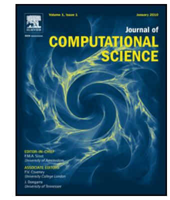
Journal of Computational Science 27 (2018) 21–34

Contents lists available at ScienceDirect

Journal of Computational Science

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



Numerical study of the development and angular speed of a small-scale fire whirl

A.C.Y. Yuen[a,*], G.H. Yeoh[a,b], S.C.P. Cheung[c], Q.N. Chan[a], T.B.Y. Chen[a], W. Yang[a,d], H. Lu[d]

[a] School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney, NSW 2052, Australia
[b] Australian Nuclear Science and Technology Organisation (ANSTO), Locked Bag 2001, Kirrawee DC, NSW 2232, Australia
[c] School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Victoria 3083, Australia
[d] Department of Chemical and Materials Engineering, Hefei University, Hefei, Anhui 230601, People's Republic of China

ARTICLE INFO

Article history:
Received 12 September 2017
Received in revised form 28 February 2018
Accepted 29 April 2018
Available online 2 May 2018

Keywords:
Fire whirl
Combustion
Radiation
Liquid fuel
Large eddy simulation
Flame height

ABSTRACT

The development stages of a small-scale fire whirl including the ignition, flame-rising and fully-developed whirling were successfully captured by a fire field model. Good agreements between simulation and experimental results for vertical temperature profiles and flame height were achieved. With the consideration of the interaction between the liquid and gas phases of the fuel, the radiation heat feedback towards the liquid fuel was aptly predicted. Angular velocities that govern the rotational motion of the fire whirl were evaluated based on computed data. Furthermore, the circulate motion and buoyancy force promoting the extension of flame height were characterised in numerical simulations.

1. Introduction

A fire whirl is a standing vortex structure triggered under certain air entrainment condition, where circular motion is formed by the incoming flow creating a flame revolving around its centre-core. It is notably "taller" and "thinner" than that of a typical free-standing fire. Owing to the revolving motion that allows the hot plume to rise upon a stretched vertical angular path, the radial flame dispersion of the flame is limited [1,2]. This greatly increases the flame height of a whirling fire. Since the core of a fire whirl contains intensive heat energy, it is exceptionally radiative and can greatly promote fire spread among solid combustibles. Fire whirl frequently occur in wildland fires and is recognised as one of the most deadliest and disastrous fire scenario. It can significantly disrupt the natural habitat and ecological system as well as affect prime agricultural land for animal ecosystem [3,4]. One such example is the fire occurred in October 1871 in Peshtigo, Wisconsin, US, which is considered as one of the most devastating wildland fire up to date [5]. During the process, an enormous fire whirl was formed due to the overwhelming firestorm at the forest region. The fire was difficult to extinguish by fire fighters because of its intensity and unpredictable movement. It caused thousands of fatalities and countless amounts of property damages. In spite of decades of researches to investigate this physical phenomenon, the fundamental knowledge of the formation driving mechanisms, characteristic features and physical behaviours of fire whirls are yet to be comprehensively identified [6].

Laboratory studies have been carried out to understand fire whirls. They aim to describe and quantify the phenomenon through the use of empirical correlations or physical equations. These experimental studies were generally achieved by two types of fuel sources [7]: Firstly, gas fuel burner where the fuel gas injection is controlled at a fix rate [2,7,8]; Secondly, liquid fuel pool burner where the amount of fuel gas may increase by evaporation due to the heat feedback from the fire to the fuel surface [9–15]. The latter studies reflect more on the actual wildland fire scenarios since the burning rate varies constantly depending on the amount of bushes or liquid fuel lit. The flame height increase for a pool fire burner should be significantly larger than that of a gas burner when swirling is introduced due to supplementary fuel gas volatile emission via radiation effects on liquid fuels. According to the burning rate and flame height analytical studies of n-heptane fire whirl carried out by Lei et al. [13], the flame height for turbulent flame was proportionally related to ambient circulation and fuel evaporation rate. The flame height increase of a fire whirl is highly related

* Corresponding author.
E-mail address: c.y.yuen@unsw.edu.au (A.C.Y. Yuen).

https://doi.org/10.1016/j.jocs.2018.04.021
1877-7503/

Nomenclature

C_p	Specific heat of constant pressure
D^*	Characteristic length of the fire plume
E_b	Blackbody radiation
$\vec{g}$	Gravitational acceleration force
h	Enthalpy
h_c	Heat transfer coefficient
h_v	Heat of vaporisation
$\bar{I}$	Identity matrix
L	Convection length scale
$\vec{n}$	Normal unit vector
p	Pressure
Pr	Prandtl number
Sc	Schmidt number
$\dot{q}''_{rad}$	Radiation heat transfer source term
R	Gas constant
r	Fully-developed fire whirl radius
$\vec{s}$	Radiative intensity directional vector
T	Temperature of gas mixture
T_l	Temperature of liquid fuel
$\vec{u}$	Velocity vector
V	Volume fraction
v	Fire whirl tangential velocity
X	Concentration
Y	Mass fraction
W	Molecular weight
z	Vertical direction in computational domain

