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Reciprocal transitions between buoyant diffusion flame and fire whirl

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ABSTRACT

This paper presents a theoretical and experimental investigation on the reciprocal transitions between a general buoyant propane diffusion flame and fire whirl. A small-scale rotating screen facility was used to produce laminar fire whirls. It was observed that under a very low imposed circulation, the initial vertical propane flame would start to incline and revolve around the facility central axis. For a given burning rate, the inclined flame was observed to be converted into fire whirl at a certain critical imposed circulation, while at another lower critical circulation the fire whirl would decay back to inclined flame. It was found that the formation of fire whirl involved the vortex growth from the flame tip to the burner exit. The linear hydrodynamic instability analyses demonstrated that laminar and turbulent fire whirls form at certain critical values of the governing parameters $\mathrm{Re}_l/{B_l}^{1/4}$ and $\mathrm{Re}_t/{B_t}^{1/3}$ respectively, where Re and B are respectively the dimensionless imposed circulation and the dimensionless buoyancy flux. The theoretical results agreed well with the data from small scale to very large scale experiments and field observations in this work and literature. For laminar fire whirl, the critical limit of inclined flame (denoting the maximum $\mathrm{Re}_l/{B_l}^{1/4}$ under which an inclined flame can be sustained) is found to be 1.50 times the critical limit of fire whirl (denoting the minimum $\mathrm{Re}_l/{B_l}^{1/4}$ under which a fire whirl can be sustained).

1. Introduction

Fire whirls in urban and wildland fires may occur under various fuel, topography and weather conditions [1]. Byram and Martin [2] pointed out that in physics the generating eddy, the fluid sink and the ground friction are the three essential factors for the formation of fire whirls. The generating eddy may be induced by the flow channeling by topological obstacles or multiple fires/plumes [3], wake of hill [4], ridge or large fire/plume [5], and transformation of horizontal vorticity into vertical vorticity [6]. The hot products of fires serve as the fluid sink which draws the ambient air with vorticity from the generating eddy into the vortex core. Researchers have constructed laboratory-scale facilities for fire whirls in terms of the concept of generating eddy. The previous works mainly focused on the study of the quasi-steady combustion dynamics of fire whirls [1,7–14], which confirmed that compared to general pool fires, fire whirls are potentially more destructive since they usually involve significant enhancement in burning rates, flame heights, flame temperatures and radiation fluxes to the surroundings. In another aspect, it is of great fundamental importance to study the basic generation mechanism of fire whirls.

During the past several decades, a number of reduced-scale fire whirl experiments were conducted on the formation of fire whirls in wind tunnels. In 1980 s, Emori and Saito [4] designed a 1/2500th scale model in a wind tunnel. They placed heated nichrome wires at several locations behind a hill and blew wind toward this hill. The vortex was found to form at certain locations under suitable wind velocities. Soma and Saito [1] further performed a series of reduced-scale model experiments in a wind tunnel to simulate three different types of real fire whirls (HAFW, HFW and DFW) in the open field. HAFW and DFW refer to the moving fire whirls occurring in a downstream location from the burning area and in an open space surrounded by a burning area respectively. HFW denotes the stationary fire whirl occurring at the burning area. The wind velocity was also controlled to study the conditions under which fire whirls may occur. A large scale experiment with scaling ratio of 1/100 was also carried out in the open field for prototype HAFW which occurred in Hifukusho-ato after the Great Kanto Earthquake in 1923. Kuwana et al. [15,16] also conducted 1/1000th scale model experiments for this prototype HAFW. In 2013, Kuwana et al. [17] reconstructed the Brazil fire whirl that formed and moved on a line fire in a small scale wind tunnel. The flow visualization technology showed that a generating eddy formed outside the moving fire whirl. The above reduced scale experiments all confirmed that fire whirls can only exist within a certain range of wind velocities under any given burning rate. Kuwana et al. [15] further indicated that the critical velocity would be proportional to the upward buoyant velocity. Based on the data from scale model experiments and real scale fire whirls, Kuwana et al. [16,17] concluded that the dimensionless critical wind velocity depends on the dimensionless heat release

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Nomenclature

B	dimensionless buoyancy flux (-)
d	fire source diameter (m)
F	fire buoyancy flux (kg·m/s^3)
g	gravitational acceleration (m^2/s)
k	azimuthal wavenumber (-)
p	pressure (Pa)
Pr	Prandtl number (-)
$\dot{Q}$	total heat release rate (kW)
r	radial coordinate (m)
R	radius of the generating eddy; screen radius (m)
Re	Reynolds number/dimensionless imposed circulation (-)
u	velocity component in radial direction (m/s)
v	velocity component in tangential direction (m/s)
w	velocity component in axial direction (m/s)
z	vertical coordinate (m)
Greek symbols	
α	thermal diffusivity (m^2/s)
ϕ	amplitude function of perturbations (m^2/s)
$\Delta\gamma$	buoyancy increment (kg/m^2·s^2)
η, ζ, ξ	dimensionless coordinates (-)
μ	dynamic viscosity (kg/m·s)
ν	kinematic viscosity (m^2/s)
θ	azimuthal coordinate (m)
ρ	density (kg/m^3)
σ_r	circular frequency of perturbations (s^{-1})
σ_i	temporal growth rate of perturbations (s^{-1})
Γ	circulation (m^2/s)
Ω	angular speed (s^{-1})
ψ	stream function of perturbations (m^2/s)
Subscripts	
F	flame
l	laminar
s	screen/shear wind
t	turbulent
0	reference state
∞	ambient conditions
Superscripts	
$'$	perturbation quantity
$*$	dimensionless form
L	critical limit of fire whirl
U	critical limit of inclined flame
Overheads	
$\sim$	dimensionless form
-	basic flow

