Turbulent Mixing Flow Characteristics of Solid-Cone Type Diesel Spray

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The intermittent spray characteristics of the single-hole diesel nozzle (d_n=0.32 mm) used in the fuel injection system of heavy-duty diesel engines were experimentally investigated. The mean velocity and turbulent characteristics of the diesel spray injected intermittently into the still ambient were measured by using a 2-D PDPA (phase Doppler particle analyzer). The gradient of spray half-width linearly increased with time from the start of injection, and it approximated to 0.04 at the end of the injection. The axial mean velocity of the fuel spray measured along the radial direction was similar to that of the free air jet within $R/b=1.0-1.5$ regardless of elapsing time, and its non-dimensional distribution corresponds to the theoretical velocity distributions suggested by Hinze in the downstream of the spray flow fields. The turbulent intensity of the axial velocity components measured along the radial direction represented the 20-30 % of the $\bar{U}_{cl}$ and tended to decrease in the outer region. The turbulent intensity in the trailing edge was higher than that in the leading edge.

Key Words : Solid-Cone Type Diesel Spray, Intermittent Spray Characteristics, Turbulent Characteristics, PDPA (Phase Doppler Particle Analyzer)

1. Introduction

In diesel engines, the improvement of the engine performance and reduction of exhaust emissions is closely related with the combustion characteristics, which are greatly affected by the time and spatial distribution of fuel sprays. Hence, the study on the atomization and flow characteristics of the fuel spray is very important in respect of the improvement of the engine performance and reduction of exhaust emissions.

Recently, as the measurement techniques of fuel sprays have been improved, the atomization characteristics of diesel nozzles have been actively studied. However, the results on the diffusion and turbulent characteristics governing the energy transfer have not been properly organized. Moreover, many studies on the flow and atomization characteristics regard the intermittent spray as the continuous one and these mainly treat the mean characteristics during the injection period. Consequently, more detailed information about the development process of diesel sprays, which are formed intermittently through the disintegration process during very short injection period, cannot be acquired. Also, insufficient results used to verify the disintegration mechanism such as collision, coalescence, and sunderance increase the necessity of further investigation.

Many studies of the flow characteristics of fuel

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sprays, including the comparisons with gas or air jets, have been made. Hyun et al. (1995) classified the intermittent acetylene gas jet as : (a) the potential core region ; (b) the main jet region ; (c) the mixing flow region where the turbulent mixture by the vorticity of the ambient gas was the most active ; and (d) the leading edge where the momentum of gas dissipated. They suggested that these characteristics were also observed in diesel sprays, and the experimental results of the intermittent gas jet could be applied to the diesel spray. Abraham et al. (1994) showed that the sprays were more effective to transfer the momentum to the surrounding gas than the gas jet through the calculation of the tetradecane spray and methane. Gong and Peng (1994) suggested that the air entrainment into the diesel sprays was lower than the case of the single injection of gas. Moreover, Cossali et al. (1990) found that the mass flow rate of air entrainment in the intermittent diesel spray increased with the injection rate, and it was lower than the case of the continuous gas injection. Hosoya and Obokata (1993) analyzed the droplet velocity distribution of the multi- and single-hole nozzles under the steady-state condition. They found that there was the acceleration of the spray along the central axis of the spray, and the turbulent intensity distribution along the radial direction in the diesel spray injected into the static atmosphere reached the maximum value in the half-width position.

In this paper, the turbulent mixing flow characteristics of the solid-cone type diesel spray, which affect the momentum transfer of the fuel spray to the surrounding air, were experimentally investigated, and were compared with the results of the free air jets.

