A Basic study on the Evaporative Diesel Spray with Visible Measurement
가시화 측정을 이용한 증발디젤분무의 기초 연구

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(received 2 March 2009, revised 6 April 2009, accepted 24 June 2009)

주요용어 : 흐트러짐(Disturbance), 프랙털해석(Fractal Analysis), 증발분무(Evaporative Spray), 혼합기형성과정(Mixture Formation Process), 엑시플렉스 형광법(Exciplex Fluorescence Method)

요 약 : 디젤기관에서 배출되는 유해배출성분인 NOx(Nitrogen oxides)와 PM(Particulate matter)은 기관 실린더내의 혼합기 분포에 의해 그 생성이 지배된다. 이 때문에 그 유해배출물들을 저감하기 위해서는 연소의 전단계인 혼합기 분포 및 그 생성과정의 해석은 매우 중요하다. 디젤기관에서 노즐로부터 분사된 연료는 주위기체와 혼합기를 형성하는 과정에서 액체에서 기체로 상변화를 동반한다. 따라서 분무의 혼합기형성과정을 해석하기 위해서는 액상과 기상을 동시에 분리하여 계측하는 것이 필요하다. 그러므로 본 연구에서는 디젤분무를 대상으로 Melton 등이 제안한 엑시플렉스(Exciplex) 형광법을 이용하여, 분무의 액상과 기상을 동시에 2차원분리해서 가시화촬영을 행하였다. 그 엑시플렉스 형광법을 이용하여 획득한 이미지에 화상응용해석을 실시하여 비정상증발디젤분무의 혼합기형성과정에 대한 정보를 얻고자 하였다. 엑시플렉스 형광법을 이용해서 증발분무의 거동특성을 해석한 결과 프랙털해석을 이용한 분무 흐트러짐(Disturbance)의 평가에서 프랙털차원은 분사압력의 변화에 관계없이 하나의 값, 약 1.1로 정리 할 수 있고, 그 결과 각 분사압력에 대한 분무 기상외곽곡선(외주)은 거의 동일한 정도의 요철형상을 갖는다.

1. Introduction

The production of the harmful components, nitrogen oxides (NOx) and particulate matter (PM) exhausted from the diesel engine is controlled by the mixture distribution in cylinder. Then, in order to reduce harmful emission, it is important to analyze the distribution of mixture and its production process which is the previous step of combustion. In the high-speed DI diesel engine of the light duty, the fuel sprayed from a nozzle forms the mixture through the processes of atomization, evaporation, diffusion and mixture. This process is accompanied with the phase change of the fuel from liquid to vapor. Thus, it is necessary to separate and measure liquid phase and vapor phase simultaneously in order to analyze the mixture formation process of evaporative diesel spray. In this study, the exciplex fluorescence method[(1)~(4)] is used for diesel spray, and the liquid phase and the vapor phase of the spray are separated in 2-D for visualization. Also in this paper, image application analyses were performed for the obtained images and then the information on the mixture formation process of the unsteady evaporative diesel spray was obtained.

2. Fundamental principle of the exciplex fluorescence method

The mixture formation process in a diesel engine is accompanied with the phase change from the liquid phase to the vapor phase. Thus, the simultaneous quantitative measurement of the

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fuel distribution of the two phases is very difficult with measuring methods applied to non-evaporating field or gas jet. However, recently, with the development of laser measuring method, research on diverse measuring methods has been carried out. Especially, the exciplex fluorescence method is very useful as a tool for simultaneous measurement of 2-D profile image of the liquid and vapor phases inside the spray. By absorbing optical energy, the fluorescent molecule M in the ground state becomes the fluorescent molecule $^1M^*$ in the excited state, and as it collides with other molecule N, it forms the complexation [$^1(M{\cdot}N)^*$], emitting fluorescence. This complexation is called "the excited complex or exciplex", and its equation is expressed as follows:

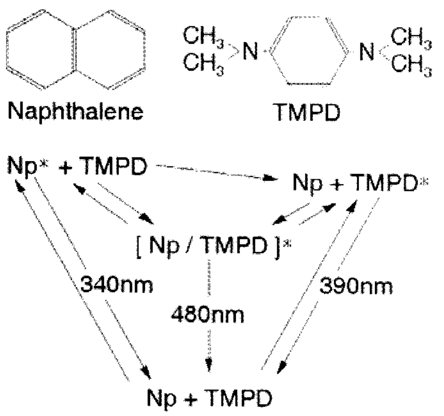


Fig. 1 Schematic summary of photophysics of Naphthalene/TMPD exciplex system(1)

$$^1M^* + N \Leftrightarrow {}^1(M{\cdot}N)^* \quad (1)$$

Here, the transfer to 1(M · N)* occurs very fast under nano(10-9) seconds. When 1M* and 1(M · N)* in the excited state is declined to M and M+N in the ground state, the energy of fluorescence is emitted. At this time, for fluorescence radiation of 1M*, the fluorescence radiation of $^1(M{\cdot}N)^*$ is transferred to the side of long wavelength. This is because the energy is spent to create the exciplex. The reaction of N and $^1M^*$ that generates $^1(M{\cdot}N)^*$ is reversible, and, in the liquid phase with extremely high inter-molecular collision rate, it is possible to obtain radiation species mainly with exciplex of $^1M^*$ by controlling the concentration of N. Meanwhile, in the vapor phase in which molecules exist in relatively disperse way, it is feasible to obtain the radiation species dominated by $^1(M{\cdot}N)^*$ called "monomer". In this study, the exciplex system that uses naphthalene (Np, $C_{10}H_8$) and N,N,N′,N′ tetramethyl-p-phenylene diamine (TMPD, $C_{10}H_{16}N_2$) proposed by Melton (1983) as fluorescent material.

Figure 1 shows the transition process of the energy in the exciplex system. Here, TMPD and Np responds to M and N, respectively. Also, the monomer fluorescence of TMPD and the exciplex fluorescence of TMPD and Np have the peak wavelengths of 390nm and 480nm, respectively, which can be separated and measured optically. If the fluorescent M is evaporated with the fuel, the 2 types of fluorescence radiation (390nm, 480nm) obtained through appropriate optical filter can be used asa tool to decide the existence of liquid phase or vapor phase of the fuel. Each fluorescence intensity includes the information of quasi-quantitative concentration for the liquid phase and the vapor phase of the fuel.

3. Quantification of the vapor concentration by the exciplex fluorescence method [Senda(5) and Kanda(6)]

The fluorescent images obtained by using the exciplex fluorescence method include the quasi-quantitative concentration information. Thus, quantitative analysis is made possible by calibrating in consideration with the quenching phenomenon of fluorescents. Generally it is understood that the fluorescence intensity of fluorescents is in proportion to the concentration of that material. When monochromatic light with incident laser intensity, I_0 [$J/(m^2s)$] passing through the material by Lm, which allowed the material of I_a to be absorbed and I_t to be passed, then, according to the Lambert-Beer Law, the following equations are formed:

$$I_t = I_0 \exp(-eCL) \quad (2)$$

$$I_a = I_0 - I_t = I_0\{1-\exp(-eCL)\} \quad (3)$$

Where, ε: molar extinction coefficient of incident light wavelength [m^3/(molm)], and C: concentration of fluorescent material [mol/m^3].

Also, as shown in Fig. 2, when the spray profile is divided by n equally-spaced meshes to the direction of laser incident direction, the laser intensity I_i at the ith observation position on the side of laser incidence is:

$$I_i = I_0 exp(-eLSC_{i-1}) \quad (4)$$

Emission intensity Fi at the ith observation position is expressed as in the following equation:

$$F_i = AKI_0 \exp(-eLSC_{i-1})\{1-\exp(-eC_iL)\} \quad (5)$$

Where, A: device constant of the optical system, K: probability of emission transfer, C_i: concentration of fluorescent in the ith mesh, [mol/m^3], and, L: length that incident light passes inside a material, [m].

