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ATOMIZATION PROCESS OF DIESEL FUEL SPRAY IN THE INITIAL STAGE OF INJECTION

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ABSTRACT–An experimental investigation has been carried out to reveal the atomization process of the diesel fuel spray. The spray injected through a single hole nozzle was taken by a camera on the opposite side of a stroboscope for macroscopic observation or a nanolite for microscopic observation. The effect of nozzle aspect ratio was analyzed with disintegration phenomena of the diesel spray. Based on the enlarged spray photograph, atomization process was observed in detail and further the spray cone angle was measured under various ambient pressures. The result shows that atomization of diesel spray in early stage of injection is mainly progressed in the vicinity of spray periphery region except the region close to the nozzle exit and spray head region. The spray cone angle is nearly constant under the pressurized condition, while it decreases with elapsing time under the atmospheric condition.

KEY WORDS : Diesel spray, Spray tip penetration, Spray tip velocity, Spray cone angle, Nozzle aspect ratio

1. INTRODUCTION

Many research works on the behavior of diesel spray injected into a combustion chamber have been carried out for the purpose of better engine performance, improvement of fuel economy, reducing exhaust gas emission (Hiroyasu *et al.*, 1983; Reitz *et al.*, 1987; Smallwood *et al.*, 1994; Rajalingam *et al.*, 1999; Kim *et al.*, 2001; Lee *et al.*, 2002; Jung *et al.*, 2004). According to being developed common rail injection pump, it became possible to further reduce harmful exhaust gas and to operate the diesel engine more silently. Nevertheless, the exhaust gas in the diesel engine such as NO_x and particulate matters still leaves as problems to solve for cleaner environment. More studies should be conducted to understand the atomization process, mixing formation process and spray combustion process in diesel engines.

Especially, the investigation for the initial stage of diesel spray was not much carried out, consequently the diesel spray characteristics in the early stage of injection do not much clarify compared with those in the later stage (Reitz *et al.*, 1982; Miwa *et al.*, 1998; Narumiya *et al.*, 1999). The reason might be because it was difficult to take clearly photographs of initial diesel spray. However, the period up to about 1 ms from the start of injection corresponds to the ignition delay in a high-speed direct injection diesel engine. The spray behavior before the ignition decides spray combustion state and exhaust gas emission, after the spray is ignited. Therefore, it is very important to study on the diesel spray in initial stage of injection.

Huh *et al.* (1994) took photographs of diesel spray macroscopically and microscopically using stroboscope and nano-spark light photography method. They reported that overtaking droplets in the spray as well as friction forces between surface waves of liquid column and the ambient gas led the spray to disintegrate. Takahashi *et al.* (1994) reported that the emergence of a liquid column was observed at the beginning of injection. Initially, the liquid column had almost the same diameter as the nozzle hole and then spread rapidly, forming the spray angle in the vicinity of the nozzle exit. With an increase of the valve opening pressure, the timing of the spray angle formation became earlier.

It was reported by Miwa *et al.* (1998) that at the early stage of injection, the structure like a branch occurred at the periphery of a dense spray behind a spray tip and many fine droplets were produced in this region. Narumiya *et al.* (1999) took photographs of a diesel spray at initial stage of injection using pulsed Nd:YAG laser, and observed a cap-like film at a liquid column tip. They reported that the first breakup of the injected fuel began at the periphery of the cap-like film. Fath *et al.* (1998) detected cavitation bubbles close to the nozzle tip using a

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2D measurement technique on the basis of Mie scattering.

In this study, using the stroboscope as a light source, the spray tip penetration was first measured, and then, the spray tip velocity was calculated on the basis of it. Also, the enlarged spray photograph in the very early stage of injection was taken using nanolite and telemicro lens. According to the change of nozzle aspect ratio, disintegration processes of the spray were compared with each other. In particular, atomization process of the initial spray as well as spray cone angle was discussed in detail based on enlarged spray photographs.

