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A Study on the Mixture Formation Process of Diesel Fuel Spray in Unsteady and Evaporative Field

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The focus of this work is placed on the analysis of the mixture formation mechanism under the evaporative diesel spray of impinging and free conditions. As an experimental parameter, ambient gas density was selected. Effects of density variation of ambient gas on liquid and vapor-phase inside structure of evaporation diesel spray were investigated. Ambient gas density was changed between ρ_a=5.0 kg/m^3 and 12.3 kg/m^3. In the case of impinging spray, the spray spreading to the radial direction is larger due to the decrease of drag force of ambient gas in the case of the low density than that of the high density. On the other hand, in the case of free spray, in accordance with the increase in the ambient gas density, the liquid-phase length is getting short due to the increase in drag force of ambient gas. In order to examine the homogeneity of mixture consisted of vapor-phase fuel and ambient gas in the spray, image analysis was conducted with statistical thermodynamics based on the non-dimensional entropy (S) method. In the case of application of entropy analysis to diesel spray, the entropy value always increases. The entropy of higher ambient density is higher than that of lower ambient gas density during initial injection period.

Key Words : Mixture Formation, Diesel Impinging and Free Spray, Phase Change, Exciplex Fluorescence Method

Nomenclature

H : Spray Height
I : Fluorescence Intensity
L : Liquid-phase length
M : Number of the Total Pixels
R : Spray Radius
S : Non-dimensional Entropy
T : Temperature
U : Velocity

Greek symbols

ρ : Density of Ambient Gas

Subscripts

a : Ambient gas
cr : Critical
f : Fuel
liq : Liquid Phase
vap : Vapor Phase
w : Wall

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1. Introduction

In the diesel engines, injected liquid fuel develops with atomizing, evaporating, diffusion and formatting mixture with interaction of fuel and ambient gas. In order to improve the emissions from diesel engines, it is very important to research the mixture formation process concerned with formation process of soot and NO_X, and so on. Then, this study's focus is laid in making a clear the mixture formation process in an evaporative field of high temperature/pressure. In this study, as for factor affecting the spray development process, ambient gas density was employed.

In the factors affecting diesel spray behavior, especially, ambient gas density dominates spray development process, for example, spray angle and spray tip penetration (Wakuri et al., 1959 ; Hiroyasu et al., 1978 ; 1980). Therefore, ambient gas density was selected as experimental parameter and the effect of ambient gas density on the mixture formation process was investigated in this study. The subject of this study is diesel impinging and free spray based on spray development process. On the other hand, the in-cylinder state of the actual engine is supercritical state which exceeds the critical temperature and pressure of injected fuel. In order to investigate behavior analysis of diesel fuel spray in high temperature and pressure field, it is needed to speculate critical conditions of injected fuel for experimental conditions. This study investigated the effect of critical condition of injected fuel on spray structure in free spray of unsteady and evaporating field. By adjusting the ambient gas density, the ambient pressure for the experiments was respectively set supercritical region, the vicinity region of critical point and subcritical region based on the physical characteristic (critical temperature [T_{cr}] and critical pressure [p_{cr}]) of used fuel of n-tridecane ($C_{13}H_{28}$, $p_{cr}=1.72$ MPa, $T_{cr}=677$ K). In order to verify effect of critical conditions of injected fuel on liquid-phase penetration length (i.e., liquid-phase length), the effect of ambient gas temperature on the liquid-phase length in a diesel free spray was investigated. On the other hand, in the case of free spray, in order to quantify mixture state change of vapor-phase region of injected spray, image analysis was carried out based on the non-dimensional entropy of statistical thermodynamics (Chikahisa et al., 1999). The non-dimensional entropy of each image can be obtained by the following equation.

$$S=\frac{It\cdot\ln(I_{max})-\sum[I(i)\cdot\ln\{I(i)\}]}{It\cdot\{\ln(M)-\ln(It)+\ln(I_{max})\}} \qquad (1)$$

where, I_{max} is maximum value of fluorescence intensity, It is total value of fluorescence intensity ($It=\sum I(i)$), $I(i)$ is fluorescence intensity value for each pixel, M is the number of the total pixels. In the above equation, entropy value is related with the number of meshes, however, in this study, the number of meshes is equal to that of image pixels. Hence, when the fluorescence intensity distribution is homogeneous in the spray images, the S value is close to 1. The 1 of S value expresses the most homogeneous mixture state between injected fuel and ambient gas. On the other hand, when the fluorescence intensity distribution is heterogeneous in the spray images, the S value is close to 0. The 0 of S value expresses the most heterogeneous mixture state between injected fuel and ambient gas. As for a visualization measurement method, exciplex (Excited complex) fluorescence method was used in this study. The exciplex fluorescence method can take the liquid-phase and vapor-phase of injected spray simultaneously and respectively by using two fluorescent materials [naphthalene and TMPD (N,N,N',N' tetramethyl-p-phenylene diamine)] in high temperature and pressure field. The liquid-phase generated its fluorescence at 480 nm due to the high molecule collision probability of the fluorescent materials, however, the vapor-phase generated its fluorescence at 390 nm from a excited fluorescent material (naphthalene) due to the low molecule collision probability.

