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A Study of the Mixture Formation Process of a Diesel Spray Under Phase Change

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Abstract

The purpose of this study was to analyze the structure and to clarify the mixture formation process within evaporative diesel spray. Liquid fuel was injected from a single-hole nozzle (*l/d*=1.0mm/0.2mm) into a constant-volume vessel under high pressure and temperature in order to visualize the spray phenomena. An exciplex fluorescence method was applied to the evaporative fuel spray to measure and investigate both the liquid and the vapor phase of the injected spray. The region of interest in this experiment was downstream towards the end of the spray. For accurate investigation, images of the liquid and vapor phase regions were recorded with a 35mm still camera and CCD camera, respectively. For the case of the evaporative fuel spray, the images showed that within the region of liquid phase very small droplets could be found outside of the spray and larger droplets at the spray's tip. This can be explained through the droplet classification defined by *Stokes number* (*stk*) (Chung et al., 1990). From the 2-dimensional analysis results of the heterogeneous distribution of the inner spray, a 3-dimensional analysis was attempted by using the offset incidence of the laser beam from the spray's center axis. Finally, in order to quantify the mixture's state change within the vapor phase region of the injected spray, images analysis were carried out based on the entropy of statistical thermodynamics.

Keywords: Ambient gas viscosity; Diesel spray; Exciplex fluorescence method; Entropy; Phase change

1. Introduction

Injected liquid fuel in diesel engines develops by atomizing, evaporating, diffusing and forming a mixture through its interaction with ambient gas. In order to improve emissions from diesel engines, such as particulate matter (PM) that includes soot and nitrogen oxides (NO), it is very important to research the mixture formation process because it affects the combustion characteristics within actual engines. In diesel engines, the surface wave found upstream of the spray in the liquid core of the injected fuel forms the core of the spray vortex in the liquid region; this is due to the interaction between the fuel and ambient gas (Levich, 1974). The initial protrusion is called first perturbation. As the spray develops, the first perturbation grows downstream (Azetsu et al., 1990). The momentum of the ambient gas is changed by the injected fuel and dominates the spray behavior downstream and the region takes on the characteristics of a jet flow. However, there is a heterogeneous droplet distribution in the inner spray as the droplets from the injected fuel obey the spray flow according to their size. The dispersed fuel droplets evaporate and form a mixture with the ambient gas entrainment. The analysis of the liquid and vapor

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phase structure is very important in the mixture formation process of an injected spray. There has been much research into the behavior and structure of the diesel spray; however, there have been few studies on the mixture formation process that involves the analysis of the liquid and vapor phase structure of an injected spray, simultaneously, while in a high temperature and pressure environment. Dan et al. (1996) study on non-evaporating fuel sprays ignored the phase change of the injected fuel, and Siebers (1998; 1999) experimental field included phase change; however, both of these studies only involved the liquid-phase length. Choi et al. (2000), Kim and Ghandhi (2003) and Kosaka et al. (1992) dealt with the vapor phase distribution of evaporating diesel spray in a high temperature· pressure environment, but they were not concerned with the effect of the liquid phase fuel on the vapor phase flow. Therefore, the focus of this study is to analyze the mixture formation process of a diesel spray by making clear the spray structure of both the liquid and the vapor phase. The change in viscosity of the mixture caused by ambient gas entrainment was considered in the analysis of the vapor phase flow. Furthermore, a 3-dimensional analysis was attempted by using the 2.5 mm and 5.0 mm offset incidence of the laser beam from the spray center axis, which was based on the 2-dimensional analysis of the spray structure. Finally, in order to quantify the mixture's state change to the vapor phase of the injected spray, an entropy analysis was applied to each of the images (Chikahisa et al., 1999). The dimensionless entropy (S) of each image can be obtained by using the following equation:

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

where I_{max} is the maximum value of the image fluorescence intensity, It is the total value of the fluorescence intensity ($It = \sum I(i)$), $I(i)$ is the fluorescence intensity value for each image pixel, and M is the number of total image pixels. When the fluorescence intensity distribution is homogeneous in the spray images, the S value is close to 1. The 1 of S value implies 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 implies the most heterogeneous mixture state between injected fuel and ambient gas.

