International Journal of Automotive Technology, Vol. 4, No. 4, pp. 157–164 (2003)

Article No. 1229–9138/2003/14–01

MACROSCOPIC STRUCTURE AND ATOMIZATION CHARACTERISTICS OF HIGH-SPEED DIESEL SPRAY

S. W. PARK[1)] and C. S. LEE[2)*]

[1)]Graduate School of Hanyang University, Seoul 133-791, Korea
[2)*]Department of Mechanical Engineering, Hanyang University, Seoul 133-791, Korea

(Received 14 May 2003; Revised 6 October 2003)

ABSTRACT–An experimental and numerical study was performed to investigate the macroscopic and microscopic atomization characteristics of high-speed diesel spray issued from the common-rail injection system. For the experiments, spray visualization system and a phase Doppler particle analyzer system were utilized to obtain the spray atomization characteristics such as the process of spray development, spray tip penetration, and SMD distribution. In order to analyze the process of spray atiomization with KIVA-3 code, the TAB breakup model is changed to the KH-DDB competition model, which assumes the competition between the wave instability and droplet deformation causes the droplet breakup above the breakup length. The calculated results were also compared with the experiments in terms of spray tip penetration and SMD distribution. The results provide the process of spray development, axial and radial distribution of SMD, and calculated overall SMD as a function of time after start of injection.

KEY WORDS : Atomization characteristics, Breakup model, KIVA code, Common-rail injection system

NOMENCLATURE

a : major semi-axis of the ellipsoidal cross section of the oblate spheroid
B_1 : KH breakup constant
d_0 : diameter of nozzle
K : liquid-gas of density ratio
L : axial distance from nozzle
L_b : breakup length
N : liquid-gas of viscosity ratio
r : radius of droplet
r_c : critical droplet radius
Re_f : Reynolds number of fuel $(=U_r r/\upsilon_f)$
Re_g : Reynolds number of ambient gas $(=U_r r/\upsilon_g)$
U_r : relative velocity between the droplet and the ambient gas
We_f : Weber number of fuel $(=\rho_f U^2_r r/\sigma)$
We_g : Weber number of ambient gas $(=\rho_g U^2_r r/\sigma)$
y : distance from the center of mass to its equator of the deforming half-drop
σ : surface tension
μ : viscosity
ρ : density
υ : kinematic viscosity
Λ_{KH} : wavelength corresponding to the maximum growth rate of KH wave
Ω_{KH} : maximum growth rate of KH wave

SUBSCRIPTS

f : fuel properties
g : ambient gas properties

**Corresponding author.* e-mail: cslee@hanyang.ac.kr

1. INTRODUCTION

To improve the understanding on the spray structure of a common-rail diesel injector is important because the emission characteristics are closely related to the atomization performance of the injected spray in the engine. In this point of a view, many researches on the atomization mechanism of high-speed diesel spray have been carried out. Lee and Park (2002), Ishikawa and Niimura (1996), Hwang *et al.* (2003), and Farrell *et al.* (1996) have investigated the spray structure and atomization characteristics of high-speed spray injected from a common-rail injection system experimentally. They reported that the characteristics of fuel spray of the common-rail injector obtained by using the shadowgraphs and particle image velocimetry at various injection and chamber conditions.

With the experimental approach on the diesel spray, many researchers tried to simulate the atomization process of the high-speed diesel spray. It is well kown that the TAB model (O'Rourke and Amsden, 1987) that is included in the original KIVA code is improper for the high-speed diesel spray because TAB model underestimates the SMD and spray tip penetration (Allocca *et al.*, 1994; Park *et al.*, 2002).

Various breakup models are proposed by many researchers to analyze the high-speed diesel spray numerically with good prediction accuracy. Reitz (1987) proposed WAVE model based on the KH instability that is generated when a high relative velocity exits at the interface between the liquid and gas flow. Ibrahim *et al.* (1993) also suggested the DDB model, in which it assumes that the liquid drop is deformed a pure extensional flow from an initial spherical shape.

