Numerical and Experimental Analysis of Spray Atomization Characteristics of a GDI Injector

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In this study, numerical and experimental analysis on the spray atomization characteristics of a GDI injector is performed. For numerical approach, four hybrid models that are composed of primary and secondary breakup model are considered. Concerning the primary breakup, a conical sheet disintegration model and LISA model are used. The secondary breakup models are made based on the DDB model and RT model. The global spray behavior is also visualized by the shadowgraph technique and local Sauter mean diameter and axial mean velocity are measured by using phase Doppler particle analyzer. Based on the comparison of numerical and experimental results, it is shown that good agreement is obtained in terms of spray developing process and spray tip penetration at the all hybrid models. However, the hybrid breakup models show different prediction of accuracy in the cases of local SMD and the spatial distribution of breakup.

Key Words: GDI(Gosoline Direct Injedion), Hybrid Model, Atomization

Nomenclature

a : Ellipse major axis, acceleration
C : Constant of the CSD model
C_D : Drag coefficient
C_{RT} : Breakup constant of RT model
C_τ : RT breakup time constant
d_0 : Orifice diameter
d_D : Diameter after breakup
d_L : Diameter of the ligament
K : Density ratio of liquid-gas
K_L : Most unstable wave number of LISA model
K_{RT} : Wave number of the RT model
L : Axial distance from the injector
L_b : Breakup length
N : Viscosity ratio of liquid-gas
P : Injection pressure
r_c : Droplet radius after breakup
t_0 : Thickness of the liquid sheet at the nozzle exit
t_b : Sheet thickness at the breakup length
t_s : Sheet thickness
U : Total sheet velocity
y : Magnitude of drop deformation in TAB model
η_0 : Initial amplitude
η_b : Critical amplitude
τ : Breakup time
λ^* : Wavelength for the maximum growth rate
Λ : Growth rate corresponding to maximum growth rate
ρ : Density
μ : Viscosity
Ω : Maximum growth rate

Subscripts

g : Gas properties
l : Liquid properties
LISA : LISA model
RT : Rayleigh/Taylor wave

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1. Introduction

The spray atomization characteristic of the fuel injector is an important factor in the improvement of engine performance and the reduction of exhaust emissions in the GDI engine. To analyze and improve the spray atomization characteristics of a GDI injector, many researchers have studied the spatial and time distributions of SMD, spray developing process, and spray tip penetration numerically and experimentally. Many researchers have suggested various breakup models based on the breakup mechanism or experimental results. O'rourke and Amsden (1987) proposed Taylor analogy breakup (TAB) model based on the analogy between an oscillating and distorting droplet and a spring mass system. Kelvin-Helmhotz wave instability breakup (KH) model (Reitz, 1987), droplets deformation and breakup (DDB) model (Ibrahim et al, 1993) and Rayleigh-Taylor analogy breakup (RT) model (Bellman and Pennington, 1954) are also suggested to model the droplet breakup. To overcome the errors resulting from adopting single breakup model to both primary and secondary breakup, various hybrid models have been studied by combining two different models. Iyer and Han (2002) proposed hybrid model that consists of conical sheet disintegration (CSD) model for the primary breakup and TAB model (O'rourke and Amsden, 1987) for the secondary breakup, respectively. Kim et al. (1999) suggested hybrid model with WAVE model and DDB model (Ibrahim et al, 1993) which added the non-linear effect to TAB model for considering the deformation of droplet. For experimental investigation, Zhao et al. (1995) and Lee et al. (2001) have analyzed the effect of injection pressure on spray atomization characteristics by using phase Doppler particle analyzer (PDPA) and spray visualization system. York et al. (1953) and Fraser et al. (1962) have studied the disintegration of liquid sheet such as flat, conical and fan sheet on the pressure swirl nozzle.

The atomization characteristics of a GDI injector are influenced by various factors such as nozzle shape, injection pressure, and spray cone angle. Many researchers have reported the effect of injection pressure, though the studies about the effect of spray cone angle on the spray atomization characteristic are still needed.