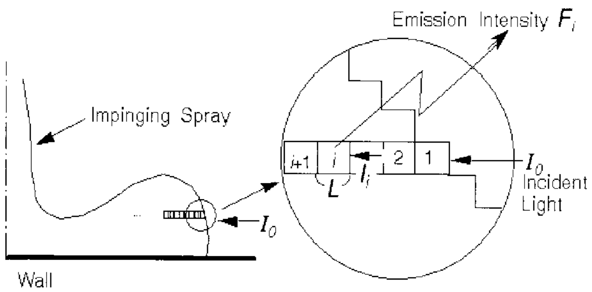


Fig. 2 Model on vapor concentration analysis with light absorption

Fig. 3 shows the relationship between vapor concentration and fluorescence intensity in the high temperature and pressure field. It is assumed that the error in the theoretical curve obtained from Eq.(5) is attributed to concentration quenching, so the Eq. (5) was modified to the following:

$$F_i = A \cdot K \cdot K_c \cdot I_0 \exp(-eLSC_{i-1})\{1-\exp(-eC_iL)\} \quad (6)$$

Here, the concentration-quenching coefficient K_c is a coefficient that is determined by concentration. In this study, the mixture mean temperature T_r is estimated from the heat balance by using the following equation:

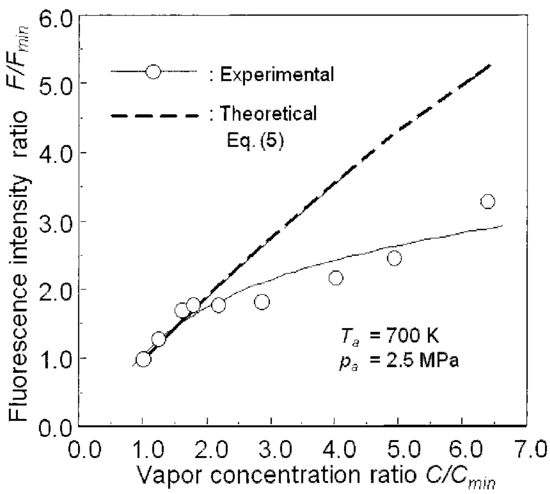


Fig. 3 Change in vapor fluorescence intensity with fuel vapor concentration

$$T_r = \frac{-C_v c_{fl}(T_{sat} - T_{10}) + h_f + \rho_a c_a T_{ent} + C_v c_{fv} T_{sat}}{C_v c_{fv} + \rho_a c_a} \quad (7)$$

ρ_a: density of ambient gas, kg/m^3,

c_{fv}: specific heat of vapor fuel, J/(kgK),

c_{fl} : specific heat of liquid fuel, J/(kgK),

c_a: specific heat of ambient gas, J/(kgK),

h_f : Latent heat of vaporization of the fuel, J/kg,

T_{sat} : Saturation temperature of fuel, K,

T_{10} : initial temperature of liquid fuel, K, and,

T_{ent} : temperature of ambient gas entrained into the evaporative spray, K.

However, the temperature of the ambient gas entrained into the evaporative spray, T_{sat}, was estimated with the mean value of the mixture mean temperature and the ambient gas temperature. With these equations explained above, the vapor concentration and the mixture mean temperature in any region can be calculated.

Fig. 4 shows the analysis results of the vapor phase taken by the exciplex fluorescence method, which is a case of analysis on the 2-D profile images that include the medial axis of spray. In this figure, (a) is the fluorescence intensity distribution, (b) is the result of the vapor