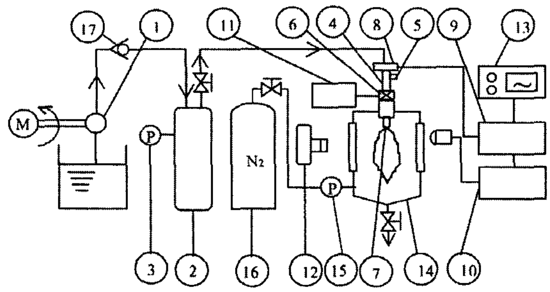
2. EXPERIMENTAL APPARATUS

A schematic diagram of the experimental apparatus is shown in Figure 1. It is composed of the fuel injection system, a pressure chamber and an optical system. The injection pump axis was coupled to a DC motor, and its speed was 600 rpm. The diesel fuel, which was used as the injection fuel, was pressurized to 14.0 MPa by the injection pump. The two accumulators play an important role in reducing the pressure pulsation during the injection period.

The pressurized fuel is injected through a single hole type injection nozzle into the pressure chamber with the input signal of solenoid valve driven by its driving circuit. At that time, the signal of the injection start from photo-interrupter triggers the delay circuit for a defined period. And then, a stroboscope or a nanolite emits a flash of light, and the spray photograph is taken by the camera on the opposite side of the light source. Namely, shadowgraph image technique was utilized for taking photographs of a spray. The pulse duration is 4 ms for stroboscope, and 17 ns for nanolite.

The pressure chamber was made of steel with transparent rectangular windows of 230 mm x 130 mm on two of the opposite sides. It was filled with nitrogen gas and the ambient pressure was set at 0.1 MPa, 1.0 MPa, 2.0 MPa and 3.0 MPa at room temperature.

Figure 2 shows details of single hole nozzle used in this study. The nozzle diameter is the same scale of 0.45 mm, and nozzle aspect ratios L/D are 2.22, 2.78 and 3.33, respectively.



1. Injection pump	10. Stroboscope or Nanolite
2. 1st accumulator	11. Solenoid driving circuit
3. Pressure gauge	12. Camera
4. 2nd accumulator	13. Oscilloscope
5. Pressure transducer	14. Pressure chamber
6. Solenoid valve	15. Pressure gauge
7. Fuel injection nozzle	16. Nitrogen gas bomb
8. Photo-interrupter	17. Check valve
9. Delay circuit	

Figure 1. Experimental set up.

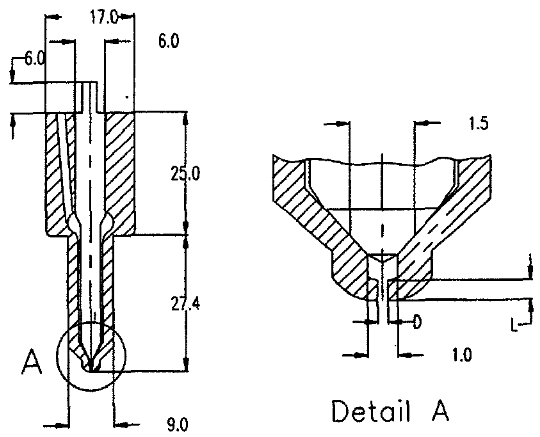


Figure 2. Details of single hole nozzle.

3. RESULTS AND DISCUSSION

3.1. Spray Tip Penetration and Its Velocity

First of all, the spray tip penetration was measured in order to understand the fundamental characteristics of the diesel spray. The spray tip penetration on L/D of 2.22 under various ambient pressures is shown in Figure 3. There are little effects on the ambient pressure up to 0.5 ms from injection start. However after that time, the spray tip penetration grows up more slowly, with increase of the ambient pressure. That is caused by the increase of the drag force in the pressure chamber according to the increase of ambient density. The break-up phenomena of the spray seems to occur at around 1 ms from injection start under pressurized conditions, while the phenomena did not occur under atmospheric condition.

