Journal of Visualization, Vol. 5, No. 2 (2002) 145-152

Visualization of Concentration Field in a Vortex Ring Using Acetone PLIF

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Received 1 October 2001.
Revised 7 January 2002.

***Abstract*:** To improve the understanding of flame propagation through a nonpremixed vortex ring, the characteristics of fuel concentration in a vortex ring have been investigated experimentally. The vortex ring was generated by the ejection of propane with a single stroke motion of a speaker. Planar laser-induced fluorescence (PLIF) technique was adopted by seeding acetone as a tracer to fuel stream, in which the PLIF signal intensity is directly proportional to the concentration of acetone. This technique provides non-intrusive and instantaneous measurement of concentration field. Results showed that fuel concentration and its gradient decreased with the evolution of a vortex ring. When a nonpremixed flame propagated through a vortex ring, the flame location coincides with the inner most spiral mixing layer of fuel and air in a vortex ring.

***Keywords*:** vortex ring, acetone PLIF, nonpremixed flame, flame propagation.

1. Introduction

Nonpremixed flames are frequently encountered in practical combustors, such that their characteristics under the influence of turbulence have been investigated extensively. Recently, concerning the flame propagation in nonpremixed flow systems, tribrachial (or triple) flames formed in a fuel/air mixing layer have been investigated (Chung and Lee, 1991; Lee et al., 1997; Lee and Chung, 1997; Ko and Chung, 1999). In a turbulent flow field, the importance of flame propagation through a vortex tube has been emphasized in premixed system. Considering the influence of turbulent flow in nonpremixed system, flame propagation through a nonpremixed vortex ring has also been investigated recently (Choi et al., 1998). The propagating flames were visualized with direct photography and the flow field with a schlieren technique.

The flame propagation through a nonpremixed vortex ring demonstrated consistent result with the "vortex bursting mechanism" (Chomiak, 1977). This mechanism was proposed based on the studies of flame propagation through premixed vortex tubes, in such a way that the flame propagation speed through the vortex ring is linearly proportional to the circulation of a vortex ring. The experiment in nonpremixed vortex ring also showed the similar behavior. The limiting propagation velocity with zero circulation suggested the possibility of a tribrachial flame structure.

The present study is an extension of the previous work (Choi et al., 1998) to visualize and investigate the mixing process in a nonpremixed vortex ring by adopting planer laser-induced fluorescence (PLIF) technique using acetone as a tracer. Acetone has many advantages as a tracer, for example, it absorbs broadband wavelength and has broadband fluorescence emission, high fluorescence efficiency, and short lifetime of fluorescence. In addition, acetone is non-toxic and inexpensive (Lozano et al., 1992). This technique could provide planar images of fuel/air mixing processes as an instantaneous and non-intrusive method. By comparing with flame images from direct photography, flame propagation characteristics in a nonpremixed vortex ring can better be understood.

2. Experiment

The experimental apparatus consisted of a vortex ring generator, an ignition system, and a visualization setup as schematically shown in Fig. 1. The vortex ring generator had a fuel reservoir with 184 mm i.d. and 200 mm in length connected to a loud speaker (200 W, ϕ = 200 mm). A quartz nozzle with 46 mm i.d. and 500 mm in length was connected to the top of the reservoir. The nozzle was enclosed by a 300 mm × 300 mm × 550 mm square cylinder with an open end on top to prevent outside disturbances. The cylinder was equipped with optical windows for flow visualization and for the optical access of incident laser beam. The speaker was driven by a ramp signal from a D/A converter, as depicted in Fig. 1. This signal was amplified with an audio amplifier and actuated the speaker. The relation between the amplified signal and the ramp signal was found to be linear. The resulting speaker motion generated a vortex. Consequently, the ramp signal determines the traversing velocity of a vortex ring and thus the circulation of a vortex. Detailed description can be found elsewhere (Choi et al., 1998) and here the ramp signal is represented for convenience.

