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PLIF and PIV Measurements of Jet Flames with Acoustically Forced Coaxial Air Jets

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Abstract. Acoustic excitations were imposed to coaxial air jet of non-premixed jet flame with hydrogen gaseous injected axially in the center of the flow. The frequencies of excitation were three dominant resonant frequencies at 1L, 2L, 3L modes including specially 514 Hz (2L-mode) which was estimated theoretically as longitudinal mode of combustor characteristics. The mixing enhancement by acoustic forcing has been investigated quantitatively using PLIF and PIV. The effect of acoustic excitation on combustion process was significant to enhance mixing rate that coincides with specific resonant frequencies. And the behavior of vortex-interaction on flame structure was a good evidence to investigate the phenomenon of shear/mixing layer of fuel-air jet structure. The results obtained in this study concludes that generated streamwise vortex by acoustic excitation has a potential to enhance the mixing rate and abating NOx emissions.

Key Words : Acoustic Excitation, Resonance, Vortex, Coaxial Air

1. Introduction

In turbulent nonpremixed jet flames, the interaction between turbulent mixing and combustion is important role of steadiness, completeness of the combustion and pollutant surrogates. In industrial and commercial burner system, underlying mechanism of abatement of air pollutant and inability to control combustion have been issued to understand the physics the combustion process.

Recently, nonpremixed hydrogen flame using coaxial air has been researched in terms of enhancing fuel-air mixing and potential reduction of pollutant emissions (NOx)[1,5,8]. Moreover, organized oscillation of turbulent mixing established the role of coherent, large-scale vortical structures in enhancing spreading rate of the shear layer of the initial mixing layer by acoustic excitation. In existing combustor, forced fluctuations in fuel-air flow has been considered as a successful and practical applications.

Pont et al.[2] and, Parr et al.[3] investigated external forcing at very high frequency natural modes yields that OH chemiluminescence images indicated enhancement of waste destruction at natural modes with flame shortening due to vortex shedding. Even though, various elementary forms contain such as flow characteristics, mass/momentum transport and combustion phenomenon, the important parameters of large and small mixing on the combustion process could be determined.

The large and small-scale structures on molecular mixing are considerable in the combustion and chemical reacting. Planar-laser-induced fluorescence (PLIF) has been applied to visualize the jet flow and flames in many studies. Mostly, Meyer et al.[6] has investigated vortex formation and mixing in the near field of a driven axisymmetric jet using simultaneous PLIF of nitric oxide (NO) and acetone. PLIF measurements of OH radical in a laminar methane-air flame interacted with vortices of various sizes and strengths and their result showed that the vortex causes significant variations in the OH layer thickness[9]. And in terms of characteristic of vortical flame, the bulk flow velocity and rotating velocity of the generated flow field and

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vortex ring has investigated that the imposed oscillation lift-off the flames or reattach lifted flames and flame behavior has described at different frequencies using particle image velocimetry and CH chemiluminescence[5].

At natural modes of the system, external acoustical excitation on dump combustor performed to study flame deformation by vortex shedding, and nitric oxide (NO) and unburned hydrocarbon (HC) emissions were also measured under resonant condition[2]. Furthermore, Chao et al.[6] found that lifting and acoustic forcing at frequencies higher than the natural frequencies could reduce NOx emissions in partially premixed flames.

In this paper, the purpose of the present investigation is to understand the benefits of acoustic excitation on hydrogen nonpremixed jet flame with involving coaxial air jet. In terms of mixing parameters, to quantify the enhancement of mixing efficiency, the acoustic excitation was forced coaxial air jet and fluorescence concentration method as a flow field marker was applied in reacting and nonreacting case. And the flow fields were visualized to prove the existence of vortex structure by acoustic excitation. In addition, the evolutions of the vortical structure on mixing, by measuring concentration field and velocity observation, were investigated quantitatively.

2. Experimental Apparatus

Test section of burner is a square of 20 cm × 20 cm, and its height is 80 cm. Hydrogen is injected through fuel nozzle in central burner position. Inner diameter of fuel nozzle is 3.0 mm, that of coaxial air nozzle is 15.0 mm and has same center.

2.1 Acetone PLIF Measurement

Acetone PLIF and PIV experimental methods were applied here. For the acetone PLIF, acetone was seeded separately at 0.46% (by volume) to stainless tube of the coaxial air fluid and fuel jet fluid respectively.