2. Experimental Apparatus and Procedure

The n-tridecane as the reference fuel oil of JIS second class gas oil was injected into the quiescent atmosphere of nitrogen gas through a single hole injector. 9% in mass of naphthalene and 1% in that of TMPD were mixed in n-tridecane to obtain the fluorescent emissions of vapor and liquid phases. The mixing of TMPD with n-tridecane was carried out in the nitrogen atmosphere to prevent the oxidation of TMPD. The high pressure injection system (ECD-U2 system) developed by Denso Co., Ltd. was used. The diameter and the length of nozzle were 0.2 mm and 1.0 mm, respectively. The ambient gas density and ambient gas temperature were changed in the range from 5.0 kg/m^3 to 12.3 kg/m^3 and from 400K to 700K, respectively. The ambient gas pressure was varied in the range from 1.04 MPa to

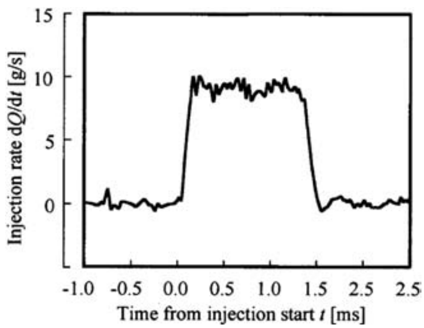


Fig. 1 Temporal change in fuel injection rate at $p_{inj}=72$ [MPa]

2.55 MPa by the change in the ambient density. The injection pressure and the fuel injection quantity were constantly kept as 72 MPa and 12.0 mg, respectively.

Figure 1 shows temporal change in fuel injection rate (dQ/dt) with rectangular shape.

Table 1 shows the summarized experimental conditions.

Figure 2 is a schematic of the optical system used in this study. The light source was the third harmonic of an Nd : YAG laser at 355 nm (power 60 mJ/pulse, pulse width : 8 nsec., maximum frequency : 10 Hz, beam diameter : 6.4 mm, beam shape : doughnut type). A thin sheet of laser light is formed when the light is passing through three sets of cylindrical lenses made of quartz. The width and the thickness of the light were 50 mm and 0.2 mm, respectively. The uniformity of the

Table 1 Experimental conditions

Injection nozzle	Type : Hole nozzle DLL-p		
	Diameter of hole	d_n [mm]	0.2
	Length of hole	L_m [mm]	1.0
Ambient gas			N_2 gas
Ambient temperature	T_a [K]		700
Ambient pressure	p_a [MPa]		1.04, 1.70, 2.55
Ambient density	ρ_a [kg/m^3]		5.0, 8.2, 12.3
Injection pressure	p_{inj} [MPa]		72
Injection quantity	Q_{inj} [mg]		12
Injection duration	t_{inj} [ms]		1.54
Impngement distance	Z_w [mm]		40 [Impinging spray]
Wall temperature	T_w [K]		550 [Impinging spray]

