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Droplet Size Distribution in Diesel Fuel Spray*

By Kiichiro TAKEUCHI**, Hiromi MURAYAMA***,

Jiro SENDA[†] and Koji YAMADA^{††}

Measurements on the behavior of diesel fuel spray from a microscopic viewpoint are important to clarify atomization mechanism and temporal change in droplet size distribution. In this study, diesel spray injected from diesel nozzles into a quiescent atmosphere at room temperature and high pressure is observed by means of a direct microscopical photographing method varying the photographing time and the nozzle type. The results show that the mechanism of spray atomization is divided into 4 processes, and spatial distributions of breakup droplets are assessed. As time passes, spray droplets are distributed in a stratiform shape. And total distribution of droplet sizes and droplet size distribution in local region are expressed in equations as a function of time from injection, and changes in the distribution with the nozzle type are discussed. Subsequently, temporal changes in the uniformity of the distribution and in spatial distribution of droplets volume rates are clarified.

Key Words : Internal Combustion Engine, Combustion, Diesel Spray, Atomization Mechanism, Droplet Size Distribution.

1. Introduction

The process of mixture formation in the combustion chamber in diesel engines is affected by the characteristics of fuel atomization and the conditions of gaseous flow in the combustion chamber, and it exerts a great influence on combustion characteristics. Conventional studies on diesel sprays mostly have dealt with a spray penetration or a spray angle^{(1),(2)}, and in some cases, fuel distribution within the spray measured by the collecting method⁽³⁾ has been reported. As for the droplet mean diameter and droplet size distribution of spray droplets which are important factors of spray characteristics, the majority of papers are based on macroscopic study of the entire spray by means of sedimentation tower method⁽⁴⁾ or liquid immersion sampling technique⁽⁵⁾. In the case of diesel sprays where non-steady state and intermittent characteristics can not be ignored, it is necessary to observe microscopically spray characteristics from the injection of spray to the flying in which the spray structure is maintained in order to reveal the mechanism of atomization and temporal and spatial

characteristics of droplet size distribution. Hiroyasu, et al.⁽⁶⁾ investigated the transient characteristics of droplet size distribution in diesel spray which varies with the lapse of time, and Kuniyoshi, et al.⁽⁷⁾ studied the spray structure and examined the droplet diameter in each atomizing region by means of the direct microscopical photographing method. However, no investigations have been attempted to elucidate transitional characteristics of the mechanism of spray atomization and droplet size distribution in the spray or at a particular local region. As for particle size measurement by optical method as typically represented by light scattering⁽⁸⁾ and Fraunhofer diffraction⁽⁹⁾, problems lie in the area of measurement in non-breakup region and high droplet density region, and in assumption about particle size distribution, hence it is supposed that high precision result can hardly be obtained at present by applying these measurements to diesel sprays.

This paper deals with an investigation where diesel fuel is injected into a quiescent gaseous environment at room temperature under high pressure from an injection system which is similar to one of diesel engines. Fuel droplets of entire spray are observed microscopically and the temporal and spatial changes in atomization process and particle size distribution are examined by means of direct microphotographic technique which is capable of observing all conditions of flying spray without any disturbance while injection nozzle and photographing time are varied.

Nomenclature

l, l_j, l_j' : Depth of field of spray droplet

mm

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** Professor, Faculty of Engineering, Doshisha University, Karasuma Imadegawa, Kyoto.

*** Aisin Seiki Co., Ltd., 2-1 Asahi-cho, Kariya-city, Aichi.

[†] Graduate Student, Faculty of Engineering, Doshisha University, Karasuma Imadegawa, Kyoto.^{††} Nissan Motor Co., Ltd., 8 Nishiki-cho, Naka-ku, Yokohama.

n, n_i, n_i'	: Number of spray droplets	-
P_b	: Back pressure	MPa
P_n	: Fuel injection pressure	MPa
t	: Time elapsed from injection	ms
t_i	: Injection period	ms
x	: Diameter of spray droplets	μm
x_i, x_o	: Inside and outside diameter of photographed droplets	μm
x_{10}	: Arithmetic mean diameter of spray droplets	μm
x_{32}	: Sauter mean diameter of spray droplets	μm
X	: Distance from nozzle tip along spray axis	mm
Y	: Radial distance from spray axis	mm