Recently, the hybrid breakup models that are composed of two different single breakup models for the primary breakup and secondary breakup are proposed. Patterson and Reitz (1998) suggested the KH-RT hybrid breakup model with the concept that the competition between KH instability and RT instability causes the droplet breakup. Yi and Reitz (2002) developed the pseudo-two-dimensional model using the technique of tracking the wave growth on the liquid-gas interface for the primary breakup and combined it with the RT breakup model. Also Park *et al.* (2003) investigated the prediction accuracy of various hybrid models for high-speed diesel fuel sprays and reported that the results of KH-RT model, KH-DDB model, and Turbulence-DDB model agree well with the experimental results.

The objective of this research is to investigate the macroscopic spray structure, spray tip penetration, and local SMD and velocity distributions of high-speed diesel spray of the common-rail type diesel engine experimentally. The spray visualization system and PDPA system were utilized to obtain the images of spray development and droplet size and velocity distributions. The experimental results of spray images and droplet size distribution are also compared with the simulation results from KH-DDB competition model with KIVA-3 code to verify the experiments.

2. EXPERIMENTAL APPARATUS AND PROCEDURES

The experimental apparatus of this work consists of the common rail type high-pressure fuel injection system, spray visualization system, and the phase Doppler particle analysis (PDPA) system as illustrated in Figure 1. Electronically controlled high-pressure diesel injection system is composed of a diesel injector, common rail manifold, high-pressure fuel pump, air compressor, control unit, pressure regulator, and pressure sensors. To adjust the fuel injection pressure, two high-pressure

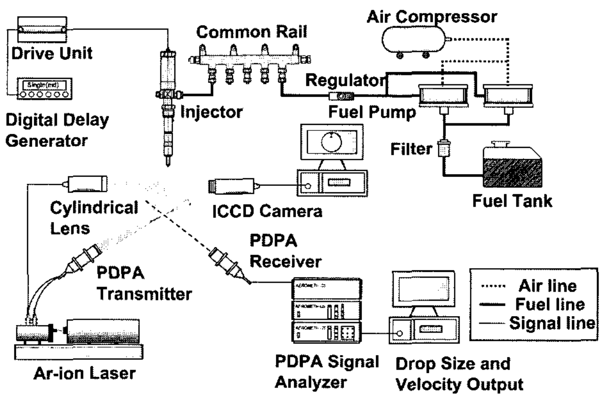


Figure 1. Schematic diagram of experimental apparatus.

pumps, a common rail, and a pressure regulator with the pressure sensors were utilized.

In this experiment, an electronically controlled common rail type diesel injector, which has single hole of 0.3 mm, was used. The phase Doppler particle analyzing system consists of a laser light source, optical arrangements, a transmitter, and a data acquisition system.

The spray visualization system that is composed of a delay generator, optical lenses and mirrors, and an ICCD camera was utilized to obtain the macroscopic structure of the injection spray.

In order to obtain the spray visualization and microscopic characteristics of diesel spray, the experiments were carried out at various injection pressures and test points. The test conditions are shown in Table 1. The macroscopic structure of the fuel spray such as spray shape, spray tip penetration, and overall behavior can be obtained directly from the frozen images of the image grabber. On the other hand, the droplet distribution and mean droplet diameter were measured by the PDPA system.

The experiments and calculations were performed at the injection pressures of 60 MPa, 70 MPa, and 80 MPa. Ambient conditions were atmospheric pressure and room temperature for all the test cases. The time delay generator controled injection timing and duration by

Table 1. Operation conditions.

Injection pressure (MPa)	60	70	80
Liquid mass flow rate (g/s)	11.8	13.2	14.4
Nozzle hole diameter (mm)		0.3	
Injection duration (ms)		1.4	
Ambient pressure (MPa)		0.1	
Ambient temprature (K)		293	
Nozzle L/D ratio		2.67	

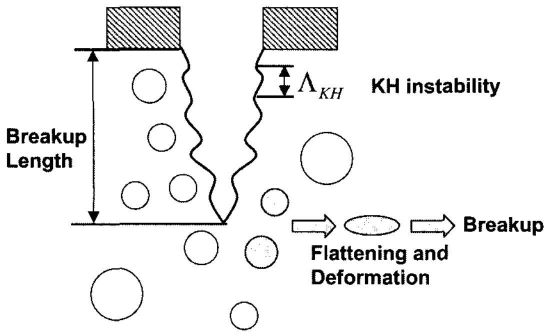


Figure 2. The concept of KH-DDB competition model.

change the timing of the pulse and the pulse width electronically as illustrated in Figure 1.