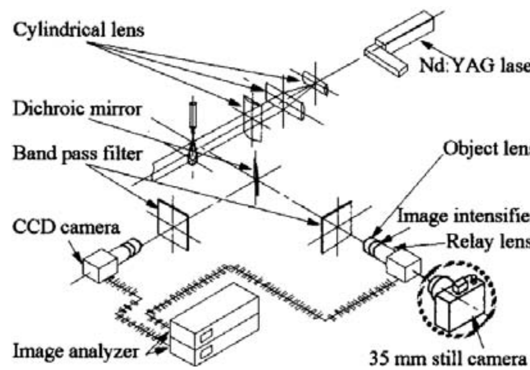


Fig. 2 Schematic diagram of laser sheet optical system and photography system

intensity of laser light was confirmed by calculation experiments. The lenses have high transmissivity in the ultraviolet region by their material and they were given the coating of non-reflection, as a consequence, the energy of laser light hardly damped. Then a thin sheet of laser light was coming to the section of an impinging and free diesel spray and the fluorescence emissions from both vapor and liquid phases were generated. The separation of spectra of fluorescence emissions from both phases was made by the system of a dichroic mirror and two sets of band pass filters. The dichroic mirror was a type of the blue reflection and its wavelength of 50% refection was 470 nm. The center wavelength of the band pass filter for liquid and vapor phases widths were 390 nm and 532 nm and their half widths were 19 nm and 2 nm, respectively. The emissions from both phases are increased in their luminosity by the image intensifiers after they are coming through the objective lenses. Thereafter, they are going to the relay lenses and are taken by the CCD cameras (number of pixels : 540×480, S/N : 50 dB). The photographing speed of CCD camera is 1/30 μsec. and the life-time of fluorescent emissions of TMPD and exciplex are ranged from 1 nsec. to 103 nsec.. This experiment was carried out in a perfect photo darkroom. Consequently, the frozen image at the incidence of the laser light could be caught by this CCD camera. The spatial resolution is about 0.1 mm/pixel. The signals from images of both phases were transferred into the image analyzers and were processed by the A/D conversion (resolution: 8 bits) to obtain the image of 256 gradation.

In Fig. 3, a schematic of the photophysics of the naphthalene/TMPD exciplex fluorescence system is shown (Melton et al., 1983). As previously stated, in the exciplex fluorescent system of naphthalene and TMPD, the exciplex corresponding to the information of the liquid phase generates its fluorescence at 480 nm. On the other hand, the naphthalene fluorescence corresponding to the information of the vapor phase generates its fluorescence at 390 nm.

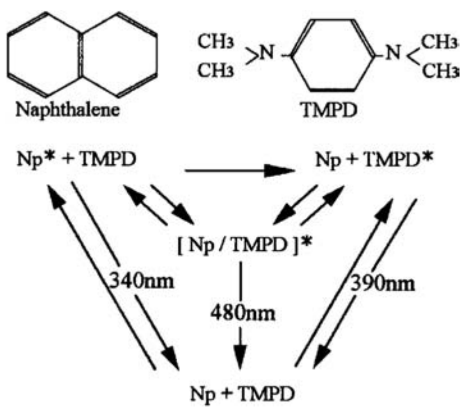
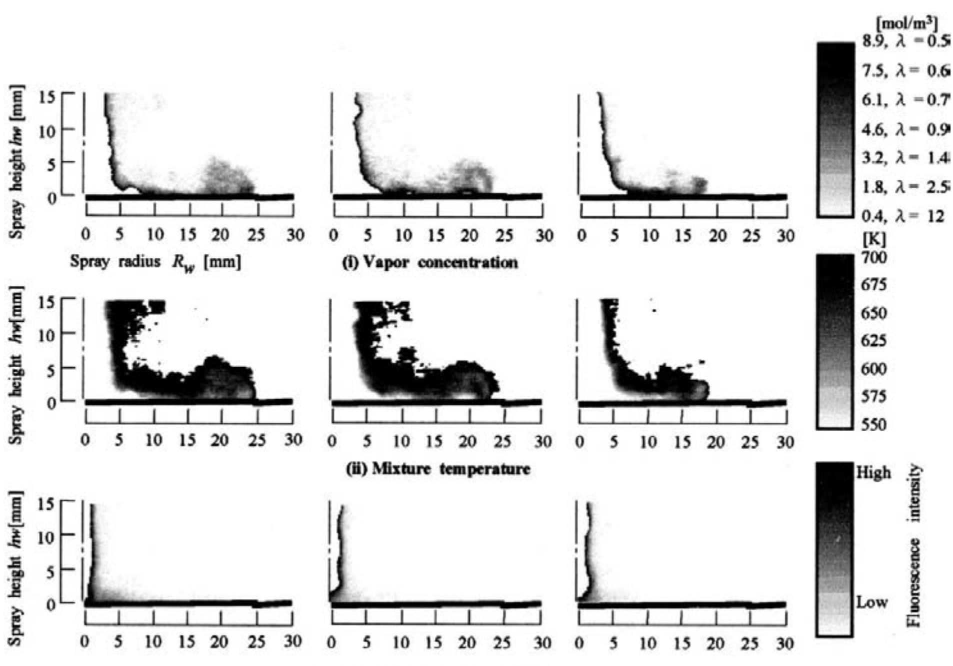


Fig. 3 Schematic summary of naphthalene and TMPD exciples system

3. Results and Discussion

3.1 Impinging spray

Figure 4 shows the two-dimensional images of impinging spray at various ambient gas density which were obtained by the exciplex fluorescence method. In the figure, the spray radius (h_w) and the spray height (R_w) are calculated by the spatial region where fluorescence intensity marked by maximum intensity of the spray decreases to 10% of it value at X-Y axis direction of each image. From each image, in the wall surface, the liquid-phase spreads in radial direction, with decreasing ambient gas density. In the case of ambient gas density ρ_a=5.0 kg/m^3, the high fluorescence intensity of free spray region reaches to



