume radius (m)
d	pool/burner diameter (m)
D	side length/diameter of the facility (m)
E	entrainment coefficient (–)
f	dimensional axial velocity profile (–)
L	normalized height adjusted by the plume origin $(z - H_{if})/H_f$ (–)
$\dot{m}$	mass flow rate (kg/s)
n	power exponent (–)
p	pressure (Pa)
$\dot{Q}$	heat release rate (kW)
R	$= D/2$ (m)
Ri	Richardson number (–)
s	stoichiometric ratio (–)
S	swirling number (–)
T	temperature (K)
u	velocity in radial direction (m/s)
v	velocity in tangential direction (m/s)
w	velocity in axial direction (m/s)
Z	normalized height (z/H_f) (–)

Greek symbols

α	power exponent for tangential velocity within the core (–)
β	power exponent for tangential velocity in the quasi-free vortex region (–)
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
Γ	circulation (m^2/s)
ω	vorticity (/s)

Subscripts

r	radial coordinate
θ	azimuthal coordinate
z	vertical coordinate
c	centerline
cf	continuous flame
C	core
f	flame
if	intermittent flame
in	inlet
m	maximum
s	screen
T	temperature
v	tangential velocity
w	axial velocity
wa	wall
∞	ambient condition
0	axial position at $z = z_0$

increase in the radial direction, while remain relatively steady in the axial direction. Later, the works by Chuah et al. [6,7] and Kuwana et al. [8] investigated the flame height and burning rate of small-scale fire whirls respectively produced in a rotating screen and a fixed-frame facility ($d \leqslant 5$ cm). Recently, our group [9–12] presented some quantitative experiment results on the burning rate, flame height, temperature, velocity distributions, mass flow rate and radiative heat fluxes of n-heptane fire whirls in a medium scale fixed-frame facility. Semi-empirical correlations have been established for the burning rates of liquid fuels and flame heights, and the predictions agreed well with the experimental data in literature and our work. Nevertheless, as compared with buoyant fire plume, the measurements were still not sufficiently detailed and the dynamical behaviors of the fire whirl plume have not been fully elucidated.

In this paper, we present more detailed quantitative data for the variation of temperature, velocity (in axial and tangential directions), mass flow rate and entrainment coefficient in the propane fire whirl plume by a medium-scale fixed-frame facility. Several radii that respectively characterize the excess temperature, axial velocity and vortex core are obtained for the first time. The mechanism for suppression of turbulent mixing is revealed and an entrainment model is established. The differences among the fire whirl plume, buoyant fire plume and swirling jet in combustion dynamics are elucidated in details.

2. Theoretical consideration

2.1. The centerline axial velocity in the continuous flame

The momentum equations for a quasi-steady axisymmetric fire whirl of compressible fluid in cylindrical coordinates are as follows.

$$\frac{\partial \rho r u}{\partial r} + \frac{\partial \rho r w}{\partial z} = 0 \tag{1}$$

$$\rho w \frac{\partial w}{\partial z} + \rho u \frac{\partial w}{\partial r} = -\frac{\partial p}{\partial z} - \rho g + \mu \left(\frac{\partial^2 w}{\partial z^2} + \frac{1}{r}\frac{\partial w}{\partial r} + \frac{\partial^2 w}{\partial r^2} \right) \tag{2}$$

$$\rho \left(w \frac{\partial u}{\partial z} + u \frac{\partial u}{\partial r} - \frac{v^2}{r} \right) = -\frac{\partial p}{\partial r} + \mu \left(\frac{\partial^2 u}{\partial z^2} + \frac{1}{r}\frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2} - \frac{u}{r^2} \right) \tag{3}$$

$$\rho \left(w \frac{\partial v}{\partial z} + u \frac{\partial v}{\partial r} + \frac{uv}{r} \right) = \mu \left(\frac{\partial^2 v}{\partial z^2} + \frac{1}{r}\frac{\partial v}{\partial r} + \frac{\partial^2 v}{\partial r^2} - \frac{v}{r^2} \right) \tag{4}$$

where variables u, v and w are the velocity components and r, θ, z are the radial, azimuthal and axial coordinates respectively. ρ, p, g and μ are respectively the air density, pressure, the gravitational acceleration and the dynamic viscosity. Employing $\partial/\partial r = 0$ and $u = 0$ at $r = 0$, and neglecting the viscous terms in Eq. (2), give

$$\rho w \frac{\partial w}{\partial z} = -\frac{\partial p}{\partial z} - \rho g \tag{5}$$

Due to the cyclostrophic balance between the centrifugal force and the radial pressure gradient force above the inflow boundary layer, Eq. (3) is reduced to

$$\rho \frac{v^2}{r} = \frac{\partial p}{\partial r} \tag{6}$$

The integral of Eq. (6) with respect to r from 0 to ∞ yields

$$p(0,z) = p(\infty,0) - \rho_\infty g z - \int_0^\infty \rho \frac{v^2}{r} dr \tag{7}$$

where $p(0,z)$ is the pressure at $r = 0$, and $p(\infty,0)$ at $r = \infty$ and $z = 0$. Substituting Eq. (7) into Eq. (5), we have

$$\frac{1}{2}\frac{\partial w^2}{\partial z} = \frac{\rho_\infty - \rho}{\rho} g + \frac{1}{\rho}\frac{\partial}{\partial z}\int_0^\infty \rho \frac{v^2}{r} dr \tag{8}$$