2. Experimental apparatus and procedure

Figure 1 is a schematic diagram of the experimental apparatus. The constant volume vessel has two quartz glass windows (Φ=120mm×45mm width) that permits the spray inside to be irradiated with a sheet of laser light and allows the fluorescence emissions from the spray to be measured. Each of the windows was installed perpendicular to each other. N-tridecane as the reference fuel oil of JIS second class gas oil was injected into a quiescent atmosphere of nitrogen gas through a single hole injector. A 9% mass of naphthalene and 1 % of TMPD (N,N,N',N' tetramethyl-p-phenylene diamine) were mixed with n-tridecane to obtain the fluorescent emissions of the vapor and liquid phases. The TMPD was mixed with n-tridecane in a nitrogen atmosphere to prevent the oxidation of the TMPD. The high pressure injection was facilitated by an ECD-U2 system proposed by Denso Co. Ltd.. The system consisted of the three main sections, a high pressure supply pump, a common rail and a control circuit (ECU) for controlling the injector. The respective diameter and the length of the nozzle were 0.2 mm and 1.0 mm. The ambient gas density, the temperature, the injection pressure and the fuel injection quantity were kept constant at 12.3 kg/m^3, 700 K, 72 MPa and 12.0 mg, respectively.

Table 1 shows the summarized experimental conditions.

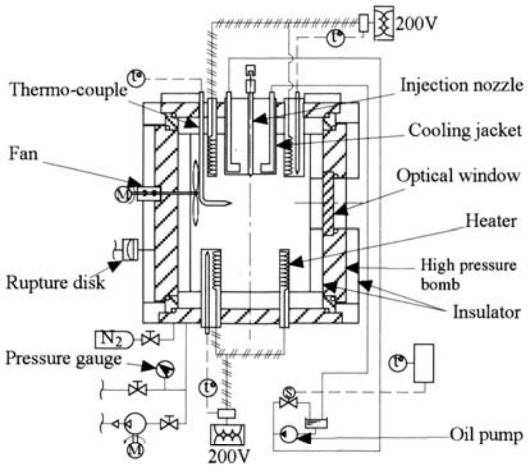

Fig. 1. Experimental apparatus.

Table 1. Experimental conditions.

Injection nozzle	Type : Hole nozzle DLL-p	
	Diameter of hole d_n [mm]	0.2
	Length of hole L_n [mm]	1.0
Ambient gas		N_2 gas
Ambient temperature T_a [K]		700
Ambient pressure p_a [MPa]		2.55
Ambient density ρ_a [kg/m³]		12.3
Injection pressure p_{inj} [MPa]		72
Injection quantity Q_{inj} [mg]		12.0
Injection duration t_{inj} [ms]		1.54

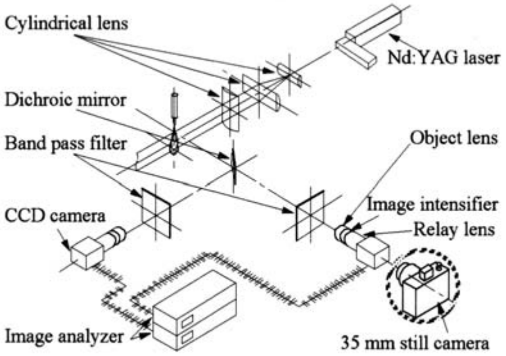

Fig. 2. Schematic diagram of laser sheet optical system and photography system.