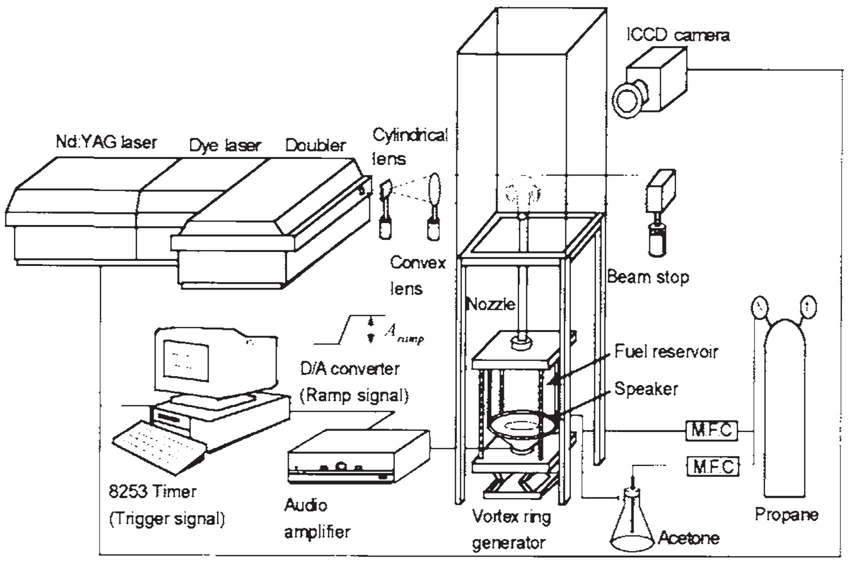


Fig. 1. Schematic of experimental setup.

The fuel was chemically pure grade propane (>99%) and was metered by a mass flow controller (MKS, 1259c). A portion of fuel was bypassed through a mass cylinder where evaporated acetone was mixed with the fuel, and then mixed with the rest of fuel stream for the control of acetone concentration. Since vapor pressure of acetone is high, equilibrium vaporization was expected. The molecular weight of acetone (58 g/mol) is slightly larger than that of propane (44 g/mol). It was confirmed that acetone was steadily evaporated as time proceeds, which was checked by the measurement of the weight of the mass cylinder that contained acetone with a high resolution electronic balance.

A single pulse Q-switched Nd:YAG laser (Spectra-Physics, GCR-150) was utilized to ignite a vortex ring in order to eliminate possible flow disturbances that could be generated if spark electrodes were used. Such disturbances could partly destroy vortex ring structures. A 7 mm diameter laser beam was focused with f 200 mm convex lens, which generated nonresonant gas breakdown leading to an ignition of a vortex ring.

For the PLIF system, a Nd:YAG laser (Continuum, PL 8000), a dye laser (Continuum, ND 6000) with the dye of rhodamine 590, and a frequency doubler were used to obtain 280 nm wavelength, at which the absorption cross-section of acetone is known to be near maximum. A cylindrical concave lens with f 100 mm and a convex lens with f 1000 mm were used to form a sheet beam with 50 mm width. An UV filter was installed in front of an intensified charge coupled device (ICCD) camera (Princeton Instrument, EEV 02-06 ; 576 × 384 pixel) to capture a fluorescence image, and simultaneously to eliminate laser beam and Mie scattering. A schlieren setup with two concave mirrors (ϕ = 240 mm, f = 2 m) was adopted for the visualization of vortex rings. A high speed CCD camera (Kodak, EM1012) with 500-1000 fps, a CCD camera (Pulnix, TM 9701) and an ICCD camera were used to obtain schlieren and direct images. The vortex generator, various cameras and lasers were synchronized and controlled by a PC using 8253 counter.