The aims of this study are to investigate the spray atomization characteristics of high-pressure injector for GDI by using the hybrid models with KIVA-3 code and to obtain the experimental results such as spray shape, spray tip penetration, and SMD distribution according to spray cone angle. The time and spatial distribution of droplet breakup have been studied, as well.

2. Experimental Apparatus and Procedures

Figure 1 shows schematic diagrams of the phase Doppler particle analyzer (PDPA) system and particle motion analysis system (PMAS, V-Tek). The phase Doppler particle analyzer system was used to measure the local Sauter mean diameter and droplet mean velocity. And the PMAS for visualizing spray development consists of spark light source with output of 0.5 J, field lens, and a CCD camera with an image acquisition system. The global spray behavior of fuel injector such as spray shape, penetration, and width are also visualized by shadowgraph technique. The injection timing and injection duration are controlled by the computer system through a signal controller. The high-pressure injection system is

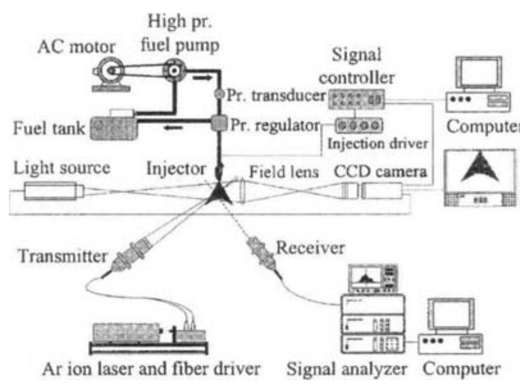


Fig. 1 Schematic diagrams of PDPA system and spray visualization system

composed of a fuel feed pump, a high-pressure pump, and a pressure-regulating system. The fuel is pressurized the high-pressure pump driven by a 0.75 kW AC motor, while the signal controller controls injection timing. The injected spray is analyzed by using the PDPA, and frozen images of a spray are captured by an image grabber of the computer. The injection duration is 1.0 msec and the injection pressures are 7 MPa and 10 MPa under different spray cone angle. The physical properties (density and viscosity) of test fuel gasoline are given as $\rho=680.3\ \mathrm{kg/m^3}$ and $\mu=2.9\times 10^{-3}\ \mathrm{N\cdot s/m^2}$, respectively.

3. Atomization Process Analysis

3.1 Primary breakup models

3.1.1 Conical Sheet Disintegration (CSD) model

The CSD model based on fan sheet disintegration is proposed by Iyer and Han (2002). According to the Rayleigh mechanism, waves with wavelength for maximum growth rate cause periodic thickening of the liquid sheet in a direction normal to the flow. The cylindrical ligaments are separated from the conical sheet and then disintegrated into drops by the action of surface tension.

After injection, the liquid spreads out in the form of a hollow conical sheet and then disintegrates at the breakup length, which is given by

$$L_b = C\left[\frac{\rho\sigma t_b d_0}{\rho_g^2 U^2 \tan(\theta/2)}\right]^{1/3} \tag{1}$$

which is given by

$$t_b = \frac{t_0}{1+2L_b\sin(\theta/2)\,d_0} \tag{2}$$

In the conical sheet, York et al. (1953) proposed that drop diameter is estimated as

$$d=2.13(\lambda^* t_s)^{0.5} \tag{3}$$

3.1.2 LISA model

For the primary breakup, Linearized Instability Sheet Atomization (LISA) model, which is suggested by Schmidt et al. (1999), is used. The LISA model assumed that the droplet undergoes no breakup, no collision and no drag until it reaches to the breakup length, which is given by (Schmidt et al., 1999)

$$L_{b,LISA} = \frac{U}{\Omega_{LISA}}\ln\left(\frac{\eta_b}{\eta_0}\right) \tag{4}$$

where, the value of $\ln(\eta_b/\eta_0)$ is proposed to 12 by Dombrowski et al. (1963). A new diameter after breakup at the breakup length is given by

$$d_D^3 = \frac{3\pi d_L^2}{K_L} \tag{5}$$

3.2 Secondary breakup model

3.2.1 DDB model

The DDB model deliberates the non-linear effects, which is not considered the TAB model. It is assumed that the droplet is distorted by pure extension flow so that the governing equation is given by

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

The critical condition of the drop breakup is given by the following equation (Ibrahim et al., 1993).