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 light is passed through three sets of cylindrical lenses made of quartz. The width and the thickness of the light were 50 mm and 0.2mm, respectively. The uniform intensity of the laser light was confirmed through calculations experiments. In the ultraviolet region, the lenses have a high transmissivity due to their material; in addition, they were given a non-reflecting coating that allowed the laser to pass through with little loss in intensity. The thin sheet of laser light that came in contact with the section of the free diesel spray generated the fluorescence emissions from both the vapor and liquid phase. The separation of the fluorescence emission spectra from both phases was made possible through a dichroic mirror and two sets of band pass filters. The dichroic mirror used in this setup was of the blue reflection type and its

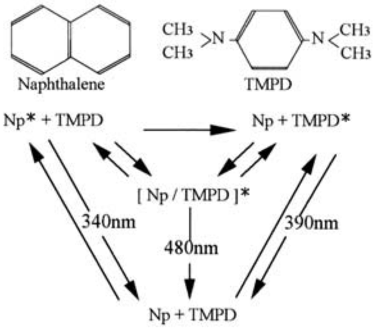

Fig. 3. Schematic summary of naphthalene and TMPD exciplex system.

wavelength at 50 % reflection was 470 nm. The center wavelength of the band pass filter for the vapor and liquid phase widths was 390 nm and 532 nm, respectively, and their half widths were 19 nm and 2 nm, respectively. 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; however, the selected wavelength of the liquid phase was different from liquid phase wavelength. This is the reason why the fluorescent intensity from this phase is much stronger than that from the vapor phase. The emissions from both phases are increased in their luminosity by the image intensifiers after they come through the objective lenses. Afterwards, they go to the relay lenses and are photographed by the CCD cameras (number of pixels: 540×480, S/N : 50 dB). The speed of CCD camera is 1/30 μsec and the life time of fluorescent emissions of TMPD and exciplex range from 1 nsec to 10^3 nsec. This experiment was carried out in a perfect photo darkroom to ensure the frozen image at the incidence of the laser light could be accurately photographed by the CCD camera. The spatial resolution was about 0.1mm/pixel, the signals of the images from both phases were transferred into the image analyzers and were processed by the A/D conversion (resolution: 8 bits) to obtain an image of 255 gradation.

In the Fig. 3 a schematic summary of the photophysics of the naphthalene/TMPD exciplex fluorescence system is shown (Melton, 1983). The ambient gas viscosity was computed with the NIST Thermophysical Properties of Hydrocarbon Mixtures Database program (*i.e.*, NIST), (James, et al., 1992). The viscosity characteristics of the fuel and the ambient gas were used for the analysis of the mixture formation process.

3. Results and discussion

3.1 Analysis of the liquid and vapor phase structure in the diesel spray using the exciplex fluorescence method

3.1.1 Analysis of the diesel spray structure with image comparisons

For photographing the liquid-phase fuel, a 35 mm still camera was used with high quality film (Fuji photo film: micro film negative HRII). Figures 4-(a), (b) and (c) show the two-dimensional images of the free spray using the exciplex fluorescence method at t= 1.12, 1.54 and 1.92 ms from the start of injection (*i.e.* t ms). Figures (i) and (ii) show the vapor and the liquid phase of the injected fuel; the horizontal axis is at a radial distance from the nozzle axis and the vertical axis is at a distance from nozzle tip. In figure 4-(a) at t=1.12 ms, the vapor phase of the high fluorescence intensity appears around the liquid phase; however, in Figs. 4-(b) and (c) (t=1.54 ms, 1.92 ms), the vapor phase region of high fluorescence intensity and the liquid phase region disappear. Consequently, it can be considered that the high florescence region of the vapor phase fuel decreases and the mixture consisting of both vapor phase fuel and ambient gas is homogenized. Figure 5 shows the entropy variation at each time step for the state change of the vapor phase fuel. It can be considered that when the vapor phase of the injected fuel defuses, the entropy increases due to the formation of a homogeneous mixture.

