Journal of Visualization, Vol. 11, No. 1 (2008)55-62

Regular Paper

An Empirical Correlation between Spray Dispersion and Spray Tip Penetration from an Edge Detection of Visualized Images under the Flow Condition of a Solid Body Rotating Swirl

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Received 19 May 2007
Revised 11 August 2007

Abstract : In this study, spray tip penetration and dispersion in high-pressure environment were simulated experimentally with an emphasis on the swirl effect. A rotating constant volume chamber was designed in order to generate a swirl that could be varied continuously with a flow field that closely resembled the solid-body rotation. An emulsified fuel was injected into the chamber and the developing process of fuel spray was observed. The effect of swirl on the spray dispersion was analyzed by measuring the dispersion area as a function of the spray tip penetration and the time after the start of the injection. The effect of swirl on the spray dispersion was quantified through getting a relationship between the swirl and the dispersion. The experimental results of the spray dispersion with time after the fuel injection process began showed similar characteristics to those of the spray tip penetration with time after the start of the fuel injection. The spray dispersion characteristics while varying the spray tip penetration were also investigated. The results showed that the spray dispersion depends linearly on the spray tip penetration, when it is small. As the spray tip penetrates into longer distance, the dispersion depends on the spray tip penetration to the power of 1.6.

Keywords : Emulsion Injection Visualization, Spray Dispersion, Solid Body Rotating Swirl, Spray Tip Penetration, Diesel Engine, Fuel Injection.

1. Introduction

A growing concern over energy resources and the environment has led to an increased level of interest in diesel engines. Advanced diesel engines have improved in terms of thermal efficiency appreciably recently, by better technology related to high-pressure fuel injection and electronic injection control (Heywood, 1989; Kamimoto and Kobayshi, 1991; Ikegami et al.,1990; Ikegami, 1996; Schuster et al., 1985; Guodong, 1990; Herzog, 1992). Air flow in a combustion chamber, in particular the swirl, affects the mixing characteristics of the fuel and air, and thereby influences factors such as the spray tip penetration, spray angle, and dispersion (Lefebvre, 1989). Therefore, swirl intensity in a diesel engine is one of the key parameters in improving engine performance. It has been demonstrated that the spray tip penetration is proportional to the square root of time after the start of high-pressure injection (Schweitzer, 1937; Wakuri et al., 1960; Dent, 1971). In this regard, extensive research related to the spray characteristics has been conducted (Rife and Heywood, 1974; Hiroyasu and Arai, 1980; Reitz and Bracco, 1979 and 1982). Velocity distributions in the combustion chambers of direct injection diesel engines were measured (Monaghan and Pettifer, 1981; Brandl et al., 1979; Ikegami et al., 1971), and it was demonstrated that the swirl velocity is approximately proportional to the radial distance inside a combustion chamber; that is, the swirl flow pattern resembles solid-body rotation. Swirl formation processes in cylinders have been investigated (Jaffri et al., 1997; Zhijun and Zhen, 2001), and a method of swirl quantification in engines has been proposed.

The effects of swirl on the spray tip penetration, breakup length, and spray angle have been investigated (Hiroyasu, 1985; Hiroyasu et al., 1980) using a constant volume chamber that simulated an open-chamber diesel engine with central injection. The swirl flow in the chamber was generated by a rotating a swirler installed in the chamber and driven by an external motor. Visualization results demonstrated that the spray behavior was less influenced by swirl compared to an experiment with an actual engine (Heywood, 1989). Yoshikawa et al. (1988) investigated the behavior of spray in a swirl flow using a liquid injection technique.

In the Yoshikawa et al.'s (1988) study, the swirl flow was generated by tangentially injecting water along the periphery of the chamber. The velocity distribution of water in a chamber has a maximum near the half-radius point of the chamber. Thus, the characteristics of the flow field deviated from those of the observed flow field in experiments with actual engines (Monaghan and Pettifer, 1981; Brandl et al., 1979; Ikegami et al., 1971).