Figure 4 shows spray tip penetration on L/D of 3.33 under various ambient pressures. The effect of ambient pressure can be observed with comparative ease from injection start. Also, as the ambient pressure increases, the spray tip penetration grows up more slowly. In the case of the ambient pressure of the atmospheric pressure and 1.0 MPa, the spray tip penetrations on L/D of 3.33

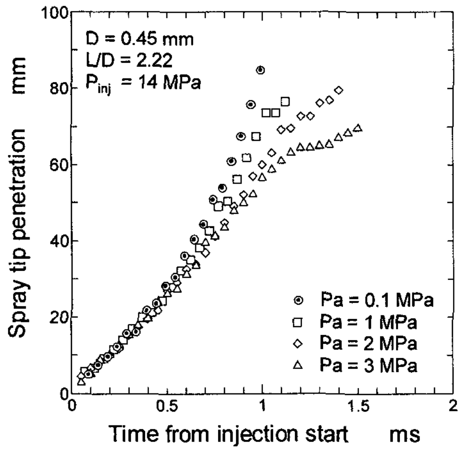


Figure 3. Spray tip penetration on L/D of 2.22 under various ambient pressures.

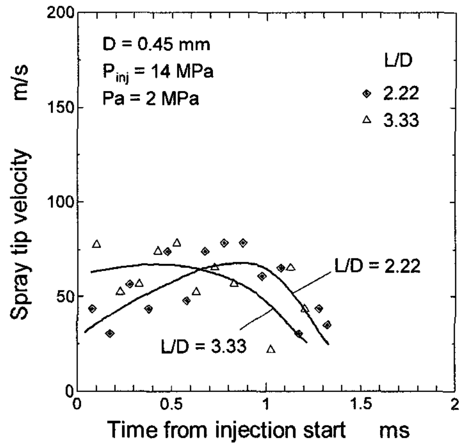


Figure 5. Effect of nozzle aspect ratio L/D on spray tip velocity (Pa = 2.0 MPa).

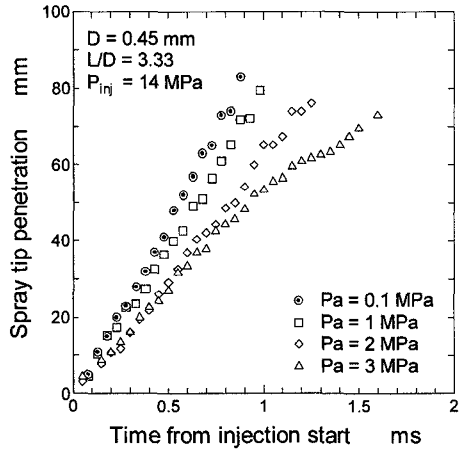


Figure 4. Spray tip penetration on L/D of 3.33 under various ambient pressures.

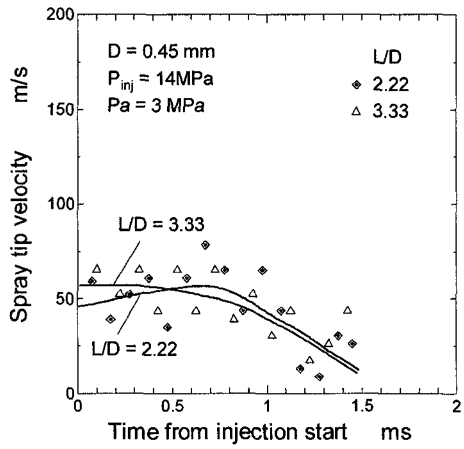


Figure 6. Effect of nozzle aspct raio L/D on spray tip velocity (Pa = 3.0 MPa).

are much longer than those on L/D of 2.22 in Figure 3. From only the spray tip penetration such as Figures 3 and 4, it may be difficult to clarify the break-up time or transition point. Thus, the spray tip velocity was calculated based on the spray tip penetration.