2. Experimental Setup and Conditions

2.1 Fuel injection system

In order to investigate experimentally the flow characteristics of the intermittent diesel spray formed by a single-hole diesel nozzle under the normal temperature and atmospheric pressure, an

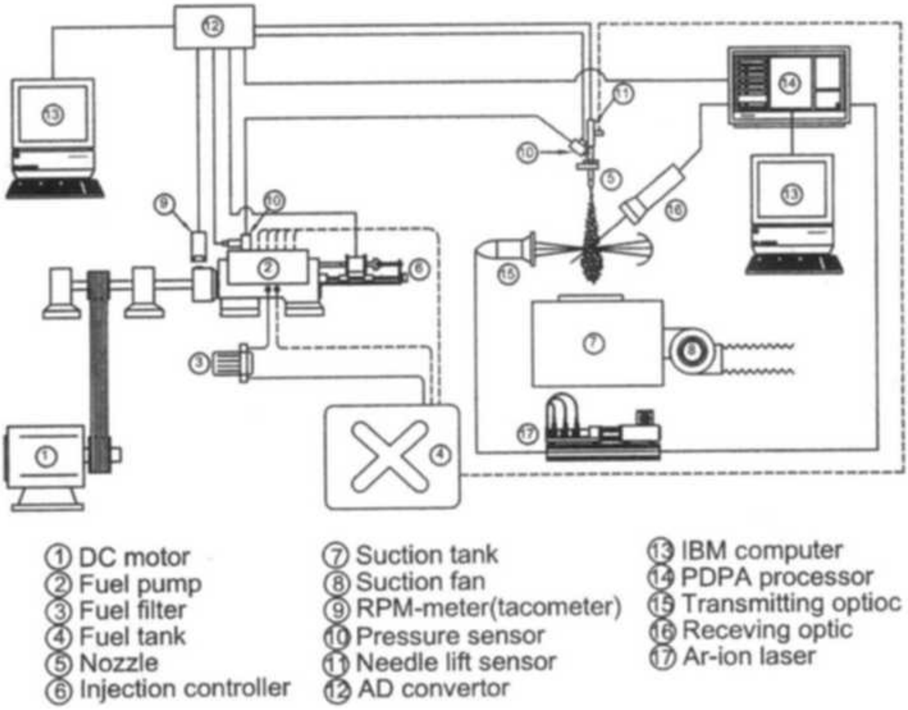


Fig. 1 Experimental setup

experimental apparatus composed of the fuel injection system and PDPA system was used. The fuel injection system was composed of the fuel injection pump, DC motor and fixed frame, as shown in Fig. 1.

The fuel injection pump was an in-line PE type, 8 barrels, which was driven by a 15 kW DC motor that is able to rotate at maximum speed of 3600 rpm. Fuel used in this test was KS #2 diesel oil with specific gravity of 0.8315 kg/m^3, kinematic viscosity of 3.71 cSt, refraction rate of 1.468 at 24 ℃.

2.2 Single-hole diesel nozzle

The fuel injection nozzle was a mini-sac type single-hole diesel nozzle with a 2-spring nozzle holder. There was a hole in the vertex of the nozzle tip, and the diameter of a hole and length/diameter ratio (l_n/d_n) of the nozzle were 0.32 mm and 2.81, respectively. The pre-lift and the total needle lift were set up to $0.06^{\pm 0.02}$ mm and 0.39 mm, respectively. The first and the second needle opening pressure were set up to 150 and 220 bar, respectively. The rotating speed of the pump was set up to 500 rpm, and the flow rate of the nozzle was 7.31 mm^3/st. The maximum injection rate was measured at 0.15 ms, and the injection duration was 0.8 ms.

2.3 PDPA system

The droplet size and velocity of the fuel spray was simultaneously measured by a 2-dimensional PDPA system. A PDPA system consisted of a transmitter optics with a 750 mW air cooled Ar-ion laser as a light source, receiver optics as a scattered light collection system, a signal processing electronics Model Dantec 58N50, a three dimensional traverse, and data acquisition system including a computer. Two laser beams, representing the wavelengths of 514.5 nm (green) and 488 nm (blue), from transmitting optics cross at one point and form a measurement volume. Receiving optics detect the scattered light, which is produced when droplets pass through the measurement volume, and then transmit it to the signal processor. Therefore, the size and velocity are measured by the frequency and relative phase difference of the Doppler signal.

The measurement of the droplet size and velocity was conducted in two dimensions at axis because the spray can be considered as an axisymmetric structure in the flow field. Figure 2 illustrates the coordinate axes of the fuel spray, the global spray structure, and the definitions of the spray half-width that was used as the non-dimensional parameter in the flow characteristics analysis of the fuel spray. The same direction as the nozzle axis was defined as Z, and the radial direction was defined as R. The origin was located at the nozzle tip.