2. Experimental Apparatus

A schematic diagram of apparatus used in this experiment is shown in Fig.1. A high pressure vessel (1) is a cylinder 94 mm in inside diameter and 80 mm in width, and reinforced glasses (2) are provided at both sides in order to take photographs of spray by the transmitted light. This vessel is pressurized by an air bomb (3) through a pressure control valve (4) and the vessel pressure (back pressure) is measured by a Bourdon tube pressure gauge (5). A fuel injection pump (8) is driven by a motor (7) and fuel is delivered to injection nozzle (6) through the injection pipe and 2-way joint (9) and is injected into the vessel. This injection system is identical with one presented by Ohashi et al.⁽¹⁰⁾ by which fuel is collected into a fuel tank (12) through an auxiliary nozzle (11) by opening a solenoid valve (10) whenever photographs are not taken and fuel is injected for photographing by closing the solenoid valve for a predetermined time. Injection pressure is measured by a semiconductor pressure transducer (13) and a needle valve lift of the injection nozzle is detected by using a laser (14) and a photo-transistor (15).

Macrolens (focal length : 50 mm, F.3.5) is used for photographing of the entire spray, the transmitted light of a micro-flash is used as the light source and the film magnification is 0.34 times. A photomicrograph device (16) which is used for the microscopic photographing is

constructed with a objective lens of 75 mm in focal length and an eye-piece of 5 times magnification, and film magnification is 7.2 times. Transmitted light of a Nanolite (17) is used as the light source. The Nanolite is charged by a Strobokin (18) and is used for discharging flash, and its flashing duration is approximately 18 ns. As to films, Neopan SS film (ASA 100) is used for photographing of the entire spray as a general view and Tri-X film (ASA 400) is used for the microscopic photographing.

The solenoid valve is operated by a solenoid valve driving circuit (19). A motor speed is measured by a proximity switch (20) and a counter (21) and at the same time, output signal of the proximity switch is given to the driving circuit and the solenoid valve is actuated with the first signal of the proximity switch after the circuit is operated and is closed for a predetermined time. This enables the solenoid valve to be actuated for a certain period in each injection with regard to a cam position of the injection pump, and same conditions are maintained in the injection pipe at each injection resulting in an improved repeatability of fuel injection. Whenever the fuel is injected, output signal of the photo-transistor is given to a delay circuit (22) and the light source is flashed by transmitting a signal after a certain delay time which can be set arbitrarily. This flash monitor signal is displayed on a synchroscope (23) together with the injection pressure and the needle valve lift, thus injection system and photographing system are monitored.

After photographs are taken, an exhaust valve (24) is opened in order to discharge high pressure air and atomized fuel in the vessel into an exhaust tank (25).

3. Experimental Method

A Bosh type injection pump PES 2A 55B, driven by the motor at the speed of 16.7 s^{-1} (1000 rpm), was used. The injection pipe was a solid-drawn steel pipe having an inside diameter of 1.5 mm, an outside diameter of 6.0 mm and a length of 530 mm. As for the injection nozzle, throttle nozzle NP-DN4SD24, pintle nozzle NP-DN4SNP3 and single hole nozzle NP-DLOS301 having 0.3 mm injection hole diameter, with 11.9 MPa in its opening pressure, were used, and experiments were conducted under conditions as shown in Table 1. As for fuel, a diesel light oil for automobiles of 0.831 in specific gravity and $3.54 \times 10^{-6} \text{ m}^2/\text{s}$ (3.54 cSt) in viscosity was used.

The microscopical photographs were taken with 7.2 times magnification on the film, printed with final magnification of 50 times, and the droplet diameter and number of droplets were measured at 5 μm interval. The accuracy of this measurement is affected by the light source, the lens system, a film resolution and the treatment of the film, and especially, the depth of field in the

Fig.1 Schematic diagram of experimental apparatus

optical system used will pose an important problem. York, et al.⁽¹¹⁾ and DeCorso⁽¹²⁾ corrected the diameter of droplets within the depth of field by the comparison between fringe width due to deviation from the focal plane of the photographed image of a fuel droplet suspended on fine wire, opaque circular spots or glass fibers, and the fringe width of the droplet image. In this method, however, a change in depth of field depending upon the droplet diameter has not been taken into consideration, and moreover, experiment is complicated and its accuracy is questionable. Besides, Sugimoto, et al.⁽¹³⁾ obtained the actual diameter of spray droplets by examining the relation between the distance from the focal plane and the actual size with respect to both a transmitted image and a reflected image of fine glass balls. However, it is difficult to obtain the reflection image by high magnification photographing from the lighting intensity, and it is easily supposed that a significant error is included into the measurement of their droplet diameter.