Greek Symbols

κ_a	Gas radiative absorption coefficient
ρ	Density of gas mixture
ρ_l	Liquid fuel density
$\bar{\tau}$	Stress tensor
μ	Molecular viscosity
ω	Fire whirl angular velocity
ω_T	Filtered heat release rate

Superscript

$\cdot$	Rate of change
$^+$	Forward incoming radiative flux
$^-$	Backward incoming radiative flux

Subscripts

fuel	Fuel source
m	Cell interface
l	Liquid fuel
rad	Radiation
ther	Thermocouple

to the growth in angular momentum caused by air entrainment. Nevertheless, it was also reported that the dynamical behaviours of whirling fire plume were yet to be fully clarified to further improve the analytical predictions [6]. Moreover, a series of small to medium-scale vertical shaft fire whirl experiments were presented by Chow, Zou and co-workers [10,11,15]. It was discovered that fire whirl development in general can be catergorised into four stages by observation on the flame height: (i) initial ignition stage where it resembles a free-standing fire and flame height is relatively small; (ii) flame rising-up stage where ambient circulation comes into effect and the flame height increase gradually increases to its maximum state; (iii) fully-developed stage where the flame height is considered to be at its maximum height; (iv) decaying stage where the whirling motion stops and the fire gradually extinguishes due to the reducing amount of fuel remain.

On the other hand, a number of computational fluid dynamics (CFD) simulation studies have been performed to investigate the fire whirl phenomenon from a numerical standpoint based on the combined theories of fluid mechanics, heat transfer and chemical reactions. Earlier works such as Battaglia et al. [16] proposed a simplified steady-state inviscid model without the consideration of small-scale dissipation to study the interaction of circulation with buoyant convection of a pioneering fire whirl experiment constructed by Emmons and Ying [1]. A similar simulation study has been performed by McDonough and Loh [17] by using the CFD commercial software STAR-CD to examine the interaction between vorticity and buoyancy. Furthermore, the numerical research work reported by Snegirev et al. [14], Zhou and Wu [18] also provided some insights on the modelling of fire whirl. Although numerical studies are capable of recreating the actual phenomenon observed by experiment, many assumptions are required to be made in the mathematical models according to experimental data or empirical formulations [6]. On the other hand, the NIST fire code namely Fire Dynamics Simulator (FDS) [19] which is well-recognised in the fire safety community was also utilised for fire whirl simulations. For instants, the work presented by Matsuyama et al. [20] adopted FDS version 3.1. However, a large discrepancy occurred for the computed flame height, temperature and velocity when compared with experimental data. This may be due to the lack of consideration of radiation from the fire source. Forthofer et al. [21] have applied FDS version 5 to investigate the cause of large-scale fire whirls with an L-shaped fire source within a wind tunnel. The model was able to reproduce the formation process and behaviour of fire whirls and it was suggested that further work should be carried out and quantitatively compare with benchmark experiments. Since these studies applied earlier versions of FDS, most of the sub-modelling components including combustion, radiation and liquid fuel models have been significantly improved in the current FDS version 6.1.2.

In this paper, a comprehensive numerical study on the fire whirl phenomenon is carried out to deliver detailed quantitative analysis of the fire whirl phenomenon is numerically investigated including temperature, velocity, mass burn and heat release rates through computational modelling with a revised version of FDS version 6.1.2. The aim is to provide an initial attempt to simulate fire whirl using a liquid fuel model considering radiation and convection heat feedback from the flame under the large eddy simulation (LES) framework. A small-scale fire whirl experiment conducted by Chow and Han [10] will be assessed numerically by the adopted fire models. Several key objectives will be discussed in this article with regards to the physical behaviours, assumptions and difficulty involved in fire whirl simulation including:

(i) capability of computationally modelling the four major stages involved during the development of a fire whirl (i.e. initial ignition, flame raising-up, fully-developed and decaying stages);
(ii) validity and reliability of the adopted methodology in terms of gas temperature, flame height, heat release and mass loss comparisons against experimental data;
(iii) examination of the capability of the liquid fuel model with the consideration of radiational and convectional heat feedback for fire whirl simulations;
(iv) parametric evaluation of the effective absorption coefficient for the liquid fuel model;
(v) visualisation of computational results illustrating the formation of whirling motion, as well as providing an estimation of the flame height;
(vi) evaluation of the angular velocity of the fire whirl based on numerical predictions of velocity and temperature profiles;