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PIV Measurement of Velocity Field in a Spray Combustor

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Abstract : This paper reports a velocity measurement technique using PIV for application to a luminous flame in a spray combustor. The present system consists of a standard PIV system, a rotary shutter and a band-pass filter, the combination of which removes the influence of the high intensity of the luminous flame. The effectiveness of the rotary shutter is studied by changing the shutter speed from 2 ms to 37 ms. The simultaneous observation of the velocity field and the flame structure was carried out in the combustor model for a boiler. The measured velocity field indicates that the exit velocity from the burner is increased by chemical reactions, but the flow pattern inside the combustor is kept similar to that without combustion.

Keywords : Visualization, PIV, Combustion, Flame.

1. Introduction

The measurement of velocity field in a combustor is an important topic of interest and has been studied from the fundamental point of view as well as the practical design considerations of the geometry of the combustor. Hence, the combusting flow field has been studied using Laser Doppler Anemometry (LDA), which enables the understanding of the velocity field in the combustor. Recently, there is a strong demand for the measurement of the velocity field by Particle Image Velocimetry (PIV) (e.g. Adrian, 1991), because this technique allows the measurement of spatial distributions of instantaneous velocities in the combusting flow (Kawanabe et al., 2000; Stella et al., 2001).

When the sprayed fuel combusts in a boiler chamber, a luminous flame often appears inside the chamber especially near the burner. Such a velocity field is rather difficult to measure by PIV, because the captured images suffer from the influence of high intensity of the luminous flame. Therefore, the emission light from the luminous flame has to be removed to obtain the scattered light from the tracers. In order to overcome this problem, Shioji et al. (1997) used a high-speed shutter, 100 ns, of a gated CCD camera for the velocity measurement of ethylene diffusion flame. Later, the measurement of droplet velocity of the spray combustion was carried out using a band-pass filter combined with a multi-intensity layer PIV technique (Ikeda et al., 2000; Palero and Ikeda, 2002), which allowed the study of the droplet dynamics of the spray combustion. However, the knowledge about the PIV measurement of gas velocity in the luminous flame is quite limited, so that further detailed study concerning the measurement technique is necessary.

The purpose of this paper is to study the technique of velocity field measurement in spray combustion by PIV in combination with the rotary shutter and the band-pass filter. This technique is applied to the simultaneous observation of velocity field and flame structure under combustion to understand the gas-flow mechanism in the combustor.

2. Experimental Setup

2.1 Combustor Model

An experimental model of the prototype combustor used in the present study is shown Fig. 1. The model has a height of 161 mm with a horizontal area of 105 mm × 105 mm, which is a 1/5 scale model of the prototype combustor for a domestic boiler. Top and bottom plates and a side plate supporting the burner were made of iron, while the other plates were made of heat-resistant glass in order to observe the flow inside the combustor model. The top plate has a hole of diameter 61 mm, through which the gas exits to the outside. A gun-type burner having an inner diameter of 51 mm was fixed to the mid plane of the side plate and at the vertical distance of 54 mm from the bottom. Kerosene fuel was sprayed from the burner nozzle using a fuel pump operating at 0.7 MPa. The spray angle was 68° and the Sauter's mean diameter of the spray droplets was 56 μm, which were measured by the time-averaged observation of spray and the interferometric imaging technique, respectively, under the condition without combustion (Hosokawa et al., 2002). Air was supplied from the blower located upstream of the burner and was followed by the spray nozzle and the baffle plate, which generates a swirl flow to assist the mixing of air and fuel in the combustor. In the present experiment, the mass flow rate of air and fuel was 4.3 g/s and 0.056 g/s, respectively, so that the fuel air ratio was 77. The air velocity U_0 at the burner exit was set to 1.4 m/s, which was measured at the orifice flow-meter upstream. The average temperature in the combustor was measured by a K-type thermocouple. The temperatures at the inlet, center and the outlet of the combustor were 560℃, 800℃, and 420℃, respectively.