Motivated by this, the present study simulated the spray characteristics under high-pressure injection experimentally with an emphasis on the swirl effect. In order to generate a continuously variable swirl and to achieve a swirl flow field that resembles solid-body rotation, a rotating constant volume chamber was designed. Way (1977) investigated the interaction between a swirl and a jet using a water model to enhance the effect of the swirl on the spray behavior. The spray was injected into water based on a previous finding (Yoshikawa et al., 1988) related to the similarity between an emulsion fuel spray into water and a fuel spray into a high-pressure dense gas. Also, Adopting this technique, emulsified fuel was injected into the chamber and the developing processes of the fuel sprays were observed. The effects of the swirl on the spray tip penetration and the breakup length were investigated by Lee et al. (1997).

An image processing technique for the photograph was developed to detect the edge boundary of the spray dispersion and calculate the area of the spray dispersion within the spray edge. An empirical correlation was obtained between the spray dispersion and the spray tip penetration from the processed image under the flow condition of a solid-body rotating swirl.

2. Experiments

2.1 Similarity between Sprays into Liquid and into High-Pressure Gas

When a liquid is injected into a dense gas from a hole-type nozzle, it breaks up into droplets and entrains gas flow from the surrounding. In the high-pressure injection, spray tip penetration initially is found to be linearly proportional to time, and then it becomes proportional to the square root of time. Arai et al. (1984) obtained the following relations for the spray tip penetration P_1 during the initial period based on their experimental results and on the jet disintegration theory of Levich (1962).

$$P_1 = U_0 t = C(2\Delta p / \rho_l)^{1/2} t, \quad 0 < t < t_b \tag{1}$$

Here, U_0 is the initial velocity of spray jet, ρ_l is the density of injected fuel, Δp is the pressure difference between the injection pressure and ambient pressure, t and t_b is the time and breakup time, respectively, and C is a correlation coefficient. The breakup length of liquid P_b dictates

$$P_b = \alpha(\rho_l / \rho_a)^{1/2} d, \quad t = t_b \tag{2}$$

where α is a correlation coefficient, d is the nozzle diameter and ρ_a is the density of ambient fluid. After the spray breakup, the spray tip penetration P_2 becomes

$$P_2 = \sqrt{C\alpha}(2\Delta p / \rho_l)^{1/2} (dt)^{1/2}, \ t > t_b \tag{3}$$

For the analogy between the sprays injected into dense gas and into water, the Reynolds number Re and the injection momentum M are defined as

$$\mathrm{Re} = U_0 d / \nu_l \tag{4}$$

$$M = \rho_l \pi d^2 U_0^{\ 2} / 4 \tag{5}$$

Here, ν_l is the viscosity of injected fuel.

Yoshikawa et al. (1988) found the following similarity relationships between the sprays into liquid and into high-pressure gas,

$$t_w / t_A = (\rho_w / \rho_A)^{1/2} \tag{6}$$

$$d_w / d_A = (\rho_w / \rho_A)^{1/2} \tag{7}$$

$$\Delta P_w / \Delta P_A = (\rho_w / \rho_A)^{1/2} \tag{8}$$

Table 1. Typical experimental conditions and corresponding injections into high pressure air.

	Air (engine)	Water (Model)
ρ [kg/m³]	15.6	998
t [ms]	1	8
d [mm]	0.2	1.4
P_i [MPa]	22.3	0.35
	34.8	0.55

Here, the subscripts w and A indicate an injection into water and into high-pressure air, respectively.

From their experimental results, it was substantiated that sprays injected into water has macroscopic characteristics that are similar to those of the penetration of diesel spray injected into high-pressure air. Based on the analogy between the spray into dense gas and into water by Yoshikawa et al. (1998) an injector has been designed to satisfy the Yoshikawa et al.'s similarity conditions. Table 1 shows the similarity relations which correspond to some typical experimental conditions.