(a) ρ_a=5.0 [kg/m^3] (b) ρ_a=8.2 [kg/m^3] (c) ρ_a=12.3 [kg/m^3]

Fig. 4 Temporal change in impinging spray image with exciplex fluorescence method at t=1.10 [ms] from injection start (p_{inj}=72 [MPa] Q_{inj}=12.0 [mg] T_w=550 [K] Z_w=40 [mm]) the wall surface. With decreasing ambient gas density, the distance of central spray axis and spray periphery decreases due to reduction of the drag force of ambient gas at the spray tip. This result corresponds with spray angle decreasing in non-evaporating diesel free spray (Dan et al., 1996). In the vapor-phase, the lean mixture is formed over the central spray axis to the spray tip region at the wall surface and the spray tip proceeds to radial direction. In the region between stagnation point and the leading portion of spray, the spray structure can be divided into two regions of fuel rich region near the wall and the lean region in spray periphery as shown in Fig. 4. The height from wall surface of rich concentration region decreases with decreasing ambient gas density and the lean concentration region becomes wider. Furthermore, in case of ambient gas density 8.2 kg/m^3, the rich concentration region of vapor-phase near the wall surface is similar to that of ambient gas density 12.3 kg/m^3, however, the lean concentration region of vapor-phase is similar to that of ambient gas density 5.0 kg/m^3 in spray periphery.

The effect of ambient gas density on the spray radius and the spray height are shown in Fig. 5. In the figure, the $h_{w\max}$ (Standard) and $R_{w\max}$ (Standard) are maximum height and radius in ambient gas density ρ_a=12.3 kg/m^3, respectively. From the Fig. 5, spray radius increases with decreasing ambient gas density, because drag force of ambient gas decreases at spray tip.

Figure 6 shows concentration distribution of vapor-phase fuel in the spray. In Fig. 6(i), the vapor-phase concentration distribution of ρ_a= 12.3 kg/m^3 and 8.2 kg/m^3 are higher than that of ρ_a=5.0 kg/m^3 at the distance from wall surface, h=1 mm. Figure 6(ii) shows the vapor-phase concentration distribution at h=3 mm and the tendency of concentration distribution is nearly similar to that for h=1 mm. As a result, in the case of the impinging diesel spray, with decreasing ambient gas density, the rich concentration region of vapor-phase fuel decreases in the vicinity of wall surface and the lean concentration region of vapor-phase fuel increases in spray periphery.

3.2 Free spray

Figure 7 shows the fluorescence intensity distribution images of two-dimensional free spray for various ambient gas density at p_{inj}=72 MPa. In the Figure 7(a) and 7(b) are vapor and liquid-phase of free spray, respectively. As shown in Fig. 6, there is almost no the effect of density change of ambient gas on the spray structure in the upstream spray. With increasing ambient gas density, the spray tip penetration decreases, how-