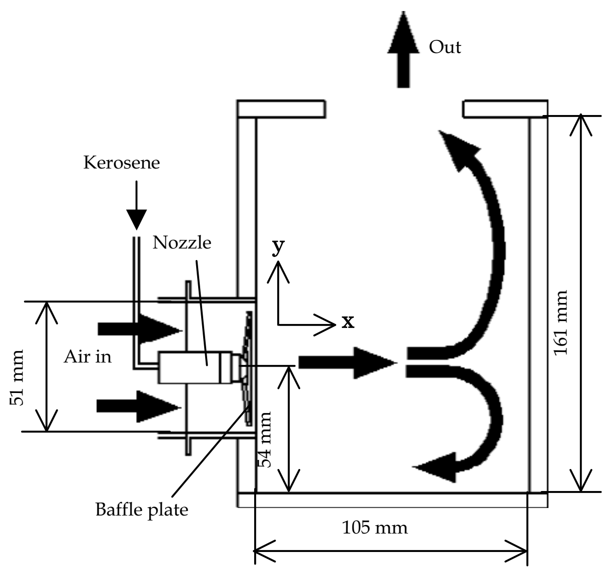

Fig.1. Experimental combustion chamber.

2.2 PIV System

The experimental setup used in the present study is shown in Fig. 2. The setup consists of a monochrome CCD camera (1008 × 1018 pixels with an 8 bit gray scale), Nd:YAG lasers (50 mJ per pulse and 532 nm wavelength) and a pulse controller. Illumination for the flow visualization in the combustor was provided by the double-pulsed Nd:YAG lasers, which were operated at pulse interval of 135 μs with a pulse width 6 ns and at pulse repetition rate up to 15 Hz. The thickness of the light sheet was set to 1 mm. When this PIV system was applied to the spray combusting flow, the luminous flame was found in the second frame of the camera, which was due to the long exposure

