Droplet Size Distribution in Diesel Fuel Spray

(Continued : Effects of Back Pressure and Ambient Density)*

By Kiichiro TAKEUCHI**, Jiro SENDA*** and Koji YAMADA†

The purpose of this paper is to clarify transient characteristics, effects of back pressure and ambient density of spray atomization and droplet size distribution in the diesel spray. In the experiment, the diesel spray injected into a stagnant ambient atmosphere under high pressure is observed by means of taking photographs with photographing time, back pressure and ambient density changed.

The result confirms that uniformity and mean diameter of the total distribution change with time. And it is proved experimentally how the efficiency of droplet production from spray changes with time. As back pressure increases, Sauter mean diameter increases because of a decrease in spray velocity. Further, its change is expressed in equations as a function of back pressure and ambient density. Transient changes in Sauter mean diameter and the uniformity are written in experimental equations as a function of back pressure.

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

1. Introduction

In a previous report⁽¹⁾, the breakup process of spray when throttle, pintle and hole nozzles used was divided into 4 processes, and number of breakup droplets, changes in droplet size distribution and droplet volume distribution with the lapse of time in local spray region were clarified. And droplet size distribution in entire spray region was expressed as a function of time. Further, droplet size distribution in the case of using a throttle nozzle where a wavy-flow disappeared was expressed as a function of the time and position for the time duration 4.20 ms after injection start till 6.10 ms.

In this study, a room temperature diesel light oil was injected into a room temperature and high pressure quiescent gaseous environment using a throttle nozzle to observe the behavior of fuel droplets over entire process of atomization microscopically by means of direct micro-photographing method. As for atomization characteristics of spray, attention was focussed on the uniformity and droplet mean diameter, droplet volume fraction per injection quantity and droplet production ratio of entire droplet size distribution of spray and their transient changes were investigated in

detail. Moreover, effects of back pressure, pressure drop and ambient density upon atomization characteristics were checked while they were changed, and droplet mean diameter and its transient change were expressed as a function of the pressure drop and ambient density.

Nomenclature

n	: Number of spray droplets	-
N	: Injection pump speed	s^{-1}
P_b	: Back pressure	MPa
P_o	: Opening pressure of injection nozzle	MPa
ΔP	: Pressure drop between injection pressure and back pressure	MPa
Q_f	: Injection quantity per revolution	mm^3/rev
t	: Time elapsed from injection start	ms
t_i	: Injection period	ms
t_s	: Transitional time for spray tip penetration	ms
t_{35}	: Time at 35 mm in spray tip penetration	ms
x	: Diameter of spray droplets	μm
x_{32}	: Sauter mean diameter of spray droplets	μm
X	: Distance from nozzle tip along spray axis	mm
X_1	: Spray tip penetration at the time of $t < t_s$	mm
X_2	: Spray tip penetration at the time of $t > t_s$	mm
$X_{1.4}$	: Spray tip penetration at 1.40 ms from injection start	mm
Y	: Radial distance from spray axis	mm
β	: Uniformity index of droplet size distribution	-
ϵ	: Droplet production ratio	-
ρ_a	: Density of ambient gas	g/cm^3
θ	: Spray angle	°

* : Received 5th June, 1981.

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

*** : Graduate Student, Faculty of Engineering, Doshisha University, Karasuma Imadegawa, Kyoto.

† : Nissan Motor Co., Ltd., 8 Nishiki-cho, Naka-ku, Yokohama.

2 Experimental Conditions

Same experimental apparatus as used in a previous study⁽²⁾ was used.

Bosch type injection pump, model PES 2A55B, was adopted as the injection pump and was driven by an electric motor at a speed of $N = 16.7 \text{ s}^{-1}$ (1000 rpm). The injection pipe was a solid-drawn steel pipe having 1.5 mm inside diameter 6.0 mm outside diameter and 530 mm length. Throttle nozzle NP-DN 4SD24 the opening pressure P_0 of which was set at 11.9 MPa was used as the injection nozzle. Diesel light oil for automobile (JIS No.2 light oil) having specific gravity of 0.831 and kinematic viscosity of $3.54 \times 10^{-6} \text{ m}^2/\text{s}$ was employed.