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

3.2.2 RT model

Rayleigh-Taylor instabilities are found when a liquid-gas interface is accelerated toward the low-density gas. It is based on the RT model and is proposed by Bellman and Pennington (1954). When the liquid viscosity is neglected and only surface tension is considered, the maximum growth rate, the corresponding wavelength and the wave number are determined. In the RT model, the breakup time and the droplet radius after breakup are defined by

$$\tau_{RT}=\frac{1}{\Omega_{RT}} \tag{8}$$

$$r_c=\frac{\pi C_{RT}}{K_{RT}} \tag{9}$$

3.3 Application of hybrid models

All hybrid models are composed of the primary and secondary breakup model. Therefore, it is important to set the criterion between the primary and secondary breakup for the construction of the hybrid model. In the CSD-DDB and CSD-RT model, the first breakup of droplet is occurred by CSD model at the near injector, and the DDB model and RT model govern the breakup after the droplet reaches to the breakup length L_b. For the combinations of LISA-DDB and LISA-RT model, the sizes of droplets are determined by LISA model when the droplets reach the breakup length $L_{b,LISA}$ and then the droplets are disintegrated by the secondary breakup model. The breakup constant C_{RT} of RT model is set equal to 0.16 as suggested by Park et al. (2001). In the present study, the initial conditions of all hybrid models are set equal to the experimental conditions, and the initial time interval and grid are determined to 20μs and 50 mm$\times$100 mm with 1 mm$\times$1 mm cells size. The initial conditions are listed in Table 2.

Table 1 Hybrid models

	Primary breakup	Secondary breakup
Case 1	CSD	DDB
Case 2	CSD	RT
Case 3	LISA	DDB
Case 4	LISA	RT

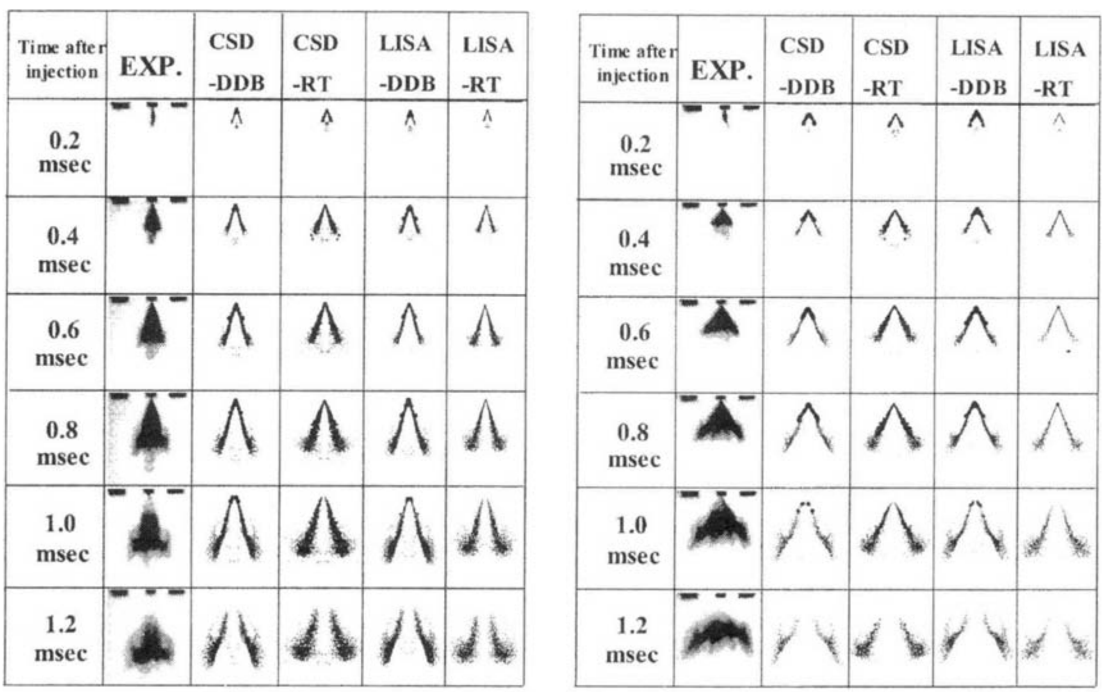
Table 2 Initial condition for calculation