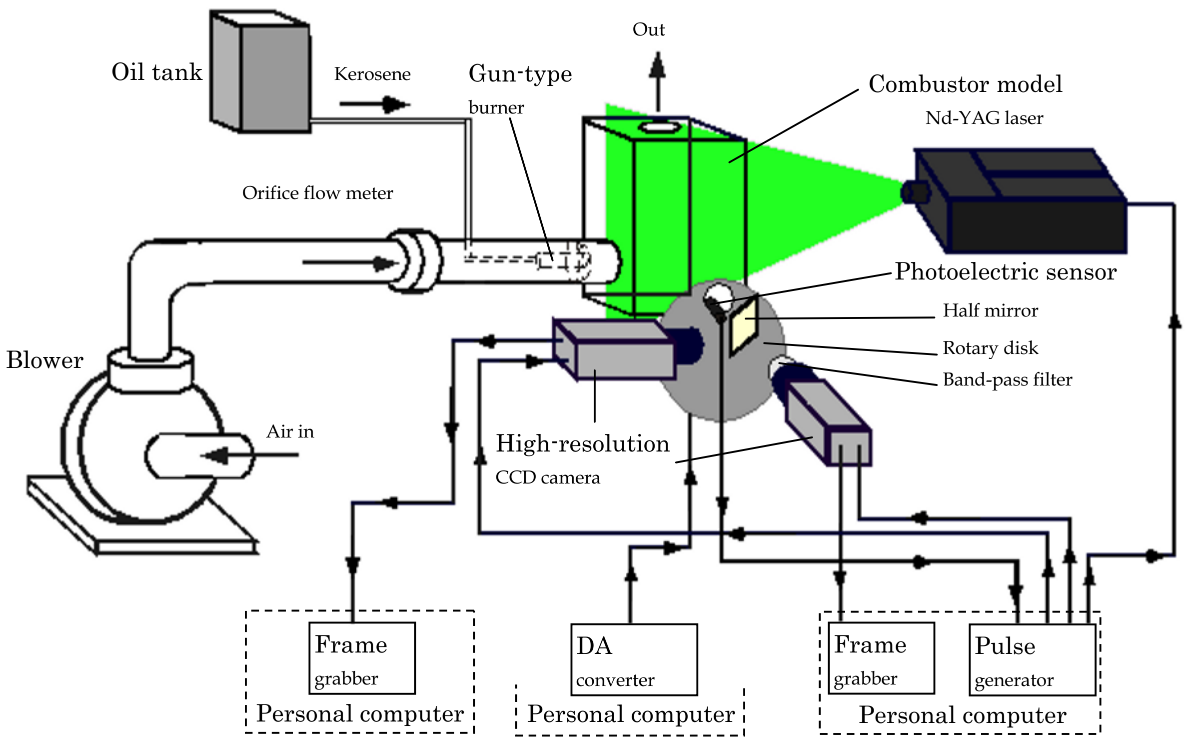

Fig. 2. Experimental setup.

time of the frame. While the exposure time of the first frame was short enough, so that the luminous flame was not observed. This situation was not changed by installing a band-pass filter (532 nm$\pm$10 nm) in front of the camera.

In order to solve this problem, a rotary shutter mechanism was proposed in the present study, which consists of a rotary disk (250 mm in diameter) and a DC servomotor. The disk has a hole of 30 mm in diameter located at radial distance 100 mm from the disk center. The rotary disk was driven by a DC servomotor, which was driven by a DA converter equipped in a personal computer. In order to synchronize the rotary shutter with the timing of double exposures of the camera, a photoelectric sensor was placed over a rotary disk to produce a pulse signal for the illumination of the laser and for the synchronization of the camera operation. The hole of the rotating disk was placed just in front of the monochrome CCD camera by adjusting the position of the photoelectric sensor. Then, the hole of the disk acted as a shutter of the CCD camera. In order to keep the synchronization of the camera and the rotary shutter, the fluctuation of the disk rotation was kept smaller than 0.1% of the rotation speed by using the servo control of the motor.

The simultaneous observation of the flame structure was carried out at the instant of velocity measurement using the second camera placed normal to the camera for PIV measurement. The details of the camera arrangement are shown in Fig. 3. The second camera was operated synchronously with the PIV camera and was observed through a half mirror. The second camera was operated without a band-pass filter.

The exposure time of the rotary shutter was varied by changing the rotation speed of the disk. The range of the shutter speed was 2 to 37 ms in the present experiment. The timing chart of the camera operation, the laser illumination and the hole position of the rotary shutter is shown in Fig.4. The exposure time of the rotary shutter Δt is defined by the half width of the observation area S.

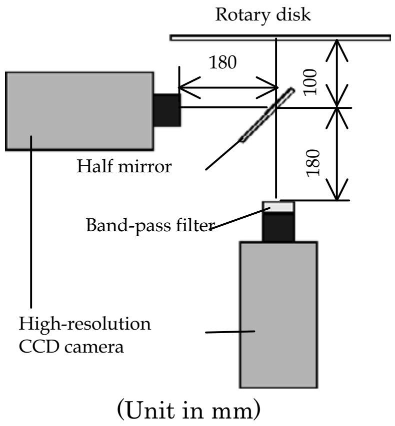

Fig. 3. Details of the observation system.

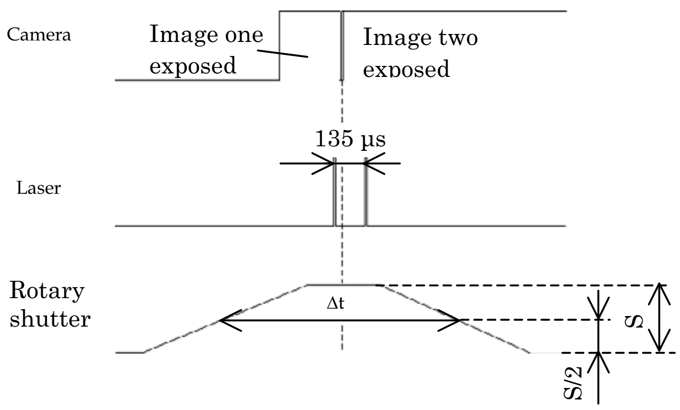

Fig. 4. Time chart.