The master function generator was the programmed software of Labview express VI (National Instruments), triggering its subsystems timing (triggering delay generator externally) and creating an acoustic pulse that causes a vortex to from in the jet shear layer. Delay generator (SRS, DG-535) was used as the timing device, triggering laser Q-switching events. The wave form from Labview was sent to the audio amplifier which powers the speaker (magnetic coil type). Frequency-quadrupled (266 nm) Nd-YAG laser (Continuum, GCR-170) was used to excite the acetone, since excitation wavelength of acetone is in the ultraviolet. The laser energy is 49 mJ for the 266 nm beam typically. An image from acetone fluorescence is captured by 16 bit ICCD camera (Princeton Instrument, PI-MAX). And Nikkor 105 mm, f# 2.8 lens was used. Total 300 images were averaged with same periodic time delay according to different phases such as 0, 90, 180, 270°, synchronized to the laser pulsing sequence. Spatial resolutions of test sections in which central fuel nozzle are located are each 32.05 mm × 32.05 mm (magnified case) and 83.86 mm × 83.86 mm (resolution of 1024 × 1024 pixels), as shown in Fig. 1.

2.2 PIV Measurement

PIV technique is performed with two 532 nm

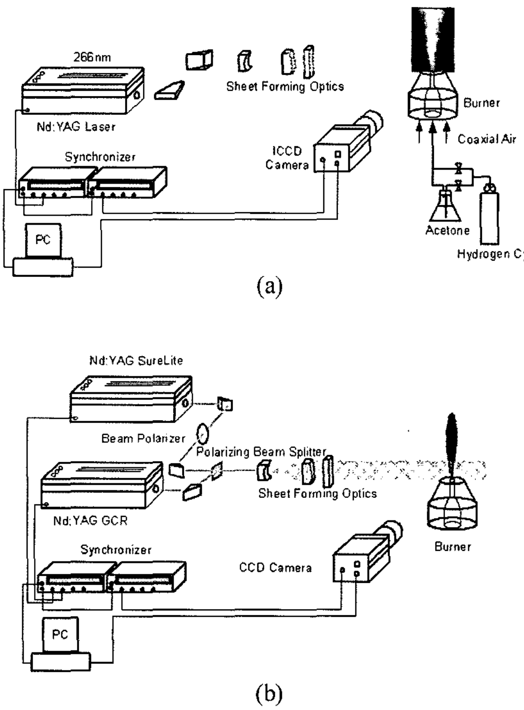

Fig. 1. (a) Acetone PLIF and (b) PIV measurement systems.

Nd-YAG lasers (Spectra Physics GCR-170, Continumm SureLite) operating at 9 Hz that has energy of 100 mJ per pulse. Q-switching of two lasers was controlled by delay generator and oscilloscope was used to check the state of laser pulse that is detected adequately by using photo-diode. Each time separation range 1.5 μs to 25 μs according to fuel jet fluid condition or coaxial air fluid condition. The time retardations oriented in electrical device were corrected perfectly. The particle, TiO2 whose size is about less than 1 μm was used as a tracer of flow. Dichroic beam splitter was then used to collect two laser beams in corresponding optical line and optical lenses were used to form laser sheets that are 200-300 μm thick and 70mm high same as to view section of acetone PLIF measurement.

Particle images in double frame with double exposure were obtained using a CCD digital camera (Kodak, Megaplus ES1.0) of which resolution is 1008 × 1018 pixels. The camera was equiped with an f# 2.8 Nikkor 105 mm lens. The mean values of flow field were acquired averaging 150 image pairs. The velocity vectors were calculated by the FFT-based cross-correlation technique. The size of an interrogation spot was 32 × 32 pixels with a 50% overlap, which was equivalent to spatial size of 2.62 × 2.62 mm.

3. Experimental Results

The frequencies of excitation were three dominant resonant frequencies at 1L, 2L and 3L modes including specially 514 Hz (2L-mode) which was estimated theoretically and measured experimentally as longitudinal mode of combustor characteristics. And these frequencies were issued because NOx concentrations has reduced dramatically at these resonant modes. NOx concentration was measured in down stream (at twice of flame length) when acoustic wave excited the coaxial air jet. Figure 2 shows NOx concentration, which were reduced by 25% at resonant frequencies.

