KSME International Journal, Vol. 12, No. 5, pp. 907~916, 1998

On the Intermittent Spray Characteristics

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(Received July 16, 1997)

The quality of spray atomization ejected from an injector has a definitive influence upon the engine's performance. Furthermore, considerable attention to the Earth's environmental pollution is increasing now more than ever before. This experimental investigation has been carried out to clarify the characteristics of the intermittent spray using a pintle type gasoline fuel injector. Both the image processing system and the Phase Doppler Anemometer are utilized for the visualization of a spray behavior and the simultaneous measurements of dropsizes and their velocities, which have been conducted at the axial downstream from the injector exit plane. The fuel injection duration was fixed at 3ms and the injection pressure was varied from 250 kPa to 350 kPa. For a high injection pressure of 350 kPa, the spray tip arrival time was fluctuated at the vigorously disintegrated regions. It evidently shows a linear correlation between the axial velocity and the fuel drop size farther downstream.

Key Words: PDA(Phase Doppler Anemometer), Temporal and Spatial Variation, SMD (Sauter Mean Diameter), Spray Tip Penetration

1. Introduction

In designing the internal combustor with high performance, the problems that should be prerequisitely considered are the improvement of fuel economy and the reduction of the Earth's environmental pollution. The more stringent controls on emission have led to much work until now in an attempt to characterize and develop the optimum models for automotive fuel injectors. Recently, the multi-point injection system installed near the intake-manifold of the cylinder has come to be applied in most of the gasoline engines. In this system, liquid fuel is injected into the relatively low-pressure atmosphere through an electric control injector.

Under some operating conditions, however, a great deal of unburnt hydrocarbon or soot particles are emitted with the exhaust gas because of its low quality of the spray atomization. Obtaining the most appropriate atomization is undoubtedly necessary to achieve a high combustion efficiency. The liquid fuel must be broken up into small drops in order to be effectively burned in the combustion chambers. Accordingly, the exact understanding of its processes and characteristics as well as physical properties and effects of various factors are indispensable for better detailed analysis of the internal combustor. The spray characteristics which include spray tip penetration and drop size distributions affect many aspects of engine performance, fuel economy, and exhaust emissions. They depend on the design of the injection system and the physical properties of the fuel. Fuel properties that influence the spray characteristics include density, viscosity and surface tension. In an attempt to clarify these parameters, so much research work on the liquid fuel atomization has been carried out for decades and is still going on. In general, the atomization performance tends to decrease with an increase of fuel flow rates, while the volume surface mean diameter of atomized fuel tends to decrease with increase of the air-liquid ratio. Cleanup of

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exhaust emissions and fuel-savings are still importantly required for automobile engines. One of the most effective approaches to these concerns is to improve the fuel supplying system. Therefore, lean combustion methods through the electromagnetic control injection unit in the gasoline engines were introduced by the previous researchers to decrease the exhaust emissions. As an approach to time series measurement of fluctuating velocity and size, an intermittent spray are examined. Intermittent sprays are utilized in many combustion systems, such as diesel engines and port-injected gasoline engines.

With the development of advanced optical diagnostics methods, detecting some trends have become easier. In the present study, for the purpose of measuring the atomization process for each individual velocity and the size of all droplets passing through the measuring volume, the intermittent spray characteristics are investigated by using a PDA system. As the fuel spray distribution strongly affects on the combustor performance, the researchers are always striving to improve the combustion stability, efficiency, and reduce the emissions. Although Various parameters are applied to produce a fine spray over a wide range of operating conditions, the precise mechanisms responsible for the formation process of droplets are highly complex.

Numerous experimental investigations have been conducted previously in order to define disintegration processes of atomized particles. Saffman et al. (1988) clarified the characteristics of fuel atomization in a gasoline injector, operating with and without air-assist. Pitcher et al. (1989) utilized the Laser and PDA to obtain the reliable automotive fuel injection processes under realistic engine operating conditions. Sizing and velocity measurements by Kobashi et al. (1990) were carried out using the dummy fuel as an example of intermittent spray flows, describing the results that the velocity measurements were in good agreement with the visualized flow pattern by the laser sheet stroboscopic illumination. Dementhon et al. (1991) demonstrated the gasoline spray phenomena using a PDA system. In particular, video images for the better understanding of the spray structure were associated. The temporal and spatial variations in the drop size distributions of intermittent fuel sprays were measured by Jawad et al. (1992). The atomization mechanism of a spray injected into a suction manifold in a pintle type injector was examined in detail by Senda et al. (1994). Rho et al. (1995) made the measurements of the atomization characteristics, and derived an expression that there would be a correlation between SMD and ALR. Rho et al. (1994) investigated the radial spray characteristics in a plain-jet twin fluid nozzle. Iwano et al. (1990) conducted a wide range of investigation relating to the droplet deposition onto the wall inside an intake manifold.