The flow visualization of the combusting flow was carried out with hollow particles of silica of 2 μm in diameter and 0.2 g/cm^3 in density. These tracer particles were selected in consideration with the traceability of the particles to the gas flow. These tracers are seeded at the inlet of the upstream blower and are supplied to the test chamber. The velocity distributions are evaluated from two sequential images using a gray-level-difference method combined with a sub-pixel interpolation technique. The basic idea of the gray-level difference method is to search a similar gray level pattern defined by the accumulation of gray level differences between corresponding pixels of the image (Kaga et al., 1994). It is known that this algorithm works much faster in computation than the cross-correlation algorithm with a similar uncertainty level in velocity measurements (Hu et al., 1998; Fujisawa and Hashizume, 2001). The size of the interrogation window was set to 41 × 41 pixels and the maximum pixel displacement of the particles was 4 pixels. These conditions were found to minimize the erroneous vectors with reasonable spatial resolution in the velocity measurement. The erroneous vectors in the present measurement were less than 1% of the total number of measured velocity vectors.

3. Results and Discussion

3.1 Performance of Rotary Shutter

The performance of the rotary shutter was tested in the combusting flame generated from the burner in an open environment. Figure 5 shows the examples of visualized images, the analyzed velocity vectors and the histograms with and without the rotary shutter. It is to be noted that the histograms are measured in the red area of the images. The results with the rotary shutter are shown at two different exposure times, 8 ms and 4 ms. The result without the rotary shutter (Fig. 5 (a)) corresponds to that of the exposure time of 37 ms. The luminous flame appears in the second frame of the captured image of the cross-correlation camera. Therefore, the histogram shows the deviation in the gray level between the first and second frame of the image, especially at high gray level larger than 100, which corresponds to the luminous flame. The intensity difference in the captured images causes the production of erroneous vectors around the region of the luminous flame, which can be seen in the velocity distribution. When the rotary shutter is applied to the measurement at exposure time 8 ms, the intensity difference between the two images is reduced especially around the luminous flame, which results in the reduced number of erroneous vectors.