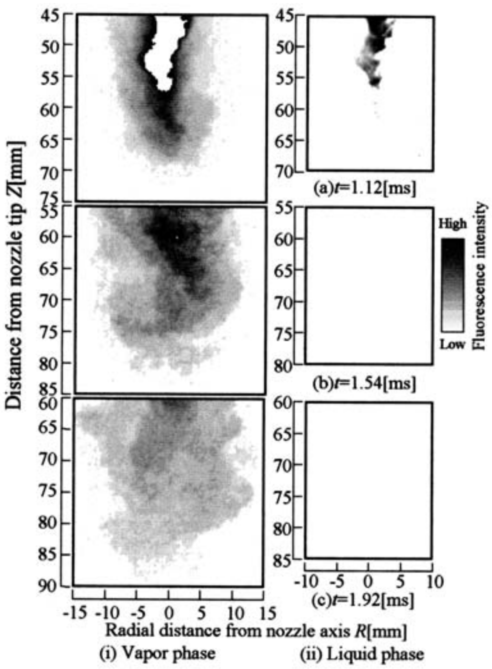

Fig. 4. Spray image taken by exciplex fluorescence method. (p_{inj}=72[MPa], Q_{inj}=12[mg], ρ_a=12.3[kg/m^3], T_a=700[K])

Figures 6 and 7 show the temporal changes of the vapor phase fluorescence at the spray center axis and radial distance. The x-axis is the radial distance from nozzle axis and the distance from nozzle tip and the y-axis is the dimensionless fluorescence intensity. The results of Figs. 6 and 7 show that halation occurs in the vapor region because of the overlapping in the liquid phase of the injected fuel at t=1.12 ms at the spray center axis. As the spray develops, the halation region turns into the vapor region of high fluorescence intensity as shown in Fig. 4-(b) at t=1.54 ms. The high fluorescence region in the image at t=1.54 ms disappeared in the case of t=1.92 ms because of the spreading vapor phase region of low fluorescence intensity. It was found that the liquid phase of the inner spray evaporates rapidly and at the same time as the injection end and the vapor phase of the injected fuel diffuses. In the case of liquid and vapor phase distribution region in the inner spray, it was confirmed that there was a meandering phenomenon of the liquid phase caused by a large vortex and brightness spots of the inner spray as shown in Fig. 4-(a) at t=1.12 ms. However, in this study the branch-like structure could not be clearly observed as a non-evaporating fuel spray (Dan et al., 1996). There is liquid phase like fog in the contour of the liquid spray because the overlapping of small droplet fluorescence occurs in the spray outside the region and there are lager droplets in the spray tip.

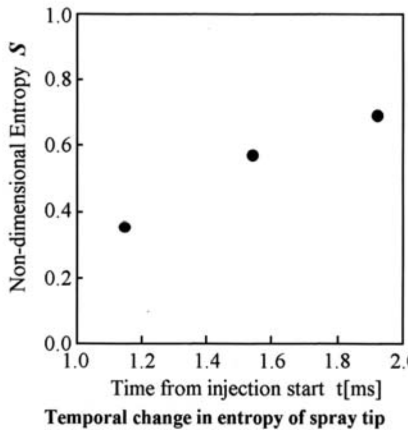

Fig. 5. Temporal change in dimensionless entropy of spray tip.

Consequently, in the case of the evaporating fuel spray the high fluorescence intensity of the vapor phase fuel is distributed in the two regions of the larger droplets and the atomized. In Fig. 4-(b) (t=1.54 ms), the liquid phase region is the only one similar to the diffused misty structure because of the atomized droplets and the high fluorescence region of the vapor and liquid phase regions overlapped. In the Fig. 4-(c), there is little fluorescence region of the vapor phase in the injected fuel. As a result, it was revealed that the droplet distribution region of the inner spray is closely related to the structure of the vapor phase fuel and high concentrations of vapor phase fuel are formed in and around the outside region of liquid phase fuel and droplets region. The formed vapor spreads out the ambient gas through diffusion. Finally, the distribution of the formed vapor phase was determined by the droplet motion in the liquid phase on the outside and in the spray tip.