	Pre-spray	Main-spray
Injection duration (ms)	0.1	1.0
Spray cone angle (degrees)	3	54, 73
Dispersion angle (degrees)	3	10
Hole diameter (mm)	1.0	
Injection pressure (MPa)	10	
Ambient pressure (MPa)	0.1	
Fuel	Gasoline (C_8H_{17})	

4. Results and Discussions

4.1 Development of global spray

Figure 2 shows experimental and calculated



(a) 54° (b) 73°

Fig. 2 Visualization of the spray development according to spray angle (T=1 ms, 10 MPa)

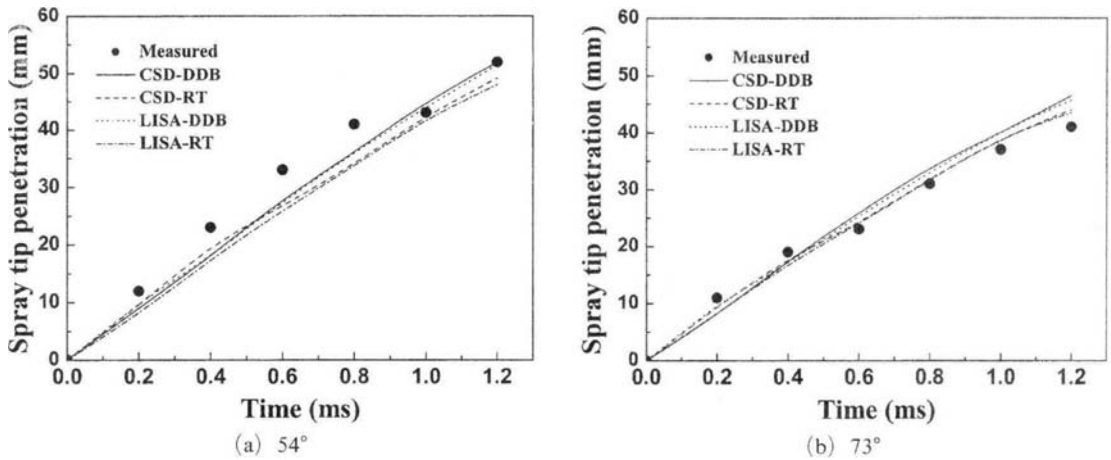


Fig. 3 Effect of spray cone angle on spray tip penetration (T=1 ms, P=10 MPa)

