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Flame and flow characteristics of an excited non-premixed swirling double-concentric flame

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ABSTRACT

The flame behaviors and velocity fields of unexcited and excited swirling double-concentric jet flames were experimentally studied. Acoustic excitation was applied to the central fuel jet. The central jet Reynolds and swirl numbers were 2386 and 0.426, respectively. Three characteristic flame behaviors, wrinkled base flame, converged base flame, and diverged base flame were observed by the traditional photographic technique. Jet pulsation intensity dominated the change in the characteristic flame modes. We used a high-speed particle image velocimeter to measure the time-averaged velocity field; results of the excited swirling double-concentric jet flames showed that the streamlines that separate from the central fuel jet exit were significantly deflected toward the central jet axis, while the size of the rotating-inward single-ring vortex decreased as the jet pulsation intensity decreased. Partial flow emitted from the annular air jet flowed over the outer contour of the rotating-inward single-ring vortex and was then entrained into the central fuel jet, with the result that entrainment between the fuel and air was enhanced. The central jet region was formed by two adjacent vorticity-concentrated areas of opposite signs. As acoustic excitation was applied to the central fuel jet, these two areas expanded with increasing jet pulsation intensity. The jet pulsation induced vortical structures periodically evolving from the jet exit with the result that oscillation waveforms of the instantaneous velocities were obtained. The vortical structures entrained fresh air into the central fuel jet in radial direction, resulting in the extreme radial and axial turbulence intensities and improved mixing between fuel and air.

1. Introduction

Double-concentric jets in which a central jet is surrounded by an annular jet have been studied extensively because of their widespread applications, particularly in chemical mixing, industrial combustion, and cooling systems [1–5]. It is well known that the near-field flow and mixing characteristics of double-concentric jets are dominated by the vortical flow structure whose interactions influence the progress and entrainment of the jet flow. In combustion facilities, flame behavior and combustion performance of the double-concentric jet flame are significantly influenced by the mixing characteristics of the central and annular jets. The swirling double-concentric jets that are generated by imparting a swirl motion to the double-concentric jets have been studied by several researchers [6–8]. The imposition of swirl motion on the annular jet of the double-concentric jets can form a recirculation zone with complex vortical flow structures located near the exit of the jet. Huang and Tsai [6,7] found that four complex flow structures—single bubble, dual rings, vortex breakdown, and vortex shedding—appear in the recirculation zone. High central jet velocity induces a large entrainment of the fluids in the recirculation zone and thus reduces the size of the recirculation bubble. The streamline patterns of the dual-ring mode show no stagnation point existing on the central axis, unlike non-swirling double-concentric jets. Kalt et al. [8] found a secondary recirculation zone on the centerline of the flame further downstream of the primary recirculation zone. A highly rotating, collar-like flow feature appears between the primary and secondary recirculation zones. These regions of flow are characterized by high tangential shear stress.

Several investigations have focused on enhancing the combustion performance of the jet flame by improving mixing between the fuel and surrounding air through different techniques [9–14]. These have included applying a piston, solenoid valve, pulsed valve, and a loudspeaker-driven cavity [9,10]. In this latter case, the excitation frequencies were chosen for the non-resonant

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Nomenclature

A_a area at exit of annular jet (=$\pi(D_o{}^2 - D^2)/4$), mm^2
A_c area at exit of central jet (=$\pi d^2/4$), mm^2
D diameter of circular blockage disk, mm
d exit diameter of central jet, mm
D_h hydraulic diameter of annular swirling jet at exit (=$D_o - D$), mm
D_m mean diameter of annular jet exit for calculation of swirl number (=$(D + D_o)/2$), mm
D_o outer diameter of annular swirling jet at exit, mm
f_{exc} acoustic excitation frequency, Hz
E_{exc} root-mean-square excitation voltage measured at loud speaker terminals, volts
Q_a volumetric flow rate of annular jet, mm^3
Q_c volumetric flow rate of central jet, mm^3
Re_a annular jet Reynolds number
Re_c central jet Reynolds number
r radial coordinate, mm
S swirl number, dimensionless
u instantaneous axial velocity, m/s
$\bar{u}$ time-averaged axial velocity, m/s
u' fluctuation velocity in axial direction (=$\bar{u} - u$), m/s
u_a mean axial velocity of annular swirling jet at exit (=Q_a/A_a), m/s
u_c mean axial velocity of central jet at exit (=Q_c/A_c), m/s
u_{c0} instantaneous velocity of central jet at exit at zero swirling flow, m/s
u'_{c0} root-mean-square velocity at the jet exit during acoustic excitation at zero swirling flow, m/s
v instantaneous radial velocity, m/s
$\bar{v}$ time-averaged radial velocity, m/s
v' fluctuation velocity in radial direction (=$\bar{v} - v$), m/s
$\bar{w}$ time-averaged azimuthal velocity component, m/s
x axial coordinate, mm