Experiments conducted in this study are broadly divided into experiment I where transient change in atomization characteristics of spray is checked and experiment II where effects of back pressure, pressure drop and ambient density upon atomization characteristics are checked. Conditions of experiments I and II are shown in Table 1 and Table 2 respectively. In experiment I, same conditions as observed in previous throttle nozzle case were employed. Air was used as the ambient gas, back pressure P_b was kept at 4.02 MPa and fuel droplets were observed at 6 elapsed times of 1.00,

2.10, 3.00, 4.20, 5.00 and 6.10 ms after injection start. In experiment II, air, mixed gas composed of air and CO_2 (50% vol.) and CO_2 were used as the ambient gas, and ambient density ρ_a was changed and back pressure P_b was also changed in order to obtain ΔP as shown in Table 2. Here, the pressure drop means a difference between the back pressure and the maximum injection pressure.

It seems that the spray shape and the atomization characteristics are changed with the lapse of time and if conditions such as back pressure and the like are altered, the trend of transient change is also changed. Therefore, the reference to be used for comparison of atomization characteristics under different conditions should be taken into consideration. In this experiment, comparison of atomization characteristics is made under one condition where elapsed time (photographing time) t after injection start is constant ($t = 1.40 \text{ ms}$) and under another condition where spray tip penetration X is constant ($X = 35 \text{ mm}$) taking ignition delay, injection period and flying time of spray in diesel engines into consideration. Furthermore, spray is observed with photographing time of t as shown in Table 2 under different back pressure conditions in order to check the effect of back pressure upon the atomization characteristics with the lapse of time. In Table 2, $X_{1.4}$ represents the distance of the spray tip penetration at 1.40 ms after injection start and t_{35} represents the elapsed time after injection start where the spray tip penetration reaches 35 mm.

In these experiments, injection period t_i was measured by the waveform of needle lift and the microscopic photograph taken around injection nozzle hole. As for injection quantity Q_f , injection was carried out several times into the receiving vessel under atmospheric pressure and its weight was measured by a

Table 1 Experimental conditions
(Experiment I)

Injection Nozzle	Throttle Nozzle NP-DN4SD24
Nozzle Opening Pressure P_0 MPa	11.9
Injection Quantity Q_f mm ³ /rev	22.3
Injection Period t_i ms	2.10
Pump Speed N s ⁻¹	16.7
Back Pressure P_b MPa	4.02
Time for taking Photographs of Spray t ms	after injection 1.00, 2.10, 3.00, 4.20, 5.00, 6.10

Table 2 Experimental conditions (Experiment II)

Ambient Gas	P_b MPa	ΔP MPa	ρ_a g/cm ³	$X_{1.4}$ * mm	t_{35} * ms	t_i ms	Q_f mm ³ /rev	t ms
Air	4.02	9.80	0.0494	24.0	2.65	1.35	7.55	0.70, 1.40, 2.00, 2.65, 3.35
	3.04	10.8	0.0374	30.0	1.85	1.30	7.62	0.65, 1.40, 1.85, 2.60
	2.06	11.8	0.0253	41.5	1.15	1.30	7.96	1.15, 1.40, 1.95
	1.08	12.7	0.0133	60.0	0.55	1.25	7.97	0.55, 1.00, 1.40
	0.098	13.7	0.0012		0.25	1.25	8.27	0.25
Air + CO ₂	2.47	11.4	0.0381	31.0	1.70	1.30	7.83	1.40, 1.70
	2.06	11.8	0.0320	35.0	1.40	1.30	7.96	1.40
CO ₂	3.04	10.8	0.0571	23.0	2.65	1.30	7.62	1.40, 2.65
	2.06	11.8	0.0387	32.5	1.65	1.30	7.96	1.40, 1.65
	1.08	12.7	0.0203	49.5	0.90	1.25	7.97	0.90, 1.40
	0.098	13.7	0.0018		0.55	1.25	8.27	0.55
Injection nozzle								Throttle nozzle NP-DN4SD24
Nozzle opening pressure P_0 MPa								11.9
Pump speed N s ⁻¹								16.7

* $X_{1.4}$: Spray tip penetration at 1.40 ms after injection start

** t_{35} : Time at which spray tip penetration is 35 mm

precision balance. And the ambient gas was maintained at room temperature.

