Measurement of Ambient Air Motion of D.I. Gasoline Spray by LIF-PIV*

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Ambient air velocity distributions in and around a D.I. gasoline spray were measured using a combination of LIF and PIV techniques. A rhodamine and water solution was injected into ambient air to disperse the fine fluorescent liquid particles used as tracers. A fuel spray was injected into the fluorescent tracer cloud and was illuminated by an Nd:YAG laser light sheet (532nm). The scattered light from the spray droplets and tracers was cut off by a high-pass filter ($>560\text{nm}$). As the fluorescence ($>600\text{nm}$) was transmitted through the high-pass filter, the tracer images were captured using a CCD camera and the ambient air velocity distribution could be obtained by PIV based on the images. This technique was applied to a D.I. gasoline spray. The ambient air flowed up around the spray and entered into the tail of the spray. Furthermore, the relative velocity between the spray and ambient air was investigated.

Key Words: Gasoline Engine, Laser-Aided Diagnostics, Fuel Injection

1. Introduction

Mixture formation processes of a fuel spray in a D.I. gasoline engine greatly influence the subsequent combustion. A fuel spray induces ambient air motion and the shape of which changes considerably with time. Therefore, it is important to clarify the fuel spray and the ambient air motion to improve the fuel consumption and validate CFD.

Although the fuel spray velocity was measured by PDPA and PIV, the ambient air motion around the fuel spray has been measured in only a few studies up to now^{(1)~(4)}. As it is difficult to observe the ambient air tracers separately from the spray droplets, information on ambient air is insufficient at this time.

Recently, the LIF-PIV technique⁽⁵⁾ was developed by combining the laser-induced fluorescence technique and the particle image velocimetry technique to measure ambient air velocity in and around the D.I. gasoline engine spray⁽⁶⁾. This technique had

sufficient accuracy to measure ambient air velocity separately from that of the spray droplets. In this paper, the technique was applied to the D.I. gasoline spray and the relationship between velocities of the spray and the ambient air in the spray was investigated under atmospheric and high pressures.

2. Experimental Setup

Figure 1 shows the experimental apparatus of the LIF-PIV system used in this study. The ambient pressure in the spraying chamber and the fuel pressure were set using N_2 cylinders. The measurement of spray velocity was performed by standard PIV (TSI Corporation). The timing and duration of injection were controlled by a delay pulse generator. The double-pulse Nd:YAG laser (power:25mJ; pulse width: 5ns) and CCD camera (resolution: 1008x1018 pixels) were controlled by a synchronizer which was triggered by the delay pulse generator. Figure 2 shows the timing chart. The two recorded images of a spray were input to a personal computer and the velocity of the spray was calculated by cross-correlation of the spray droplets images.

Figure 3 shows a schematic of the measurement of ambient air velocity by LIF-PIV. Rhodamine B-water solution and was injected into ambient air by a swirl-type injector to disperse the fine fluorescent liquid particles as tracers of the ambient air motion.

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Fig. 1 Experimental setup

Fig. 2 Timing chart of double-pulse PIV

Fig. 3 Principles of LIF-PIV

A fuel spray was injected into the fluorescent tracer cloud by the D.I. gasoline injector and was illuminated by a Nd:YAG laser (532nm) light sheet. The scattered light from the spray droplets and tracers was then cut off by a high-pass filter (>560nm). As the rhodamine absorbs the light of the laser, it fluoresces at a wavelength greater than 600nm. The fluorescence from the tracers was transmitted through the high-pass filter and the images were captured using the high-resolution digital CCD camera. The tracer images were analyzed by double-frame cross-correlation PIV and the ambient air velocity distribution was obtained.

3. Tracking Ability of Tracer to Ambient Air Motion

When flow fields are visualized using tracer particles, the size of the tracer is a very important variable because the trackability of the airflow is closely related to the tracer size. In particular, in the visualization of an intermittent spray with short injection duration and spray lifetime, the generation of fine droplets that follow the air motion fairly well is required.