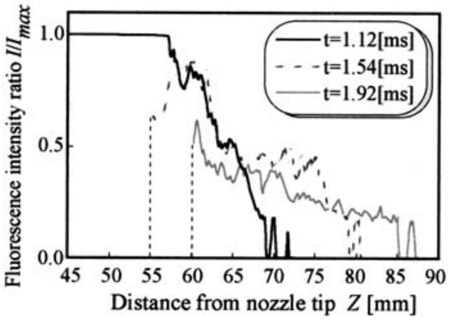

Fig. 6. Axial distribution of fuel vapor fluorescence intensity on spray axis.

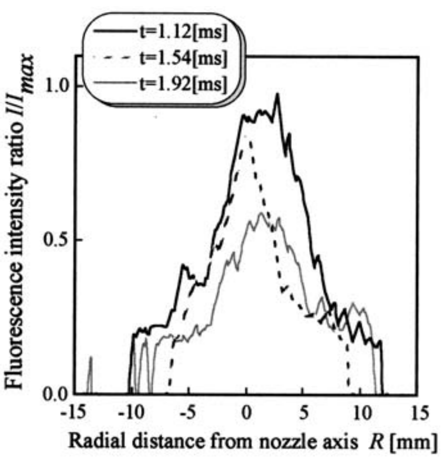

Fig. 7. Radial distribution of fuel vapor with fluorescence intensity at Z=60[mm].

3.1.2 Effect of the viscosity change of the vapor phase fuel on the structure of the diesel free spray

In the case of a non-evaporating fuel spray, there is hardly any vapor phase of the injected fuel in the inner spray, and therefore, the ambient gas viscosity (μ_a) can be considered to be mostly constant. In this study; however, the ambient gas viscosity, including the gas in the vapor phase of the injected fuel, is changed by the degree of the vapor phase distribution in the spray development. The mixed gas viscosity change of both the nitrogen of the ambient gas and the n-tridecane's vapor of the used fuel were considered by using NIST at a high temperature and pressure field. From the calculated results using NIST, it was found that the viscosity of the high vapor concentration region was higher than that of the low vapor concentration region. The spray structure analysis based on the calculated viscosity for the vapor phase fuel is described in the following.

Figure 8 shows the viscosity variation of the fuel vapor phase to the mole fraction of the ambient gas (Nitrogen). In Fig. 8, X_{N2} is the mole fraction of the ambient gas. As shown in Fig. 8, as the spray grows the viscosity coefficient of the fuel's vapor phase increases at the same time as the fuel evaporates. This phenomenon explains the viscosity increase of the vapor phase region caused by the entrained ambient gas. In the evaporating fuel spray, the mixture formation process consisted of the diffusion of the vapor phase fuel and the entrainment of ambient gas, which causes an increase in the viscosity coefficient.

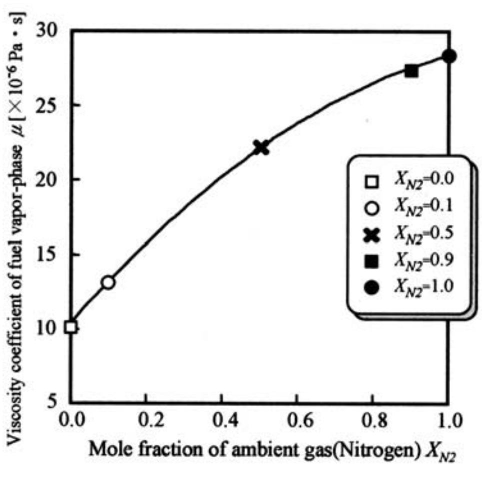

Fig. 8. Vapor phase viscosity variation in accordance with mole fraction of ambient gas.