For the investigation of present intermittent spray characteristics a Phase Doppler Particle Anemometer is installed. The measurements of drop sizes are carried out over three ranges of injection pressures to show a significant feature of spray flows. The spray conditions are not strictly the same as those used in real time engines. The injection duration time is set at 3 ms. Sprays are emitted vertically to the cross-section and the droplets flow are captured in photographs. The atomization of fuel by an intermittent gasoline(density of 0. 755g/cm^3, refraction rate of 1. 435 unleaded gasoline fuel) injector is being studied with the view to describe the spray quality in terms of dropsize and its dropsize distribution. Thus, in an effort to characterize the disintegration processes the temporal and the spatial measurements are conducted, the spray tip penetrations, and the visualization of flow patterns are compared at the different injection pressures.

2. Experimental Apparatus and Method

A description of the schematic experimental apparatus is given in Fig. 1. This apparatus consists of a pressure vessel, a liquid injection system, a CCD camera, and a pressure tank for reducing pressure pulsation. Fuel is injected vertically through an electromagnetic pintle type injector (0. 789 mm in pintle diameter, 0. 923 mm in inside diameter of an orifice, and 33° of pintle

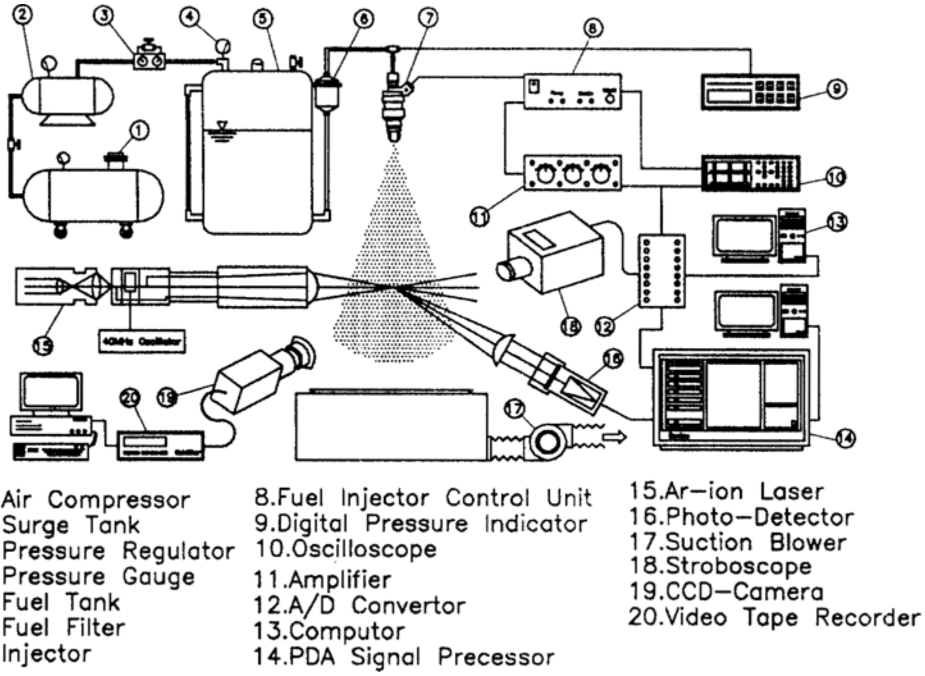


Fig. 1 Schematic description of an experimental apparatus.

dispersion angle). And an intermittent injection is made using the gasoline injector. The motor-driven compressor is applied to pressurize the fuel, and this fuel injection pressure can be regulated by adjusting the pressure regulator.

The variation of the injection pressure is within 0. 08% and almost remained constant. Injection pressure is changed from 250 to 350 kPa. The duration of injection is set at about 3 ms. In order to obtain a reliable data, no less than 10,000 droplet samples are acquired at every measurement position. The experiments are conducted at room temperature. This is mainly focused on the mean droplet diameter and velocity variations along the centerline downstream from the injector exit (10 through 70 mm). For the visualization, the flow patterns (see Fig. 2) generated by particles passing through the control volume are taken by a CCD camera with an aid of a stroboscope. The microflash emits light arbitrarily by retarding the time from the start of injection. Particle diagnostics includes a PDA system consisting of a transmitter with a 750 mW air cooled Ar-ion laser as a light source, receiver optics as a scattered light collection system, and a signal processing electronics Model Dantec 58N10, which is one of the most significant elements of this PDA instrumentation for an interface to computer including a software package for the data acquisition and the analysis. Operating the PDA based upon a forward scattering angle of 60° between the transmission and the receiving optics obviously offers the required spatial resolution. In order to measure the axial component of velocity, the transmission and the receiving optics are both mounted on a movable optical bench supported rigidly by a three dimensional traversing unit. Thus, accurate positioning over the whole test section is available. The transmitting optics, representing the wavelengths of 488 (blue) nm and 514 (green) nm, include a Bragg cell that produces an optical frequency shifting of 40 MHz.