Now, the present paper investigated the flow field in terms of mixing and vortex structures.

3.1 Mean Concentration Fields

3.1.1 Stoichiometric Line

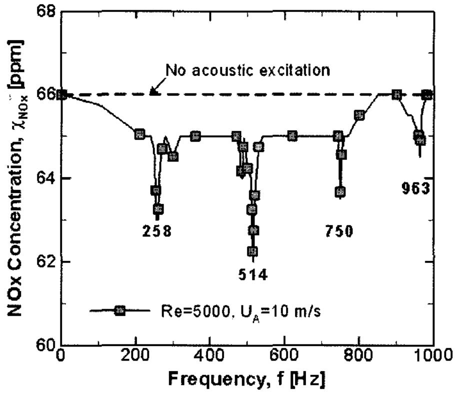

Fig. 2. NOx concentrations of flames by acoustic excitation, U_F = 175 m/s, U_A = 10 m/s, f_{ex} = 514 Hz.

At a seeing level of 0.46% acetone (γ_{act}= 0.0046), the values of the stoichiometric constants increase by 3% or less. By simply adding excess fuel to both sides, the fuel rich reaction is derived as :

$$\Phi\left[X_{H_2}H_2+X_{act}(CH_3-CO-CH_3)+a_{st}O_2+a_{st}\frac{79}{21}\right]\rightarrow$$
$$b_{st}H_2O+c_{st}CO_2+(\Phi-1)[X_{H_2}+X_{act}(CH_3-CO-CH_3)] \quad (1)$$

When considered normalized intensity '1' as 100 % of fuel, and '0' is as 100% air, the stoichiometric mixture fraction for the hydrogen-air flame seeded with 0.46% acetone is 0.031 (see Eq. 2), therefore fluorescence signal fluorescence line having f_{st} = 0.031 (Fig. 3; $\left[\frac{(S_F/E_l)_o}{(S_F/E_l)}\right]$ = 0.3) is the stoichiometric mole distribution of hydrogen fuel[7].

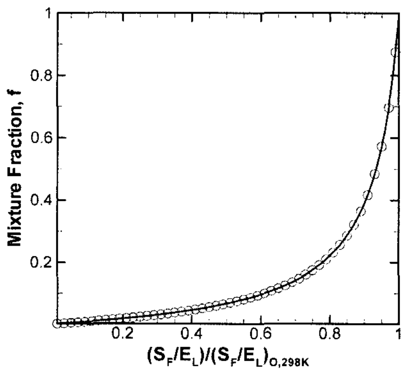

Fig. 3. Mixture fraction related to the acetone LIF signal.

$$f_{st} = \frac{2.0345\Phi}{63.345 + 2.0345\Phi} \quad (2)$$

Figure 4 is fuel concentration fields and stoichiometric lines of which the upper rows(Fig. 4(a)) are no excited cases and the lower rows (Fig 4(b)) are excited cases at 2L-mode. And a bold solid line displays a stoichiometric line, which can be described as chemical equilibrium analysis for the hydrogen-air mixture.

When resonant frequency excited the fuel-air diffusion jet, it is proved that fuel rich region was shrunk in abundance. It means that fuel jet and coaxial air jet are deformed by external forcing excitation to the coaxial air fluid field. So coaxial air affects to entrain coflow air to the fuel rich region, and then caused some azimuthal vortical flow alteration to the fuel jet. It is obviously found when coaxial air velocities becomes larger, jet width of fuel concentration is more intensive. Therefore, fuel rich region altered to be narrow (it is obvious for stoichiometric line to be shrunk in abundance. (Fig. 4)

3.1.2 Concentration Fields of Coaxial Air

Figure 5 shows the mean concentrations at coaxial air fields, where spatial resolution was magnified by 2.5 times than Fig. 4, there outer vortex ring created in neck of the nozzle, thus the external vortex interfered fuel-air jet fluids. Vortex ring development depends on the forcing amplitude and phase difference where acoustic wave coherent structure is penetrating on the fuel-air shear layer. The phases are identical to that of sinusoidal acoustic wave.