spray developing process with 1msec of injection duration using shadowgraph technique and hybrid models at the injection pressures of 10 MPa. At 0.8 msec after start of injection, the upward ring-shaped vortex on the spray surface region, which is headed opposite direction to the main spray, was beginning to shape because of pressure difference due to the relative velocity between the spray and ambient gas. The vortices are shown more clearly in the case of spray cone angle of 54°. It is supposed that the increase of spray cone angle induces the promotion of spray atomization, and the clearer vortices are observed in the well-atomized spray. Concerning the calculated shapes, the vortex of cloud is observed at the edge of spray but the shape of vortex is differed from the secondary breakup model. The secondary breakup model using the DDB model is exactly reflected in the circulated gas flow. It can be seen that the secondary breakup models with the DDB model has clearer vortex of circle than the other breakup models. Concerning the calculated shapes of spray, the vortex of cloud is observed at the edge of spray, but the shape of vortex is differed from the secondary breakup model. In the hybrid breakup model with DDB model, the dispersed droplets that have little momentum go upward due to the circulation of the surrounding gas at the edge of spray. However, in the case of hybrid model with RT model, it is observed that the droplets are disintegrated rapidly at the downstream region of the spray. Therefore, it is shown that the images predicted by DDB model has clearer circle of vortex than RT model, and RT model predicts wider spray cone angle than DDB model at the later stage of injection.

Figures 3(a), (b) show the comparison of spray tip penetration of hybrid models with two different injection angles. The experimental and numerical results show a reasonable agreement at the all hybrid models. Especially, the CSD-DDB model and LISA-RT model have a good agreement at both 54° and 73°. However in the middle stage of injection duration at 54° of the spray cone angle, the calculated results are shorter than the experimental results. The droplets are probably more atomized than the measured results after reaching the breakup length.

4.2 Atomization characteristics

Figures 4 and 5 show the experimental and numerical SMD distribution for the various hybrid models at the 25 mm and 40 mm downstream from the injector with 54° and 73° in the injection pressure of 10 MPa. As illustrated in Fig. 4 (a), the numerical SMD distribution of CSD-RT model shows the best agreements with the experimental results in the case of 25 mm downstream from the injector tip. In the case of radial SMD distribution of 40 mm downstream, prediction accuracy of CSD-DDB breakup model on the

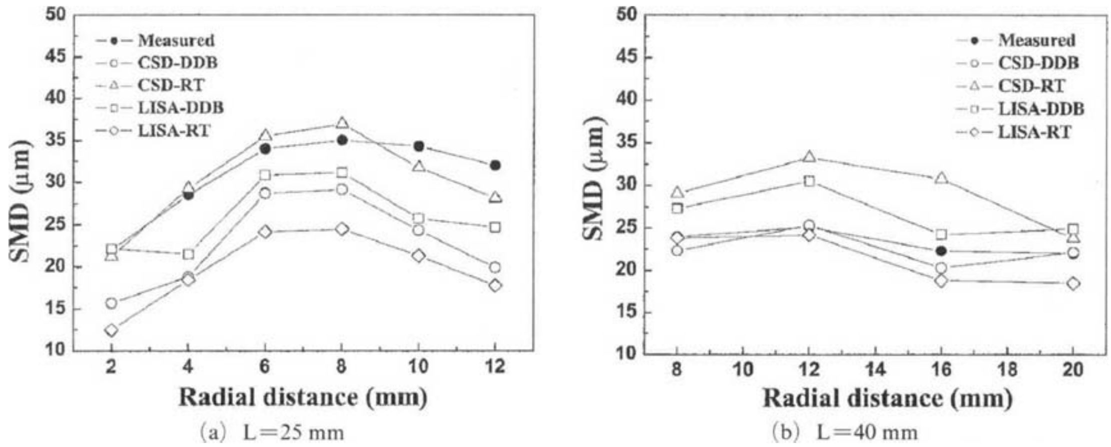


Fig. 4 SMD distribution according to the radial distance at spray angle with 54 degrees