The area of microscopic photographing in experiments I and II is shown in Fig. 1 and Fig. 2(A), (B), (C). Field of view of one photographing measuring area is 2 mm in both injection axis direction X and radial direction Y. The measuring volume is $2.00 \times 2.00 \times 0.675$ mm, namely 2.70 mm^3 , because the distance in light path direction is adjusted to the depth of field of droplets having $5 \mu\text{m}$ droplet diameter⁽¹⁾.

3. Results and Discussions

3.1 Transient change in spray characteristics

Transient changes in index β which shows the uniformity of droplet size distribution in the distribution function $dn/dx = nA x^\alpha \exp(-B x^\beta)$ introduced by Nukiyama and Tanasawa, Sauter mean diameter x_{32} , droplet volume fraction per injection quantity $(\pi/6)\sum n x^3/Q_f$ and in droplet production rate ϵ are shown in Fig. 3. Time axis is expressed by non-dimensional time t/t_i which is a ratio of time t from injection start divided by injection period t_i .

Fig. 1 Measuring area of fuel droplets (Experiment I)

(A)

(B)

(C)

Fig. 2 Measuring area of fuel droplets (Experiment II)

The uniformity of droplet size distribution is expressed by index β of the distribution function. Transient change in β is approximated by a quadratic equation as shown in the previous report. Values of β are large and the uniformity of distribution is higher since a number of small droplets are generated at the beginning of injection. They are lowered with the lapse of time and the most remarkable non-uniform distribution is observed at 1.5 times the injection period. After that, β gets larger again showing that the uniformity of distribution is remarkable. This observation well agrees with the breakup behavior of spray as stated in the previous report. The time where the distribution becomes non-uniform coincides with the time of breakup start of the wavy-flow and after that, the breakup of larger diameter droplets caused by the wavy-flow is extensive and the distribution again takes a uniform shape.

Sauter mean diameter x_{32} of the entire spray is small at the beginning of injection, increased till the time approximately twice the injection period and is then lowered. Transient change in droplet mean diameter also well agrees with the breakup process as shown in the previous report. However, it is noticeable that results obtained by this experiment are contrary to those derived from conventional reports⁽²⁾ which show that droplet mean diameter is large at the beginning and the end of injection and is small at intermediate stage of injection. This was attributable to the fact that in those experiments, measurement of fuel droplets was done by means of liquid

Fig. 3 Transient change in spray characteristics (Experiment I)

immersion sampling technique at a place sufficiently far from the injection nozzle and that the transient change in droplet mean diameter was not measured exactly in injection transient period where the spray shape was maintained and the breakup of the main jet region was not completed yet. If the transient change in droplet size distribution as shown in the previous report were taken into consideration and if the spray in this study were received in front of spray sufficiently far from the injection nozzle, it seems, same results as given in conventional reports might be obtained on account of stratified effect of the fuel droplets.

Subsequently, the transient change in droplet volume fraction per injection quantity $(\pi/6)\sum n x^3 / Q_f$ which is defined by the ratio of total volume of generated droplets $(\pi/6)\sum n x^3$ and the injection quantity Q_f is discussed. The injection quantity at $t/t_i = 0.48$ ($t = 1.0$ ms) is obtained from the needle lift and injection pressure, and the droplet volume fraction per injection quantity is calculated from it. Therefore, it is shown by broken lines during injection. It is known from Fig. 3 that the wavy-flow disappears wholly during approximately 2.5 times the injection period and the fuel being injected is all broken into droplets. Furthermore, the total volume of droplets is only approximately 2% of the injection quantity at the end of injection ($t/t_i = 1.0$).