When the ambient pressure is 2.0 MPa, the effect of nozzle aspect ratio L/D on spray tip velocity are shown in Figure 5. In the case of the L/D of 2.22, the spray tip velocity increases up to around 0.9 ms from injection start, and then, decreases rapidly. In the case of the L/D of 3.33, the spray tip has uniform velocity up to around 0.5 ms, and then, loses slowly in speed. The decay of the spray tip velocity means the disintegration of the fuel spray. That is, more air is entrained into the spray after the decay, consequently atomization of fuel droplets is further promoted by means of momentum transfer between the droplets and surrounding gas.

Figure 6 shows the spray tip velocity on the L/D = 2.22 and 3.33 under the same ambient pressure of 3.0 MPa. In the case of the L/D of 2.22, the transition of the spray occurred at around 0.7 ms from injection start. When the L/D is 3.33, the transition occurred at around 0.4 ms. From Figures 5 and 6, it is confirmed that the spray injected through the nozzle of L/D = 3.33 disintegrates earlier than that of L/D = 2.22.

3.2. Atomization Process

Using light source of nanolite, the enlarged photographs of initial diesel spray could be obtained clearly from 0.01 ms from injection start to 0.1 ms. In this case, the telemicro lens of magnification of 4.5 was specially equipped with the camera. The photographs are shown in Figure 7. These photographs may enable one to analyze qualitatively for the initial diesel spray. The entire scale

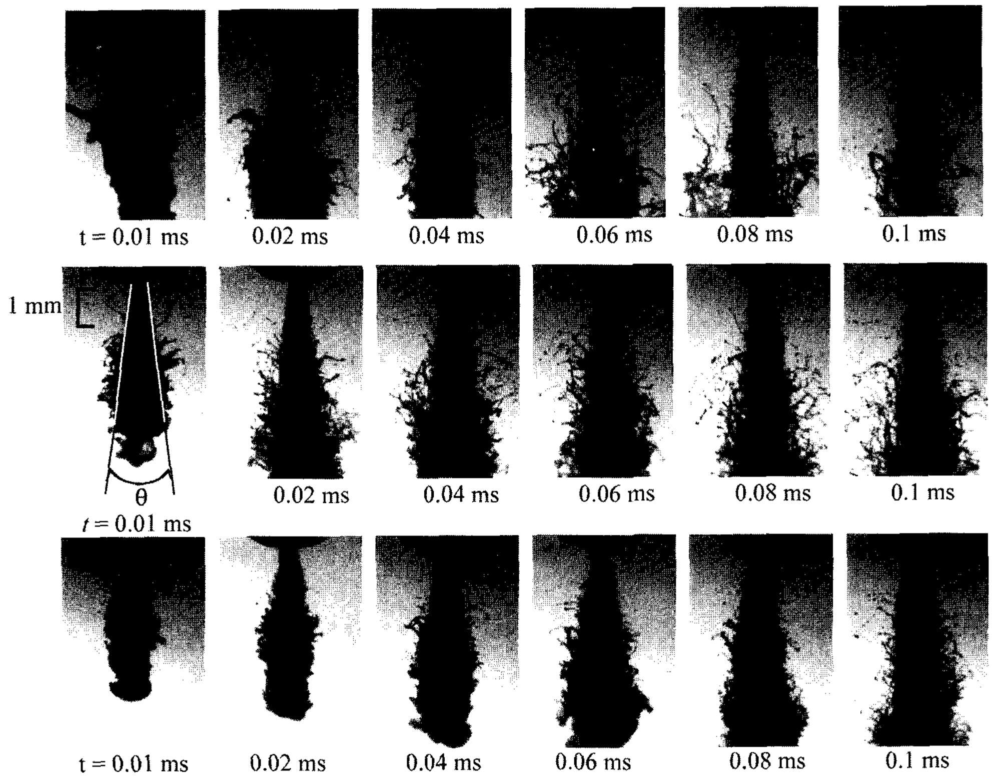


Figure 7. Atomization process under the ambient pressure of 0.1 MPa (upper series), 1.0 MPa (middle series) and 3.0 MPa (lower series) in the case of D = 0.45 mm and L/D = 2.78.