3. KH-DDB COMPETITION MODEL

3.1. Concept of KH-DDB Breakup Model

Figure 2 shows the concept of KH-DDB competition model. In the case of catastrophic breakup regime, the instabilities of wave on the droplet surface are known as a reason of droplet breakup. However, considerable flattening of the liquid droplet was observed at the experiment of high relative velocities between droplet and ambient gas in the chamber as reported by Hwang *et al.* (1996). In the common-rail injection spray, most of the atomization process is occurred in the catastrophic regime due to the high injection pressure. The droplet velocity of the common-rail diesel injector is very high within the breakup length in comparison to the velocity of droplet beyond the breakup length. In this point of a view, the atomization process within the breakup length can be assumed to be affected by both wave instability and droplet deformation. At the downstream of the injection spray, the most part of the atomization process is governed by the deformation of the droplet. Based on this theory, the KH-DDB model is developed for the research on the atomization process of the high-speed spray.

This breakup process is shown in Figure 2 schematically. As shown in the figure, after the fuel jet is issued from the nozzle, the droplets are disintegrated by the results of competition between the instability of KH wave and the deformation of the droplet. As the time is elapsed, both the deformation and the wave instability are increased. To model this competition, it is assumed that the KH breakup does not occur if the DDB breakup happens. On the other hand, the droplets beyond the breakup length are affected by the deformation of the droplet since the velocity of droplet at that region is low relatively. Therefore, to take this account, it is assumed that only DDB model governs the atomization of the spray beyond the breakup length.

In this study, the breakup length, L_b, is calculated by using the equation proposed by Beale and Reitz (1999).

$$L_b = \frac{1}{2}B_1 d_0 \sqrt{\frac{\rho_f}{\rho_g}} \tag{1}$$

where, B_1 is the breakup constant of KH model, which is set equal to 60 as recommended by Su *et al.* (1996). L_b and d_0 indicate the breakup length and the diameter of the nozzle respectively.

3.2. KH Model

The Kelvin-Helmholtz (KH) instability breakup model assumes a cylindrical liquid jet in the axial direction issuing from a circular orifice into a stationary incompressible gas. In this model, the atomization is the result of wave growth on the surface of liquid jet by aerodynamic interaction between the liquid and ambient gas medium. From the solution of a general dispersion equation (Reitz, 1987), the maximum growth rate Ω_{KH} and the corresponding wavelength Λ_{KH} are given by

$$\frac{\Lambda_{KH}}{r} = 9.02\frac{(1+0.45Z^{1/2})(1+0.4T^{0.7})}{(1+0.87We_g^{1.67})^{0.6}} \tag{2}$$

$$\Omega_{KH}\left[\frac{\rho_f r^3}{\sigma}\right]^{1/2} = \frac{(0.34+0.38We_g^{3/2})}{(1+Z)(1+0.4T^{0.6})} \tag{3}$$

In the above equations, $Z = \sqrt{We_f}/\mathrm{Re}_f$, $\mathrm{Re}_f = \rho_f U_r r/\mu_f$, and $T = Z\sqrt{We_g}$.

In this model, critical droplet radius r_c and breakup time τ_{KH} are given by

$$r_c = 0.61\Lambda_{KH} \tag{4}$$

$$\tau_{KH} = \frac{3.726 B_1 r}{\Omega_{KH}\Lambda_{KH}} \tag{5}$$

The radius of the droplet after breakup can be calculated under the assumption that the droplet radius reduces to the critical radius r_c during the breakup process.

3.3. DDB Model

The droplet deformation and breakup (DDB) model (Ibrahim *et al.*, 1993) assumes that the droplet breakup is based on the drop dynamics of excessive deformation of the droplet. DDB model assumes the non-linear effects, which is not considered the TAB model. It is assumed that the initial droplet is deformed by a pure extensional flow. The governing equation of the DDB model is given by

$$K\frac{d^2y}{dt^2} + \frac{4N}{\mathrm{Re}}\frac{1}{y^2}\frac{dy}{dt} + \frac{27\pi^2}{16We}y[1-2(cy)^{-6}] = \frac{3}{8} \tag{6}$$