In this experiment, correction of the number of droplets was conducted by the following method⁽¹⁴⁾. When the droplet is deviated from the focal plane within the depth of field, a photographed image will be as shown in Fig.2 (A). Here, the outside diameter of photographed droplet is defined as x_0 and its inside diameter is defined as x_i . Then the relation

between the ratio x_0/x_i and the deviation from focal plane for the case of photographing magnification being 7.2 times is as shown in Fig.2 (B) where calibrations are carried out using glass balls with 55, 90, 186 and 243 μm in diameter. The profile of a droplet diameter of which can be measured shows a constant value regardless of the diameter of droplet if x_0/x_i is used. In this experiment, $x_0/x_i=1.8$ is the limit to which the profile of droplet can be measured. If the distance from the focal plane of glass ball having each diameter at $x_0/x_i=1.8$ in Fig.2 (B) is defined as depth of field l , the relation between the real diameter of droplet x and depth of field l becomes as shown in Fig.2 (C). The number of droplets with which measurement is possible decreases because the depth of field is reduced as the droplet diameter is made smaller. When droplet size distribution and mean droplet diameter are obtained, the following correction of number of droplets is made based upon Fig.2 (C). The real droplet number n_i can be obtained by the following equation where depth of field for a certain droplet diameter is l_i , the number of droplets having diameters other than reference value which is measured from the photograph is n_i' and depth of field is l_i' .

$$n_i = n_i' (l_i/l_i') \quad (1)$$

In other words, the number of droplets is corrected for each droplet diameter so that the same measuring space may be obtained. To take the measurement of droplet diameter is to measure x_i , and an error in measuring the droplet diameter is 25 % at the maximum.

4. Results and Discussions

4.1 Behavior of spray

Droplets in the entire region of spray were observed by taking micrographs every time as shown in Table 1 and the behavior of injected spray was investigated.

Fig.3 shows the relation between the time from the start of injection at each nozzle and spray tip penetrations. Measurements by the microscopic photographs and the entire photographs over the spray are compared for the case of the throttle nozzle and it is revealed that their difference is attributed to the photographing magnification. As the droplet density in the peripheral region

Fig.2 Relation between depth of field and droplet size

Table 1 Experimental conditions

Injection nozzle	Throttle nozzle NP-DN4SD24	Pintle nozzle NP-DN4SNP3	Hole nozzle NP-DL0S301
Nozzle opening pressure MPa	11.9	11.9	11.9
Injection quantity mm ³ /rev.	23.3	13.7	10.3
Injection period ms	2.10	1.20	1.35
Back pressure MPa	4.02	5.00	5.00
Time at taking photographs of spray (from injection) ms	1.00, 2.10, 3.00, 4.20, 5.00, 6.10	0.60, 1.20, 1.50, 1.80, 2.40	0.70, 1.35, 2.10, 2.80

of spray becomes lower with the lapse of time, the spray penetration is measured shorter on account of its magnification in the entire photographing. The spray tip penetration by each injection nozzle which is observed by the microscopical photographs is 4 % at the maximum being expressed by root mean square error from the mean value of measurements per 10 photographs.