Change rate of droplet volume fraction per injection quantity was obtained and defined as the droplet production ratio $\epsilon = \{(\pi/6)\sum n x^3 / Q_f\} / (t/t_i)$. When the mean injection quantity per unit time Q_f/t_i is multiplied to the said droplet production ratio, droplet production rate $\Delta(\pi/6)\sum n x^3 / \Delta t$ mm³/s is obtained. Droplet production ratio and droplet production rate increase nearly linearly till twice the injection period and after that, they are lowered suddenly on account of disappearance of the wavy-flow or reduction in the number of large fuel droplets in film form. In other words, the maximum droplet production appears just before the droplet volume fraction per injection quantity becomes unity after the wavy-flow disappears wholly.

Fig. 4 Change in spray tip penetration with back pressure

4 Effects of Back Pressure, Pressure drop and Ambient Density upon Spray Characteristics

4.1 Spray tip penetration and spray angle

First of all, the experimental results of spray tip penetration and the spray angle which show the macroscopic shape of the spray are discussed in order to investigate the atomization characteristics as stated under 4.2.

Figure 4 shows a change in spray tip penetration X while back pressure P_b is changed. The spray tip penetration increases in proportion to nearly 0.531 power of time t within the measuring time at each back pressure. As noticed from the figure, however, the tip penetration is expressed by 2 straight lines the slope of which is changed at a certain time for each back pressure. The time when the slope is changed is designated as the transitional time t_s of spray tip penetration. Transitional time t (t_s/t_i) is changed to 3.17(2.26), 2.87(2.13), 2.53(1.95), and 2.17 ms(1.67) respectively for back pressures P_b of 5.00, 4.02, 3.04, and 2.06 MPa. The transitional time does not appear within the measuring time in the cases of back pressures being 1.09 and 0.098 MPa. The slope of straight lines before and after the transitional time is independent of the change in back pressure and is nearly constant as shown in Fig. 4.

Figure 5 shows the relation between the tip penetration and time where the ambient density ρ_a is kept constant and pressure drop ΔP is changed. Figure 6 shows the case where the pressure drop is kept constant and the ambient density is changed. It is noticed from the above that the transitional time is not affected at all by the ambient density and is hastened with an increase in pressure drop. The spray tip penetration X was rearranged from Fig. 5 and Fig. 6 as functions of the pressure drop ΔP , the ambient density ρ_a and time t and the following empirical equations were obtained within the ranges of $10.9 \leq \Delta P \leq 11.0$ MPa, $0.0253 \leq \rho_a \leq 0.0381$ g/cm³ and $0.15 \leq t \leq 5.80$ ms:

Fig. 5 Change in spray tip penetration with pressure drop

$$X_1 = 0.462 \Delta P^{0.916} \rho_a^{-0.536} t^{0.608} \quad (1)$$

$$X_2 = 2.30 \Delta P^{0.354} \rho_a^{-0.540} t^{0.303} \quad (2)$$

where X_1 and X_2 represent the spray tip penetrations before and after the transitional time. Solid lines shown in Figures 4, 5, and 6 indicate calculated values obtained by above equations and the correlation coefficients in Equations (1) and (2) are 0.976 and 0.986 respectively.

Hiroyasu, et al.⁽³⁾ reported the presence of a transitional time in the spray tip penetration in experiments using a steady intermittent spray from the hole nozzle. However, this transitional time is attributable to the potential core of the jet and it appears at the beginning of spray corresponding to the start of breakup of the jet and is essentially different from the transitional time referred to in this study.

Transient change in spray angle θ when the back pressure is changed is shown in Fig. 7. The spray angle is defined by $\theta = 2 \tan^{-1}\{Y/(X/2)\}$ as shown in the figure. The authors considered that if the spray angle was defined by maximum radial distance from spray axis and by the distance from nozzle tip along with spray axis at the said location, its distance along with spray axis might be varied irregularly owing to disturbances at external periphery of spray and that this attempt was not appropriate. The spray angle is large at the beginning, diminishes with the time elapsed and is again increased till it reaches a constant. Furthermore, it is reduced with a decrease of back pressure and the moment when it becomes constant tends to come earlier.