3. Results and Discussion

In order to represent the flow visualization, the stroboscopic photographs along the time intervals after the electrical impulse were taken at the injection pressure of 250 kPa and 350 kPa respec-

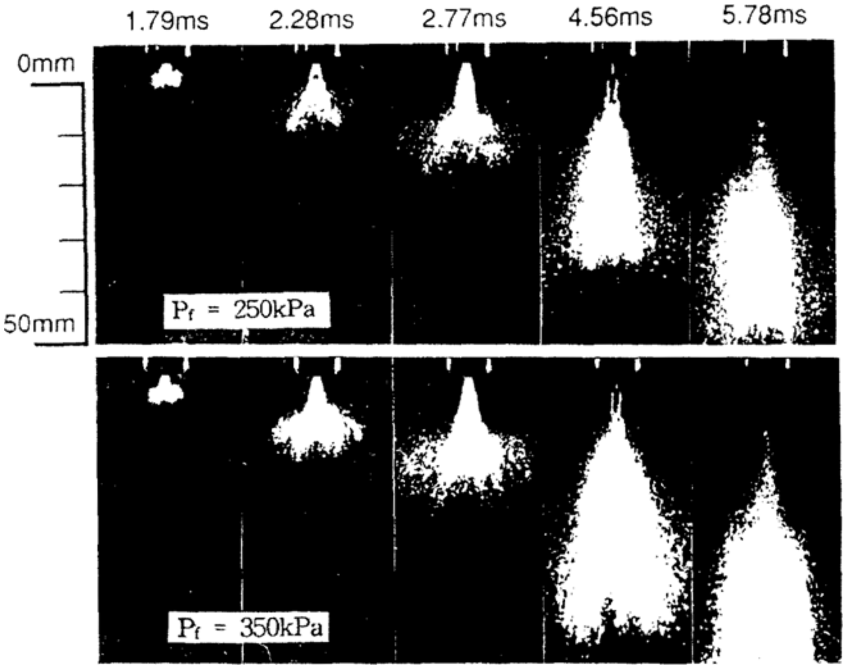


Fig. 2 Changes in spray pattern with temporal resolution.

tively as shown in Fig. 2. Visualization through photographic techniques is intrinsically uncomplicated and can provide spatially and temporally resolved data of drop clusters. The exposure time currently delivered by the strobe is about 30 μs. 1.5 ms of the delay time is required to notice the spray tip starting after the injection due to the effect of the pintle type injector's geometry.

It is demonstrated that the flow pattern is a typical hollow-cone of conical shape and that the fuel film flows along the pintle shape. Distinct changes in spray pattern with time resolution exhibit a ring-shaped liquid sheet disintegration. In the early opening stages the injected fuel flow shows a stationary liquid pattern. As time goes on, the spray tip gradually disperses and propagates radially. After the trailing edge of 4.5 ms the flow rates from an injector are abruptly decreased and the liquid velocities are slow down. This illustrates that the flow has lost its ring-shaped pattern at the downstream of spray. In general, The spray tip represents the motion of the leading drops. The leading drops encounter the drag resistance while they impart some of their momentum to the surrounding air. Eventually, these drops lose their forward momentum and stop while the trailing drops take over the leading position. A similar trend compared with the results obtained by Dementhon (1991) appears, but in this study the surrounding liquid sheet lengths are shorter. It is probable that this phenomenon is mainly attributed to the differences of the injection pressure and the injection duration. The injected fuel from an injector appears in the form of a liquid film near the injector due to surface tension stabilization. An instability and a turbulence in the fuel film near the injector hole cause unstable wave growth leading to the disruption of the film flow, resulting in liquid ligaments and then droplets in the downstream region. As the injection pressure is increased to 350 kPa, the spray penetrations are much longer and also the spray angles are wider, and it is also found that the spray with a short film length breaks up promptly into small droplets, and then disintegrates rapidly.

