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Effect of the Injection Parameters on Diesel Spray Characteristics

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The characteristics of the diesel spray have affected certain aspects of engine performance, such as the power, fuel consumption, and emissions. Therefore, this study was performed to investigate the effects of various injection parameters. In order to obtain the effect of injection parameters on diesel spray characteristics, the experiment is performed by using a high temperature and pressure chamber. The behaviors of the spray are visualized by using a high speed video camera, spray angle, penetration, and various other things.

The results of the experiment are summarized as follows.

(1) The correlation of the spray penetration can be expressed as follows.

$$0<t<t_b\ ;\ S_1=11.628\Delta P^{0.485}\rho_a^{-0.478}t^{1.337}$$
$$t_b<t\ ;\ S_2=7.457\Delta P^{0.523}\rho_a^{-0.382}t^{0.548}$$

(2) The correlation of the spray angle can be expressed as follows

$$T_a=293\text{K}\qquad \tan(\theta/2)=0.59(\rho_a/\rho_f)^{0.437}$$
$$T_a=473\text{K}\qquad \tan(\theta/2)=0.588(\rho_a/\rho_f)^{0.404}$$

(3) The measured macro characteristics that include the spray tip penetration and spray angle corresponded with the established correlations.

Key Words: Spray Tip Penetration, Ambient Gas Density, Ambient Gas Temperature, Spray Angle

Nomenclature

P_i : Injection pressure, MPa
P_a : Ambient pressure, MPa
S_1, S_2 : Spray tip penetration before and after breakup, cm
t : Time from injection, ms
T_a : Ambient gas temperature, K
θ : Spray angle, degree
κ : Function of momentum of the spray, ambient gas density, viscosity and temperature
ρ_a : Ambient gas density, kg/m^3
ρ_f : Fuel density, kg/m^3
ϕ : Nozzle diameter, mm

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1. Introduction

A diesel engine not only has a high thermal efficiency among heat engines, but it can also use various kind of fuel. In addition, it occupies an important position in the automobile market because diesel engines have high durability and reliability. However, it has a serious drawback because it causes air pollution by producing NOx and PM etc.

In order to verify and solve the problem, it is necessary to directly observe the internal combustion chamber of a diesel engine. Many studies have been performed in recent years to verify the macroscopic and microscopic behavior of the injected spray of a static chamber because observing it is not easy due to the difficulties of the experiment.

Lee et al.(2002) investigated the spray characteristics of a multi-hole and a single-hole diesel nozzle, but the study shows a lack of evaluation for the spray characteristics for high temperatures and pressure. A study and experiment are still largely required to verify the correlation of injection parameters that will affect the spray characteristics.

Moreover, a theoretical equation for the subject is also still not perfectly defined yet due to the complexity of the spray mechanism. In addition, there have been a number of proposals for the equations of correlation through some experiments.

Quoc and Brun (1994) suggested the development of the spray was goverened by the three physical phenomena that are disintegration, evaporation and coherence. Zhao et al.(1995) and Lee et al.(2002) have analyzed the effect of injection pressure on spray atomization characteristics by using PDPA and spray visualization. Hosoya and Obokata (1993) analyzed the spray characteristics of the multi-hole and the single-hole nozzle using a LDV, PDA system and suggested that the two measurement system were efficient for analyzing the unsteady diesel spray.

Hiroyasu and Arai (1990) investigated the droplet size of the intermittent spray of the single-hole nozzle and they concluded it decreased with the increase in injection pressure. Araneo et al. (1999) studied about the effect of gas density on the penetraion of a diesel spray and the entrainment of the surrounding air and they explained the spray behaviour and the reliability of existing zero-dimensional models.

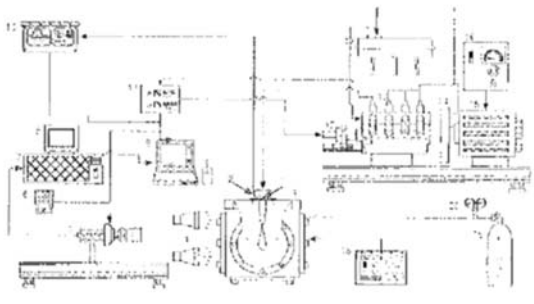
This study performs a spray experiment with the conditions of the ambient gas density and ambient gas temperature as a parameter by designing and producing a chamber, which has a high temperature and pressure, to recreate the conditions for the actual operation of an engine. The spray characteristics, such as the spray tip penetration, spray angle, and various other factors are examined. In addition, an experimental equation for the correlation, which will affect the spray characteristics by the applied experimental parameters is also produced.