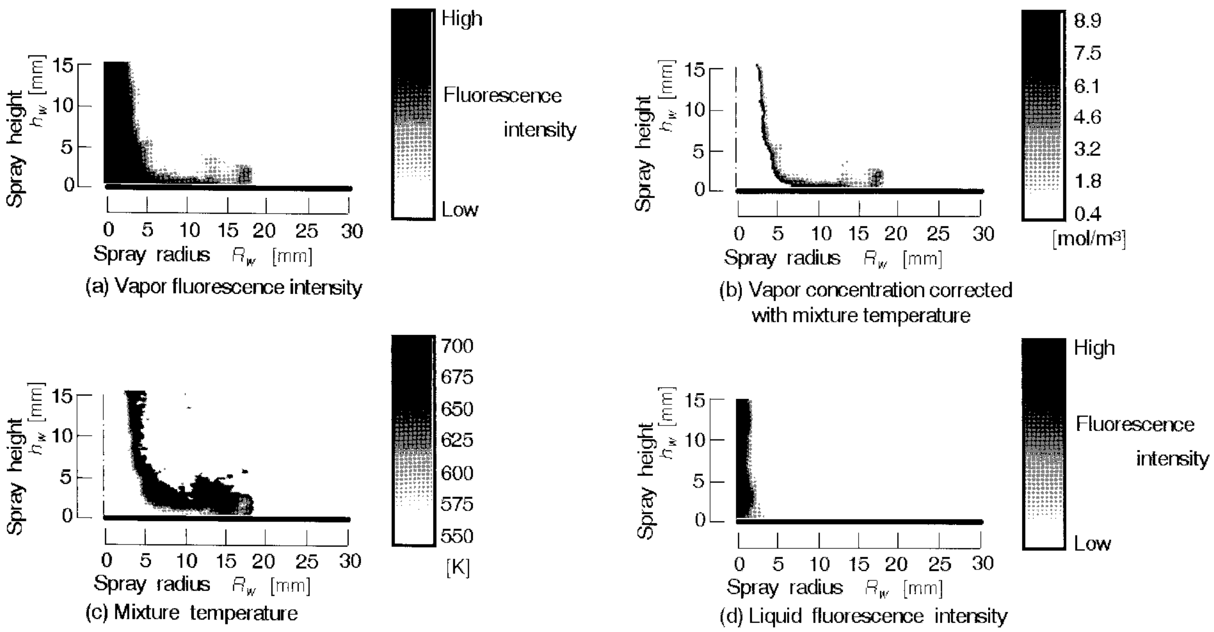


Fig. 4 Spray images taken by the exciplex fluoresence method

concentration distribution by calibration, (c) is the mean temperature distribution of the mixture, and (d) is the fluorescence intensity of the liquid phase.

4. Experimental apparatus and conditions

4.1 Experimental apparatus

In this study, a constant volume chamber with the fuel injection system of ECD-U2(common rail-type) was used, and the evaporative spray was formed by injecting the fuel into the chamber which can realize high-temperature and high-pressure atmosphere.

Table 1 Experimental conditions

Injection nozzle	Type : Hole nozzle DLL-p	
	Diameter of the hole d_n [mm] 0.2	
	Length of the 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/m^3]		12.3
Injection pressure p_{inj} [MPa]		22, 42, 72, 112
Injection quantity Q_{inj} [mg]		12.0
Injection duration t_{inj} [ms]		2.82, 1.98, 1.54, 1.20

4.2 Experimental conditions

The experimental conditions of this research were summarized in the Table 1. The ambient condition inside the chamber is the high-temperature and high-pressure atmosphere that simulated the ambience inside the cylinder at the time of the beginning of the spray from the high-speed DI diesel engine of the actual light duty as the ambient temperature T_a=700K, the ambient pressure p_a=2.55MPa, and the ambient density ρ_a=12.3kg/m^3. For ambient gas, highly pure nitrogen gas (purity 99.9%) was used to prevent the oxidation of fluorescent and the ignition of the fuel. The injection nozzle was a single-hole nozzle, and the diameter and length of the hole were 0.2mm, 1.0mm (l/d=1.0mm/0.2mm), respectively. Photography was performed under injection pressure p_{inj}=72MPa and injection duration t_{inj}=1.54ms. Replicability of injection was sufficiently confirmed prior to the experiment, and as a result, sufficient replicability was obtained.