For the purpose of scrutinizing the various spray tip width (described as B) and the length (as H), Fig. 3 describes the dimensionless diagram of B/H with time resolution depending upon the

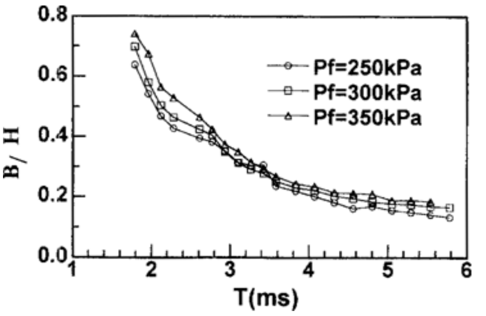


Fig. 3 Variation of spray tip with duration time.

injection pressures. At the beginning of the spray with an increase of the injection pressure, the flow pattern illustrates widening distribution of the spray width that shows the same tendency as mentioned before in Fig. 2. First coming droplets have apparently enough high momentums to disperse and propagate, on the other hand, at the trailing part or downstream of spray it decelerates.

The spray tip variation with pintle closing is almost maintained constant reaching the value of $B/H=0.15$, which is significantly smaller than those compared to the beginning of the injection. Also, results indicate that the temporal and the spatial variation cause the radial uniform dispersion of the fuel droplets. Figure 4 shows the time resolved arrival plots along the radial direction in the range of axial distance $Z=10$ - 70 mm. In this literature, the arrival time is determined by the transport of the spray tip with time variation, which are obtained through the measurement volume utilizing the PDA.

AT the axial location of $Z=10$ mm the radial distributions are evidently independent of the injection pressure. This phenomenon is attributed to the dense spray near the injector, the region of which has a high propensity to keep the large momentum, whereas for the region of $Z > 30$ mm at the higher injection pressure of 350 kPa the spray arrival time fluctuates remarkably due to the effect of dispersion, consequently, illustrating a vigorous disintegration. This means that the dependence of the injection pressure on the droplet arrival time appears evident and it is well consistent with the results obtained in Fig. 3.

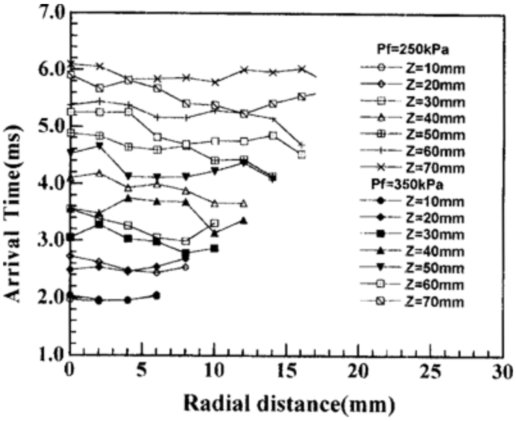
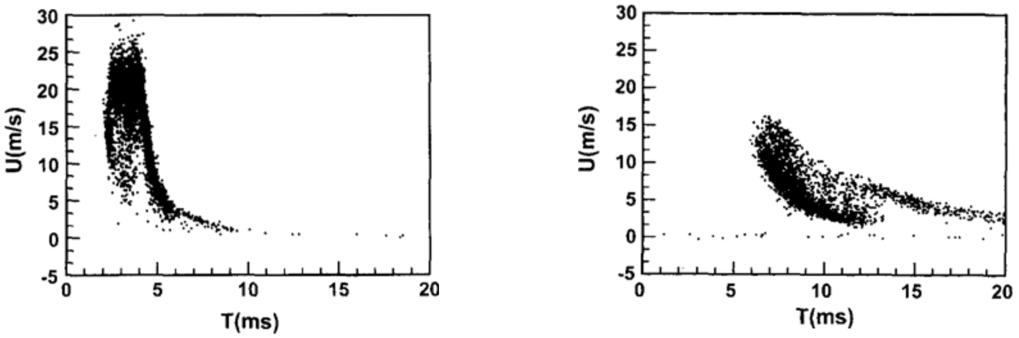


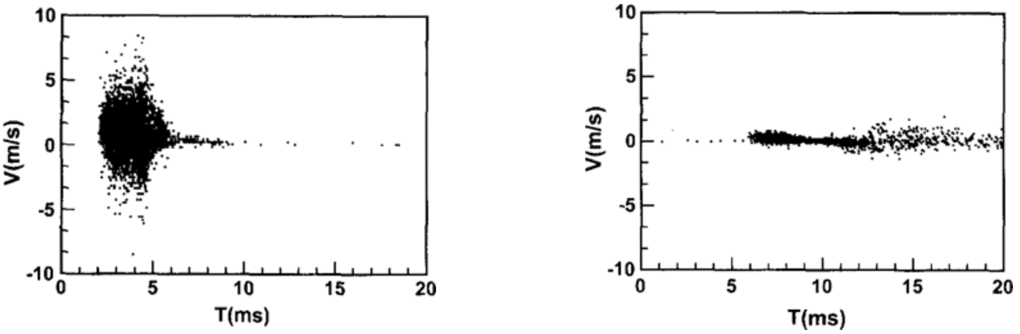
Fig. 4 Profiles of spray tip arrival time.