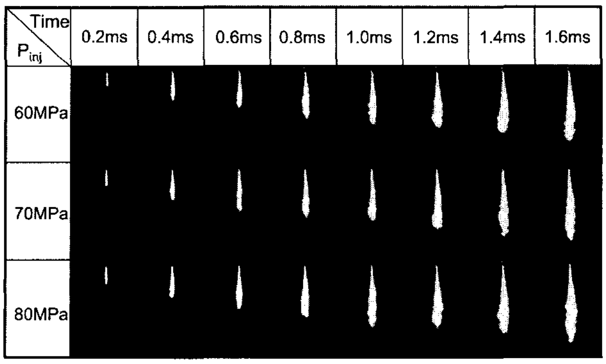


Figure 3. Effect of injection pressure on the process of spray development.

In the above equation, K is the liquid-gas of density ratio and N is the liquid-gas of viscosity ratio. Also, the critical condition of the drop breakup is given by the following equation (Ibrahim *et al.*, 1993).

$$\frac{a}{r} = \frac{We}{6\pi} \tag{7}$$

4. RESULTS AND DISCUSSIONS

4.1. Spray Structure and Atomization Characteristics

In this study, the PDPA system and spray visualization system were utilized to obtain the spray development process, spray tip penetration, and SMD distribution. The experimental conditions are listed in Table 1.

Figure 3 shows photos of transient diesel spray under the atmospheric conditions with the injection pressures of 60, 70, and 80 MPa. At the later stage of injection duration such as 1.4 ms and 1.6 ms, it is observed that the shape of the spray tip becomes steep with the increase of injection pressure. The higher injection pressure may increase the velocity of droplets near the center of the nozzle. As can be seen in the images of Figure 3, the fluctuationa are generated on the surface of the spray due to the friction with the ambient gas.

Figure 4 shows the effect of injection pressure on the spray tip penetration. As expected, the spray tip penetration is increased with the increase of injection pressure. The spray tip penetrations are also increased almost lineary during the injection period.

Figure 5 shows the experimental results SMD and axial mean velocity at various injection pressures. In the case of SMD distribution, the effect of injection pressure on SMD distribution according to the axial distance is slight. It can be guessed that the SMD is decreased in the upstream, and converged on the constant value, which is related to the limit of droplet breakup. The breakups occur actively above 25 mm at 60 MPa of injection pressure. On the other hand, the fuel spray is atomized actively above 15 mm at 80 MPa of injection pressure. This trend indicates that the SMD decreases more rapidly as the injection pressure increases.

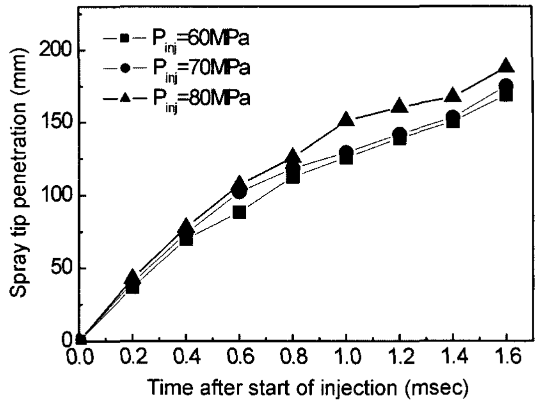
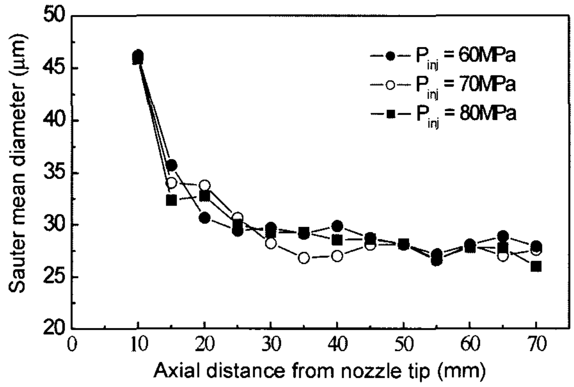
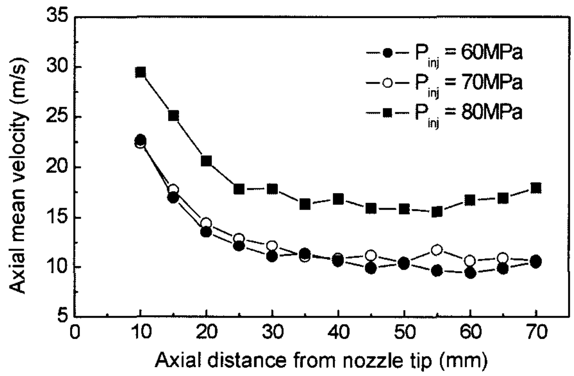


Figure 4. Effect of injection pressure on spray tip penetration.