2.2 Visualization

The experimental apparatus consists of a rotating constant volume chamber, a driving motor, an injector and fuel supply system, a visualization setup, and an electronic control system. The rotating constant volume chamber, as schematically shown in Fig. 1, generates a continuous swirl, and the flow field inside resembles a solid-body rotation model. The swirl is linearly dependent on the rotation speed of the chamber. The injector is fixed at the center of a shaft that is connected to the constant volume chamber using two radial bearings and one thrust bearing. The chamber is rotated by a 0.1 kW DC motor through a V-belt and pulleys; it has a maximum speed of 1150 rpm. The diameter and height of the cylindrical chamber are 66 mm and 25 mm, respectively. For observation, a quartz window with a diameter of 85 mm was installed at the bottom of the chamber.

An emulsified fuel is supplied through the injector from a 10 ℓ accumulator, which is pressurized with compressed air, as shown in Fig. 1. The pressure in the accumulator represents the injection pressure in the present experiment.

The injector used was modified from a general hole-type nozzle for a direct injection diesel engine in such a way that a single nozzle hole points radially from the shaft axis. The nozzle tip of the injector was designed to satisfy the similarity condition between an injection into water and an injection into high-pressure air. A commercial diesel injector was modified by grinding the nozzle tip part, resulting in a passage 2-mm in diameter. A cap was placed at the tip where a hole diameter

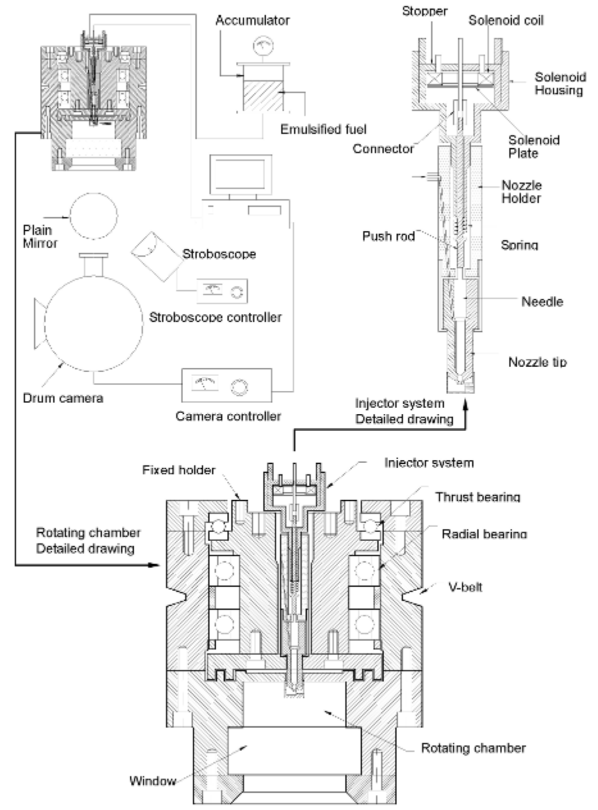


Fig. 1. Experimental setup for the visualization of the spray dispersion under the flow condition of a solid body rotating swirl.

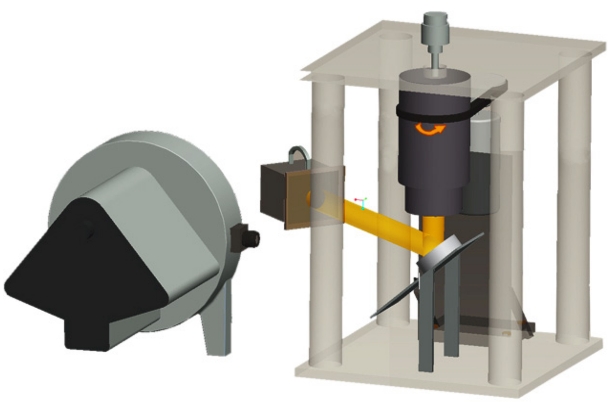


Fig. 2. 3-D Reference drawing for the visualization of the spray dispersion under the flow condition of a solid body rotating swirl.

measuring 1.4 mm was machined. To minimize a possible internal cavity effect, the cavity volume was minimized. The cap has a role of injecting the emulsion fuel in the horizontal direction, which helps capturing the image of the spray dispersion 2-dimensionally. The effect of the orifice length on the spray was studied previously by Lee et al. (1997). A solenoid valve (Lucas Ledex, 5SF-29) that controls the fuel supply had a response time of 3 ms. An 80 V DC power supply at 3 A was applied to drive the solenoid valve.