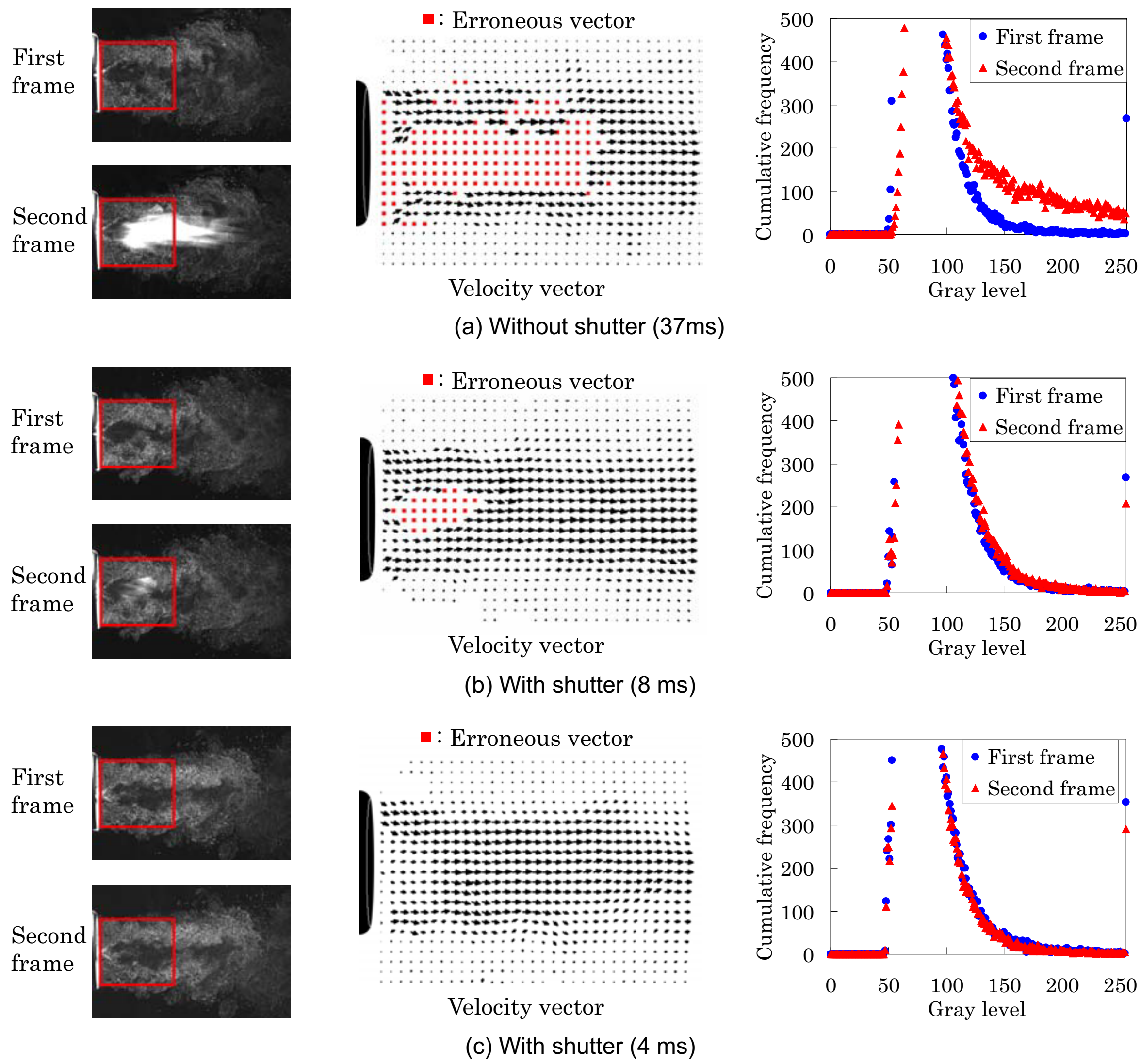

Fig. 5. Performance of rotary shutter.
(The histogram is for the red area in the picture.)

Further reduction in the intensity difference and the following decrease in the number of erroneous vectors are observed by reducing the exposure time of the rotary shutter from 8 ms to 4 ms. These results indicate that the rotary shutter is very effective in reducing the erroneous vectors generated from the luminous flame in the spray combustion. Based on the present results at various exposure times ranging from 2 ms to 37 ms, the erroneous vectors are found to be small enough, when shutter speed is set smaller than 4 ms. It is to be noted that the critical shutter speed may change depending on the performance of the band-pass filer and the laser power, and also on the luminosity of the target flame. However, the effective shutter speed to avoid the luminous noise is expected to be on the order of ms, which is much longer than the high-speed shutter 100 ns of a gated CCD camera used by Shioji et al. (1997).

3.2 Instantaneous Velocity Field in Combustion Chamber

Figure 6 shows the simultaneous observation of flame structure and velocity field in the spray combustor model. The instantaneous velocity field in the combustor was measured by the present PIV system. The result shows the visualization of the flame structure (a), the band-pass filtered image at the laser wavelength of 532 nm$\pm$10 nm (b), and the velocity distribution and the contour of velocity magnitude (c), and the corresponding vorticity distribution (d). Each of them shows three typical examples of observation at time t=0 s, 0.07 s and 0.13 s, respectively. The measurement was started at random times. The exposure time of the rotary shutter was set to 4 ms in the present experiment. The vorticity ζ is evaluated by the following equation, which is non-dimensionalized by the diameter of the burner throat L and the mean velocity U_0 of the supplied air flow:

$$\zeta = \frac{L}{U_0}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) \qquad (1)$$

Here, u and v indicate the velocity components in x and y direction, respectively (Fig. 1).