3.2 Mean Velocity Characteristics

Figure 6 shows the mean velocity vector in left half, and streamlines and vorticity fields in right haft at each figure. The large scale vortices only exist in coaxial air jet fields. As shown in the vector fields, the flow direction has interfered by vortex structures means that the perturbation could be found to be as a streamline and vortices owing to vortex rollup. The flow goes along the streamline but, inside of vortex field, it rolls, and another streams are incoming from coflow air region. The locations of vortex core center go up according to vortex rollup, and flow streamlines change at each phase, furthermore, the flow by circulation of vortex, is so easily separated that strong circulation made the stream to be transient. From the vorticity fields in Fig. 6, it was interesting to find that, in terms of vector field and streamline, strong circulation is induced at the vortex core, which was generated by acoustic excitation. but the long sticklike vorticity plots at r/d_F = 0 to 2 are no meaning

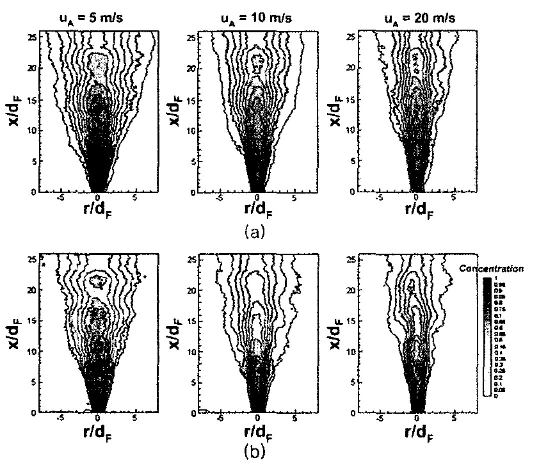

Fig. 4. Fuel concentration fields/stoichiometric line with various coaxial air velocities, in case of Re_F= 5000, U_A = 5, 10 20 m/s (a) no excitation (b) excited at 514 Hz.

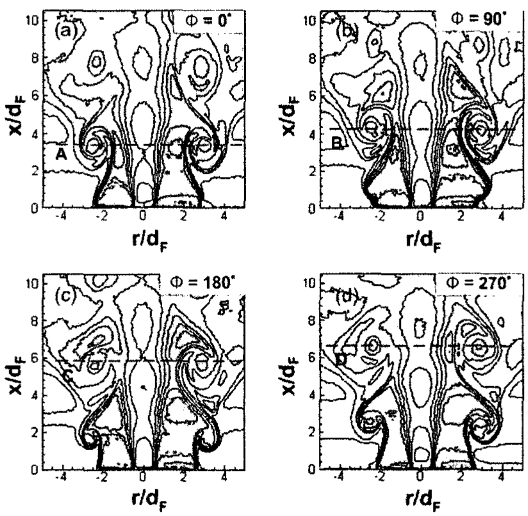

Fig. 5. Concentrations of magnified coaxial air field at fex = 514 Hz, Re_F=5000, U_A = 10 m/s (a) Φ = 0°, (b) Φ = 90°, (c) Φ = 180°, (d) Φ = 270°.

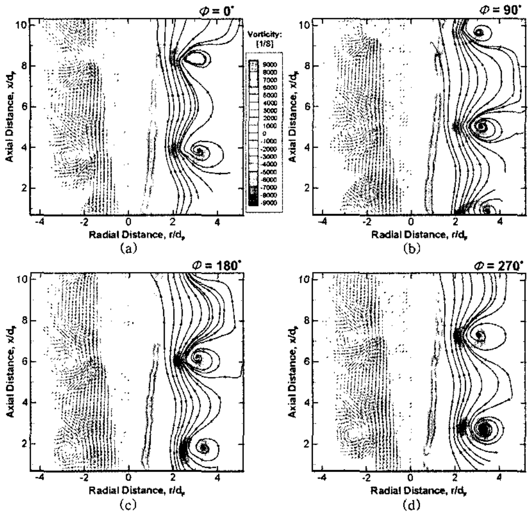

Fig. 6. Mean velocity vector plots and streamlines/vorticity field according to phase difference.

because it was caused due to vector errors inside fuel. So it was found that the mean vorticity tended to induce the coflow toward vortex core, and the flow might experience fine-scale mixing brought about by vorticity fluctuations.