Figure 2 shows the experimental setup for the visualization of the spray dispersion. After setting the frequency of the stroboscope flash as 250 Hz, the consecutive images of the injected spray are captured by controlling exposure time and rotating speed of drum in the camera. White-colored emulsified fuel injected into water makes it possible to observe the developing and mixing processes of the spray using a stroboscope. High speed photographs were taken at 250 fps using the drum camera. A personal computer and a 8253 counter/timer were used to time the control of the fuel injections, and a solid-state relay was used to transmit power to the solenoid valve. The rotational speed of the chamber was measured using a portable tachometer.

An electronic balance and an ultrasonic generator were used to prepare the emulsified fuel, which had a hydrophile-lipophile balance (HLB) of 5.5 in order to allow water-in-oil (W/O) emulsion. SPAN80 (sorbitan monooleate, HLB = 4.3) and TWEEN80 (polyoxyethylene sorbitan monooleate, HLB = 15) were used as surfactants (Becher, 1965). With regard to making the emulsion fuel, the processes can be summarized as two steps. In the first step, after the SPAN80 6 cc and the TWEEN80 1.5 cc were added to n-heptane 250 cc, they were mixed by operating the ultrasonic generator for 30 seconds. In the second step, water 50 cc was added to the mixture of the surfactants and the n-heptane, and the emulsified fuel was produced by stirring both the water and the mixture of the surfactants and the n-heptane with a tip of ultrasonic generator for 180 seconds.

When the rotating speed of the constant volume chamber reached a steady state, emulsified fuel was injected into the chamber. From the visualization results, the spray tip penetration, spray transition, and dispersion are analyzed.

3. Results and Discussion

The tangential velocity profiles in the chamber were checked from a double-exposure image by suspending tracer particles. It was found that the tangential velocity is linear with the radial position in the chamber, thus closely simulating the swirl flow characteristics inside a diesel engine combustor, that is, solid-body rotation (Lee et al., 1997).

Consecutive visualization images are shown in Fig. 3(a) with the time interval Δt = 8 ms for the rotational speed N = 0 rpm and the injection pressure P_{inj} = 4.0 kg/cm^2. The dispersion characteristics of the spray are similar to general diesel engine sprays. Figure 3(b) shows the consecutive visualization results for N = 800 rpm and P_{inj} = 4.0 kg/cm^2. The spray is highly deflected by the influence of swirling water flow. It is to be noted that even as the swirl intensity is increased, the spray pattern near the exit of the nozzle does not differ much since the tangential velocity in this region is small near the axis of the chamber. However, the dispersion behavior is much influenced in the neighborhood of the chamber wall.

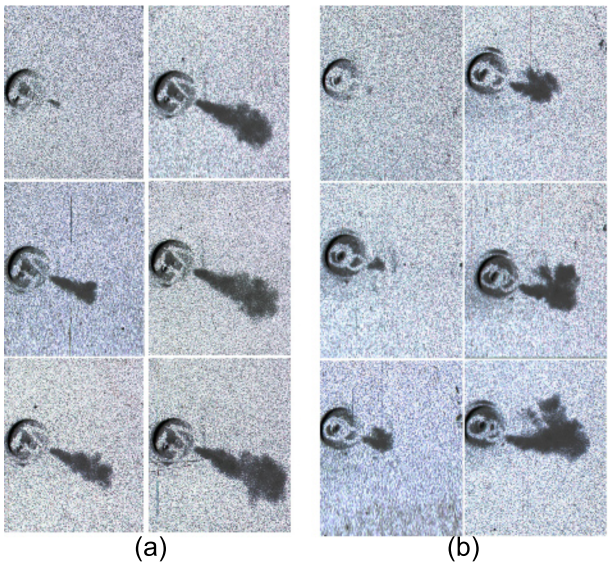


Fig. 3. Typical Visualization of fuel injection with Δt=8ms and P_{inj}= 4 kg/cm^2, (a) N = 0, (b) N = 800 rpm.