2. Experimental Apparatus and Procedures

2.1 Experimental apparatus

The experimental equipment used in this study consist of a fuel injection device, high temperature and pressure chamber, and visualizing system to observe, record, and analyze the free spray of a diesel engine. Fig. 1 shows a schematic diagram of an experimental setup.

The fuel injection system consists of a fuel, injection pump, position detection sensor, motor, and solenoid valve, and some other things. In addition, the fuel injection pump applied in this



1. Injection nozzle
2. Needle lift sensor
3. High pressure chamber
4. Light source
5. High speed video camera
6. Video camera controller
7. Video camera main body
8. Monitor
9. Note book
10. Osilloscope
11. One shot injection system
12. Solenoid valve
13. Injection pump
14. Photo sensor
15. DC motor
16. rpm controller
17. Fuel tank
18. Temperature controller
19. N_2 Gas
20. Gas regulator

Fig. 1 Schematic diagram of experimental setup experiment was the 4-cylindered in-line PE pump. A synchronized signal can be used by detecting the top dead center of the motor cam with a pump speed controller, and the fuel is injected one at a time using the rack operated by the solenoid valve. Fig. 2 illustrates a detailed drawing of the single-hole pintle nozzle that is a commercial product with the hole diameter of 1.02 mm, niddle lift of 0.45 mm, and a linear angle of 10° of the nozzle tip.

In addition, a high temperature and pressure chamber, which can control the maximum temperature and pressure of 693K and 5 MPa relatively, is designed and produced to observe the spray characteristics for similar conditions to an actual diesel engine. Moreover, transparent quartz glass windows are installed on three faces of the chamber in order to make a visualization, and the inside pressure of the chamber can be controlled using N_2 gas.

The images of diesel spray are produced by using a high speed video camera (FASTCAM ultima 40K) with 9000fps where the video camera can be operated by the synchronized source by using a signal of the one time injection system.

2.2 Experimental procedures

Generally, the spray structure can be examined by the measurement of SMD, length of the spray, spray tip penetration and spray angle as the important parameters that will affect the spray characteristics are the injection nozzle, injection pressure, ambient gas density and ambient gas temperature, and various other things.

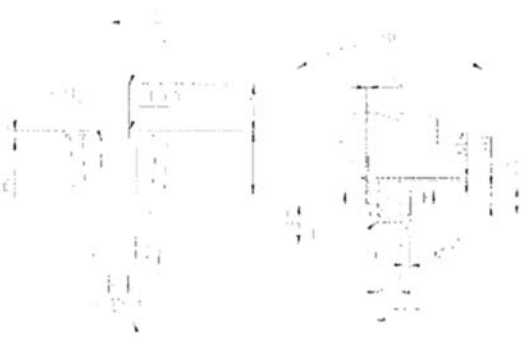


Fig. 2 Nozzle tip configuration

We has a former record of the project on the effect of injection pressure and speed of the injection pump for the injection characteristics where this study can be performed by the major parameters of the ambient gas density (18, 24, 30 kg/m^3) and ambient gas temperature (293, 473K) under the fixed injection pressure (14 MPa).

3. Results and Examinations

3.1 Spray structure

The spray structure defined in this study is shown in Fig. 3. The spray tip penetration can be defined from the nozzle tip to the end of the spray tip after spraying, and the spray angle θ is defined by an angle between the outer most point and the nozzle tip.

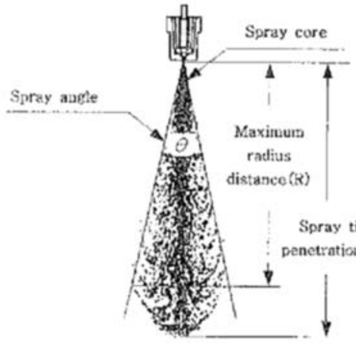
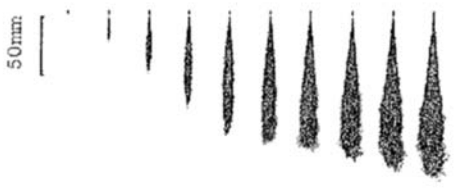