Greek Symbol
β blockage ratio (=$D^2/D_o{}^2$)
ν_a kinematic viscosity of air, m^2/s
ν_f kinematic viscosity of fuel, m^2/s

frequency and resonant frequency, which was identified as a pipe resonance from acoustic excitation that produced strong mixing near the nozzle. In this case, the fuel jet flow in the vicinity of the nozzle exit broke into disturbed fluid parcels. This phenomenon greatly affects the combustion characteristics of the tone-excited jet, presumably by flow separation from the wall inside the fuel nozzle. A non-premixed jet flame was excited by the loudspeaker at a fuel tube resonant frequency [10]. In the flame stability curve, flame behavior is based on forcing amplitude and Reynolds number and is globally is globally classified as being from an attached flame or from a blown-out flame. As a turnabout vortex motion appears, the flame length is shortened because the inner structure that is formed sharply blocks the entrainment of the surrounding air.

In another study, high-amplitude forcing was achieved by using a pulsed jet flame produced from a fast-acting solenoid valve to pulse the fuel flow at the fundamental organ-pipe resonance frequency of the fuel delivery tube [11,12]. Quantitative mixture fraction imaging in non-reacting jets indicated that the strongly pulsed jets exhibit dramatically enhanced mixing compared to non-pulsed jets [12]. Arrayed micro flap actuators have also been used to introduce disturbances locally into the initial shear layer [13,14]. The flap motion modified shedding of large-scale vortex rings and manipulated the flame characteristics, such as liftoff height, blow-off limit, and emission trend by introducing disturbance directly into the initial shear layer. Several studies [15–18] of axisymmetric jet flames have shown that forcing strongly influences fluid dynamics in the near region of the jet. Sufficiently large perturbations induce periodic discharges of vortical structures that promote rapid and strong turbulent mixing in this region.

The present work is an experimental study of a non-premixed swirling double-concentric diffusion flame subject to acoustic excitation. The characteristic behaviors of flame and flow in an acoustically excited swirling double-concentric jet combustor have been studied [17,18], and acoustic excitation was found to dramatically improve the combustion performance. However, little information on the velocity field and turbulence flow characteristics of the excited swirling double-concentric jet flame can be found in the literature. Based on the flame and flow characteristics obtained by Loretero and Huang [17,18], in the present work we used a high-speed particle image velocimeter (PIV) technique to study the velocity field of this type of jet flame. The results help to better understand the differences in flow fields between unexcited and excited swirling double-concentric jet flames and the physical mechanisms of the latter.

2. Experimental methods

2.1. Experimental setup

The experimental setup is shown in Fig. 1. The central and annular jets were fuel and air, respectively. The fuel applied in this study was propane, composed of 95% C_3H_8, 3.6% C_2H_6, and 1.5% C_4H_{10}. The fuel gas passed through a pressure regulator, a rotameter, and a fluidized-bed particle generator prior to entering the nozzle and then exited through a stainless steel tube (600 mm length, 5.0 mm inner diameter) before being injected into the ambient. The central jet velocity (u_c) was monitored by a calibrated rotameter. The central jet Reynolds number Re_c was calculated using Eq. (1)

$$\mathrm{Re}_c = \frac{u_c d}{\nu_f}, \tag{1}$$

where u_c is the volumetric mean velocity of the fuel jet, d is the fuel jet exit diameter equal to 5 mm, and ν_f is the fuel's kinematic viscosity.

A loudspeaker installed in the upstream cavity of the nozzle was used to produce acoustic excitation to the central fuel jet. A square wave with a duty cycle of 50%, generated by a function generator and amplified by a power amplifier, was used to drive the loudspeaker. Excitation frequency (f_{exc}) and amplitude of jet pulsation were controlled by the function generator and the power amplifier, respectively as described by Ginevsky et al. [19] who termed this longitudinal acoustic irradiation. The resonance frequency of the nozzle-tube assembly in the present study was 180 Hz [17].

The annular jet was a swirling air flow and was supplied with a ring blower. Air driven from the ring blower passed sequentially through the acoustical filters, pressure regulator, rotameter, and fluidized-bed particle generator, before being fed into a cylindrical test rig. A set of guide vanes placed inside the cylindrical test rig was used to generate the annular swirling flow, as described previously [6]. A well-contoured nozzle with a contraction ratio of 9.0 and an exit diameter of D_0 = 40 mm was attached to the cylindrical test rig. A circular disc made of stainless steel (diameter