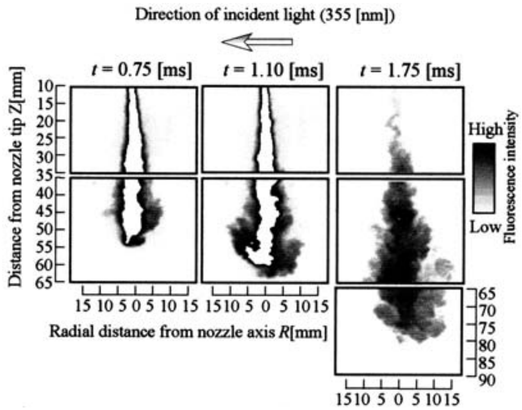

Fig. 9. Temporal change in vapor phase of free spray image taken by exciplex fluorescence method.
(p_{inj}=72[MPa], Q_{inj}=12[mg], ρ_a=12.3[kg/m^3], T_a=700[K])

In Fig. 9, as the spray develops, the vapor phase region outside of the spray takes on a lumping profile. When the viscosity coefficient of vapor phase fuel increases the spray boundary flow of the vapor phase and ambient gas becomes laminar as the Reynolds number (*Re*) decreases; however, the experimental result proves just the opposite. Also, the increase in the viscosity coefficient affects the vapor phase fuel diffusion by the coefficient of diffusion (1/*Re*) used in the vorticity transport equation (Nakayama, 1994). Specifically, as the viscosity coefficient increases, the coefficient of diffusion (1/*Re*) becomes larger. This implies an increase of vorticity diffusion and momentum transfer rate; therefore, it is expected that there is a laminar flow in the boundary surface of the vapor phase and the ambient gas. However, throughout this study the opposite proved to be true. Namely, within the diffusing vapor phase the lumped region increases outside of the spray. The reason for such a result is that in the diesel spray, the process of spray developing can be divided into two regions. One is the momentum exchange region between the injected fuel and the ambient gas, and the other is the region of the ambient gas flow dominating the mixture formation downstream. As a result, the fuel vapor phase region turns into a laminar flow; however, in the spray developing process there is a lumping profile outside of the spray because the spray vapor phase flow is affected by the ambient gas flow. Therefore, in order to analyze the mixture formation process of a diesel spray, it is necessary to study not only the injected fuel flow but also the variation in flow characteristics of the ambient gas. Furthermore,

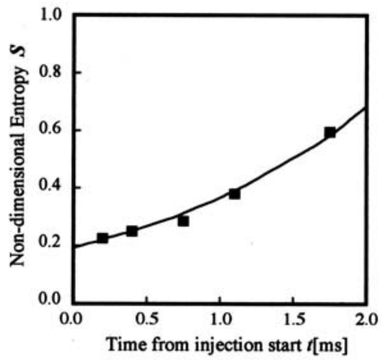

Fig. 10. Temporal change in dimensionless entropy of free spray.

in order to quantify the mixture state change to vapor phase diffusion of the injected fuel for each of the images, an entropy analysis was applied. (*Refer to appendix figure*)

Figure 10 shows the dimensionless entropy increase for the vapor phase of the injected fuel caused by the vapor phase diffusion and the formation of a homogeneous mixture. As shown in Fig. 10, as the evaporation of the injected fuel occurs actively during the injection period, the diffusion of fuel vapor phase is difficult to see during period. However, entropy rapidly increases after the injection end, which implies that the diffusion of the fuel vapor phase occurs almost after injection end.

3.2 An analysis of 3-dimensional structure for diesel spray based on the offset of the incident laser beam

Figure 11 shows the image of the center spray region and Fig. 12 shows exciplex fluorescence images that were taken by 2.5 mm and 5.0 mm offset of the incident laser beam from the spray center section at *t*=1.54 ms. As shown in Fig. 12-(a), for the case of 2.5 mm offset from the spray center axis, the images are clearly different from those of the spray center section, especially in the region of the liquid phase. In other words, in the 2.5 mm offset case of incident laser beam the images of the high fluorescence intensity region of the vapor phase are not continuous but discontinuous due to the heterogeneous distribution of the spray. Also, there is vortex-like branch structure similar to the results of Dan et al. (1996) that implies the distribution of the heterogeneous droplets in the injected spray has a rotating motion caused by the interaction between the