Fig. 3 Definition of diesel spray characteristics



(a) T_a=293K, ρ_a=30 kg/m^3

Fig. 4 Effect of the ambient gas temperature on the spray structure

Fig. 4 presents the images of spray for the ambient gas density of ρ_a=30 kg/m^3 and ambient gas temperature T_a=293K, T_a=473K, visualized by using a high speed video camera. The time interval between the sprays is 0.22 ms, and the images are produced for a total spray time of 2.22 ms. The sprays are to develop for the axial and radial direction according to the passage of time, and the increase of the axial direction is large in its early stages and shows a slowness of spray structure for the latter period.

Fig. 5 shows the images of the outer section of the spray for each time (Δt=0.22 ms) by using a kind of image processing method from the spray images produced from the experiment. In the case of room temperature and high temperature, it presents a structure that both cases show a remarkable decrease in spray tip penetration and an increase of the spray angle according to the large amount of ambient gas density.

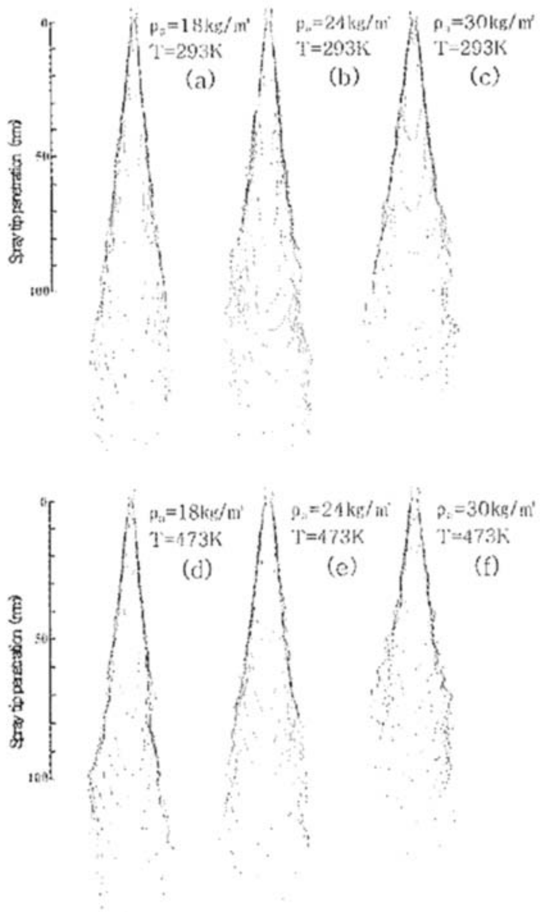


Fig. 5 Contour lines of diesel spray by time variation

3.2 Characteristics of the spray tip penetration

The results of the experiment for the spray tip penetration according to the changes of time are shown in Fig. 6. It can be verified that the gradient of the spray tip penetration is decreased around 0.6~0.8 ms. This section has been investigated by a break-up point that shows the changes of spray types from a liquid column to liquid droplets according to the studies on the atomization mechanism.

It shows that the spray tip penetration is decreased by increasing the ambient gas density or ambient gas temperature. This is because of an interruption in the growth of spray due to the increase of pressure in the chamber according to the increase of ambient gas density. The reason for the decrement of the spray tip penetration for the increase of the ambient gas temperature is that the kinetic energy of the atomized liquid droplets decreased because the initial evaporation and atomization of micro liquid droplets increased fast.