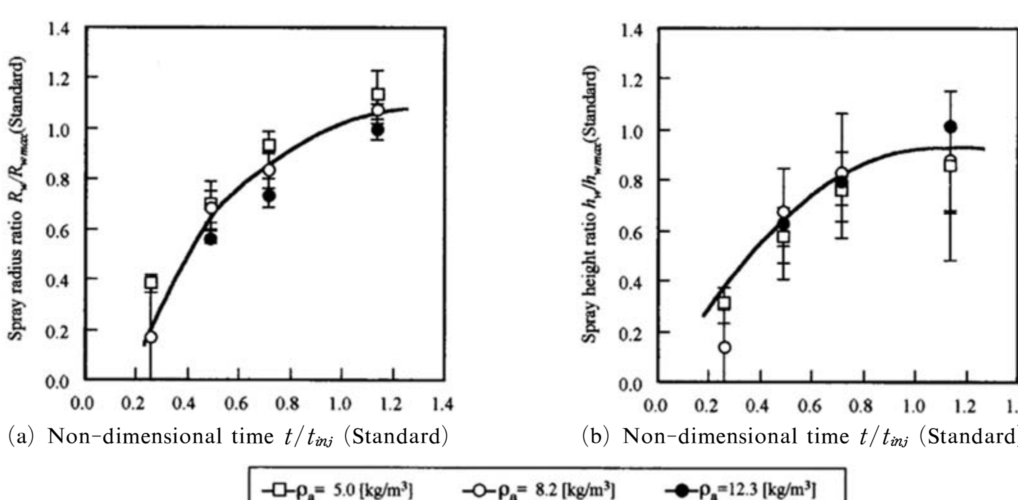
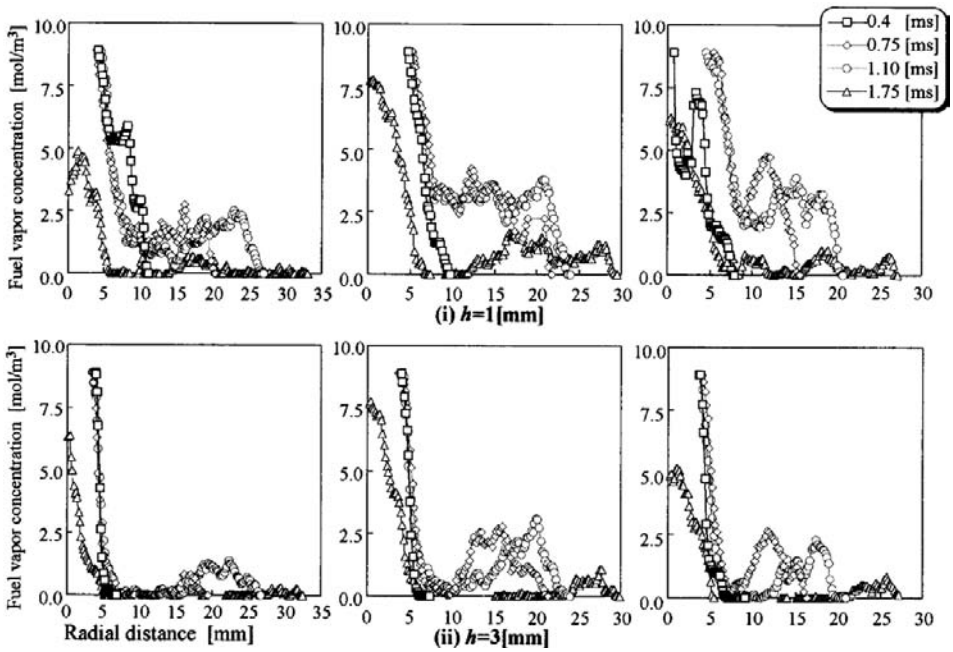
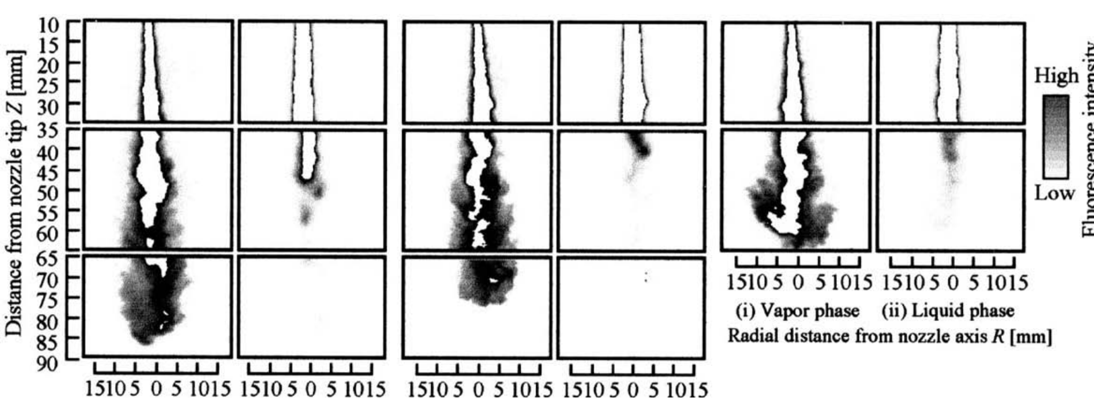


Fig. 5 Temporal change in spray radius R_w and height h_w (p_{inj}=72 [MPa] Q_{inj}=12.0 [mg] T_w=550 [K] Z_w=40 [mm])



(a) ρ_a=5.0 [kg/m³] (b) ρ_a=8.2 [kg/m³] (c) ρ_a=12.3 [kg/m³]

Fig. 6 Radial distribution of fuel vapor concentration (p_{inj}=72 [MPa], Z_w=40 [mm])

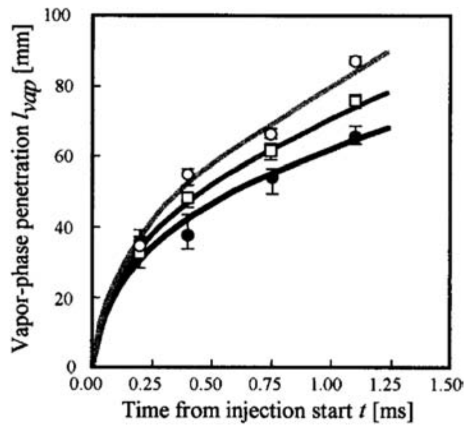


(a) ρ_a=5.0 [kg/m³] (b) ρ_a=8.2 [kg/m³] (c) ρ_a=12.3 [kg/m³]