(a) Sauter mean diameter



(b) Axial mean velocity

Figure 5. Experimental results of SMD and axial mean velocity at various injection pressures.

In the case of axial mean velocity, the patterns are

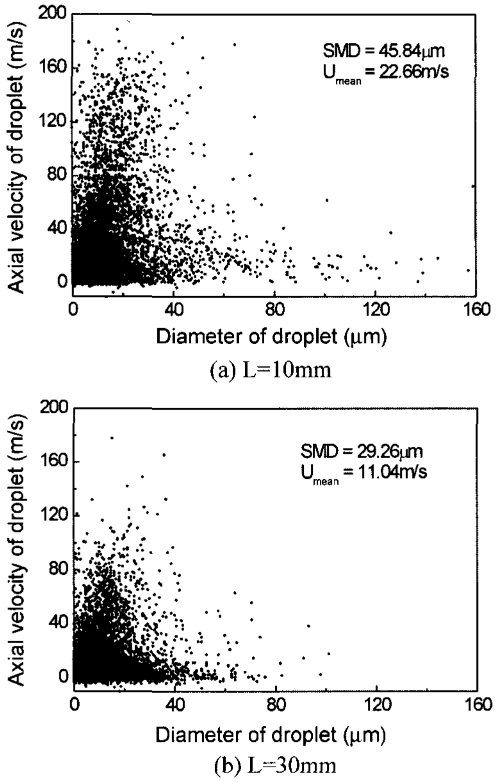


Figure 6. Correlation between diameter and axial velocity (P_{inj} = 80 MPa).

similar with the graph of SMD distribution. The axial mean velocity is decreased from the nozzle tip to 25 mm downstream almost linearly, and is converged on the constant velocity.

The correlation between the droplet size and axial velocity is illustrated in Figure 6. In the case of 10 mm downstream, almost droplets have the diameter 0 μm and 50 μm with the axial velocity from 0 m/s to 180 m/s. Some droplets which are larger than 100 μm are observed in the figure. On the other hand, in the Figure 6(b), the sizes of droplets are atomized and the axial velocities are decreased.

4.2. Comparisons with the Calculated Results

With the experiments, the calculations were performed by using the KH-DDB breakup model with the KIVA-3 code to verify the experimental results.

Figure 7 shows the comparison between the experimental and calculated results of the spray development according to the elapsed time from the start of injection. The results of calculation were obtained by using KIVA-3 code with KH-DDB hybrid breakup model at the same conditions with the experiments. As can be seen in this figure, the computed images reasonably agree with the experimental images of the spray visualization system.

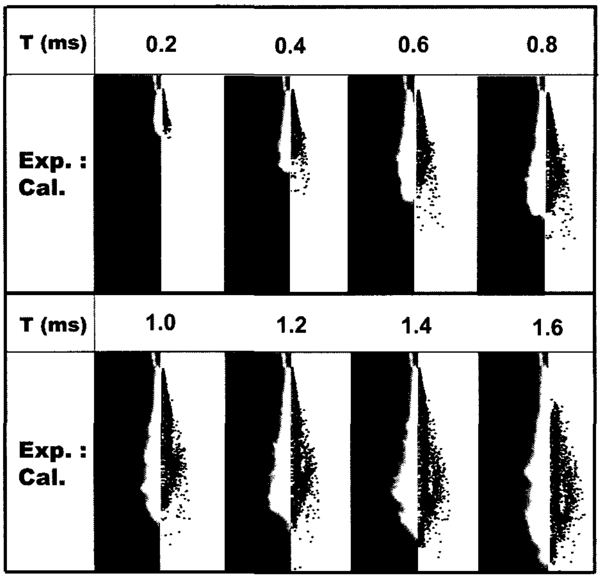


Figure 7. Experimental and calculated results of the spray developments at 80 MPa of injection pressure.