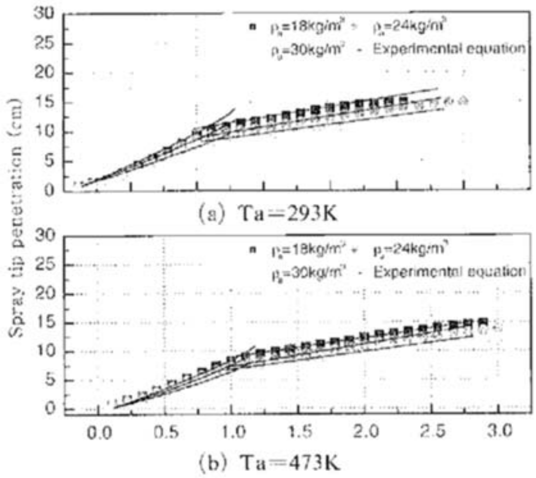


Fig. 6 Spray tip penetration at various operating conditions

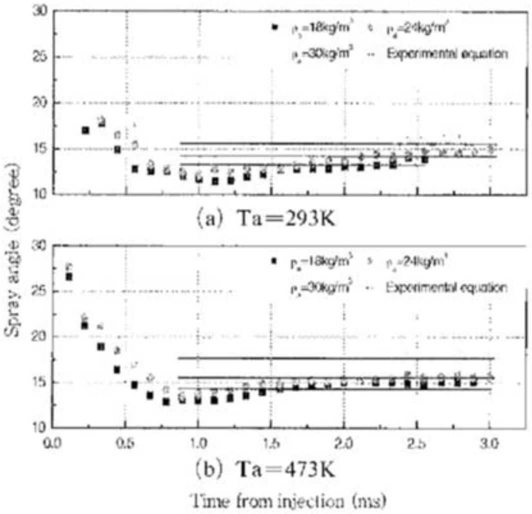


Fig. 7 Spray angle in various conditions

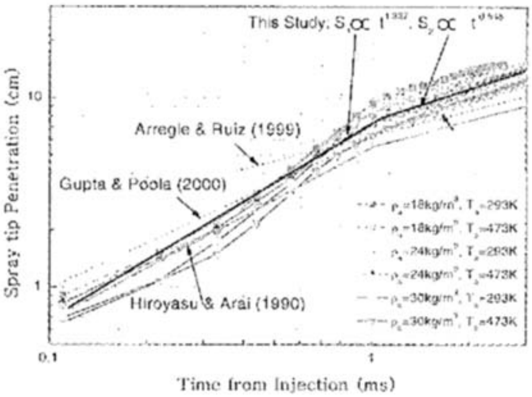


Fig. 8 The effect of time on spray tip penetration

3.3 Spray angle characteristics

The results of the experiment for the spray angle according to the injection time are shown in Fig. 7. The spray angle shows a tendency of the constant values at the region of breakup even though it has a large spray angle (18～30°) in the early stage of the injection.

The spray angle for the ambient gas density and increase in temperature is increased. It can be seen that the growth of the spray is decreased by increasing the ambient gas density, and the momentum of the liquid droplets is decreased by the effect of evaporation due to the increase of temperature for the ambient gas temperature.

4. Examinations for the Correlation of the Spray

4.1 Correlation of the spray tip penetration

Fig. 8 shows the spray tip penetration for the whole period of the injection for the each condition of the experiment as a logarithmic coordinate where the spray tip penetration is increased by the increase of time. Measurements of the spray tip penetration were carried out under the experimental condition of $\phi=1.02$ mm, $P_i=14$ MPa, $\rho_a=18, 24, 30$ kg/m^3 and $T_a=293, 473$K. In addition, the spray tip penetration before and after the stage of breakup (S_1, S_2) can be produced as a function of time as presented in Equation (1) and (2).

$$0<t<t_b\ ;\ S_1=\kappa t^{1.337} \tag{1}$$

$$t_b<t\quad ;\ S_2=\kappa t^{0.548} \tag{2}$$

where κ can be presented by the functions of momentum of the spray, ambient gas density, viscosity, and temperature. This figure shows the results of Hiroyasu & Arai ($\phi=1.1$ mm, $P_i=10$, $P_a=1$ MPa, $T_a=295$, 423, 593K), Arregle & Ruiz ($\phi=1.11$ mm, $P_i=30$ MPa, $\rho_a=10$, 20, 30 kg/m^3, $T_a=296$ K) and Gupta & Poola ($\phi=0.173$ mm, $P_i=120$ MPa, $\rho_a=1.2$, 34.6, 54.9, 74.5 kg/m^3, $T_a=296$K) together. The results show a similar result as a qualitative aspect for this study but are different from the viewpoint for its quantitative aspect. The different results of these are expected because the each experimental parameters, conditions, etc. are different.

The function presented in this study is $\kappa=f(P_a, P_i, T_a, \rho_a)$. Because of these experimental parameters, the values of κ for each experimental condition are different for each other. The effect of the ambient gas density on the spray characteristics can be produced by the relationship of functions between the value of κ and the density. The effect of the ambient gas density before and after breakup is illustrated in Fig. 9. comparing with the results of Gupta & Poola and Arregle & Ruiz.