Figure 4 (A), (B), and (C) show the measuring region of microphotographing at each photographing time in each nozzle which is determined by the entire photograph. The interval of photographing positions is 2 mm for in the spray axis direction and the radial direction, and the region of the microscopic photographing is $2.00 \text{ mm} \times 2.00 \text{ mm} \times 0.338 \text{ mm}$ (depth of field of $5 \mu\text{m}$ in diameter of droplet)-- 1.35 mm^3 space. Fig.5 is a comparison between droplet size distributions appearing on 2 arbitrary microscopic photographs which are taken at axial distance of $X=18 \text{ mm}$ and radial distance of $Y=0 \text{ mm}$ (18,0) from the nozzle tip and at $X=18 \text{ mm}$ and $Y=6 \text{ mm}$ (18,6) after 4.2 ms from the injection in the case of the throttle nozzle. From Fig.4 (A), it is known that $X=18 \text{ mm}$ is located at nearly the center of the spray penetration and $Y=0, 6 \text{ mm}$ are located on the spray axis and around the external periphery of spray, respectively. From Fig.5, it is known that the reappearance of droplet size distribution is high in the center of the spray and it is lowered at the periphery of the spray owing to a sparse distribution of droplets. For this reason, number of photographing is increased adequately at the periphery of spray so that the same number of measurements of droplets may be obtained as at the center, and this experiment is designed such that the number of droplets per one measuring region is more than 500 droplets.

In Figure 6 (A),(B),(C) and (D) are shown examples of composite photographs in which measuring regions of the microscopic photographs for the case of the throttle nozzle are combined. The behavior of spray atomization is classified into the following 4 processes from these photographs.

(A) During injection, a jet-cone which is close to a liquid column having extremely rich density in fuel is

Fig.3 Spray tip penetration

generated due to a succeeding fuel as shown in Fig.6 (A). The tip of the jet-cone is crushed by an air resistance and is overtaken by a fuel having large momentum which is referred to later. Waves are generated on the surface around the jet-cone since the relative velocity between the ambient air and the jet is excessively large, and the fuel breaks up into filaments, generating droplets less than $100 \mu\text{m}$ in diameter.

(B) Succeeding fuel is interrupted immediately after the end of injection as shown in Fig.6 (B) and the jet-cone becomes a wave-like stream, i.e. a wavy-flow. Around the wavy-flow are generated the filaments and droplets larger than $100 \mu\text{m}$.

(C) Status of the wavy-flow changes in its disturbance as shown in Fig.6 (C) and the flow is eventually broken into filaments or films which appear around the

Fig.4 Measuring region of fuel droplets

Fig.5 Consistency of droplet size distribution

Fig.6 Photographs of fuel spray (Throttle nozzle)

spray axis. The wavy-flow almost disappears within the twice the injection period.

(D) Larger diameter droplets which are caused from the wavy-flow are broken with further lapse of time and atomization of spray is promoted. As shown in Fig.6 (D), the condition of spray atomization is nearly stabilized after three times the injection period.

The behaviors of spray atomization from the pintle nozzle and the hole nozzle are nearly the same as those observed in the case of the throttle nozzle. In the pintle and the hole nozzles, under the experimental conditions where the spray velocity is greater than that in the throttle nozzle as shown in Fig.3, a dense jet-flow is formed; the spray angle is small; in consequence, fuel is broken into fine filaments and small droplets. Maximum droplet diameters of the atomized droplet are 200, 165 and 130 μm for the throttle nozzle, the pintle nozzle and the hole nozzle, respectively.

Figure 7 (A), (B), and (C) show the number of breakup droplets in the throttle nozzle. The breakup droplets referred to here are those droplets which have broken from the jet-cone or the wavy-flow. These figures indicate the number of droplets during breakup process being observed per one photograph measured at each measuring region - number of the breakup droplets - and are not the number of droplets generated after the breakup. As to a

Fig.7 Spatial distribution of breakup droplets (Throttle nozzle)

contour line of mean diameter, detailed description will be given afterward. Few breakup droplets are observed at the beginning of injection and after 1.5 to 2 times the injection period, large droplets generated from the wavy-flow are broken up, thus, breakup droplets are most remarkably observed around the central region of spray. After that, flying

breakup droplets are observed even at the periphery of spray and around the spray tip with the lapse of time as shown in Fig.7 (B) and (C), and these results are in agreement qualitatively with the processes of spray atomization mentioned above.