However, the experimental and calculated results of axial distances that have the maximum width are somewhat different each other. The spray of experiments shows the maximum width at the almost bottom of the spray in comparison to the results of calculations.

As shown in the calculated images at the initial stage of injection, some droplets are dispersed away from the main stream of the spray. However, the images near final stage of injection duration show that the droplets of spray distribute around the main stream of the spray.

Based on the comparison of spray images, it can be seen that some droplets at the initial stage, which undergo almost no breakup, flow downstream with high velocity. As the time further elapsed, the droplets of the spray merged with the main spray as shown in the final stage of

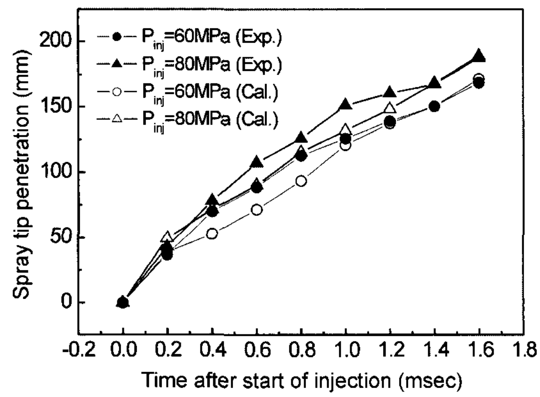


Figure 8. Comparison of spray tip penetration.

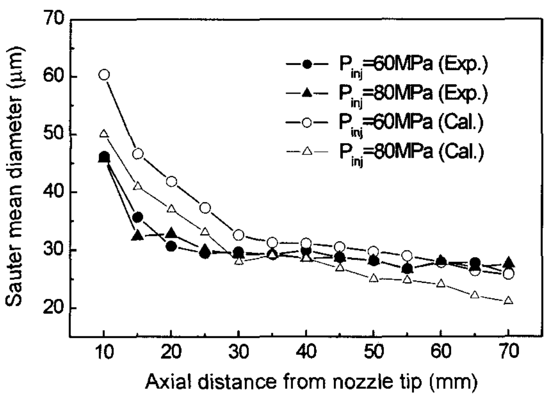


Figure 9. Prediction accuracy of KH-DDB breakup model on the axial SMD distribution.

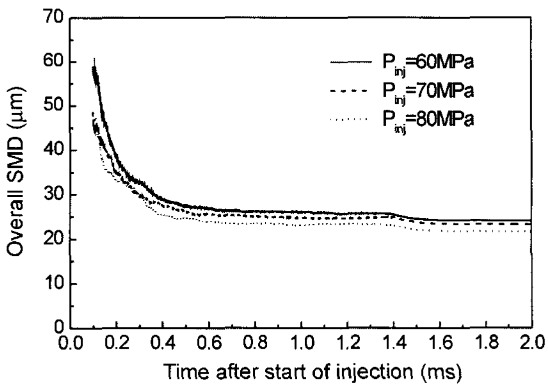


Figure 11. The effect of injection pressure on the calculated overall SMD.

the calculated image illustrated in Figure 7.

In Figure 8, the comparison between experimental and calculated results of spray tip penetraion are illustrated to carry out a quantative analysis on the spray development process.

The spray tip penetraion is important in evaluating the prediction accuracy of the breakup model because the penetration is determined by the droplet size. Judging from the calculated spray tip penetration of Figure 8, the prediction accuracy of KH-DDB hybrid breakup model is fairly good. It can be also shown that the KH-DDB breakup model reflects the effect of injection pressure on the atomization characteristics well.

Figure 9 shows the prediction accuray of KH-DDB breakup model on the axial SMD distribution. In this study, the droplets that pass through the imaginary circle of the test point are taken into the calculation of local SMD to obtain calculated local SMD from KIVA. From 10 mm to 40 mm, the calculated SMD is larger than the results of experiments, and agrees well with the experiments between 30 mm to 60 mm. The overall calculated distribution of SMD agrees with the results of experiments beyond 30 mm as can be seen in the figure.