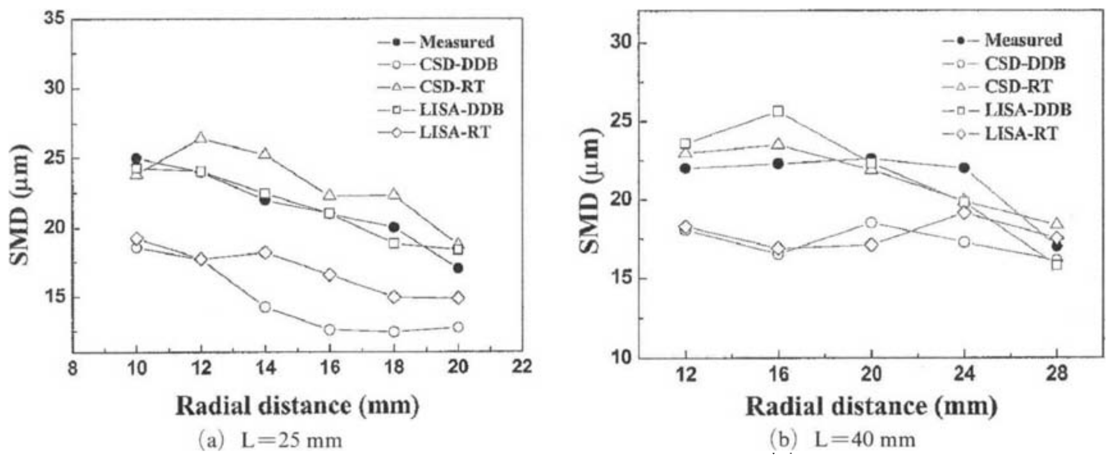


Fig. 5 SMD distribution according to the radial distance at spray angle with 73 degrees

radial SMD is good. CSD-RT model seems to underestimate breakup rate occuring at the down region of the spray. But in the case of CSD-DDB, the droplets rapidly disintegrate at the early stage of injection. As shown in Fig. 5, numerical results of the LISA-DDB model correspond well with experimental results. In the case of CSD-RT model, it is also illustrated that the numerical results of SMD distribution are larger than experimental results. CSD-DDB model and LISA-RT model predict the smallest SMD distribution in the case of spray cone angle of 73° as well.

Figures 6(a), (b) shows overall SMD distribution as a function of time after start of injection. There is a sudden increase at 0.1 ms after injection, because the main spray starts to inject. The overall SMD presents the SMD of pre-spray before 0.1 ms. The droplets undergo breakup and coalescence until 1.25 ms and maintain a uniform value after the time. It is observed that a larger spray cone angle induces a smaller SMD because of the effect of drag force and relative velocity.

Figures 7(a), (b) illustrate the percentage distributions of primary and secondary breakup at the cases of spray cone angle of 73° in the injection pressure of 10 MPa. In this figure, the percentage is obtained by dividing the count of droplet breakup in 1 mm × 1 mm area by counting breakup in all area. The primary breakup of CSD model and LISA model is concentrated on the near injector. In Fig. 7(a), the RT breakup mainly exits at the downstream and the DDB