The temporal profiles of the droplet axial U (5a-5b) and the radial V (5c-5d) velocity components at $Z=10$ and 70 mm are shown in Fig. 5, which are measured at the spray center downstream from the injector exit plane operating with an injection pressure of 350 kPa.

The velocity profiles near the injector differ from those at the downstream stations. In other words, for any given duration time, the axial velocity varies over a relatively large range. For example, given the maximum values from approximately $u \approx 26$ms/s at $Z=10$ mm to $u \approx 15$ m/s at $Z=70$ mm, it is verified that the velocity distributions are in deceleration stage with an increasing axial distance for both cases. In the vicinity of the injector ($Z=10$ mm), the droplet velocity profile in the leading edge becomes uniform. At the trailing edge, however, the velocity diminishes abruptly. As shown in Fig. 2, the spray visualization perceptibly clarified the reason why the axial velocities comprise the wider values of distribution. The liquid sheet formed by the pintle effect is vigorously disintegrated into the ligaments and the drops. From the leading through trailing edge, thus it causes ample values of velocity, approximately 5 - 27 m/s. When compared to the farther downstream region of $Z=70$ mm, the values of velocity are a little higher and broader in the vicinity region of $Z=10$ mm because of the droplet axial momentum. On the other hand, it is apparent that the droplet velocity reduces steadily in the farther downstream region

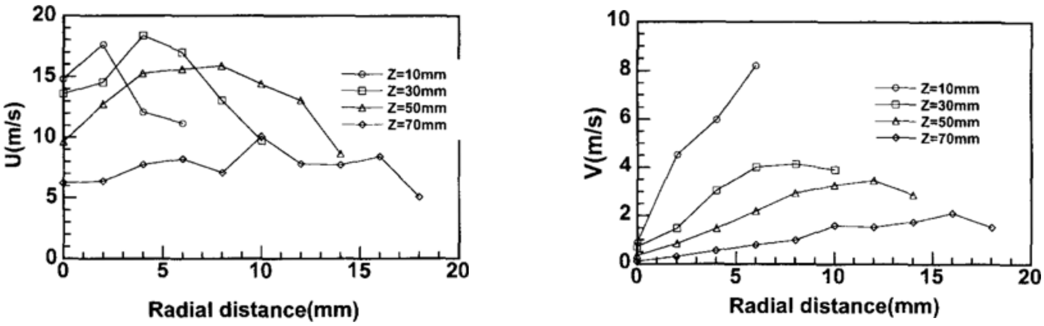


(a) Axial velocity Z=10 mm (b) Axial velocity Z=70 mm



(c) Radial velocity Z=10 mm (d) Radial velocity Z=70 mm

Fig. 5 Profiles of droplet velocity with duration time.



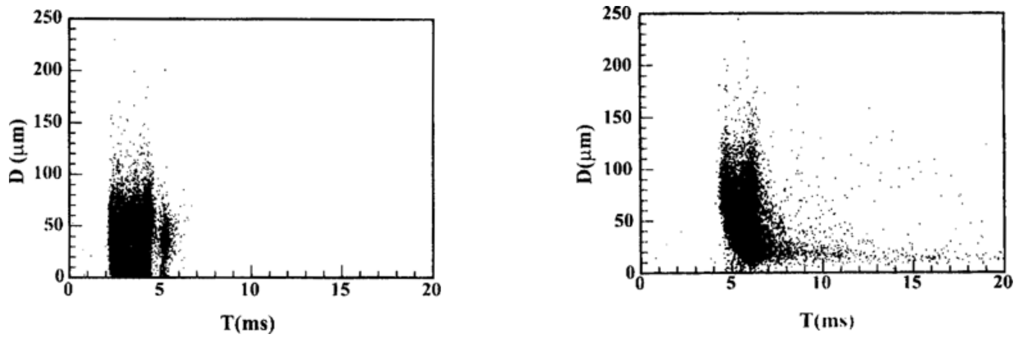
(a) Axial velocity (b) Radial velocity

Fig. 6 Distribution of mean velocity.