rate by the 1/3 power law. Recently, Satoh et al. [18] performed CFD simulations for the formation of single fire whirl by a huge single fire or multiple fires (up to 17 × 17 array fires). A uniform shear wind was applied along one edge of the oil tank array. They proved that fire whirls could only form within a limited wind speed range which depends on the total heat release rate. It should be noted that the flow field may not be strictly symmetrical and the results may rely on the apparatus.

Other works examined the formation of fire whirls in the rotating screen facilities, in which the circulation was imposed mechanically by the rotating screen. Lee and Garris [19] placed a propane line fire equidistant between two vertical parallel screens that moved in the direction parallel to the line fire with equal velocities but opposite in direction. They observed that the line fire could suddenly become multiple equal-spaced fire whirls at a critical condition. By employing the instability theory, they found that the dimensionless critical screen velocity for the occurrence of multiple fire whirls came out to be a function of the buoyancy flux of the line fire to the 1/5 power. Chuah et al. [20,21] placed a 5 cm diameter methanol pool fire at the center of the bottom of a rotating cylindrical screen (60 cm in diameter and 2 m in height). They reported that a minimum screen angular velocity (0.8 rad/s) was required to induce fire whirl. Recently, we studied the behavior of a 5 cm diameter propane fire under weak imposed circulation in a 50 cm diameter rotating screen facility [22]. The vertical buoyant flame was found to be inclined as soon as the screen started to rotate at very low speeds. At first the inclined flame had no obvious self-rotation, while with the increase of screen angular speed, the inclined flame was suddenly converted to vertical swirling fire whirl. The inclination of the single pool fire before formation of the fire whirl was also observed in the fixed-frame facilities [2,23–25].

In summary, the previous studies mainly indicated that the attainment of certain critical circulation or shear wind speed is necessary for fire whirl formation. However, there are very limited comprehensive studies addressing the exact critical conditions and the dominating parameters for the reciprocal transitions between a single buoyant flame and a fire whirl. The current work fills in the gaps. This depends on the experimental work under finely controlled burning rates and imposed circulations. In this work, we utilized a small-scale rotating screen facility for experiments to produce laminar fire whirls, in which the two key parameters of the burning rate and the imposed circulation were finely controlled independently. Two critical conditions for the reciprocal transitions between a single round buoyant flame and fire whirl were achieved for the first time. The dimensionless parameters that determine the transitions between buoyant flames and fire whirls were derived for laminar and turbulent flows respectively, and were verified by using experimental and literature data.

2. Experimental

Figure 1 shows the schematic diagram of a small-scale rotating screen facility (Emmons-type) [7,22]. A stationary circular table was surrounded by a cylindrical wire-mesh screen with diameter of 50 cm and height of 200 cm. The screen was driven by a variable frequency motor and thus can be rotated at any selected speed within 0–120 rpm. The minimum increment of screen rotating speed was about 0.05 rpm ($\sim 2.1\times10^{-3}$ m^2/s). A gas burner (5 cm in diameter, 7 cm in depth) was placed at the table center and filled with glass beads (diameter: 2.70 mm). The porous bed surface was made flat and flushed with the burner rim and the table surface. The slit between the table edge and the screen was less than 3 mm. The apparatus was closed at the base and the entrained air could only enter the cage through the mesh screen. The flow rate of 99% propane transported to the burner was controlled by mass flow meter (Siargo Co. Ltd., MF4008) and flow control valve with less than 2% of the relative errors. The screen rotating speed was measured by a photoelectric tachometer and the error was less than ± 0.02 rpm ($\sim \pm 8.2\times10^{-4}$ m^2/s). A high-speed video camera (SVSI, Inc., GigaView) was used to record the flame at 200 frames per second. All the doors and windows were closed during tests. The total heat release rates ($\dot{Q}$) ranged from 0.33 to 9.50 kW in this work. Each experiment was repeated for at least five times.

3. Theoretical consideration

The transitions between pool fires and fire whirls occur at certain critical conditions and should be related to hydrodynamic instability. Due to the complex interaction between swirling flow and combustion process, it would be of extreme difficulty to make a detailed instability analysis. Since the buoyant flame acts as a fluid sink that