The visualization picture (a) shows that a luminous flame appears as the high-intensity area near the burner exit, where the burner is located on the right-hand side of each picture. The luminous flame is surrounded by the dark cloud of tracer particles and the unburnt droplets of the fuel spray. They are fluctuating unsteadily due to the presence of turbulence in the shear layer of the burner flow. The flame image includes the integrated information in the depth direction. This is different from image (b), the velocity field (c), and the vorticity field (d), which show the cross-sectional distribution.

On the other hand, the filtered image (b) shows that most of the luminous area of the flame is reduced to a small portion of the flame in comparison with image (a), which indicates the influence of the band-pass filter. The reduction in the area of luminous flame indicates that most of the flame consists of the emissions from the soot particles in the broad-band spectrum. While, the bright area in the filtered image is considered to be due to the formation of the soot structure in the flame, because it reflects the laser light strongly rather than the emission light from the soot particles. These bright areas are indicated by A, B and C in the filtered image (b). These bright areas exist not in the center of the flame but on the boundary of the luminous flame. The image also indicated the presence of the unburned fuel droplets. Sauter's mean diameter of the unburnt fuel droplets was measured to be 78 μm by Hosokawa et al.(2002) under combustion, which is much larger in diameter than the tracer particles (2 μm) used in the present experiment. The diameter of the tracer particle should be smaller than 8 μm to ensure the traceability of the particles at a frequency 300 Hz (Fujisawa, 2002), which corresponds to the shear layer frequency of the burner flow in the present observation. Therefore, the unburnt spray droplets are considered not to follow the velocity fluctuations. The droplets of larger size were removed from the PIV images by treating them as pixels of very high intensity. This is due to the principle that the light intensity scattered from a particle is proportional to the square of its diameter (Ikeda et al., 2000). The threshold value of the gray level was set to 250 in the present image analysis.

The instantaneous velocity distribution (c) was measured from a set of particle images using a gray level difference method of PIV. The velocity distributions indicate that the horizontal impinging jet is created over the opposed wall of the combustor. The width of the jet flow agrees closely with the diameter of the burner throat. After the jet impinges on the opposed wall, the jet flow separates into the up-flow and the down-flow along the opposed chamber wall. The up-flow is formed in the clockwise direction in the upper area of the combustor, while the down-flow is produced in counterclockwise direction in the bottom area of the chamber. The mean velocity magnitude of the recirculating flow in the upper area of the combustor model seems to be smaller than that of the flow in the bottom area. The recirculating flow in the upper area goes through the exit of the top plate to the outside of the chamber. The flow pattern observed in the present experiment is found to be similar to that without combustion by Fujisawa and Satoh (2001). However, the magnitude of the velocity in the combusting flow is larger than that without combustion, this is due to the presence of chemical reactions of the fuel droplets in the combustor model.

The vorticity distribution is shown in Fig. 6 (d). Due to the variation of the velocity distribution (c), the positive vorticity is generated over the lower shear layer of the burner flow and the negative vorticity is distributed over the upper shear layer. The magnitude of the vorticity is found to be larger near the burner and is weakened as the flow approaches the opposed wall of the combustor. This is due to a decrease in the jet velocity and the corresponding increase in the vertical spreading of the jet flow along the combustor wall. These flow behaviors are similar to the observation without combustion, but the magnitude of the vorticity under combustion is larger than that without combustion, which reflects the influence of increased flow rate by chemical reactions of the fuel droplets under combustion.