According to the observations of the entire photographs of the spray and the microscopic photographs showing fuel droplets, the spray tip rushes into a quiescent environment at the beginning of spray and is shed since the relative velocity with regard to the ambient atmosphere is significantly large. After that, when the tip penetration is

increased because a subsequent jet cone having a large momentum advances, the spray angle is reduced. The momentum of breakup droplets is reduced suddenly and the spray angle is increased because dispersion in radial direction starts after 1.5 to 2.0 times the spray period till breakup ratio of droplets from the wavy-flow is increased and the wavy-flow disappears. After this, the rate of increase of the spray tip penetration is reduced and a stable spray shape is obtained resulting in a constant spray angle. It is supposed that the transitional time t_s in the tip penetration X , which is dealt with previously, appears corresponding to the time when the dispersion of the breakup droplets in radial direction is started. Further, the lower the back pressure, the larger the injection velocity of fuel, and the disappearance of the wavy-flow comes earlier and therefore, the transitional time in the tip penetration and the time when the spray angle reaches a constant come earlier accordingly.

4.2 Droplet size distribution and atomization characteristics

The effect of the pressure drop upon atomization characteristics is shown in Fig. 8 (a) and (b), and the effects of ambient density upon the same are shown in Fig. 9 (a) and (b). Current experiments are conducted under two conditions as stated previously—comparison of atomization characteristics is checked while time t from injection start is constant ($t = 1.40$ ms) and under another condition where spray tip penetration X is constant ($X = 35$ mm). Here, index β in droplet size distribution function for entire spray, Sauter mean diameter x_{32} , total number of droplets n , droplet volume fraction per injection quantity $(\pi/6) \sum n x^3 / Q_f$, the tip penetration $X_{1.4}$, and the tip penetration time t_{35} are given as atomization characteristics.

Now discussion is made referring to Fig. 8 (a), when the ambient density ρ_a is constant and pressure drop ΔP is changed, the tip penetration $X_{1.4}$ is increased if ΔP

Fig.6 Change in spray tip penetration with ambient density

Fig.7 Spray angle

is increased and the injection velocity is eventually increased, and the droplet mean diameter is reduced since frictional resistance between the injected jet and the ambient atmosphere is increased. Total number of droplets is then increased and droplet volume fraction per injection quantity is also increased, but the quantity change in volume fraction is not remarkable because droplet mean diameter is reduced. When ΔP is constant and ρ_a is changed as shown in Fig. 8 (b), the injection velocity is same, but the tip penetration is reduced since the drag applied to the spray is increased owing to an increased ρ_a and the flying velocity of the spray is eventually reduced. Although the shear stress due to the ambient viscosity is increased as ρ_a is increased, the droplet mean diameter tends to be increased slightly with an increased ρ_a since it is greatly affected by the flying velocity of the spray. Moreover, although the droplet volume fraction per injection quantity is reduced as ρ_a is increased, quantity change in volume fraction is smaller than that of total number of droplets n in the same manner as in the case of the pressure drop being changed, because the droplet mean diameter is increased. Index β which shows the uniformity of distribution is not changed significantly compared with the case of $X = 35$ mm shown in Fig. 9. Therefore, it seems that, although the droplet mean diameter and the total number of droplets are changed according to the growth of spray, droplet volume fraction per

injection quantity and the uniformity of the distribution are not changed remarkably when the time from injection start is kept constant.

When discussion is made subsequently referring to Fig. 9 (a), the tip penetration time t_{35} is reduced as ΔP is increased when ambient density ρ_a is constant and ΔP is changed. However, the effect of the increased injection velocity is significant resulting in a promoted breakup, and the total number of droplets is increased and the droplet mean diameter is reduced. Therefore, the droplet volume fraction per injection quantity is kept almost constant. When ΔP is constant and ρ_a is changed as shown in Fig. 9 (b), the flying velocity of the spray is reduced as ρ_a is increased while the total number of droplets and droplet volume fraction per injection quantity are increased since tip penetration time increases substantially. The droplet mean diameter is increased as ρ_a is increased. Index β is increased as ρ_a is increased since t_{35} is increased even if the spray penetration is kept constant.