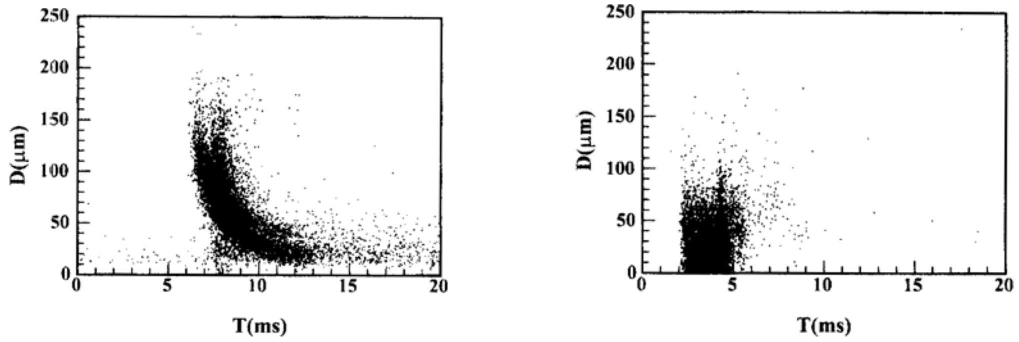
(Z=70 mm). In this location, relatively lower droplet velocities of less than 5 m/s exist due to its weakening momentum, and thus infinitesimal buoying droplets can be measured. This is ascribed to the floating droplets those lose their own inertia as they go downstream, resulting in the evaporation of themselves. The results in Fig. 5 show that the magnitude of the axial and radial droplet velocity definitely decays with increase of the axial position and the time duration. In contrast to the axial velocity distribution, droplets in the radial direction have the velocity both of positive and negative values of V at the spray center. At Z=10 mm the respective values of the velocity components for both the axial and the radial direction indicate that velocity distributions are comparatively wider (i. e., higher values of velocity) but at Z=70 mm the velocities are more narrowly distributed (i. e., smaller values of velocity) toward the spray trailing edge where the value reaches a minimum. In particular, as it goes radial downstream (Z=70 mm), the profiles almost converge to an uniform profile. This difference in axial locations, as confirmed in a photographic visualization (see Fig. 2), is attributed to the spray dispersion with a large amount of momentum at the first stage. The dispersion emanating from the injector, consequently, inclines to dislodge the bulk of the droplets and penetrate farther downstream.

The spatial profiles of the droplet mean axial U and radial V components measured at Z=10, 30, 50, 70 mm are shown in Figs. 6a and 6b, respectively.

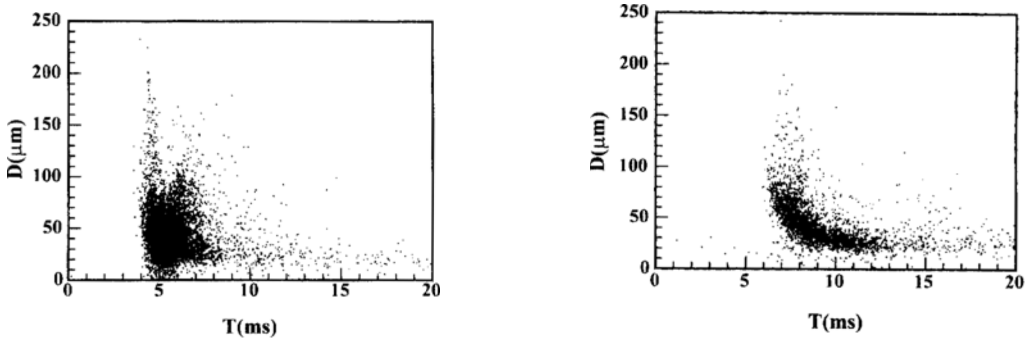
The droplet velocities near the spray upstream significantly differ from those of other downstream and the scattering of velocity data is large. This means that as the axial distance goes down-



(a) Pf=250kPa, Z=10 mm (b) Pf=250kPa, Z=40 mm



(c) Pf=250kPa, Z=70 mm (d) Pf=350kPa, Z=10 mm



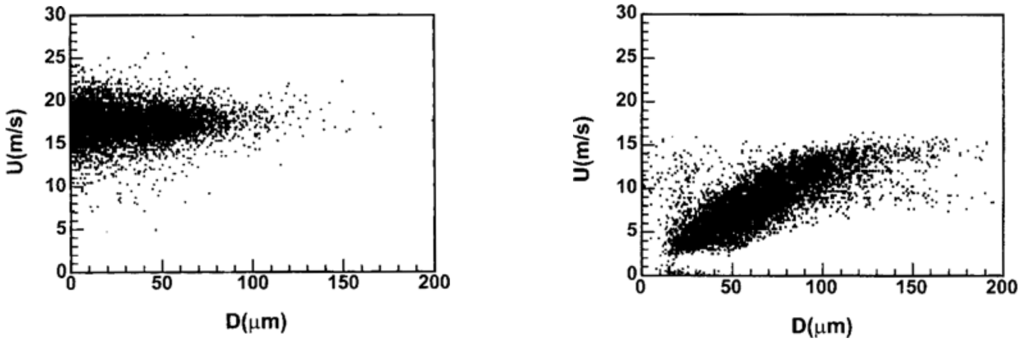
(e) Pf=350kPa, Z=40 mm (f) Pf=350kPa, Z=70 mm