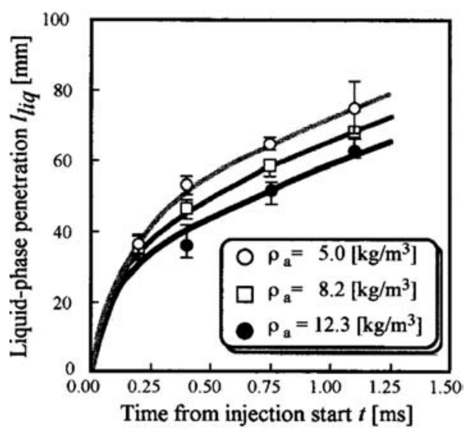
Fig. 7 Temporal change in free diesel spray with exciplex fluorescence method at t=1.10 [ms] from injection start (p_{inj}=72 [MPa])

ever, the spray spreads in the radial direction at the middle and downstream region of the spray.

Figure 8 shows temporal change in the length of vapor and liquid-phase. It can be found that with increasing ambient gas density, the vapor and liquid-phase length become small gradually. On the other hand, in the case of spray spread, the momentum of injected fuel near the spray tip penetration region is reduced by the resistance of ambient gas and the fuel reduced momentum is pushed to radial direction with continued fuel injection. As a result, with increasing ambient gas density, the spray spread increases in radial direction due to increase in drag force of ambient gas. Furthermore, the vortex formed in the upstream region of the spray is developing, with pro-



(a) Vapor-phase penetration I_{vap}



(b) Liquid-phase penetration l_{liq}

Fig. 8 Temporal change in liquid-phase length

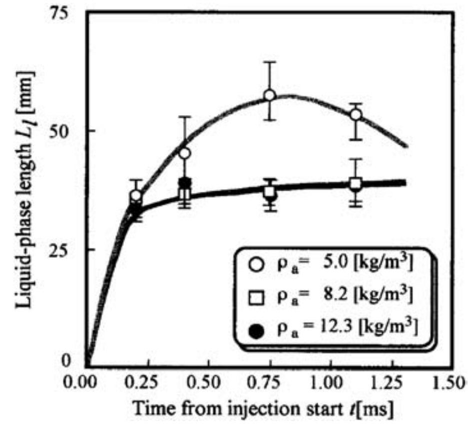


Fig. 9 Temporal change in liquid-phase length

ceeding to downstream spray.

In this study, in order to study the effect of vortex motion of ambient gas on spray development, liquid-phase length of the free spray was investigated as shown in Fig. 9. The liquid-phase length (L_l) was defined by the spatial region where fluorescence intensity marked by 255 gradation of the spray's center decreases of 10% (230～255) of it value in each image. To reduce fluorescence intensity in region beyond the liquid-phase length expresses dramatically increase in the gas consisted of fuel's vapor and ambient gas in inner spray. It can be speculated that the ambient gas is actively entrained into inner spray by transmission of momentum between injected fuel and ambient gas. Hence, the fluorescence intensity rapidly decreases beyond the liquid-phase length. Consequently, the liquid-phase length implies a momentum transition point in the process of spray development, namely, the process of spray development is principally dominated by vortex motion of ambient gas in region beyond the liquid-phase length. In the cases of ambient gas density $\rho_a=8.2\,\mathrm{kg/m^3}$ and $12.3\,\mathrm{kg/m^3}$, the liquid-phase lengths are not almost change. However, the liquid-phase length of ambient gas density $\rho_a=5.0\,\mathrm{kg/m^3}$ is the longest liquid-phase length in each density. From the Fig. 9, a peculiar region in the liquid-phase length development can be clearly seen. The state of the n-tridecane used in this study reaches the critical region at the cases of the $\rho_a=8.2\,\mathrm{kg/m^3}$ and $12.3\,\mathrm{kg/m^3}$. Then, it is necessary to investigate effect of the critical condition of the fuel on the liquid-phase length development in behavior analysis of the evaporating diesel spray. With increasing ambient gas density, the transition-point approaches a nozzle. Also the phenomenon can be found in Dan et al. (1996) in non-evaporating fuel spray. From jet theory, the mass of ambient gas entrained into a spray can be obtained by the following equation (Siebers et al., 1999).

$$\dot{m}_a(x) \propto \sqrt{\rho_a \cdot \rho_f} \cdot d \cdot x \cdot U_f \tan(\theta/2) \qquad (2)$$

where, the term $\dot{m}_a$ is the mass flow rate of the ambient gas. The terms ρ_a and ρ_f are the ambient gas and injected fuel density, and the velocity U_f is set by the injection pressure through Bernoulli equation. In the above equation, the