The measurement points at the axial direction were varied from $Z/d_n=31$ far from the nozzle tip to $Z/d_n=63$, 94, 156, 219, 281, 375, 469 and 562. The measurement points at the radial direction were densely set near the axis because the velocity of the fuel spray varies sharply, but their intervals became larger near the outer region of the spray.

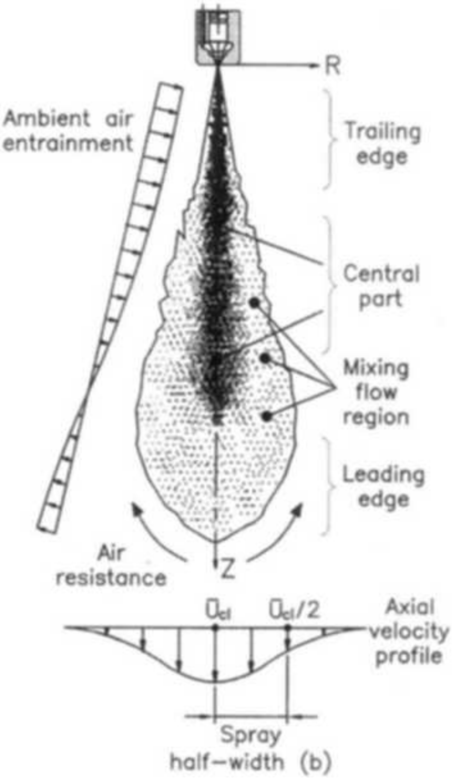


Fig. 2 Definition of coordinate axes and illustration of spray structure

The number of points at the radial distance was 15. The number of measured data at each measurement position was 20,000, and the measurement mode was set not to exceed 300 sec.

3. Results and Discussion

3.1 Spray flowfields

Figure 3 shows the vector plots overlaid on the iso-velocity contours of the compound velocity. Time windows, Δt, used to calculate the mean velocity of the intermittent spray was 0.15 ms.

The structure of the intermittent diesel spray is varied with time differently from the continuous free air jet flow, and it has the unsteady intermittent characteristic that the spray is formed and developed, mixed and diffused and finally dissipated during the injection. The spray was found to be four parts, as shown in Fig. 2 : (a) the central part which moves to the downstream with the high momentum and axial velocity ; (b) mixing flow region where the strong turbulent mixture with surrounding air is occurred ; (c) leading edge where the resistance is very strong with surrounding air; and (d) trailing edge. The central part which has the high axial velocity continuously exists after the end of the injection, 0.8 ms, and its momentum is not diffused to the radial direction but to the axial direction, and consequently the spray is elongated. However, the radial direction components in the leading edge are developed in the outer region of the spray due to the resistance with surrounding air.

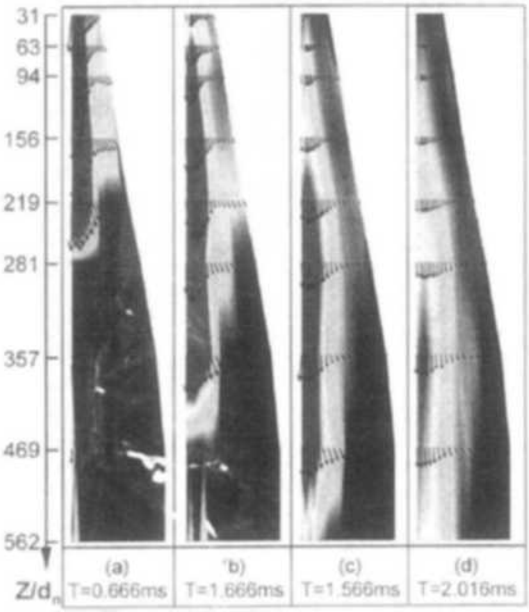


Fig. 3 Iso-velocity contours and vector plots of resultant velocity

3.2 Spray half-width

Figure 4 shows the spray half-width, b, which is defined as the distance between the spray center and the radial position where the axial velocity of the spray center is a half, with time variations to investigate the developing and diffusion processes of the intermittent spray.