of the photograph is about 5.2 mm. These photographs series reveal the atomization process under the ambient pressure of 0.1 MPa (upper series), 1.0 MPa (middle series) and 3.0 MPa (lower series) for the nozzle diameter D = 0.45 mm and L/D = 2.78.

In upper series under atmospheric condition, the diesel fuel of time from injection start $t = 0.01$ ms is almost likely to be liquid column because fuel droplets was rarely observed in this photograph. However the other photographs show that the ligaments, which are commonly observed regularly in rotary disc atomizers, are formed irregularly around the boundary of the diesel spray. Each ligament is atomized into lots of droplets as time progresses.

In middle series of the ambient pressure of 1.0 MPa, the spray cone angle θ is defined as undisturbed angle of the spray close to the nozzle exit, as illustrated in the first photograph. Its zone is very dense and does not include ligaments and droplets apparently on the enlarged photograph. In general, the spray cone angle is smaller than the spray angle, where ligaments and droplets are included apparently. In the first two photographs of middle series, very dense region in which there are no ligaments and droplets, is found close to the nozzle exit. Also, in the first photograph, the ligaments and droplets do not observed in spray head region. However some of ligaments and droplets are observed on the spray periphery except the two regions. From $t = 0.04$ ms to 0.1 ms, a large number of ligaments and droplets are detected irregularly in the vicinity of the spray periphery region. Due to viscosity and surface tension of the diesel fuel, lots of unbroken and long ligaments are observed under the ambient pressure of 1.0 MPa. These ligaments, finally, come to disintegrate into numerous droplets with the elapsing time.

In lower series of the ambient pressure of 3.0 MPa, ligaments and droplets are rarely found, but comparatively stable surface wave is observed around the spray periphery region except the very dense region close to the nozzle exit and spray head region at $t = 0.01$ ms and 0.02 ms. Comparing with the spray under $P_a = 1.0$ MPa, it is low speed because of higher aerodynamic resistance of the surrounding gas. In the rest four photographs, some of ligaments and droplets are observed around the spray periphery, but their number is small in comparison with that under $P_a = 0.1$ MPa and 1.0 MPa. The ligament of spray is comparatively short in length and quickly disintegrates into fine droplets.

Comparing ligaments of these three series, they are the longest under atmospheric pressure, while they are the shortest under $P_a = 3.0$ MPa. That is, as the ambient pressure is higher, the ligaments of diesel spray are shorter. Also, the atomization of diesel spray in early stage of injection is progressed in the vicinity of spray priphery region except region close to the nozzle exit and spray head region. Furthermore, it is controlled more by spray tip velocity, rather than by surrounding gas density. Therefore, it is reasonable that the common rail injection pump be used for better atomization of diesel fuel and further better combustion in the engine.

3.3. Spray Cone Angle

Figure 8 shows the spray cone angle at various timings under atmospheric pressure. As time progresses, the spray cone angle deceases. Owing to the low ambient density caused by atmospheric pressure, the spray velocity about the axial direction is increased, while the velocity about the radial direction is reduced, with elapsing time. As the result, it is considered that the spray cone angle becomes smaller with elapsing time.

Under ambient pressure of 1.0 MPa, the spray cone angle at various timings is shown in Figure 9. In the strict sense, the spray cone angle varies with elapsing time, but it has nearly constant value of 9.3 degrees on an average.

Figure 10 shows the spray cone angle at various timings under ambient pressure of 2.0 MPa. While the value of spray cone angle fluctuates slightly, it is 9.48 degrees on an average, which is a little larger than that under $P_a = 1.0$ MPa in Figure 9.