Fig. 7 Variation of droplet size with time.

stream, the amplitude of the axial droplet velocity tends to diminish after reaching a maximum value at a certain radial position, whereas it is interesting to note a slight different trend that the maximum radial velocity component moves toward the spray boundary regions. In the early stage of $Z=10$ mm, the radial velocity increases abruptly along with the radial distances that can be explicitly comprehended in terms of the drag force when the sprays are trajected into a stationary atmosphere. Also, this can be confirmed from the spray visualization (see Fig. 2) in conjunction with the effect of entrainment, which is resulted from the pressure difference between the spray region and the ambient air. Ultimately, this leads the way of the interaction within the spray field.

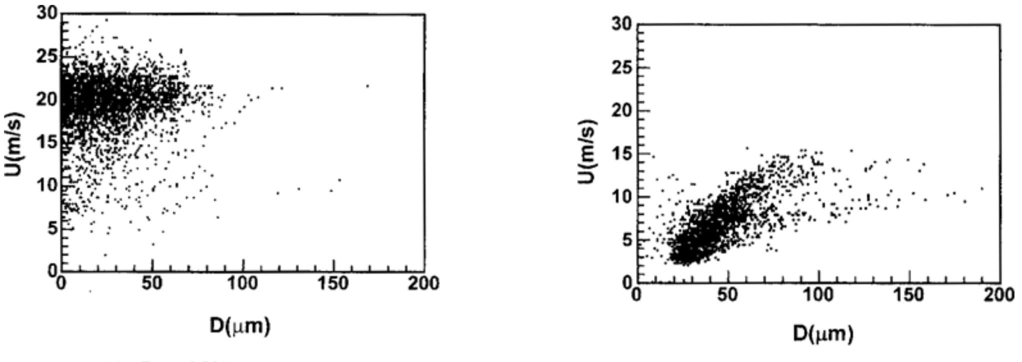
The time resolved profiles of the droplet size distribution at three different axial positions $Z=10$ mm, 40 mm, and 70 mm for the injection pressure of $P_f=250$ kPa and 350 kPa are presented in Fig. 7, respectively.

The variation of droplet size, considering with increasing the axial position and the injection pressure is even more apparent. As shown in Figs. 7a-7c, coarser droplets are acquired for low pressure injection. That is, the maximum values of dropsize for the low pressure are significantly higher than those obtained for the higher pressure. Whereas, the droplet size at each axial position becomes much smaller with increasing the injection pressure because of its own larger momentum, which also produces slight broadening of radial spray width due to a relatively higher disintegration and dispersion. Ultimately, the increased injection pressure as shown in Figs. 7d-7f causes the ejecting droplets to displace radially outward and penetrate them vertically farther downstream. It is recognized that these phenomena can be easily inferred from those of the results in Figs. 2 and 3 and apparently sub-



(a) $P_f=250$kPa, Z=10 mm 2.4ms<T<4.0ms)

(b) $P_f=250$kPa, Z=70 mm 7.0ms<T<11.0ms)



(c) $P_f=350$kPa, Z=10 mm 2.4ms<T<4.0ms)

(d) $P_f=350$kPa, Z=70 mm 7.0ms<T<11.0ms)

Fig. 8 Correlation between droplet size and axial velocity.

stantiated from the correlation as illustrated in Fig. 8. Note again that the values of dropsizes with axial distance for both cases increases slightly. This is presumably attributed to the means of such possible mechanisms as coalescence between the droplets and small inertia resulting from the loss of enough momentum to penetrate farther. The correlation between the droplet diameter and the velocity components provides additional information relevant to understanding the mechanisms of droplet transport in sprays. It is evident that there are some considerable differences along with an axial distance.

The results presented in Figs. 8a and 8c for the upstream regions indicate that the axial droplet velocity component is not well correlated with diameter in both cases, that is, weak linear dependence between diameter and axial velocity. In other words, for any given diameter, the axial velocity varies over a relatively large range. The data obtained shows simultaneously the broadening of spray width as a result of a comparatively vigorous disintegration as the injection pressure becomes higher. By contrast, the profiles in Figs. 8b and 8d (i. e., for the downstream regions) show the different trend that the linear correlation between the axial velocity and the diameter is more evidently convinced. Also, it is strongly certified that the correlation between them is independent of the injection pressure, and the fact that velocity distributions are in deceleration stage with an increasing axial distance is consistent with the trends shown in Fig. 5. From the linear correlation in Figs. 8b and 8d, it apparently confirms the tendency of larger droplets to have larger axial velocity components rather than smaller droplets.