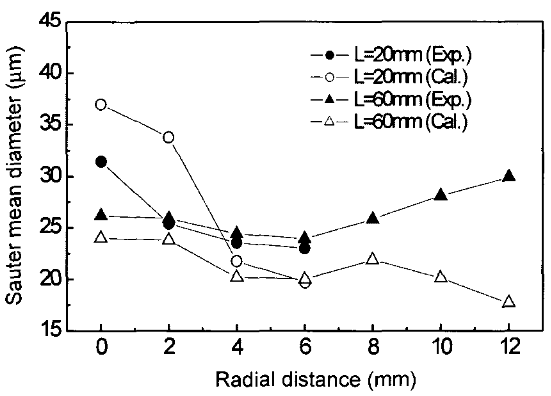


Figure 10. Radial distribution of SMD at 80MPa of injection pressure.

The SMD distribution according to the radial distance is also important to investigate the spray structure of common-rail diesel injector Besides the axial SMD distribution. Figure 10 shows the predicted and experimental results of radial SMD distribution at 20 mm and 60 mm downstream from the nozzle tip at 80 MPa of injection pressure. In the case of experiments, the values of SMD at each radial test points are almost constant at every axial distances. However the SMD is decreased with increase of radial distance in the case of calculation.

Figure 11 shows the effect of injection pressure on the calculated overall SMD as a function of time after start of injection. As can be seen in the figure, the overall SMD is decreased with the increase of injection pressure. It can be conducted that a large relative velocity between the droplet and ambient gas causes the high drag, and promotes the atomization of the injected fuel spray. The calculated overall SMD is reduced rapidly after the start of injection, and shows almost constant value 0.4 ms after the start of injection.

Figure 12 illustrates the spatial distribution of droplet breakup in the calculation region. For comparing the percentage distribution of the figure, the count of droplet breakups in a specific area of 1.0 mm × 1.0 mm are divided by the count of breakup in the entire area. In both cases of KH and DDB breakups, the breakup occurs most actively in the 10 mm downstream from the injector tip at both injection pressures. Also the atomization process of the injected spray is almost finished above 25 mm from the injector tip. In the image of KH breakup at 80 MPa of injection pressure, two peaks are observed. On the other hand, there is only one peak in the image of KH breakup at 60 MPa of injection pressure. It is guessed that the gap between two peaks is generated because of the gap of

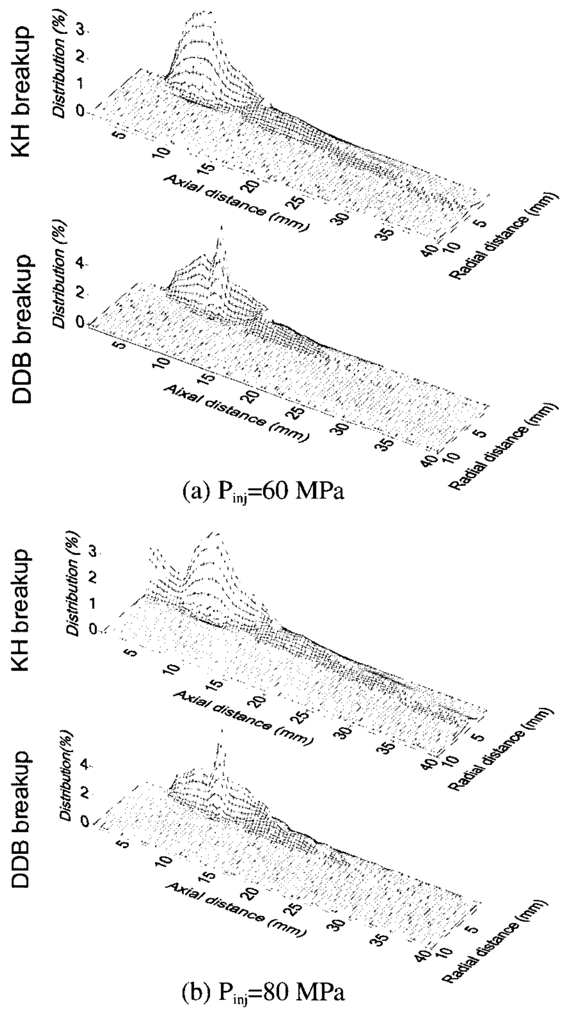


Figure 12. Spatial distribution of KH-DDB breakup.

time between the calculation cycles.