The half-width tends to increase regularly with time except the area near the nozzle tip, $Z/d_n<94$. Moreover, the half-width increases linearly with the axial distance, but it forms the inflection point near $Z/d_n=219$-281. Then, the half-width decreases due to the resistance with surrounding air.

Figure 5 shows the gradient of the half-width with the time variations, which explains the diffusion of the fuel spray. The gradient is determined with expressing the region where the variation of the half-width shown in Fig. 4 is linearly changed, $Z/d_n<219$, as a first-order equation.

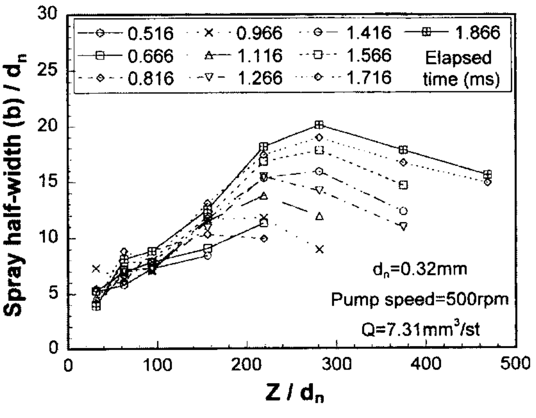


Fig. 4 Time history of spray half-widths along axial distance

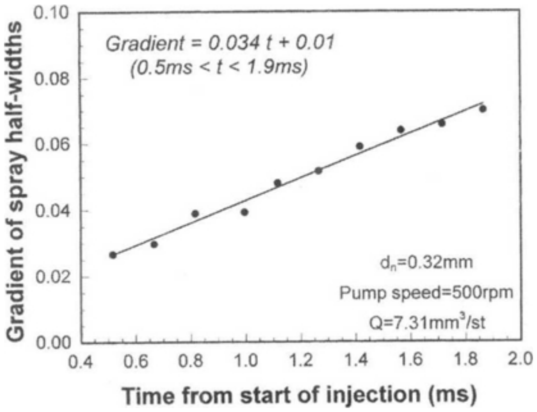


Fig. 5 Time history of gradient of spray half-width

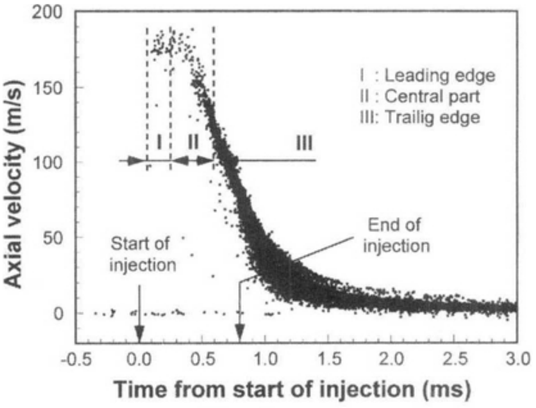
The value of the gradient is approximately 0.027 at the beginning of the injection, and it reaches the value of about 0.04 at the end of injection, 0.8 ms. Then, the gradient tends to increase linearly with passing time. It is supposed that the linear increase is because the entrainment of surrounding air into the fuel spray increases with the development of the spray, and the volume of the spray increases through the atomization process of injected fuel.

Hinze (1975) found that the half-width increased with the axial distance and obtained the gradient of 0.08 for the continuous free air jet. The gradient for the single-hole diesel nozzle is particularly smaller than for the free air jet, so that the diffusion of the spray of the single-hole diesel nozzle is inactive.

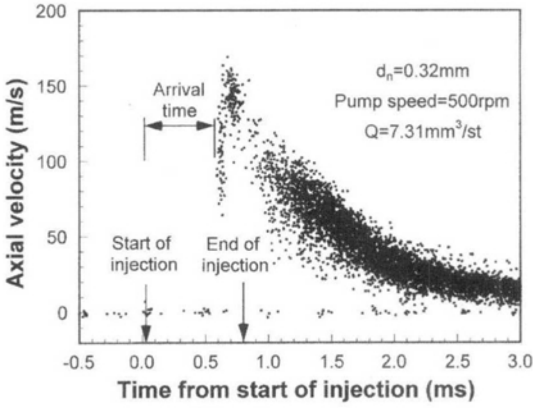
3.3 Axial velocity distributions of fuel spray

Figure 6 shows the axial velocity distribution of the fuel spray with the time variations. The axial velocity reaches the maximum value after droplets of the leading edge arrive at the measurement point. Then, the axial velocity decreases gradually, and it reaches the equilibrium state.