Figure 4 shows the temporal variation of the SMD with tracer injection pressure. The SMD of the tracer was measured at an ambient pressure of 0.1MPa using a laser droplet size analyzer (LDSA, TOHNICHI Computer Co., model 1400A). The SMD of the tracer decreases with increasing injection pressure, and it shows the SMD of $15.9\mu\text{m}$ and AMD of $8.8\mu\text{m}$ at an injection pressure of 9MPa which is the upper limit for the tracer injection nozzle. Therefore, the injection pressure of 9MPa was used as the tracer injection pressure to produce the fine tracer particles. Moreover, the transmittances of laser light at some points were measured using the LDSA to check the spatial uniformity of the tracer, and it was confirmed to be almost uniform.

The droplets of the rhodamine B-water solution, which were used as tracers for the ambient air, must remain static at the time of spray injection. Figure 5 shows a temporal variation of the tracer axial velocity without the fuel spray injection. Tracers were injected into still ambient air of 0.1MPa at an injection pressure of 9MPa. Nine points, as shown in Fig. 5, were selected for the investigation of the variation in the tracer axial velocity. The tracer axial velocities decrease with time after the start of tracer injection, and they are less than 0.1m/s over 300ms after the tracer injection. Therefore, the timing of tracer injection was set to be 300ms before fuel spray injection.

Figure 6 shows axial and radial velocities of two tracers, the rhodamine B-water solution and microballoons (EXPANCEL[®] microspheres, 551DE40, density of 42kg/m^3), to verify the trackability of ambient air motion. Since microballoon tracers emit scattering light of the same wavelength as the fuel spray, the phenomena within the sprays could not be compared. In an ambient air region, the velocity distributions of the two tracers are similar.

In addition, the arithmetic mean diameter of rhodamine B-water solution spray particles was $8.8\mu\text{m}$. The relaxation time of these droplets, which is defined as the time required for the injected particle velocity to fall by a factor of e^{-1} , is 0.24ms. This time scale is short enough compared with the time scales of the fuel spray, namely, the injection duration and the time of flight of the fuel spray, that particles of this size can respond fairly well to the variations in the instantaneous velocity of ambient air. This means

Fig. 4 Temporal variation of SMD of ambient air tracer

Fig. 5 Ambient air tracer velocity

(a) Radial velocity (V_r) (b) Axial velocity (V_z)

Fig. 6 Velocities of rhodamine B and microballoon tracers

that the rhodamine B-water solution tracers are applicable to the measurement of ambient air motion.

4. Results and Discussion

4.1 Experimental conditions

Table 1 shows the experimental conditions. The fuel pressure was set at a pressure of 5.0MPa and the dry solvent was injected with a D.I. gasoline injector. The dry solvent has properties similar to those of gasoline in terms of atomization, though the dry solvent negligibly vaporizes at room temperature. Rhodamine B was injected by a swirl-type atomizer at an injection pressure of 9.0MPa and 300ms before the fuel injection. The ambient air pressure was set at 0.1MPa and 0.4MPa. The laser interval time and window size were adjusted to achieve satisfactory velocity analysis.

The averaged velocity value was used, except in the case of velocity distributions (Figs. 8 and 11). As the spray was symmetrical along the spray axis, the

right and left velocities were averaged.

In this study, velocity distributions of the ambient air and spray were measured only in the vertical plane including the spray axis. Velocities of the ambient air and spray in the horizontal plane to the spray axis were not measured, since the swirling velocities of the spray in the horizontal plane were very small and had been measured in the preliminary experiment.

4.2 Spray tomograms

Figure 7(a) shows the tomograms of the D.I. gasoline spray under an ambient pressure of 0.1MPa. The spray shape is a hollow cone at 1.0ms. After that, part of the spray periphery flows up and a large vortex is formed. Figure 7(b) shows the tomograms of the D.I. gasoline spray under an ambient pressure of 0.4MPa. The cone angle and penetration become small and a large vortex is formed, which is similar to the case of the spray under atmospheric pressure.