The perturbation of vortex interference was exactly shown in Fig. 7, where the fluctuation of coaxial air velocities grows or decays temporally. The velocity field was investigated for the hydrogen and coaxial air jet, but fuel to coaxial air velocity ratio is too large to display in corresponding figure. Thus only fluctuation of coaxial air velocities were measured at the nearest nozzle neck (height of $1d_F$) where no excited coaxial air velocity is 10 m/s at that location; fuel velocity field is void region. When coherent vortex develops, intial pressure is coming out of the nozzle in single-step according to phase. The maximum velocity was generated fully at $\Phi = 90°$, and as a step goes, the corresponding velocities were decreasing, then the minimum was at $\Phi = 270°$. Reacting results are shown to be similar with non-reacting.

3.3 Modeling of Vortex Structures

Flame zone and vortex-interaction behavior have depicted in detail by inserting particle into fuel jet and furthermore into coaxial jet, on double concentrical jet diffusion flame. The phase of the instantaneous feature is 270° in Fig. 6, there PIV field is corresponding. The flame zone can bulge out in response to the vortical motion in both internal and external structures. Interestingly, the vortex-interaction of flame was moving in and out by inserting coflow air and rolling the vortex, and moreover, flame stretching to the vortex ring was observed and products rotated together means that fuel jet mixed together in the vortex ring inside of the flame bulge boundary, so flame zone is enlarged in the near vortex zone at each vortex enhanced region. As a result, the non-premixed jet flame burns faster than natural condition internally and externally, At external condition, the mixing layer

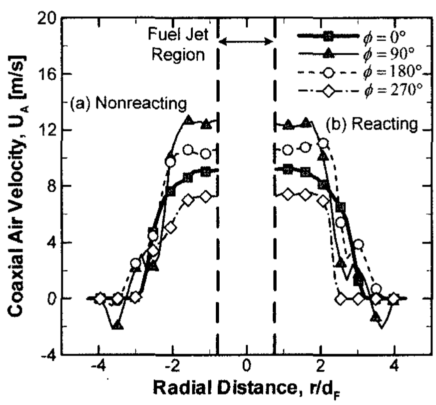

Fig. 7. The radial velocity profiles of coaxial air jet varying with speaker phases, about (a) non-reacting, (b) reacting in case of U_F = 175 m/s, U_A = 10 m/s forcing at 514 Hz, Amp= 1.125 W.

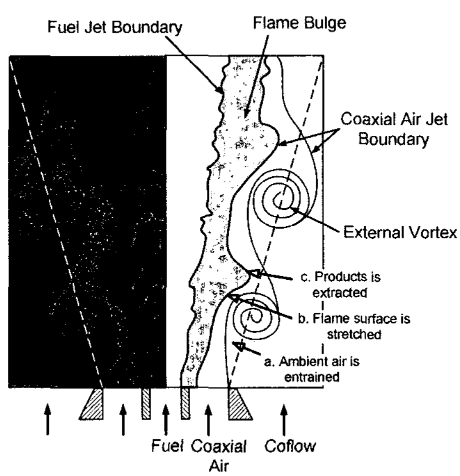

Fig. 8. Conceptual schematics of flame-vortex interaction.

has enhanced by incoming the access air stream, at internal condition, fuel-air mixture burns like partial premixed flame in the vortex shedding area in dotted zone in Fig. 8 (right side).

4. Conclusions

Acoustic excitation to non-reacting/reacting jet or flame was investigated and quantified in terms of concentration and velocity fields and consequently resulted in enhancing efficiency of mixing by the vortex structure and development of vortex ring to fuel jet and flame.

There are summaries of main discussion below

1. The stoichiometric mixture fraction of fuel jet was affected to be narrower strongly than the distribution of non excited case by acoustic excitation, which can be described as deformation of chemical equilibrium in the hydrogen-air mixture. When resonant frequency excited the fuel-air diffusion jet, it is proved that coaxial air affects to entrain coflow air to the fuel rich region, and then caused some azimuthal vortical flow alteration to the fuel jet.

2. Acoustic excitation causes velocity fluctuations of coaxial air jet as well as fuel jet The maximum velocity was generated fully at $\Phi = 90^{o}$, then the minimum was at $\Phi = 270^{o}$.

3. And a streamwise vortex generated in the shear layer between coaxial air jet and coflow air rolls up downstream, it entrains ambient coflow air into coaxial air jet and extracts combustion products out of the flame region.

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