3. Results and Discussion

Characteristics of acetone fluorescence signal have been checked in two ways. First, fluorescence intensity has been monitored by varying the amount of fuel passing through the acetone seeder. The result is shown in Fig. 2(a). It has been demonstrated that the fluorescence intensity was linearly proportional to the amount of fuel passing through the acetone seeder with the correlation coefficient $R = 0.99$. This implies that the acetone supply to the bypass fuel is in equilibrium vaporization such that the concentration of acetone becomes independent of the amount of bypass fuel. Secondly, the linearity of fluorescence intensity with incident laser energy has also been confirmed (Fig. 2(b)) with $R = 0.99$, where the fluctuation level of the fluorescence intensity is about ±2.1%.

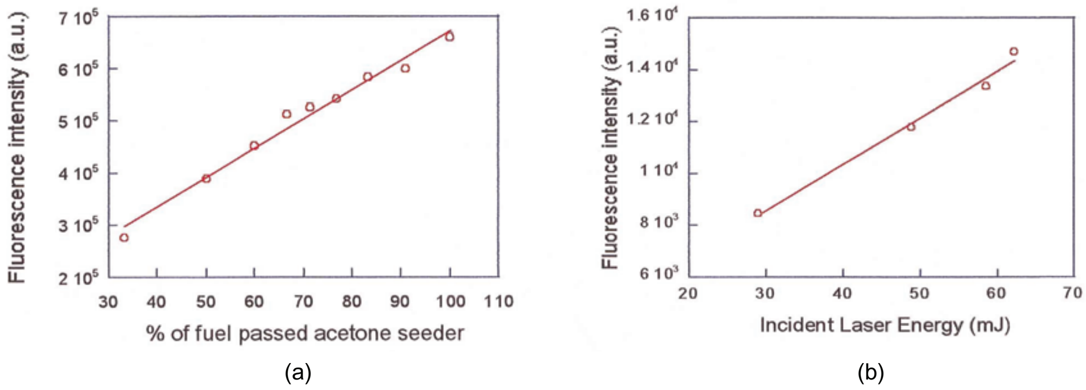


Fig. 2. Relation of acetone fluorescence intensity with (a) acetone mole fraction and (b) incident laser energy.

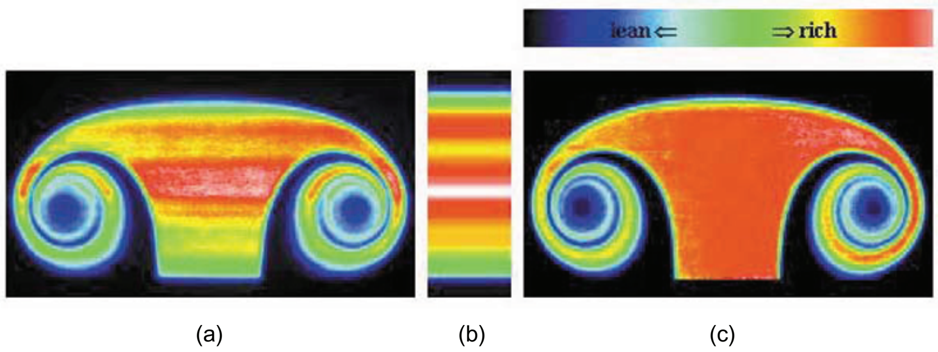


Fig. 3. Acetone PLIF images of vortex ring: (a) raw image, (b) incident laser beam profile and (c) normalized image.

A typical single-shot image of acetone fluorescence is shown in Fig. 3(a). Due to the variations of intensity in the vertical direction of the laser sheet, the fluorescence intensity along the centerline of vortex shows non-uniformity where the gas is expected to be pure fuel. To compensate this, the incident laser beam profile as shown in Fig. 3(b), was obtained from the intensity along the vertical centerline of the vortex ring. The attenuation of laser beam as a result of absorption in the horizontal direction is not considered, since such an effect is much weaker than that in the vertical direction due to sheet beam profile. The normalized image can be obtained by dividing the images of Fig. 3(a) by Fig. 3(b) and the result is shown in Fig. 3(c). It demonstrates that fuel and air are mixed only in the thin mixing layers around the fuel jet. Especially, the role-up vortex ring region forms a spiral mixing layer of fuel and air such that significant degree of fuel-air mixing is expected.