Figure 11 shows the spray cone angle with elapsing time under ambient pressure of 3.0 MPa. As in Figures 9 and 10, the spray cone angle has almost constant value of 9.83 degrees on an average, which is slightly larger than that under $P_a = 1.0$ MPa, and 2.0 MPa. From Figures 8, 9, 10 and 11, the spray cone angle is nearly constant under the pressurized condition, while it decreases with elapsing

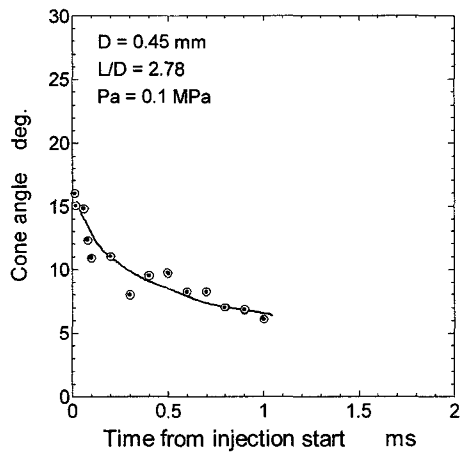


Figure 8. Spray cone angle at various timings under atmospheric pressure.

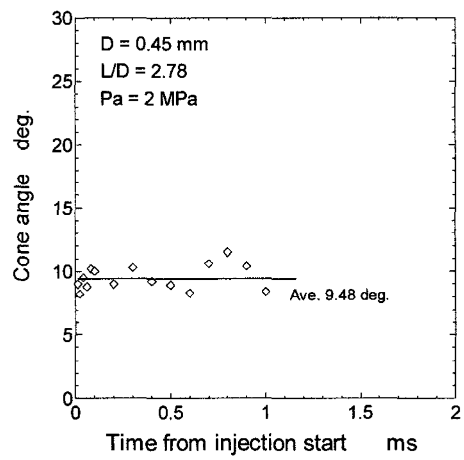


Figure 10. Spray cone angle at various timings under ambient pressure of 2.0 MPa.

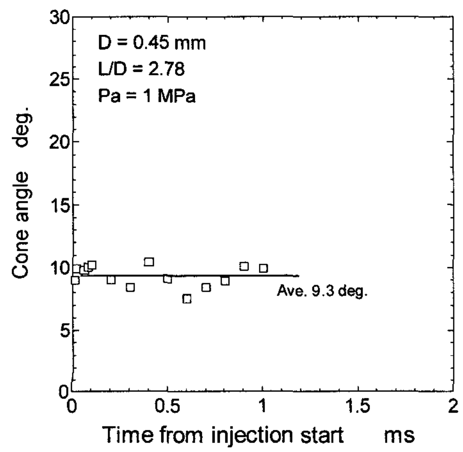


Figure 9. Spray cone angle at various timings under ambient pressure of 1.0 MPa.

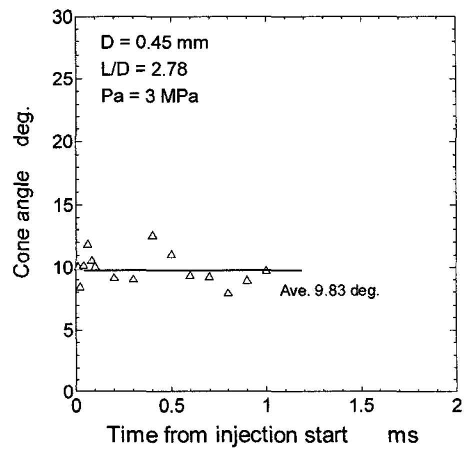


Figure 11. Spray cone angle at various timings under ambient pressure of 3.0 MPa.

time under the atmospheric condition. Also, it is clear that under pressurized condition, with an increase of the ambient pressure, the spray cone angle becomes larger. The reason may be as follows; according to an increase of the ambient pressure, the spray velocity about the axial direction is decreased due to higher air resistance in pressure chamber, while the spray velocity about the radial direction is increased.