The reason for the smaller velocity in the leading edge than in the central part is because the droplets in the leading edge are greatly affected by the drag force generated by the velocity difference with surrounding air, and they are moved into the outer region of the spray. The velocity of droplets in the central part becomes high because droplets



(a) $Z/d_n=63$



(b) $Z/d_n=281$

Fig. 6 Time-resolved evolution of axial velocity at two axial positions of $Z/d_n=63$ and 281

injected later are not quite affected by the air resistance. Consequently, the phenomenon that first injected droplets are overtaken by the following droplets is occurred. However, this phenomenon disappears with increasing the axial distance, and the maximum velocity decreases.

Figure 7 shows the axial mean velocity along the spray centerline, $\bar{U}_{cl}$, at intervals of 0.15 ms with the variation of the axial distance.

The velocity along the centerline decreases with the time variations, and the velocity near the nozzle tip reduces remarkably at the end of injection, 0.8 ms, owing to the decrease in injection velocity. After the end of injection, however, the velocity is relatively high at the central part, $Z/d_n=219$-400. It can be predicted from this result that the diffusion at the central part of

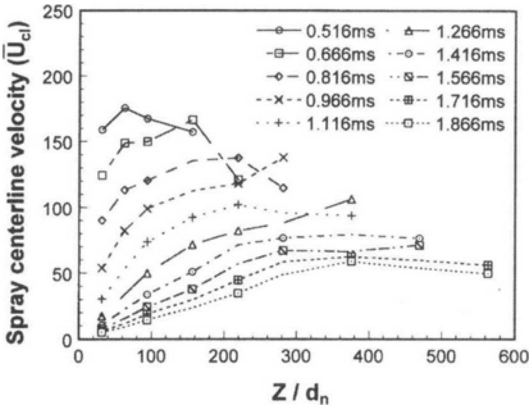
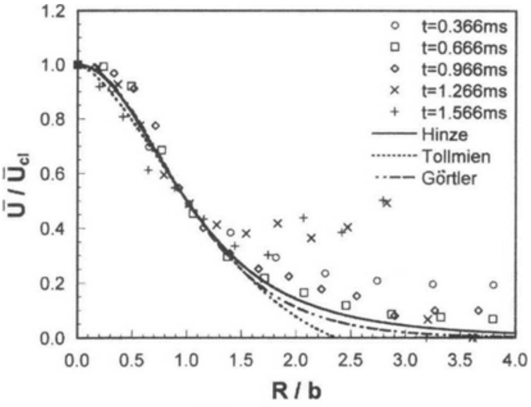


Fig. 7 Time history of axial mean velocity profiles along centerline

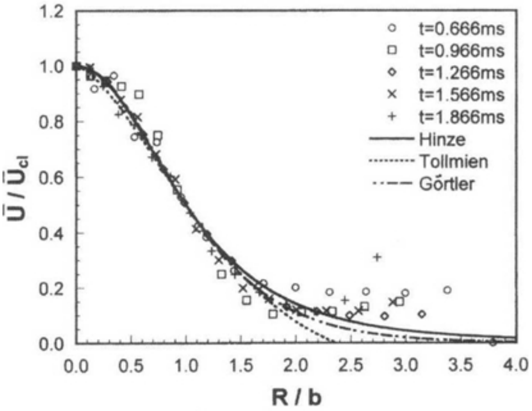
the spray is slowly occurred because the radial velocity component is not fully developed, which results from the decreased resistance with ambient air.

Figure 8 shows the axial mean velocity of the fuel spray, $\bar{U}$, measured at $Z/d_n=63$ and 156 with the time variations, which was normalized by the axial velocity of the spray centerline, $\bar{U}_{cl}$. The Hinze (1975) and the Tollmien (1945) equation for the free air jet and the Görtler (1957) equation for the two-dimensional plain jet are presented.