Schlieren images of the developing process of a vortex ring with time after the vortex generation by the speaker is shown in Fig. 4, where t_s is the time after the actuation of the speaker. The sequence demonstrated that the vortex inner ring enlarges as time proceeds. It is expected that fuel-air mixing will proceed in this inner ring region by the entrainment of ambient air.

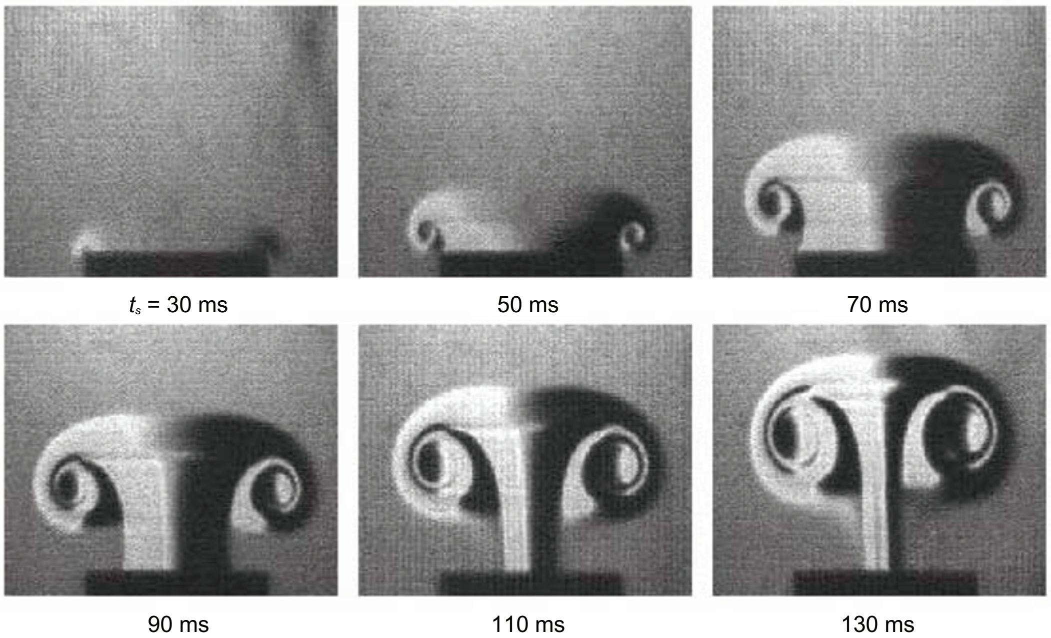


Fig. 4. Schlieren images showing developing process of a vortex ring.

Figure 5 shows acetone PLIF images of the developing process of a vortex ring. As compared to the schlieren images, which can be considered as the integration of density variation in the direction of line-of-sight, the PLIF images reveal local information on the laser sheet. The fluorescence images further substantiate the fuel-air mixing process. These images confirm that vortex inner ring diameter increases as vortex roll-up proceeds, and fuel-air mixing is enhanced in the vortex tube region along the spiral layers by exhibiting comparatively low intensity in the inner most spiral layer.

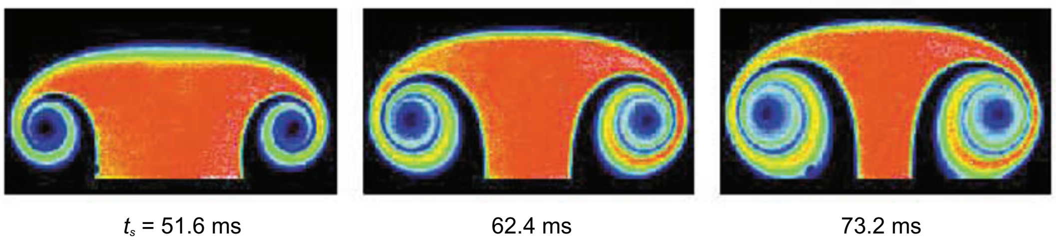


Fig. 5. Acetone PLIF images showing developing process of a vortex ring.