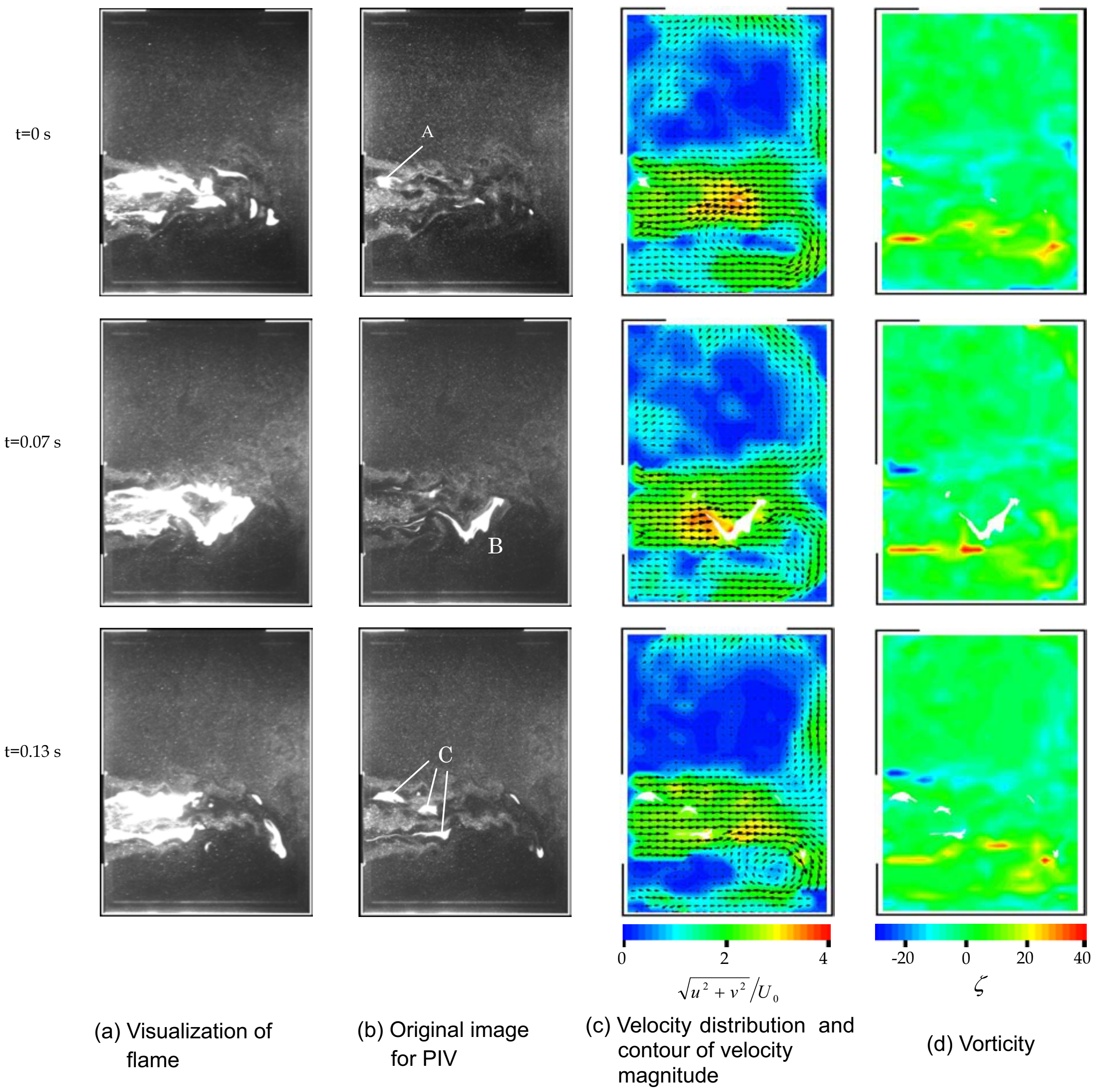

Fig. 6. Instantaneous flow fields in the combustor model.
(The symbols A, B and C in image (b) show the soot structure.)

4. Conclusion

The technique of velocity field measurement under spray combustion was studied using a PIV system in combination with a rotary shutter and a band-pass filter. It was found that the number of erroneous vectors in the PIV analysis was reduced with a decrease in the exposure time, which is due to the elimination of the luminous flame by the rotary shutter. The effective shutter speed was found to be on the order of ms. In combination with this technique, the simultaneous observation of velocity field and flame structure is carried out in the combustor model for boiler. The results indicate that the flow pattern inside the combustor is similar to that without combustion, but the magnitude of the gas velocity is increased by the chemical reactions of the fuel droplets under combustion.

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