Table 1 Experimental conditions

Spray	Injector	Swirl Type
	Cone Angle	50deg (Ambient pressure 0.1MPa)
	Injection Pressure	5.0MPa
	Injection Period	0.88ms
	Fuel	Dry solvent
	Laser Interval	5~20 μ s
	Window Size	64 X 64 Pixel (3.8 X 3.8mm @ 1.5ms) (5.1 X 5.1mm @ 3.0ms)
Tracer	Injector	Swirl Type
	Injection Pressure	9.0MPa
	Injection Period	7.5ms
	Injection Timing	300ms before Spray Injection
	Working Fluid	Rhodamine B
	Laser Interval	100 μ s
	Window Size	128 X 128 Pixel (10.2 X 10.2mm)
Ambient Pressure		0.1MPa, 0.4MPa
Ambient Temperature		Room Temperature

Fig. 7 Tomograms of D.I. gasoline spray

4.3 Spray and ambient air motion under 0.1MPa

Figure 8 shows the velocity distributions of the spray and ambient air at 1.5ms and 3.0ms after the start of fuel injection under an ambient pressure of 0.1MPa. The velocity scale of ambient air is 10 times greater than that of the spray. Ambient air flows up around the spray and flows into the spray tail. It is thought that the spray motion induces the air motion, particularly the large-scale vortex. Pressure drops along the central spray area where the spray droplets pass through and air flows in.

Figure 9 shows radial velocities of the spray and ambient air under an ambient pressure of 0.1MPa. The axial distance is 25mm from the injector tip. At 1.5ms, the velocity of the spray is much faster than that of the ambient air. However, at 4ms, the velocity of the spray decreases and the velocity of the ambient air increases. Consequently, the velocity distribution of the spray is almost the same as that of ambient air. Figure 10 shows the two-dimensional distribution of the relative velocity of the spray to ambient air under an ambient pressure of 0.1MPa. It can be seen that the relative velocity is high around the spray periphery at 1.5ms. At 3.0ms, the relative velocity is lower than that at 1.5ms, and is distributed around the middle portion of the spray axis.

Fig. 8 Velocity distributions of spray and ambient air under ambient pressure of 0.1MPa

Fig.9 Velocities of spray and ambient air under ambient pressure of 0.1MPa ($Z=25\text{mm}$)

4.4 Spray and ambient air motion under 0.4MPa

Figure 11 shows the velocity distributions of the spray and ambient air at 3.0ms after the start of fuel injection under an ambient pressure of 0.4MPa. The velocity scale of ambient air is 10 times greater than that of the spray. These velocities of spray and ambient air are smaller than those of spray and ambient air under an ambient pressure of 0.1MPa. Figure 12 shows the velocities of the spray and ambient air under an ambient pressure of 0.4MPa. Although these velocities are smaller than those under an ambient pressure of 0.1MPa, the temporal variation of both velocities is the same as that under an ambient pressure of 0.1MPa, that is, the velocity of the spray becomes close to that of the ambient air with time. Figure 13 shows the relative velocity distribution under an ambient pressure of 0.4MPa. As the spray cone angle is smaller than that under an ambient pressure of 0.1MPa, the area of high relative velocity is distributed near the spray axis. At both 1.5ms and 3.0ms, the area of high relative velocity appears around the middle portion of the spray near the spray axis, while the relative velocity is low in the tip and tail regions.

Fig. 10 Relative velocity distribution under ambient pressure of 0.1MPa

Fig.11 Velocity distributions of spray and ambient air under ambient pressure of 0.4MPa

(a) Radial velocity (V_r)

(b) Axial velocity (V_z)

Fig. 12 Velocities of spray and ambient air under ambient pressure of 0.4MPa ($Z=25\text{mm}$)

5. Conclusions

The LIF-PIV technique was developed and applied to a D.I. gasoline spray. The main conclusions are summarized as follows.

- (1) Ambient air motion in and around the spray was successfully measured by combining the LIF and the PIV techniques.
- (2) Ambient air flows up around the spray and into the spray tail. This air motion induces a spray vortex.

Fig. 13 Relative velocity distributions under ambient pressure of 0.4MPa

- (3) In the early phase after the start of fuel injection, both the radial and axial velocity components differ greatly between the spray and the ambient air. With time, the velocity components become similar. This tendency is independent of the ambient pressure.

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