Figures 10 (a) and (b) show the effect of back pressure P_b upon the atomization characteristics. In case $t = 1.40$ ms as shown in Fig. 10 (a), the total number of droplets and the droplet volume fraction per injection quantity are increased since the tip penetration is lengthened as P_b is reduced, the droplet mean diameter is then reduced resulting in good atomization. In the meantime, the

(A) $\rho_a = 0.0381$ g/cm³

(B) $\Delta P = 11.9$ MPa

Fig. 8 Change in spray characteristics with pressure drop and ambient density ($t = 1.40$ ms)

(A) $t = 1.40$ ms

(B) $\Delta P = 11.9$ MPa

Fig. 9 Change in spray characteristics with pressure drop and ambient density ($X = 35$ mm)

uniformity of distribution is lowered. In case $X = 35$ mm as shown in Fig. 10 (b), droplet volume fraction per injection quantity is affected more significantly by the tip penetration time than by the flying velocity of the spray and is increased as P_b is increased. The droplet mean diameter is increased as P_b is increased. It is therefore known that, when the spray tip penetration is constant, the total number of droplets and the droplet volume fraction per injection quantity are increased as the back pressure is increased resulting in good spray dispersion and good uniformity of distribution while the droplet mean diameter is increased.

Results shown in Figures 8 (a) and (b), and 9 (a) and (b) are rearranged and the following empirical equations in relation to Sauter mean diameter are obtained as functions of pressure drop ΔP and ambient density ρ_a .

$$x_{32} = 219 \Delta P^{-0.580} \rho_a^{0.0638} \quad (t = 1.40 \text{ ms}) \quad (3)$$

$$x_{32} = 1700 \Delta P^{-1.02} \rho_a^{0.304} \quad (x = 35 \text{ mm}) \quad (4)$$

Above equations are applicable in the ranges of $10.9 \leq \Delta P \leq 11.9$ MPa and $0.0253 \leq \rho_a \leq 0.0381$ g/cm³, and correlation coefficients for Equations (3) and (4) are 0.946 and 0.826 respectively. According to the equation which is introduced by Sitkei⁽⁴⁾ in dimensional analysis and is applied to pin type nozzle, index of ρ_a is negative showing that the droplet mean diameter is reduced as ambient density is increased. In current experiments, the droplet mean diameter is increased as the density is increased and the index of ρ_a is positive as shown in Figures 8 (b) and 9 (b). Furthermore, empirical equations for droplet mean diameter which were obtained by Hiroyasu, et al.⁽⁵⁾ using the throttle, pintle and hole nozzles showed same tendency as obtained by the authors.

Neya, et al.⁽⁶⁾ conducted experiments using a swirl atomizer and reported that the droplet mean diameter was increased on account of the coalescence by the collision of droplets themselves due to a contraction of spray with an increased back pressure. Results presented by DeCorso⁽⁷⁾ showed same tendency. Hiroyasu, et al.⁽⁸⁾ conducted experiments using a diesel injection nozzle and reported that the coalescence of droplets themselves was caused by an increased back pressure and the droplet mean diameter was increased. In diesel spray, however, the increment of the droplet mean diameter due to an increased back pressure is more reasonably explained by the lowered flying velocity of spray as mentioned above than by the coalescence of droplets if atomization process of the spray and spatial distribution of fuel droplets as stated in the previous report⁽¹⁾ are taken into consideration.

4.3 Effect of back pressure upon transient change in atomization characteristics

Figure 11 shows transient changes in Sauter mean diameter x_{32} , index β and droplet volume fraction per injection quantity $(\pi/6)\sum n x^3/Q_f$. Non-dimensional time t/t_i was used for time axis. Droplet mean diameter x_{32} shows same transient change as shown in Fig. 3 and is reduced with a reduced back pressure at the same period of time. The time when the droplet mean diameter becomes maximum is shortened as the back pressure is reduced. It is likely that this phenomenon is caused by the facts that, as shown in Fig. 5, the transition of the spray tip penetration comes earlier, and that breakup of droplets from wavy-flow and disappearance of wavy-flow also come earlier as mentioned previously. Index β is slightly lowered on low back pressure side for the same period of time corresponding to the change in droplet mean diameter and β becomes minimum earlier as the back pressure is reduced. As for the droplet volume fraction per injection quantity, it is increased on low back pressure side for the same period of time because breakup of wavy-flow takes place earlier as the back pressure is reduced.