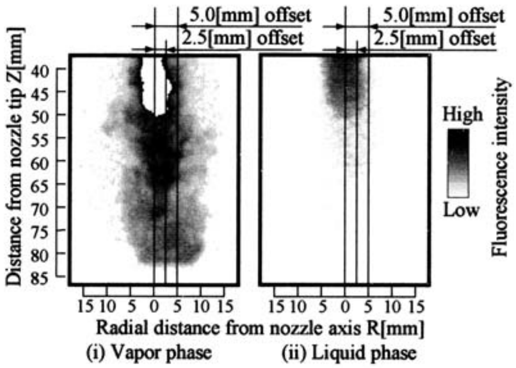

Fig. 11. Image at the center region of the spray.
(p_{inj}=72[MPa], Q_{inj}=12[mg], ρ_a=12.3[kg/m^3], T_a=700[K])

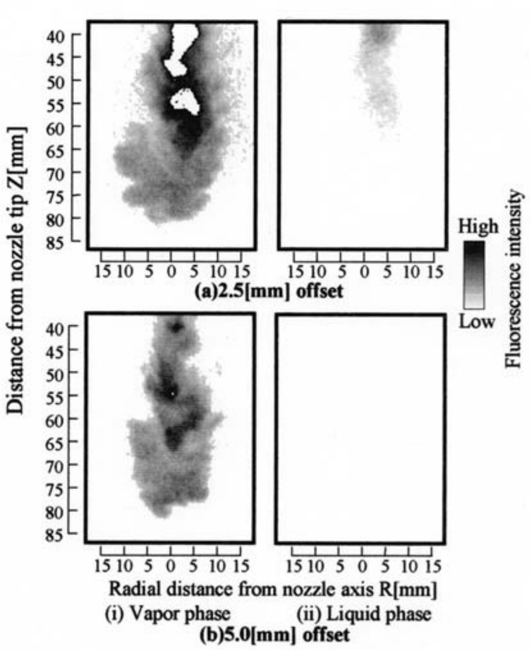

Fig. 12. Image of 2.5[mm] and 5.0[mm] offset from spray center at t=1.54[ms] from injection start.

injected fuel and the ambient gas within the inner spray. From the results of this study, it could be supposed that the developing process of an actual diesel spray has a spatiotemporally complex profile that is 3-dimensional in structure within the inner spray. Figure 12-(b) shows images that were taken by a 5.0 mm offset from the spray center axis of the incident laser beam. It shows that there are relatively few spray droplets in the 5.0 mm offset because of the spatial heterogeneous distribution of the fuel droplets. This result implies that when the laser beam was moved 5.0 mm from the spray center axis, there was

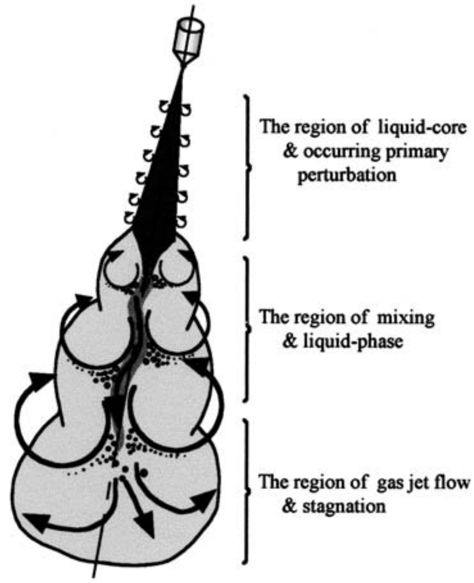

Fig. 13. Image of the inner structure of evaporative diesel spray.

little droplet distribution in the plane passing through the laser beam. Consequently, it revealed that the diesel spray has 3-dimensional structure and the initial perturbation of the diesel spray was formed in the upstream spray from the interaction (shear force) between the fuel and ambient gas. The perturbation develops downstream with the formation of the spray vortex core. Finally, the spray of the injected fuel has a spatial structure of a heterogeneous droplet distribution in a branch-like structure due to the effect of the interaction between the fuel and the ambient gas. From the results above, the structure of the diesel spray can be written as shown in Fig. 13 as the case of phase change occurring of the injected fuel.