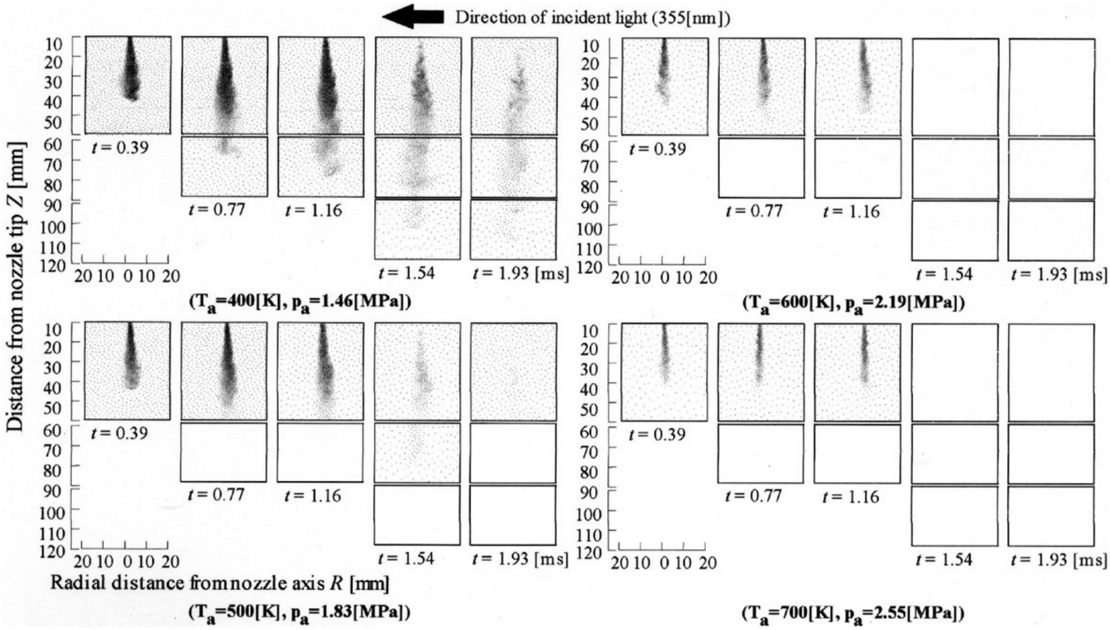


Fig. 10 Liquid-phase images with exciplex fluorescence method using 35 mm still camera (p_{inj}=72 [MPa] Q_{inj}=12.0 [mg] ρ_a=12.3 [Kg/m^3])

increasing ambient gas density causes mass increase of entrained ambient gas. As a result, it could be found that the density change of ambient gas varies vortex formation process in spray development. Furthermore, from the experimental results, it could be considered that the spatial dimensions of large vortices-like structure in the spray become larger with increasing ambient gas density, because the spray spread increases with increasing ambient gas density. On the other hand, in the case of diesel free spray, in order to investigate the effect of critical fuel conditions on liquid-phase length, liquid-phase of injected spray was measured by exciplex fluorescence method captured with 35 mm still camera.

Figure 10 shows the temporal change in the liquid-phase length by still camera on various ambient gas temperature. Ambient density is kept constant at ρ_a=12.3 kg/m^3. As the same tendency with the ambient density, the liquid-phase length was decreased with increasing ambient temperature for the cases of lower ambient gas temperatures T_a=400K and 500K. However, in the case of higher ambient gas temperature, the liquid-phase length becomes almost the same length

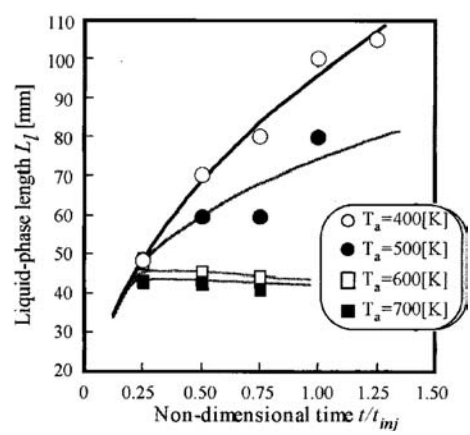


Fig. 11 Liquid-phase length (L_l) variation for ambient temperature change

regardless with changing in ambient gas temperature. It is considered that the critical phenomena exist in the evaporation process.

Figure 11 shows temporal change in the liquid-phase length for ambient temperature. In the figure, liquid-phase length (L_l) was defined by the distance continued brightness distribution region from nozzle.