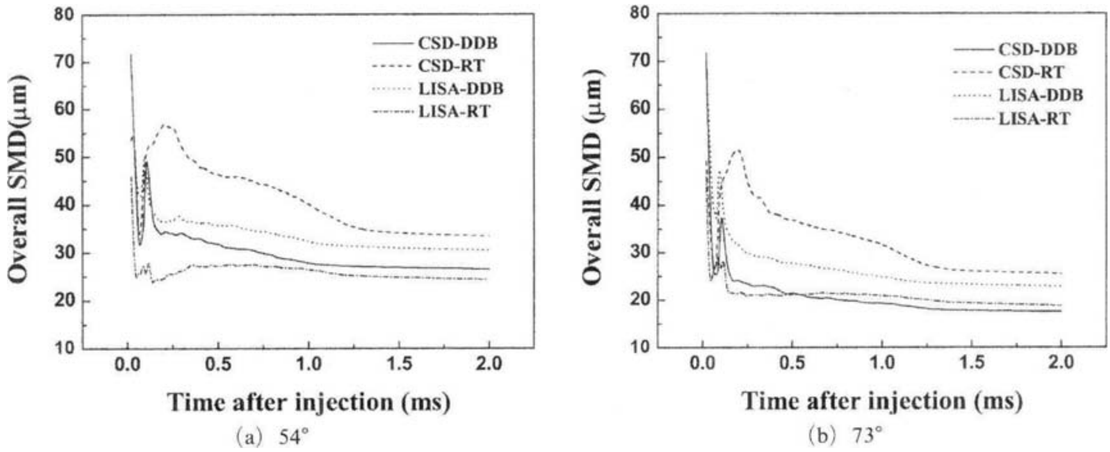


Fig. 6 Calculated overall SMD distribution according to time after injection

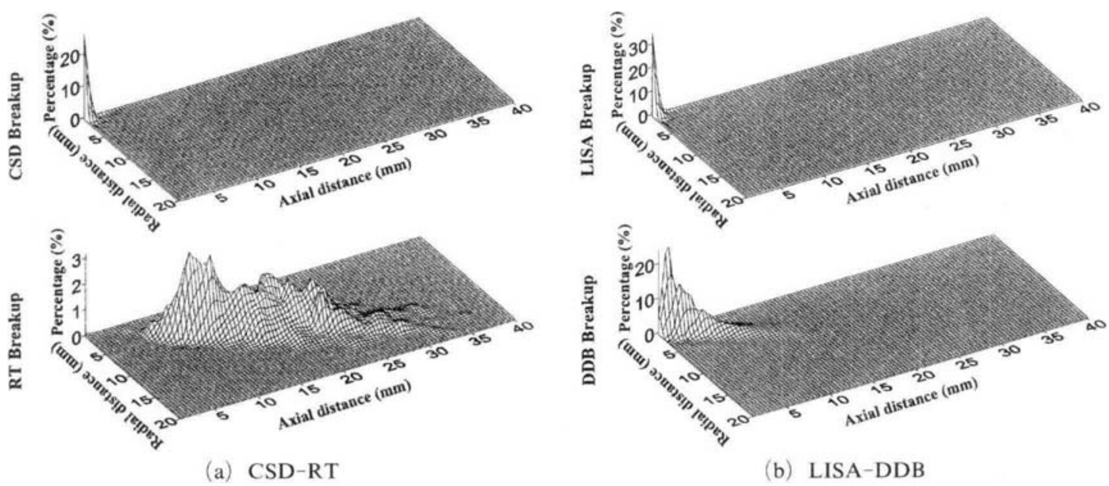


Fig. 7 Percentage of distributions of primary breakup and secondary breakup

breakup is concentrated near the injector as illustrated Fig. 7 (b). This pattern shows the characteristics of primary and secondary breakup well.

5. Conclusions

This paper presents the analysis of the atomization characteristics using hybrid models. For the hybrid models, CSD model and LISA model are applied to the primary breakup, and DDB model and RT model are utilized for the secondary breakup. The global spray behavior of fuel injector is visualized by shadowgraph technique and the characteristics of atomization are measured by using phase Doppler particle analyzer. The experimental results are also compared with the numerical results to evaluate the prediction accuracy of hybrid models. The conclusions of this study are summarized as follow.

(1) DDB model has clearer vortex of circle than RT model and the vortex is distinguished with the increase of spray cone angle. It is supposed that the increase of spray cone angle induces the promotion of spray atomization, and the clearer vortices are observed in the well-atomized spray.

(2) In the case of spray tip penetration, the experimental and numerical results show a reasonable agreement at all hybrid models. Especially, the CSD-DDB model and LISA-RT mo-

del have a good agreement at both 54° and 73°.

(3) CSD-RT model shows the best good agreements with the experimental results in the case of 25 mm downstream from the injector tip. In the case of radial SMD distribution of 40 mm downstream, prediction accuracy of CSD-DDB breakup model on the radial SMD is good.

(4) Concerning the calculation of the overall SMD distribution, there is a sudden increase of SMD at 0.1 ms after injection, because the main spray starts to inject then.

(5) The primary breakup of CSD model and LISA model are concentrated on the near injector, and RT breakup mainly exits at the downstream and the DDB breakup is concentrated near the injector.

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