The equations of the correlation from these results are presented in Equation (3) and (4).

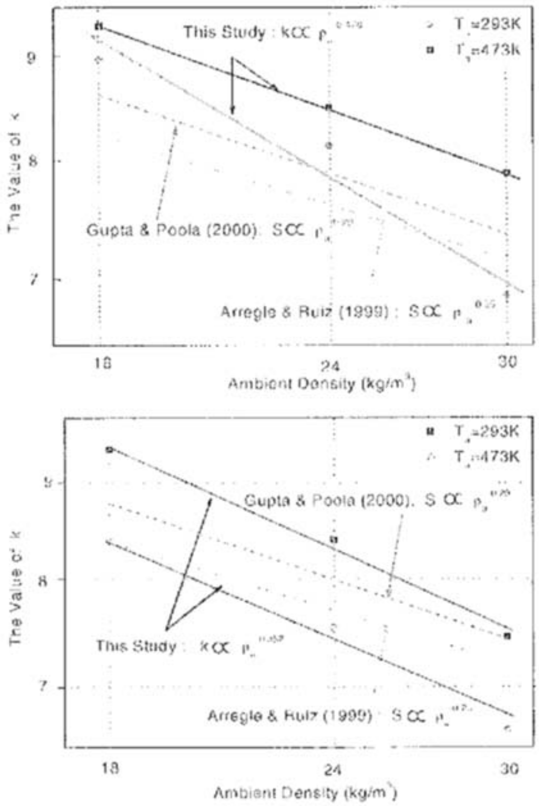


Fig. 9 Effect of the ambient density on the spray tip penetration

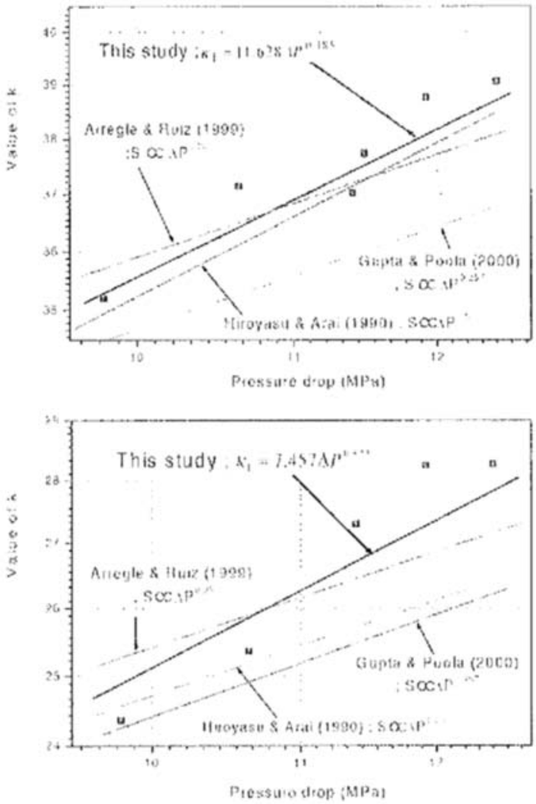


Fig. 10 The effect of the pressure drop on spray tip penetration

$$0 < t < t_b\ ;\ \kappa = \kappa_1 \rho_a^{-0.478} \tag{3}$$

$$t_b < t\ ;\ \kappa = \kappa_1 \rho_a^{-0.382} \tag{4}$$

The effect of the ambient gas temperature for the spray characteristics is considered an ambient pressure by transferring it. In addition, the relationship of function is expressed by the differences between the injection pressure and the ambient pressure. The values of ΔP for each experimental condition are presented in Table 1. κ_1 can be presented with ΔP as Equation (5).

$$\kappa_1 = \kappa_2 \Delta P^A \tag{5}$$

Fig. 10 shows relation of between κ_1 and ΔP. From this result, the index before and after the stage of break up can be find 0.485 and 0.523. This figure shows the results of Hiroyasu & Arai, Arregle & Ruiz and Gupta & Poola together. The results show a similar result as a qualitative

Table 1 Pressure drop between the injection pressure and the ambient pressure (ΔP)

ρ_a \ T_a	293K	473K
18 kg/m³	12.44 (MPa)	11.48 (MPa)
24 kg/m³	11.92 (MPa)	10.64 (MPa)
30 kg/m³	11.4 (MPa)	9.8 (MPa)

aspect for this study but are different from the viewpoint for its quantitative aspect. The different results of these are expected because the each experimental parameters, conditions, etc. are different.