4.2 Droplet size distribution in spray

The photographing space which is shown previously is turned around spray axis for every measuring region as shown in Fig.8 based upon the microscopical photographs in local region taken, and the number of droplets for every droplet diameter in the annular portion having $2.00 \text{ mm} \times 2.00 \text{ mm}$ in cross section is obtained. Sauter mean diameter x_{32} and the arithmetic mean droplet diameter x_{10} are then obtained, and droplet size distribution of spray droplets is obtained in each portion. In the microscopical photographing region of 1.35 mm^3 mentioned above correction of the droplet number is made for every droplet diameter within each photographing region based on the relation between the droplet diameter and the depth of field as shown in Fig.2 (C), therefore, the measuring region will be made the entire region of spray by turning this region around spray axis as shown in Fig.8. Furthermore, as shown in Fig.5, the reappearance of droplet size distribution had been checked in every part of spray, and hence, measuring error of droplet size distribution in this experiment was governed by the reappearance of droplet size distribution and the error in measuring droplet diameter; consequently, it is supposed that considerations for correction by the droplet velocity are not necessary.

Figure 9 (A), (B), (C), and (D) show the spatial distribution of the mean droplet diameters in the throttle nozzle. The contour lines of the droplet diameter in these figures are of equal droplet diameter x_{32} or x_{10} is identical. The portion above the spray axis indicates x_{32} and the lower portion does x_{10} , and the non-uniformity of droplet diameter distribution in local region can be known from comparison of the two. Larger droplets exist around the center of spray up to the end of injection and these are moved forward, as time passes, reach remote positions, and thus, atomized droplets are distributed in the stratiform

Fig.8 Measuring region of fuel droplets

state according to the droplet diameter. At the beginning of injection, mean droplet diameter is small and the non-uniformity of droplet diameter distribution in each region is not significant. The non-uniformity is increased with the lapse of time, it is again reduced after 1.5 times the injection period and the uniform distribution is observed at 6.10 ms after the injection. Fig.10 (A) and (B) show the spatial distribution of mean droplet diameters at 1.80 ms after the injection in the pintle nozzle and at 2.10 ms after the injection in the hole nozzle, respectively. It is found from Fig.9 (C) and Fig.10 that the non-uniformity in the local region and in the entire spray is most remarkable in the throttle nozzle, and it is reduced in the order of the pintle nozzle and the hole nozzle, and mean droplet diameter is reduced in the same order. Fine droplets generated from the jet-flow at the beginning of injection remain near the injection nozzle periphery because their velocities decrease

Fig.9 Spatial distribution of mean droplet diameter (Throttle nozzle)

instantaneously. Fig.11 (A), (B), (C) are the illustrations of injection pressure and needle lift detected at each nozzle.

Subsequently, droplet size distributions in local measuring regions are integrated, droplet size distribution in the entire spray is obtained and arrangement is made using Nukiyama-Tanasawa distribution function.

$$dn/dx = n A x^{\alpha} \exp(-B x^{\beta}) \quad (2)$$

where n is the total number of spray droplets and x is the droplet diameter. As for indexes α and β , α is fixed at 2 and β is varied in this experiment, because good approximation is obtained in droplet number distribution and the uniformity of distribution should be clarified by the index β . The total droplet distribution for a period of $1.00 \text{ ms} \leq t \leq 6.10 \text{ ms}$ from the injection in the throttle nozzle,

$$dn/dx = 150 t^{7.87} \exp(-2.26 t) x^2 \times \exp\{-(0.003 t^4 - 0.008 t^3 - 0.291 t^2 + 0.152 t - 0.529) \times x^{(0.034 t^2 - 0.210 t + 0.793)}\} \quad (3)$$

Fig.10 Spatial distribution of mean droplet diameter

1 Injection pressure 2 Needle lift 3 Firing signal

Fig.11 Injection pressure and needle lift

for $0.60 \text{ ms} \leq t \leq 2.40 \text{ ms}$ in the pintle,

$$dn/dx = 1.12 \times 10^6 t^{11.7} \exp(-6.52 t) x^2 \times \exp\{-(0.079 t^4 - 0.956 t^3 + 2.29 t^2 - 0.728 t + 0.380) \times x^{(0.142 t^2 - 0.526 t + 0.973)}\} \quad (4)$$

for $0.70 \text{ ms} \leq t \leq 2.80 \text{ ms}$ in the hole,

$$dn/dx = 633 t^{2.78} \exp(-0.883 t) x^2 \times \exp\{-(0.007 t^4 - 0.021 t^3 + 0.144 t^2 - 0.096 t + 0.371) \times x^{(0.076 t^2 - 0.302 t + 1.04)}\} \quad (5)$$