5. CONCLUSIONS

The experiments and calculations were performed to investigate the atomization characteristics of common-rail diesel injector by using the spray visualization system and phase Doppler particle analyzer system. The KH-DDB hybrid breakup model was also proposed from the theory based on the competition between the wave instability and droplet deformation. The prediction accuracy of the hybrid breakup model were evaluated based on the experimental results in terms of spray development process, spray tip penetration, and axial and radial SMD distributions. In order to investigate the characteristics of primary and secondary breakups of the proposed model, the spatial distributions were studied at different injection pressures. From the results of this research, the conclusions are summarized as follows:

(1) The shape of the spray tip becomes steep with the increase of injection pressure, because the higher injection pressure increases the velocity of droplets near the center of the nozzle.
(2) Some droplets, which undergo almost no breakup, flow downstream with high velocity, and are decelerated more rapidly by the high drag force. And then the droplets merge with the main spray.
(3) From 10 mm to 40 mm, the calculated SMD is larger than the results of experiments, and agrees well with the experiments between 30 mm to 60 mm. The overall calculated distribution of SMD agrees with the results of experiments beyond 30 mm.
(4) The experimental results of radial SMD distribution at each test point are almost constant at every axial distances. However, the SMD is decreased with increase of radial distance in the case of calculation.
(5) The calculated results of overall SMD are decreased with the increase of injection pressure because of the high drag from the large relative velocity between the droplet and ambient gas.
(6) The spatial distribution of primary and secondary breakups shows that the atomization process is almost finished above 25 mm from the injector tip.

ACKNOWLEDGEMENT–This work was supported by the Korea Research Foundation Grant. (KRF-2002-042-D00025).

REFERENCES

Allocca, L., Corcione, F. E., Fusco, A., Papetti, F. and Succi, S. (1994). Modeling of diesel spray dynamics and comparison with experiments. *SAE Paper No.* 941895.

Beale, J. C. and Reitz, R. D. (1999). Modeling spray atomization with the Kelvin-Helmholtz/Rayleigh-Taylor hybrid model. *Atomization and Sprays* **9**, 623-650.

Farrell, P. V., Chang, C. T. and Su, T. F. (1996). High pressure multiple injection spray characteristics. *SAE Paper No.* 960860.

Hwang, J. S., Ha, J. S. and No, S. Y. (2003). Spray characteristics of DME in conditions of common rail injection system (II). *Int. J. Automotive Technology* **4**, **3**, 119-124.

Hwang, S. S., Liu, Z. and Reitz, R. D. (1996). Breakup mechanism and drag coefficients of high-speed vaporizing liquid drops. *Atomization and Sprays* **6**, 353-376.

Ibrahim, E. A., Yang, H. Q. and Przekwas, A. J. (1993). Modeling of spray droplets deformation and breakup. *J. Propulsion* **9**, 651-654.

Ishikawa, N. and Niimura, K. (1996). Analysis of diesel spray structure using magnified photography and PIV. *SAE Paper No.* 960770.

Lee, C. S. and Park, S. W. (2002). An experimental and numerical study on fuel atomization characteristics of high-pressure diesel injection sprays. *Fuel* **81**, **18**, 2417-2423.

O'Rourke, P. J. and Amsden, A. A. (1987). The Tab method for numerical calculation of spray droplet breakup. *SAE Paper No.* 872089.

Park, S. W., Kim, H. J. and Lee, C. S. (2002). An experimental and numerical study on atomization characteristics of gasoline injector for direct injection engine. *Proceedings of ilass-Americas 2002*, 47-51.

Park, S. W., Kim, H. J. and Lee, C. S. (2003). Investigation of atomization characteristics and prediction accuracy of hybrid models for high-speed diesel fuel Sprays. *SAE Paper No.* 2003-01-1045.

Patterson, M. A. and Reitz, R. D. (1998). Modeling of the effects of fuel spray characteristics on diesel engine combustion and emission. *SAE Paper No.* 980131.

Reitz, R. D. (1987). Modeling atomization processes in high-pressure vaporizing sprays. *Atomisation and Spray Technology* **3**, 309-337.

Su, T. F., Patterson, M. A., Reitz, R. D. and Farrell, P. V. (1996). Experimental and numerical Studies of high pressure multiple injection sprays. *SAE Paper No.* 960861.

Yi, Y. and Reitz, R. D. (2002). A numerical model for jet primary breakup. *Proceedings of ilass-Americas 2002*, 25-29.