In the case of $Z/d_n=63$, the distribution is similar to that of the free air jet flow at $R/b<1.0-1.5$ regardless of time, but it becomes higher than that of the Hinze and the Tollmien equations at the outer region of the spray with time goes. It is considered that this phenomenon is occurred by the entrainment of surrounding air simultaneously with the formation of the spray cloud composed of the fine droplets in the spray boundary near the nozzle tip. Although the velocity distribution is high at the outer region of the fuel spray, but the overall trend of the velocity distribution is similar to the case of the free air jet at the downstream, $Z/d_n=156$. Particularly, the distribution coincides well with the result of Hinze who presented the mean velocity distribution using the empirical coefficient and the hypothesis in which the coefficient of eddy viscosity is constant in the fully developed turbulent flow field.



(a) $Z/d_n=63$



(b) $Z/d_n=156$

Fig. 8 Time history of axial mean velocity profiles

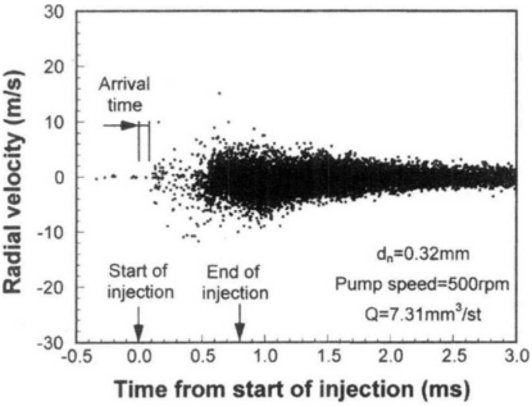
3.4 Radial velocity distributions of fuel spray

In order to investigate the diffusion process of the fuel spray, the radial velocity distribution can be considered. Figure 9 shows the radial velocity of the fuel spray with the time variations at two axial positions.

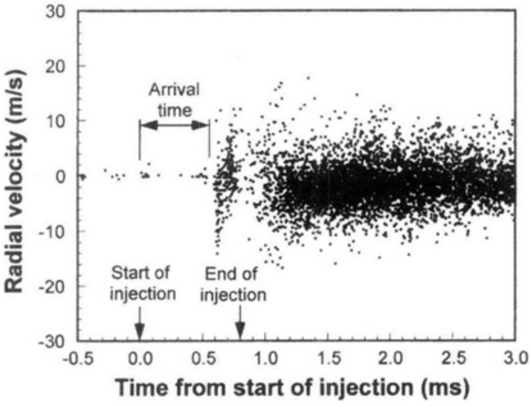
The structure of the radial velocity of the spray center is symmetrical centering around $V=0$, and the fluctuating width becomes larger and the duration becomes longer with proceeding to the downstream region. It means that the air entrainment actively takes place at the downstream region, and consequently the turbulent mixing process increases.

Figure 10 shows the radial mean velocity of the fuel spray, $\bar{V}$, measured at $Z/d_n=156$ normalized with the axial velocity of the spray centerline.

The maximum radial velocity is measured near R/b=2.0−3.0 and its value is about 7-8 % of the axial velocity for t=0.996ms. The point where the maximum radial velocity is moved to the outer region of the spray, as time passes.



(a) Z/d_n=63



(b) Z/d_n=156

Fig. 9 Time-resolved evolution of radial velocity at two axial positions of Z/d_n=63 and 156

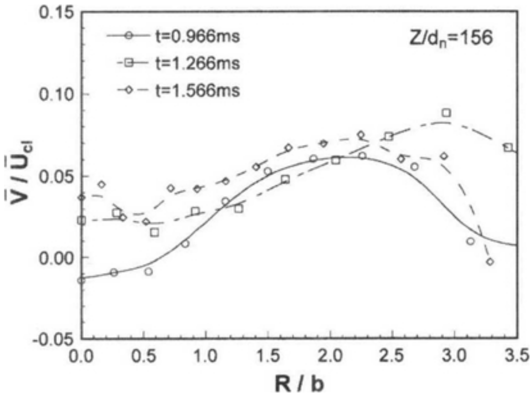
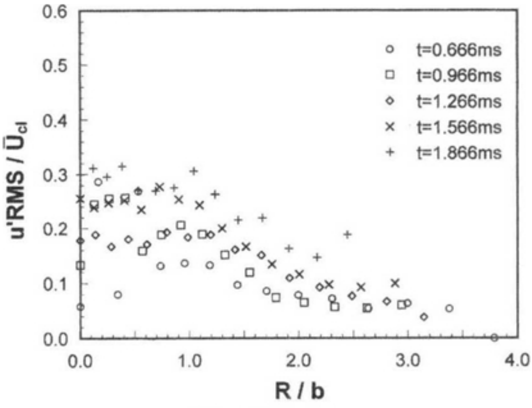