Figure 12 shows the relation between index β and non-dimensional time t/t_i where each photographing time is divided by the injection period. The value of index β is approximated by a quadratic equation. In any nozzle, a number of small droplets are generated at the beginning of injection and the magnitude of index β is large and appreciably uniform distribution is obtained. However, the most non-uniform distribution is observed after 1.5 times the injection period, and after that, the distribution again becomes uniform. This process coincides well with the behavior of above-stated spray atomization and droplet diameter distribution, the time at the nonuniform distribution is consistent with the time when wavy-flow starts its breakup; and after that, the breakup of large droplets which are generated from wavy-flow is promoted and the uniform distribution is again obtained. Mean droplet diameter in the entire spray is increased up to 2 times the injection period, and after that, it is reduced.

Subsequently, droplet size distribution in each measuring region and at each photographing time is examined in the case of the throttle nozzle for the time range from 4.20 ms to 6.10 ms after the injection. Its droplet size distribution is described with Eq.(2) and the following equations within the range of spray occupancy region which is expressed by Eq.(6).

$$Y = \{0.43 \exp(0.13)\} x - \{0.05 \exp(0.08 \times t)\} x^2 + \{0.01 \exp(-0.16 t)\} x^3 - \{5.94 \times 10^{-4} \exp(-0.43 t)\} x^4 \quad (6)$$

$$n = 7.82 \times 10^5 \exp(-0.34 t) t^{-1.64} \times Y^{(-0.16t+1.87)} \exp\{(0.30 t-2.12)Y\} + 2070 \exp(0.18 t-0.18 X) \quad (7)$$

$$A = \frac{\{\Gamma(6/\beta)\}^3}{\{\Gamma(5/\beta)\}^3 \Gamma(3/\beta)} x_{32}^{-3} \quad (8)$$

$$B = \left\{ \frac{\Gamma(6/\beta)}{\Gamma(5/\beta)} \right\}^\beta x_{32}^{-\beta} \quad (9)$$

$$\beta = 0.28 \exp(0.34 t) + (0.003 t - 0.004)X + 0.003 t^{2.07} Y \quad (10)$$

$$x_{32} = \{-2.25 \times 10^{-7} \exp(2.91 t) + 73.1 \times \exp(-0.076 t)\} \exp\{(0.009 + 0.002t)X + (0.072 - 0.004t)Y\} \quad (11)$$

Figure 13 (A), (B), and (C) show the spatial distribution of the total droplet volumes per unit space in the throttle nozzle in which the jet-cone and the wavy-flow are not included. The droplet volume near the spray axis is great up to 2 times the injection period, and variations in the droplet volume between around the center of spray and periphery are small up to 3 times the injection period. Furthermore, this variation in the droplets volume with the spatial region is most remarkable in the throttle nozzle, and it is reduced in the order of the pintle nozzle and the hole nozzle.

Fig.12 Temporal change in index β

Fig.13 Spatial distribution of droplet volume (Throttle nozzle)

6. Conclusions

Injected fuel droplets are observed by means of the microscopical photographing method while fuel is being injected into a quiescent gaseous environment of room temperature and high pressure using a fuel injection device of diesel engine and varying the injection nozzle and the photographing time. The following results are obtained:

(1) The mechanism of spray atomization is classified into 4 processes for each case of the throttle, the pintle or the hole nozzle.

(2) It has been clarified that, in droplet diameter distribution of spray droplets, large droplets are found mostly in the peripheral region of spray with the lapse of time and that atomized droplets are distributed in the stratiform state according to their size.

(3) The droplet size distribution of the entire spray is expressed by the equations(3), (4), and (5) as a function of the time elapsed from injection, and the changes in the uniformity of distribution and mean diameter with the time have been revealed.

(4) The droplet size distribution at an arbitrary measuring region within time range from 4.20 ms to 6.10 ms after the start of injection in the case of the throttle nozzle is expressed by equations(6), (7), (8), (9), (10), and (11) as a function of the time from injection, the distance from nozzle along the spray axis and radial distance from the spray axis.

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