From the examinations for each experimental parameter, the spray tip penetration presents the correlation before and after breakup as shown in Equation (6) and (7). In addition, the experimental results and arithmetic calculations are presented in Fig. 11.

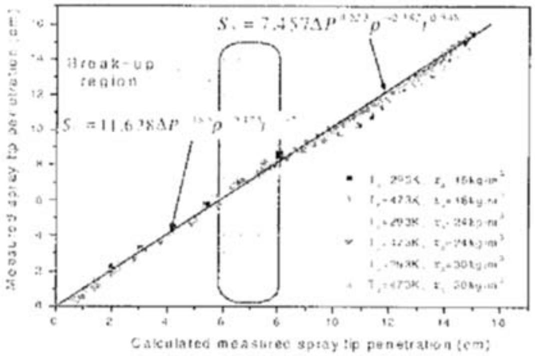


Fig. 11 Correlation fit through the measured spray tip penetration data

$$0<t<t_b\ ;\ S_1=11.628\Delta P^{0.485}\rho_a^{-0.478}t^{1.337} \quad (6)$$

$$t_b<t\ ;\ S_2=7.457\Delta P^{0.523}\rho_a^{-0.382}t^{0.548} \quad (7)$$

4.2 Correlation of the spray angle

The important parameter that will affect the spray angle of diesel spray is the ambient gas density. There have been a number of studies processed by using the ambient gas density as a major parameter.

The spray angle has a large value in the initial stage of the injection but it shows a constant value when approaching the last stage of the injection.

The correlation of the spray angle is examined by the basis of the average values of the spray angle after spraying ($0.89\text{ ms}<t$). Fig. 12 illustrates the correlation between the spray angle and the ambient gas density.

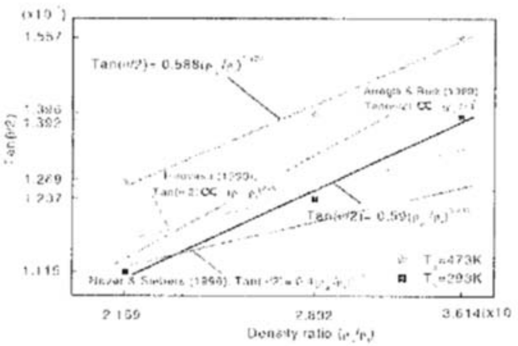


Fig. 12 The effect of the ambient density on the spray angle

The experimental equations of the spray angle for each temperature are presented in Equation (8) and (9).

$$T_a=293\text{K}\ ;\ \tan\left(\frac{\theta}{2}\right)=0.59\left(\frac{\rho_a}{\rho_f}\right)^{0.437} \quad (8)$$

$$T_a=473\text{K}\ ;\ \tan\left(\frac{\theta}{2}\right)=0.588\left(\frac{\rho_a}{\rho_f}\right)^{0.404} \quad (9)$$

5. Conclusions

This study examines the effects of the ambient gas temperature and ambient gas density for the spray characteristics. This study was done in order to verify the free spray characteristics of the pintle nozzle of a diesel engine by using the 4-cylindered in-line PE pump, high speed video camera, high temperature and pressure chamber. The results obtained here are summarized as follows :

(1) Generally, the spray tip penetration shows two types of gradient based on the breakup and presents the correlation as follows.

$$0<t<t_b\ ;\ S_1=11.628\Delta P^{0.485}\rho_a^{-0.478}t^{1.337}$$

$$t_b<t\ ;\ S_2=7.457\Delta P^{0.523}\rho_a^{-0.382}t^{0.548}$$

(2) The spray angle has a large value in the initial stage of the injection and converges after the breakup. The correlation for each temperature can be expressed as follows.

$$T_a=293\text{K}\ ;\ \tan(\theta/2)=0.59(\rho_a/\rho_f)^{0.437}$$

$$T_a=473\text{K}\ ;\ \tan(\theta/2)=0.588(\rho_a/\rho_f)^{0.404}$$

(3) The ambient gas temperature and ambient gas density are verified as the major parameters for the characteristics of the diesel injection through the experiment. In addition, it can be examined that the equations of the correlation proposed in this study corresponded to the results of this experiment.

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