The effect of the circulation of vortex ring on vortex inner ring structure was investigated, where the circulation is represented in terms of the ramp signal amplitude A_{ramp}. The amplitude of ramp signal was found to be proportional to the displacement of the speaker cone. Thus, by varying the amplitude of the ramp signal, one can effectively control the translational velocity of a vortex ring, and thereby the circulation of vortex ring (Choi et al., 1998). Figure 6 shows the acetone PLIF images, together with the concentration profiles along the horizontal axis at the center of the vortex inner ring. Here, the center of the vortex ring is defined based on the local maximum of fluorescence intensity. Corresponding side view images of typical propagating flames are also shown, where the images were taken at the right angle to the propagating direction of a flame, when the ignition was started at the left end of a vortex tube. They are the false color images from direct photographs by the ICCD camera, thus the color represents flame intensity.

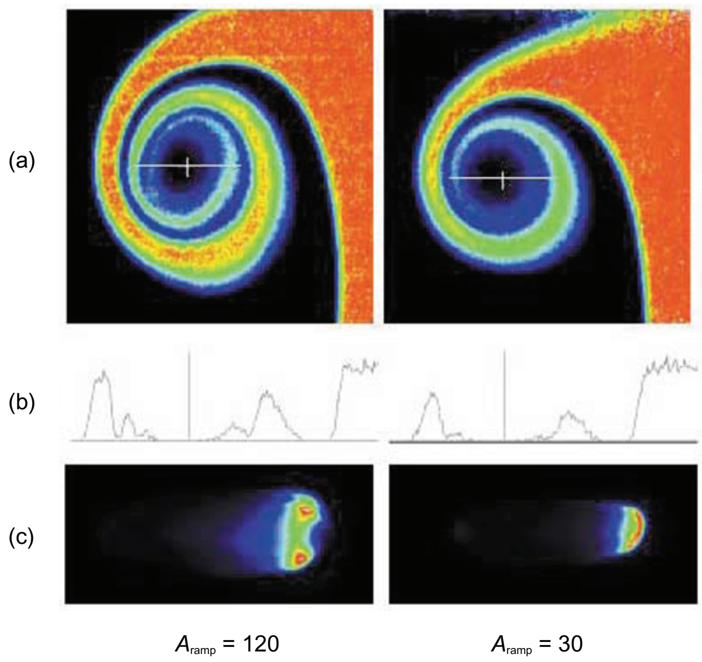


Fig. 6. Effect of ramp signal amplitude A_{ramp} on vortex ring structure: (a) acetone PLIF image, (b) concentration profile and (c) direct photograph of flame.

When the circulation or the ramp signal is strong, the roll-up becomes more pronounced as indicated by the spiral structures of fuel stream in the vortex inner ring. Corresponding side view of the flame is concave in shape at the central region and has two peaks, implying that the flame is propagating through the circular-shaped spiral mixing layer in the vortex inner ring.

When the circulation is weak (A_{ramp} = 30), the shape of flame is convex at the central region, indicating that the flame is propagating through the central region of the inner ring by having near premixed flame mode. The reason being that is when the ramp signal is weak, the traversing velocity of vortex ring becomes small and also the roll-up motion becomes weak. Consequently, there is sufficient time for the fuel and air to be mixed nearly homogeneously in the central region of the vortex inner ring.