5. Result and discussion

5.1 Analysis of diesel free spray by exciplex fluorescence method

Figure 5 shows the 2-D profile images of the

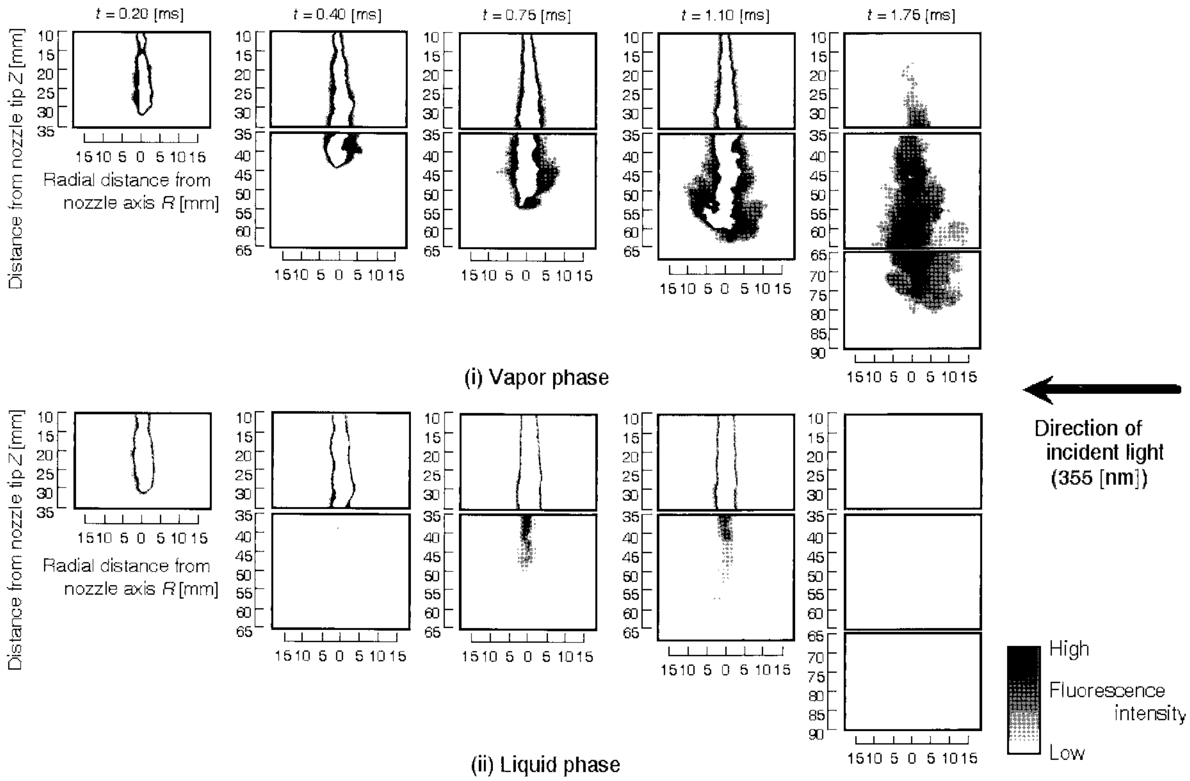


Fig. 5 Temporal change in the free spray images taken by exciplex fluorescence method[7, 8]
(P_{inj}=72[MPa], Q_{inj}=12.0[mg], T_a=700[K])

free spray obtained by the exciplex fluorescence method under the injection pressure (p_{inj}=72MPa)[(7),(8)]. As shown in Figure 5, the low-intensity vapor is spread to the radial direction in the spray upstream, and the promotion of atomization and the evaporation actively occurs by the shear action with the ambient gas. Also, as the spray flows in the radial direction at the middle region of spray,

the meandering flow of the spray begins in the spray mainstream. It was found from this result that the formation of mixture in evaporating spray occurs mainly in the spray downstream.