The tendency observed in the images of Fig. 10 is reproduced and summarized schematically

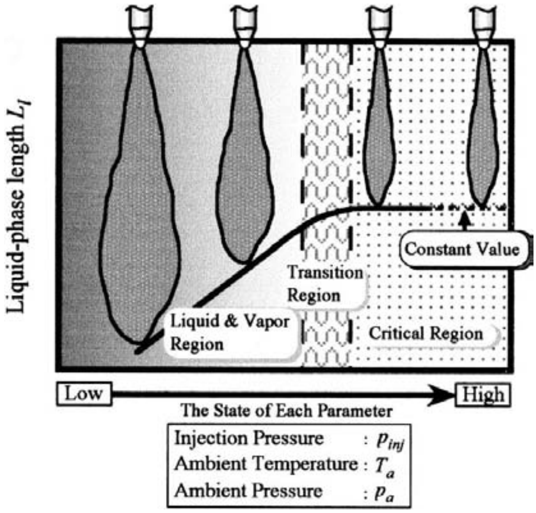


Fig. 12 History of liquid-phase length for each of the experiment conditions in diesel spray

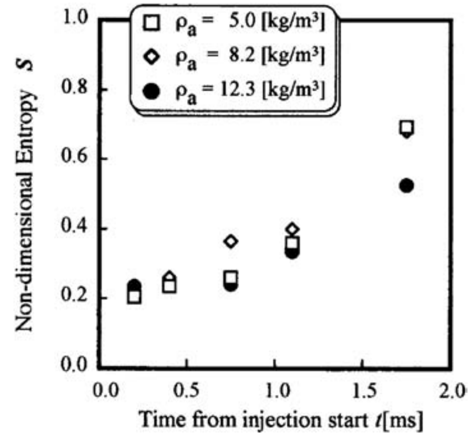


Fig. 13 Temporal change in entropy of free spray

in Fig. 12. The liquid-phase in evaporating sprays is affected by surrounding gas temperature (T_a) and density (ρ_a), namely, liquid-phase length decreases with increasing them. However, When the ambient temperature and pressure reach ($T_a \geq T_{cr}$, $p_a \geq p_{cr}$), liquid-phase length (L_l) becomes almost constant. As a result, it was found that critical point and region play a dominant role in the evaporating phenomena, as shown in Fig. 10.

Figure 13 is plot of non-dimensional entropy (S) versus time from injection start for density range from ρ_a=5.0 kg/m^3 to 12.3 kg/m^3. As shown in Fig. 13, in each of the ambient gas densities, the entropy of vapor-phase spray increases for time variation, because mixture formation of injected spray become more active caused by diffusion of vapor-phase spray with elapsing time. In the case of application of entropy analysis to diesel spray, the entropy value always increases. The entropy of higher ambient density is higher than that of lower ambient gas density during initial injection period, however, with elapsing time, the increase tendency of entropy values becomes opposite for lower and higher ambient gas density. This is because, in the case of higher ambient gas density, the formed mixture is as lean as the mixture can not be captured with camera due to increase entrained ambient gas mass into the spray. Furthermore, in the case of higher ambient gas density, the entropy value becomes smaller due to decrease proceeded area in the spray tip region by increasing drag force of ambient gas. Namely, as the entropy concept is index of homogeneity degree of injected fuel in view region, the non-dimensional entropy value of larger image area is higher than that of small image area obtained from images. Therefore, in the case of higher ambient gas density, with elapsing time from injection start, non-dimensional entropy value becomes smaller due to decrease brightness area in the images.

4. Conclusions

An experiment was performed for the evaporating diesel impinging and free spray in this study. Exciplex fluorescence method was used, which can simultaneously measure the vapor and liquid phase of the injected fuel. Also, in order to examine the homogeneity of mixture consisted of vapor-phase fuel and ambient gas in the spray, image analysis was conducted with statistical thermodynamics based on the non-dimensional entropy method.

The following conclusions are drawn from this study.

(1) In the case of the impinging spray, with decreasing ambient gas density, the spray spreads

in radial direction due to decrease in drag force of ambient gas.

(2) In the case of the free spray, with increasing ambient gas density, the liquid-phase length is getting short due to increase in drag force of ambient gas.

(3) If ambient conditions of temperature and pressure exceed critical region of injected fuel, the liquid-phase length is not almost affected by the surrounding conditions. The development process of the liquid-phase length can be divided into two regions consisted of liquid and vapor region with phase change and critical region with constant liquid-phase length value. Existence of a transient region can be speculated between the regions. In the experimental condition of the critical region for used fuel, the liquid-phase length is about 40 mm in this study.

(4) The entropy value of higher ambient density is higher than that of lower ambient gas density during initial injection period, however, with elapsing time, the increase tendency of entropy values becomes opposite for lower and higher ambient gas density.

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