Fuel concentration along the horizontal axis at the center of inner ring is shown in Fig. 7 at various ramp signal amplitudes. Here, the normalized coordinate indicates distance from the center of an inner ring divided by the diameter between the inner most local maxima in fluorescence intensity. The profile closely follows a parabolic nature in the central region. For small A_{ramp}, the profile becomes flattened in the region. The stoichiometric fuel mole fraction for propane/air is 0.04, which is quite small for a quantitative measurement using the acetone PLIF.

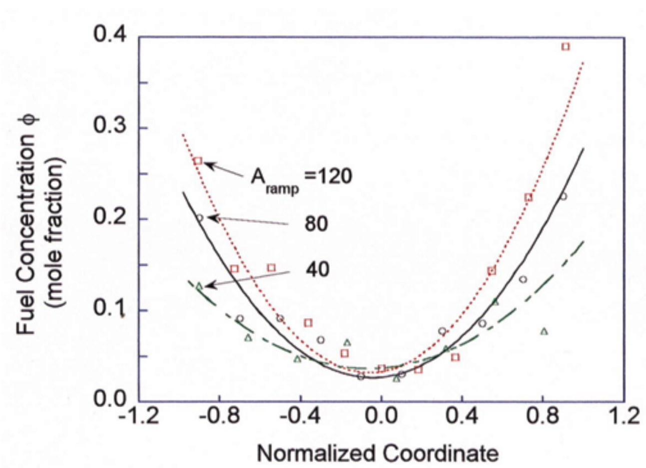
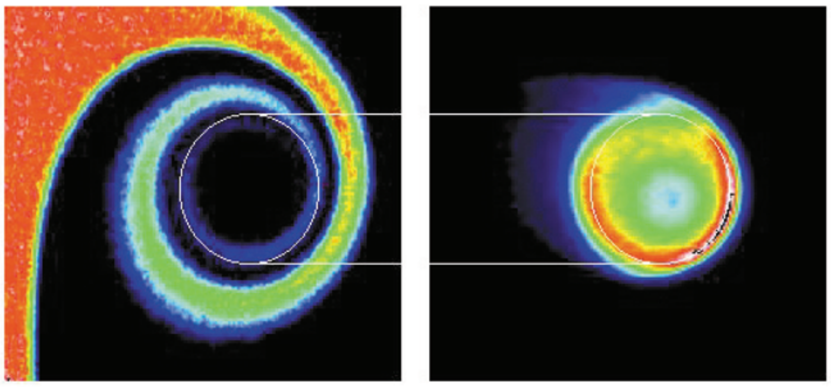


Fig. 7. Fuel concentration along horizontal direction with variation of A_{ramp}.

That is, the signal-to-noise ratio becomes too small to identity the precise location of stoichiometry. Even with the lack of the quantitative determination of stoichiometric location and its relation with flame shape, a qualitative explanation on flame shape and concentration profile can be drawn from the experiment.

To further illustrate the flame characteristics along a vortex ring, an acetone PLIF image and the front view of propagating flame is shown in Fig. 8. The highest intensity contour from the direct photography with the ICCD camera shows near circular shape and its diameter corresponds to the size of the smallest spiral of the mixing layer of the vortex ring. The results from Figs. 7 and 8 imply that the flame propagates through the stoichiometric region inside the vortex ring as suggested previously (Choi et al., 1998).



(a) (b)

Fig. 8. Comparison between (a) acetone PLIF image and (b) ICCD image of front view of propagating flame.

For an experiment in a nonpremixed vortex ring, flame propagation can be effectively confined in the circumferential direction along a vortex tube by controlling the time delay from the fuel valve shut-off to the actuation of the speaker, t_d. If this time delay is kept short, the flame can be confined only in the circumferential direction without further engulfing the whole vortex and is finally extinguished upon collision of two flame fronts at the far end of the vortex ring from the ignition point. In this case, only a blue flame appeared (Choi et al., 1998). In contrast, if the time delay is maintained long enough, the fuel and air diffuse into each other and premixing occurs near the nozzle exit region prior to the fuel ejection by the speaker. It means that the multiple layers of fuel-rich and fuel-lean regions surrounding the vortex inner ring become flammable. As a result, the flame propagates in the radial direction from the vortex center and eventually engulfs the entire vortex ring showing yellow luminosity during the later stages of flame propagation. An example of this case is shown in Fig. 9, which are direct photographs taken with a 35 mm camera (Nikon, FM2).