4. Conclusions

The droplet atomization process for an intermittent gasoline fuel injector using the Phase Doppler Anemometer has been examined. The effects of the injection pressure and the axial distance are studied by comparing them under the same operating conditions. Then the results of this study can be summarized as follows.

(1) Through the photographic visualization, it is definitely recognized that the flow pattern is a typical hollow-cone of conical shape and the fuel film flows along the pintle shape.

(2) As the injection pressure becomes higher, the spray penetrations are much longer and also the spray angles are wider, causing a short film length, breaking up promptly into the small droplets, and then causing a rapid disintegration.

(3) For the higher injection case, the spray arrival time fluctuates due to an effect of the dispersion which simultaneously illustrates an exuberant disintegration.

(4) It is found that the magnitudes of the axial and the radial velocities of the droplets decay with both the increasing axial position and time duration. Near the injector the droplet velocity profile at the spray tip becomes uniform. At the trailing edge, however, the velocity diminishes abruptly. Whereas, the droplet velocity reduces steadily in the farther downstream region, where the relatively infinitesimal buoying droplets that have velocities of less than 5 m/s are measured. In contrast to the axial distribution, droplets in the radial direction have both positive and negative values.

(5) The main parameters affecting the variation of the droplet size in this study are the axial position and the injection pressure. That is, as the injection pressure becomes higher, the drop sizes are smaller and the greater the axial distance, the larger the dropsize.

(6) The general tendency of larger droplets to have higher velocity is well corroborated from the linear correlation between the velocity and the dropsize.

Reference

Dementhon, J. B., Vannobel, F., 1991 " Phase Doppler Anemometry in Gasoline Sprays : In Atmosphere and in a steady Flow Rig, " *Proc. Conference ILASS-Europe*, pp. 48～53, Guildford.

Jawad, B., Gulari, E., and Henein, N. A., 1992

"Characteristics of Intermittent Fuel Sprays," *Combustion and Flame* 88, pp. 384~396.

Iwano, H., Saito, M., Sakamoto, K. and Nagaishi, H., 1990 "An Analysis of Induction Part Fuel Behavior in a Multipoint Injection System Using a Fuel Spray and Wall Film Model," pre-prints of JSAE, No. 902229.

Kobashi, K., Hishida, K., and Maeda, M., 1990 "Measurement of Fuel Injector Spray Flow of I. C. Engine by FFT Based Phase Doppler Anemometer-An Approach to the Time Series Measurement of Size and Velocity," *The 5th International Symposium on Application of Laser Techniques to Fluid Mechanics*, pp. 268~287, Lisbon.

Pitcher, G. and Wigley, G., 1989 "Laser and Phase Doppler Anemometry Measurement Techniques for Automotive Fuel Sprays," *3rd International Conference Laser Anemometer -Advances and Applications*, pp. 441~454, Swansea wales.

Rho, B. J., Kang, S. J. and Choi, J. C., 1994, "A Study on the Radial Spray Performance of a Plain Jet Twin Fluid Nozzle," *Transactions of KSME*, Vol. 18, No. 3, pp. 662~669

Rho, B. J., Kang, S. J. and Oh, J. H., 1995, "An Experimental Study on the Atomization Characteristics of a Two-Phase Turbulent Jet of Liquid Sheet Type Co-Axial Nozzle," *Transactions of KSME*, Vol. 19, No. 6, pp. 1529~1538

Safman, M., Fraidl, G. K. and Wigley, M., 1988 " Application of Phase and Laser Doppler Anemometry to the Measurement of Droplet Size and Velocity in Gasoline and Diesel Fuel Injection Systems," *4th International Symposium on Applications of Laser Anemometry to Fluid Mechanics*, pp. 1~6.

Senda, J., Yamaguchi, M., TsuKamoto, T., and Fujimoto, H., 1994, "Characteristics of Spray Injected from Gasoline Injector," *JSME International Journal Series B*, Vol. 37, No. 4, pp. 931~936.

Tokihiro Tsukamoto, Teruo Wakashiro, Masashi Yamaguchi, Jiro Senda and Hajime Fujimoto, 1992 "Characteristics of Spray Injected from Gasoline Injector (1st Report, Macroscopic Behavior of Spray)," *JSME Series* B, Vol. 58, No. 547(1992-3), Paper No. 91-0415B.