In view of the air/fuel mix, swirl is an important parameter that affects the performance and the emission level of diesel engines. In general, the air/fuel mix in a diesel engine is promoted by impingement with the wall of a combustion chamber and by the swirl flow. When the swirl intensity becomes excessive, spray penetration can be decreased such that impingement with the wall is delayed.

The spray dispersion characteristics with varying spray tip penetration in a direct-injection diesel engine are likely an important parameter for estimating the efficiency of using compressed air in the combustion chamber. Spray dispersion represents the area where air and fuel is mixed in the combustion chamber. Therefore, with a larger mixing area, greater efficiency using intake air will result. Figures 4(a) and (b) show the consecutive trajectories of the spray dispersion boundaries with time intervals of 4 ms with spray chamber rotating speeds of N = 0 and N = 300, respectively. For a visualization of the spray dispersion performed with a four-hole nozzle, dispersion features would appear as shown in Figs. 4(c) and (d), which correspond to Figs. 4(a) and (b), respectively.

The air shown in white in Figs. 4(c) and (d) could not be used in the burning of the injected fuel. The white area in Fig. 4(c), which shows the spray dispersion with swirl, is smaller than that shown in Fig. 4(d), which shows the spray dispersion without swirl. Figure 4 shows that the spray dispersion is an important parameter, as it estimates whether the air in the combustion chamber contributes to an effective burning of the injected fuel. In addition, the dispersion characteristics in Fig. 4 show that there could be an optimal spray dispersion corresponding to the swirl flow.

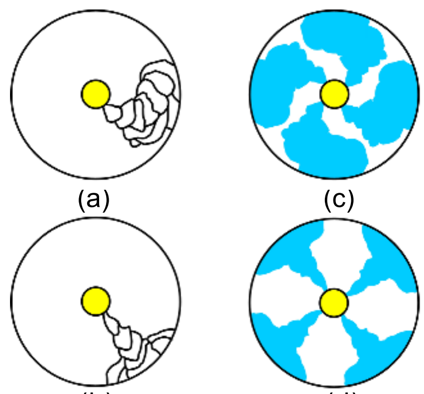
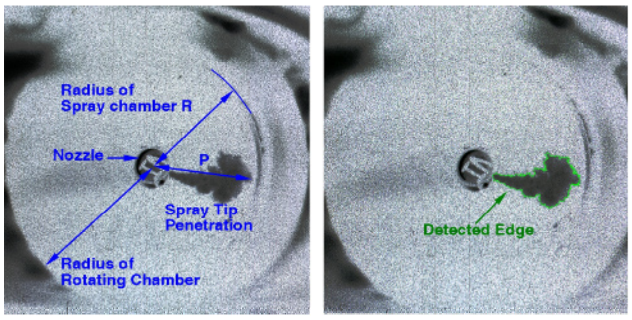


Fig. 4. Sketches of the injected fuel trajectories.

The effect of swirl on the spray dispersion characteristics was investigated by calculating the nondimensional area A_{dis}/A_{sc}, where A_{dis} and A_{sc} are the areas of the spray dispersion and spray chamber, respectively. A_{dis}/A_{sc} represents the portion of the area influenced by the spray dispersion using single-hole injection. In this study, the dispersion area A_{dis} was obtained precisely using a NI-Vision 7.0 image processing program adopting an edge detection technique. After 'Measure' menu is executed in the NI-Vsion7.0 IDE (integrated development environment), measurement 'area' is selected. Then, tolerance is set with the value of the maximum allowable deviation from the origin. All pixels satisfying the tolerance criteria (origin pixel-tolerance/ origin pixel+tolerance) become part of the area. In the next step, pushing 'Magic wand tool button' creates an image mask by extracting the region surrounding a reference pixel and using the tolerance of intensity variations based on this reference pixel. The program searches for its boundaries with an intensity equal to or falling within the tolerance value of the reference level. Figure 5(a) shows a typical image captured by the drum camera for P_{inj} = 4 kg/cm^2. Figure 5(b) show the edge detection result from Fig. 4(a), as explained previously. The area of the spray chamber can be calculated from πR^2. The spray tip penetration P and the radius of the spray chamber R are also illustrated in Fig. 5(a).