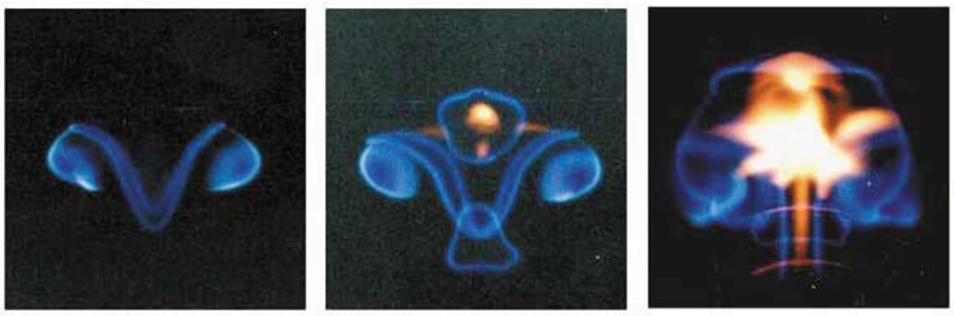
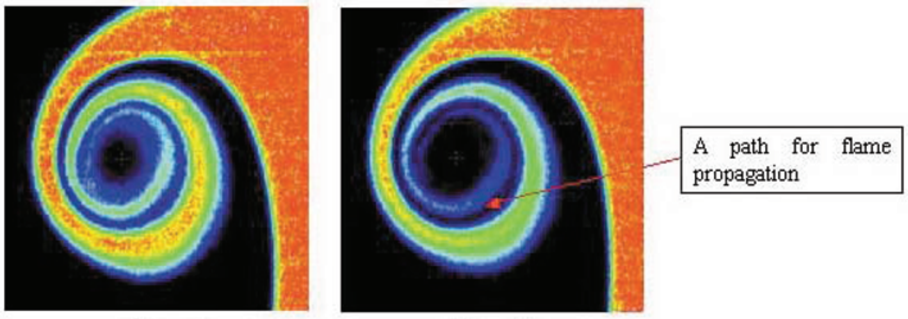


Fig. 9. Example of flame propagation through entire vortex ring.



(a) t_d = 5s (b) t_d = 15s

Fig. 10. Comparison of acetone PLIF images with different time delays.

Figure 10 provides a clue for understanding of these phenomena, showing acetone PLIF images with different time delays from the fuel valve shut-off to the actuation of the speaker. If the time delay is maintained long enough, the fuel and air diffuse into each other and premixing occurs near the nozzle exit region. Then, the air and fuel layers in the inner ring can be flammable. This plays a role as a path for flame propagation to the entire vortex ring.

4. Conclusion

Concentration field in a nonpremixed vortex ring, which was generated by a single stroke motion of a speaker, has been visualized by the PLIF technique using acetone as a tracer. The developing process of a vortex ring was visualized, demonstrating an entrainment of air and rolling up of vortex inner ring. As the ramp signal amplitude decreased, which controls the intensity of the circulation of vortex ring, fuel and air mixing was enhanced. In such a case, broadly and nearly uniformly premixed region within the vortex inner ring was formed. It has been found that the diameter of a flame when propagating through a vortex ring was comparable to the diameter of the smallest spiral mixing layer of the rollup vortex. This supports that a flame, when propagating through a nonpremixed vortex ring, may traverse along the stoichiometric contour.

Acknowledgments

This work was supported by the Combustion Engineering Research Center.

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