Fig. 10 Time history of radial mean velocity profiles

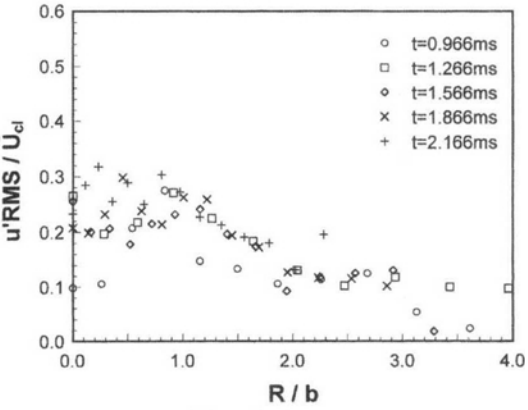
3.5 Turbulent intensity of fuel spray

Figure 11 shows the axial fluctuating velocity components of the fuel spray, $u'_{RMS}/\bar{U}_{cl}$, measured along the radial direction at Z/d_n=156 and 281 normalized with the axial velocity of the centerline.

The turbulent intensity reduces with proceeding to the outer region of the spray, and it increases in the trailing edge rather than in the leading edge regardless of the measurement position. Hence, it can be predicted that the turbulence mixture is active due to the air entrainment after the end of injection. The axial turbulent intensity near the spray axis is approximately 20-30 % of the axial

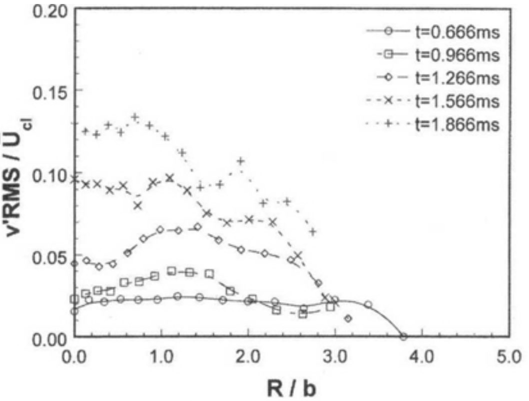


(a) Z/d_n=156

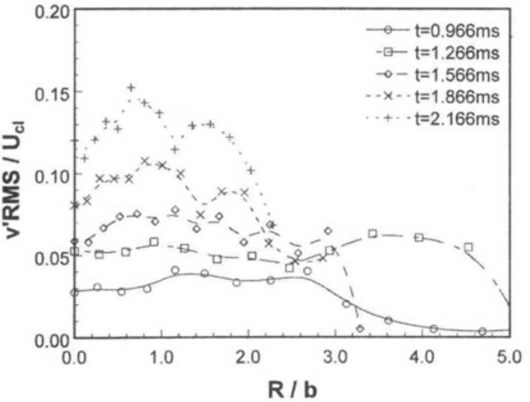


(b) Z/d_n=281

Fig. 11 Turbulence intensity profiles of axial velocity components



(a) $Z/d_n=156$



(b) $Z/d_n=281$

Fig. 12 Turbulence intensity profiles of radial velocity components

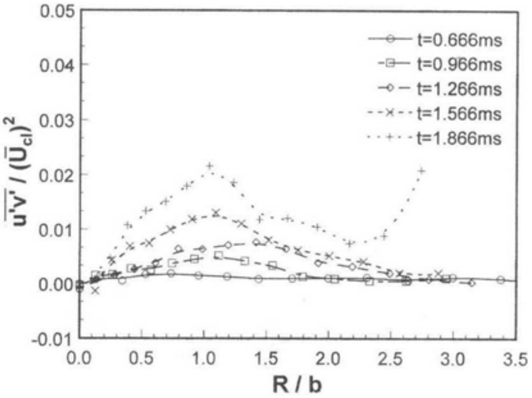
velocity of the spray centerline.