(a) (b)

Fig. 5. Image showing (a) the definition of the spray tip penetration and (b) the edge detection of the spray dispersion after image processing.

The nondimensional dispersion area A_{dis}/A_{sc} with time after the start of injections at various rotating speeds and injection pressures are displayed in Fig. 6. The figure shows characteristics that are similar those when the spray penetration is generally linear with time at the initial period; the observations then become proportional to the square root of time (Lee et al., 1997). The data for A_{dis}/A_{sc} shows two linearly different slopes before and after 6 ms after the start of the injection, at which point the spray transition occurs as expected according to the findings of related research (Lee et al., 1997), which shows typical characteristics of the spray tip penetration with time. The correlation between the data for A_{dis}/A_{sc} and the time after the start of an injection proceeds as

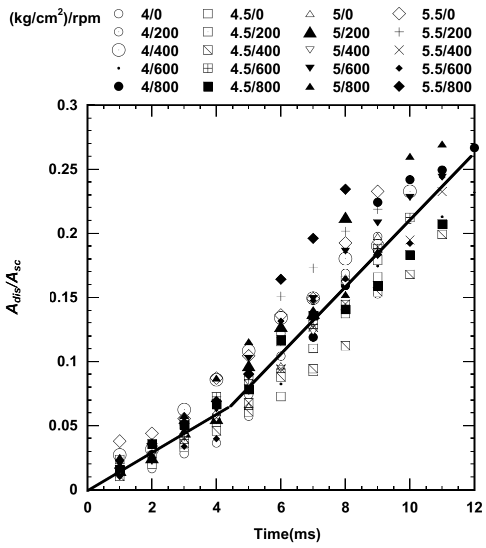


Fig. 6. Nondimensional dispersion area as function of time.

$$A_{dis} / A_{sc} = 0.0145t, \qquad t < 4.5 \text{ ms, R} = 0.86 \tag{9}$$

$$A_{dis} / A_{sc} = 0.025t - 0.042, \quad t > 4.5 \text{ ms, R} = 0.89 \tag{10}$$

with a correlation coefficient of R = 0.86 at t < 4.5 ms and 0.89 at t > 4.5 ms for Eqs. (9) and (10), respectively. The A_{dis}/A_{sc} value and the spray tip penetration versus the time after the start of an injection are similar in terms of the differing characteristics at the spray transition. However, after the spray transition occurs, A_{dis}/A_{sc} increases linearly with time and the spray tip penetration increases with some power of time (Lee et al., 1997)

Figure 7 shows initial behavior of the nondimensional dispersion area A_{dis}/A_{sc} with the nondimensional penetration P/R at various rotating speeds and injection pressures. The experimental results were analyzed and the data for A_{dis}/A_{sc} demonstrated two distinct regimes: an initial linear regime and, later, a nonlinear regime with (P/R). The spray dispersion increases linearly with the increase of P/R when P/R < 0.3. All of the experimental data can be fitted in the form of

$$A_{dis} / A_{sc} = 0.18(P / R), \qquad (P/R) < 0.3 \tag{11}$$

with a correlation coefficient of R = 0.90. This regime is mainly controlled by the fuel jet momentum, thus linear behavior is expected. It is important to note that P/R ≈ 0.3 corresponds to P ≈ 13 mm, at which point the spray transition occurs.

The dispersion characteristics during the later stage of injection are shown in Fig. 8 in terms of the logarithmic scale for A_{dis}/A_{sc}. These results exhibit the following correlation between the nondimensional dispersion and nondimensional penetration.

$$A_{dis} / A_{sc} = 0.37(P/R)^{1.6}, \qquad (P/R) > 0.3 \tag{12}$$

Here, R = 0.90.