5.2 Estimation of spray disturbance by fractal analysis

The exciplex fluorescence method is a useful tool for the analysis of the spray structure explained in the previous 5.1 section. By applying the fractal analysis to the images obtained from the exciplex fluorescence method, it is possible to estimate the disturbance of the spray which is an important factor in the formation of mixture. Now, here fractal analysis is explained. Of the equations shown in the results, the exponent of l is called "Fractal dimension", which is an index that indicates the complexity of a shape. As this value becomes larger, a shape is more uneven[(9)]. In this study, it was measured how many times of the segment lengths l=1, 3, 5, 10, and 15mm the length of the edge of vapor phase spray. The spray image of the vapor phase with non-dimenional time of spray pressure, t/t_{inj}, at about 0.75 was captured in the downstream area. The distance (Z) from the nozzle tip of the observed downstream area is 35mm and more; and the

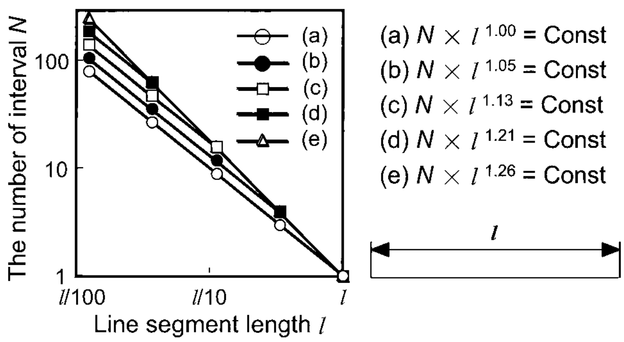
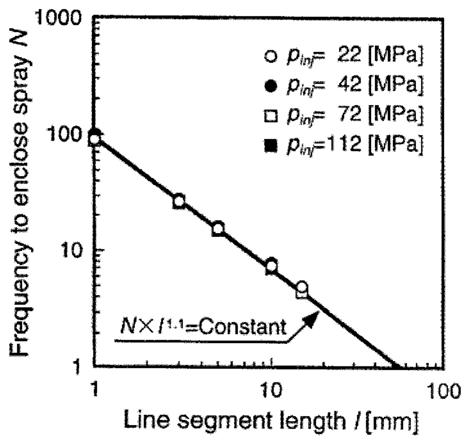


Fig. 6 Schematic diagram for fractal analysis[5)]

results are shown in figure 5. The purpose of this analysis is to confirm whether the disturbance of the spray increases and the edge form of vapor phase becomes more complex (the disturbance is intensified) according to increase of injection pressure. The results of the fractal analysis obtained from mean values for each injection pressure are shown in figure 7. As shown in this figure, fractal dimension has one value, about 1.1, regardless of injection pressure. This suggests that regardless of injection pressure, the spray has the almost the same degree of uneven profile.



p_{inj}= 22 [MPa] : $N \times l^{1.068} = 87.93$

p_{inj}= 42 [MPa] : $N \times l^{1.105} = 97.77$

p_{inj}= 72 [MPa] : $N \times l^{1.088} = 88.61$

p_{inj}=112 [MPa] : $N \times l^{1.125} = 92.95$

Fig. 7 Fractal analysis results for evap-orating spray(8)(t/t_{inj}=0.75, $Z \geq 35$[mm])

6. Conclusions

In this study, structure analysis for diesel spray was carried out simultaneously for the liquid phase and the vapor phase of the evaporating spray by using the exciplex fluorescence method. Also, image application analyses were performed for the obtained images, and the results are summarized in the followings:

1) The exciplex fluorescence method is a useful measuring method to analyze the spray structure of the evaporating spray. Also, the fractal analysis was used for the obtained images, which can evaluate the disturbance of the diesel spray.

2) In the disturbance evaluation of the evaporating diesel spray using the fractal analysis, the fractal dimension is found to have one value, about 1.1, regardless of spray pressure. This indicates that the edge (spray circumference) of the vapor phase of the evaporating spray has the almost same uneven profile for each spray pressure.

Acknowledgement

This study was supported by research funds from Dong-A University.

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