Figure 12 shows the radial fluctuating velocity components of the fuel spray, $v'_{\mathrm{RMS}}/\bar{U}_{cl}$, normalized with the axial velocity of the centerline.

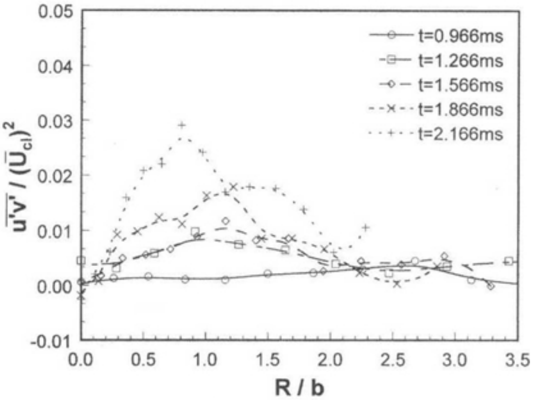
In the case of $Z/d_n=156$, the radial fluctuating velocity is approximately 2.5 % of the axial velocity at $t=0.333$ ms when the leading edge passes through the measurement position. However, the fluctuating velocity increases gradually at $t=1.266$ and 1.566 ms, and its value becomes 11-14 % of the axial velocity. Therefore, it is supposed that the turbulent intensity in the trailing edge is five times as high as in the leading edge. This trend is similarly occurred at $Z/d_n=281$.

3.6 Turbulent shear stress of fuel spray

Figure 13 shows the turbulent shear stress of the fuel spray, $\overline{u'v'}/\bar{U}_{cl}^2$, measured at $Z/d_n=156$ and 281 normalized with the square of the axial velocity of the centerline.



(a) $Z/d_n=156$



(b) $Z/d_n=281$

Fig. 13 Time history of u'v' cross-moment profiles

In the case of both $Z/d_n=156$ and $Z/d_n=281$, the turbulent shear stress in the leading edge is very low, but it increases gradually with proceeding to the central part and trailing edge. The maximum value of approximately $\overline{u'v'}/\bar{U}_{cl}^2 \approx 0.021$ and 0.028 for $Z/d_n=156$ and 281, respectively, is measured near $R/b=1.0$ regardless of elapsing time.

On the other hand, Wygnanski et al. (1969) obtained the maximum value of the turbulent shear stress, $\overline{u'v'}/\bar{U}_{cl}^2 \approx 0.017$, in the self-preserving region of a free round jet, and Rho et al. (1984, 1990) obtained $\overline{u'v'}/\bar{U}_{cl}^2 \approx 0.022$, in the cross air jet flow. Consequently, it is concluded that the turbulent shear stress in the leading edge of the intermittent single-hole diesel spray is lower than that for the continuous free air jet flow, while that in the central part and trailing edge is considerably high.

4. Conclusions

The turbulent mixing flow characteristics of the solid-cone type diesel spray injected intermittently into still ambient were investigated under the normal temperature and atmospheric pressure by using the PDPA. Concluding remarks can be summarized as following.

(1) The gradient for the single-hole diesel nozzle tended to increase linearly with the time variation, and it reached at 0.04 at the end of the injection. The value of the gradient for the single-hole diesel nozzle is smaller than that for the continuous free air jet.

(2) The axial velocity was similar to that of the free air jet flow at $R/b < 1.0 - 1.5$ regardless of time, but it became higher at the outer region of the spray. In addition, the distribution coincided well with that of the Hinze at the downstream of the spray

(3) The turbulent intensity was approximately 20-30 % of the axial velocity of the spray centerline, and it decreased gradually with proceeding to the outer region of the spray.

(4) The maximum value of the turbulent shear stress was measured at the half-width position of the spray, and it increased with proceeding to the trailing edge. The turbulent shear stress in the leading edge is lower than for the continuous free air jet flow, while that in the central part and trailing edge is considerably high.

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