4. CONCLUSIONS

In order to clarify atomization process of diesel spray in early stage of injection, the enlarged photograph of initial spray as well as the spray photograph for penetration behavior was taken comparatively clearly using nanolite as light source. The spray tip velocity was calculated, and atomization process of initial spray was observed in detail. Also, the spray cone angle is measured with elapsing time. The results are as follows:

(1) The spray injected through the nozzle of L/D = 3.33 disintegrates earlier than that of L/D = 2.22.
(2) Atomization of diesel spray in early stage of injection is progressed in the vicinity of spray periphery region except the region close to the nozzle exit and spray head region.
(3) As the ambient pressure is higher, the ligaments of diesel spray are shorter.
(4) The spray cone angle is nearly constant under the pressurized condition, while it decreases with elapsing time under the atmospheric condition.

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REFERENCES

Fath, A., Fettes, C. and Leipertz, A. (1998). Investigation of the diesel spray break-up close to the nozzle at different injection conditions. *4th Int. Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engines*, 20–23 July, Kyoto, Japan, 429–434.

Hiroyasu, H., Kadota, T. and Arai, M. (1983). Development and use of a spray combustion modeling to predict diesel engine efficiency and pollutant emissions (Part 1; Combustion modeling). *Bulletin of the JSME* **26, 214,** 569–575.

Huh, J. C., Lee, G. Y., Ohu, S. C. and Yang, O. Y. (1994). An experimental study of the disintegrating mechanism of diesel sprays. *Proc. of the 6th Int. Conference on Liquid Atomization and Spray Systems*, July 18–22, Rouen, France, 294–301.

Jung, D. and Assanis, D. N. (2004). Modeling of direct injection diesel angine emissions for a quasi-dimensional multi-zone spray model. *Int. J. Automotive Technology* **5, 3,** 165–172.

Kim, M. S. and Min, K. D. (2001). Calculation of fuel spray impingement and fuel film formation in an HSDI diesel engine. *KSME International Journal* **16, 3,** 376–385.

Lee, K. H., Chung, J. W. and Lee, C. S. (2002). A study on the measurement technique for injection rate and the effects of the nozzle hole number on injection characteristics. *Trans. of KSAE* **10, 3,** 1–7.

Miwa, K., Ishiyama, T., Liu, Y. and Okubo, T. (1998). Spatial distribution of initial droplets of a diesel spray. *Trans. of JSME* **64, 624,** 349–355.

Narumiya, K., Hattori, H. and Kadota, T. (1999). Study on structure of fuel spray in diesel engine (Observation of breakup process of liquid column jet). *The 8th Sym. (ILASS-Japan) on Atomization*, 20–21 Dec., Osaka, Japan, 259–264.

Rajalingam, B. and Farrell, P. (1999). The effect of injection pressure on air entrainment into transient diesel sprays. *SAE Paper No.* 1999-01-0523.

Reitz, R. and Bracco, F. (1982). Mechanism of atomization of a liquid jet. *Physics of Fluids* **25, 10,** 1730–1742.

Reitz, R. and Diwakar, R. (1987). Structure of high-pressure fuel sprays. *SAE Paper No.* 870598.

Smallwood, G. J., Gulder, O. L. and Snelling, D. R. (1994). Tomographic visualization of the dense core region in transient diesel sprays. *Proc. of the 6th Int. Conference on Liquid Atomization and Spray Systems*, July 18–22, Rouen, France, 270–277.

Takahashi, H., Yanagisawa, H., Shiga, S., Karasawa, T. and Nakamura, H. (1994). Development of initial-stage diesel spray with unsteady and higher injection pressure. *Trans. of JSME* **60, 571,** 371–376.