The said droplet mean diameter x_{32} and index β are expressed as functions of non-dimensional time t/t_i and back pressure P_b , and the following empirical

(A) $\rho_a = 0.0381$ g/cm³

(B) $X = 35$ mm

Fig. 10 Change in spray characteristics with back pressure

equations are obtained.

$$x_{32} = 1.17 \times 10^5 \exp(-1.74 P_b) \left(\frac{t}{t_i} \right)^{(1.57-3.02 P_b)} \{ \exp(2.22 P_b - 11.0) \left(\frac{t}{t_i} \right) \} + 35.0 \quad (5)$$

$$\beta = 0.0553 \{ \left(\frac{t}{t_i} \right) - (0.0680 P_b + 1.13) \}^2 + 0.634 \exp(0.0517 P_b) \quad (6)$$

The curves of the index β and x_{32} shown in Fig. 11 are those calculated by these equations. These equations are applicable in the ranges of $0.4 \leq t/t_i \leq 2.5$ and $1.08 \leq P_b \leq 4.02$ MPa, and correlation coefficient is 0.998 for Eq. (5) and 0.998 for Eq. (6). If these are converted to functions of pressure drop ΔP and ambient density ρ_a using Eq. (3) and Eq. (5), the following equations are obtained.

$$x_{32} = 1.17 \times 10^5 \exp(-110 \Delta P^{-0.580} \rho_a^{0.0638} + 17.2) \left(\frac{t}{t_i} \right)^{(4.55-1.90 \Delta P^{-0.580} \rho_a^{0.0638})} \{ \exp(140 \Delta P^{-0.580} \rho_a^{0.0638} - 33.9) \left(\frac{t}{t_i} \right) \} + 35.0 \quad (7)$$

Fig. 11 Change in spray characteristics with back pressure

5 Conclusions

Diesel fuel was injected into a room temperature and high pressure quiescent gaseous environment using a throttle nozzle and fuel droplets were observed by means of direct micro-photographing method with photographing period, back pressure, pressure drop, and ambient density changed, and the following results were obtained :

(1) The uniformity of droplet size distribution over entire spray region is higher at the beginning of injection, is lowered gradually, reaches the minimum at approximately 1.5 times the injection period and after that, it is again increased. Droplet mean diameter is smaller at the beginning, increases with the lapse of time, reaches the maximum at approximately twice the injection period and is then reduced.

(2) Spray tip penetration is shown by Eq. (1) and Eq. (2) as a function of pressure drop, ambient density and time. Transition does occur in the tip penetration corresponding to disappearance time of the wavy-flow and it takes place earlier as the back pressure is reduced.

(3) Droplet mean diameter at 1.40 ms after injection start and at the time when the tip penetration becomes 35 mm is expressed by Eq. (3) and Eq. (4) as a function of pressure drop and ambient density. Droplet mean diameter is increased as the back pressure is increased and is affected by the flying velocity of spray.

(4) The index showing the uniformity in droplet size distribution and the droplet mean diameter are expressed by Eq. (5) and Eq. (6) as a function of time and back pressure. The time when droplet mean diameter is maximized and the uniformity of distribution is minimized comes earlier as the back pressure is reduced.

References

- 1) Takeuchi, K., et al., Bulletin of the JSME, Vol. 26, No. 215(1983), p. 797.
- 2) Hiroyasu, H., et al., Proc. 1st Int. Conf. on Liquid Atomization and Spray Systems, (1978), p. 125.
- 3) Hiroyasu, H., et al., Trans. JSME(in Japanese), Vol. 44, No. 385(1978), p. 3208.
- 4) Sitkei, G., "Kraftstoffaufbereitung und Verbrennung bei Dieselmotoren" Springer-Verlag, (1964).
- 5) Hiroyasu, H. and Kadota, T., SAE Trans. Vol. 34(1974), p. 2615.
- 6) Neya, K. and Sato, S., Journal of the JSME(in Japanese), Vol. 70, No. 581(1967), p. 817.
- 7) DeCorso, S. M., Trans. ASME, Vol. 82(1960), p. 10.
- 8) Hiroyasu, H. and Kadota, T., Trans. JSME(in Japanese), Vol. 42, No. 353(1976), p. 290.