4. Conclusions

An experiment was performed for an evaporating diesel free spray and the effect of viscosity variations in the spray vapor phase on the process of mixture formation was analyzed. Also in order to quantify the mixture's state change within the vapor phase region of the injected spray, image analysis was conducted with statistical thermodynamics based on the dimensionless entropy method. Finally, the 3-dimensional spatial structure of an evaporative diesel spray was diagnosed by using an offset laser beam.

The following conclusions are drawn from this study.

(1) In the evaporative fuel spray, the heterogeneous distribution of the spray's liquid phase affects the mixture formation process.

(2) As the spray develops, the viscosity of the fuel vapor phase increases and the momentum exchange between the injected fuel and ambient gas is promoted.

(3) The mixture states of the evaporative diesel spray can be represented by using an entropy analysis. The entropy value rapidly increases after the injection end; this implies that the diffusion of the fuel vapor phase occurs almost after injection end.

(4) The 3-dimensional spatial structure of a diesel spray can be verified by using 2-dimensional images obtained from the offset of incident of an exciplex fluorescence laser beam.

Acknowledgments

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Nomenclature

I : Fluorescence Intensity
$I(i)$: Fluorescence Intensity Value of Each Pixel
M : Number of Total Pixels
S : Dimensionless Entropy
t : Time from Injection Start
X : Mole Fraction

Greek symbols

ρ : Density
μ : Viscosity

Subscripts

A : Ambient gas
inj : Injection
liq : Liquid Phase
N_2 : Nitrogen
max : Maximum
vap : Vapor Phase

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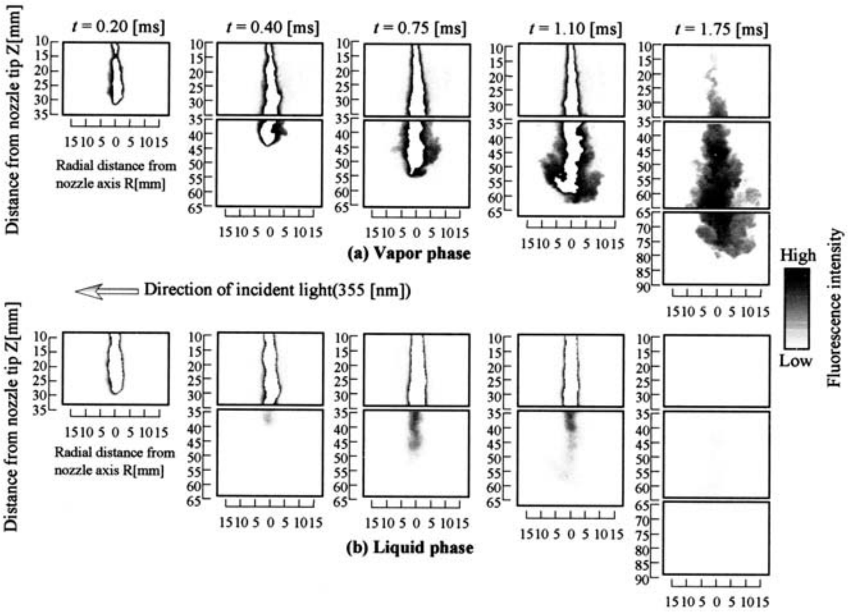
Appendix



Temporal change in free spray image taken by exciplex fluorescence method.
(p_{inj}=72[MPa], Q_{inj}=12[mg], ρ_a=12.3[kg/m^3], T_a=700[K])