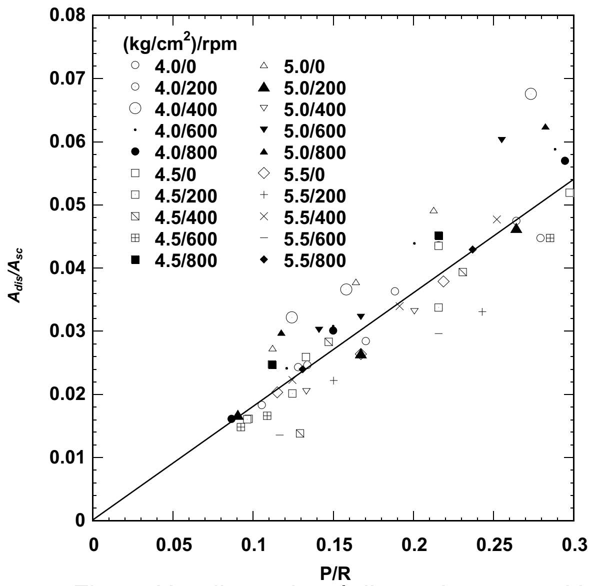


Fig. 7. Nondimensional dispersion area with penetration for P/R < 0.3.

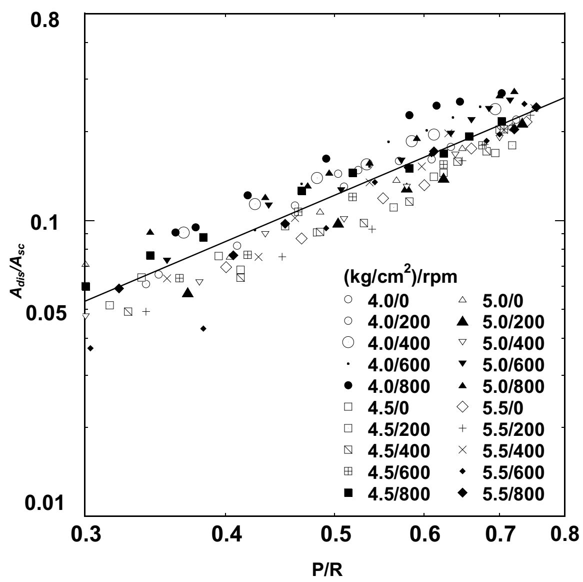


Fig. 8. Nondimensional dispersion area with penetration for P/R > 0.3.

The dispersion of the injected spray is nearly 2-dimensional from the point of view that the swirl flow has effect on the spray dispersion mainly in the horizontal direction. A_{dis}/A_{sc} has physical meaning in that A_{dis}/A_{sc} could be used to predict the dispersion area in the combustion chamber of direct injection diesel engines according to the nondimensionalized spray tip penetration, P/R. In other words, spray dispersion in a combustion chamber at a spray tip penetration could be calculated using Eqs. (11) and (12) before the spray impinges the wall of the combustion chamber. If number of holes in the injector is given, Eqs. (11) and (12) could be used to predict whether the spray dispersion overlaps or not in a given diameter of the combustion chamber.

The results shown in Figs. 7 and 8 demonstrate that the dispersion is mainly controlled by the penetration for all injection pressures and swirl conditions.

4. Concluding Remarks

A constant volume chamber that could generate a continuously variable swirl with a flow field resembling solid-body rotation was developed. Emulsified fuel was injected into the chamber and the developing process of the fuel spray was observed. Factors of the spray tip penetration and the dispersion characteristics of spray were investigated by varying the swirl intensity.

The spray dispersion was analyzed using an edge detection technique. The results demonstrated that a nondimensional dispersion can be correlated reasonably with a nondimensional penetration. The results exhibited two distinct regimes: an initial linear regime and, later, a nonlinear regime. A transition of the dispersion characteristics occurred near the spray transition points, demonstrating characteristics that are similar to those involving the spray tip penetration with time.

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