An Experimental Analysis on the Behavior Characteristics of Evaporative Impinging Spray
증발 충돌분무의 거동특성에 관한 실험연구

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요 약 : 분사된 연료의 미립화(atomization), 증발(evaporation), 그리고 혼합기형성과정(mixture formation process)이 디젤엔진의 착화 및 연소특성에 영향을 미치기 때문에, 디젤엔진 내에 분사된 연료의 구조해석으로부터 일련의 과정, 즉 고압분사, 분열(breakup), 미립화, 그리고 주위기체의 난류 도입(entrainment)에 관한 연구[1-3]는 꾸준히 행해져왔다. 본 연구는 증발디젤분무의 구조해석으로부터 디젤충돌분무의 혼합기형성과정을 조사한다. 주위기체의 밀도는 실험변수로서 선택하였고, 5.0kg/m³에서 12.3 kg/m³까지 변화시켰다. 그리고 소형고속디젤엔진에 있어서 연료분사초기의 상태의 고온·고압 설정이 가능한 정적용기를 사용했다. 주위 온도와 연료분사압력은 각각 700K 및 72MPa로 일정하게 유지했다. 충동증발분무의 액상과 기상의 이미지는 엑시플렉스형광법으로 동시 계측하였다. 실험결과로서 주위기체의 밀도가 높을수록 충돌분무의 선단도달거리가 주위기체의 항력으로 인하여 감소하였다.

1. Introduction

In order to reduce the emissions from diesel engines, it is important to study the mixture formation process concerned with formation of PM(Particulate Matter) and NOx. In diesel engines, atomization, evaporation, and mixture formation process of injected fuel affect ignition characteristics and combustion process. Therefore, purpose of this work is laid on making a clear the mixture formation process in an evaporative field of high temperature and pressure. In the factors affecting behavior of diesel spray, especially, the density of ambient gas dominates spray development process such as spray angle and spray tip penetration[1-3]. Then, the density of ambient gas was selected as experimental parameter. The subject of this study was diesel impinging spray under the variation of ambient gas density. Exciplex fluorescence method was used for visualization of experiment phenomenon.

2. Experimental apparatus and procedure

Figure 1 shows a schematic diagram of the experimental apparatus. The experiments were conducted under the conditions of 700K in ambient temperature and 2.55MPa in ambient gas pressure inside a high pressure vessel with constant volume. This vessel consists of two quartz glass windows which were installed perpendicular to each other. Nitrogen was utilized as the ambient gas to prevent quenching of liquid fluorescence by oxygen. This ambient gas was heated up using heaters inside the vessel. 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

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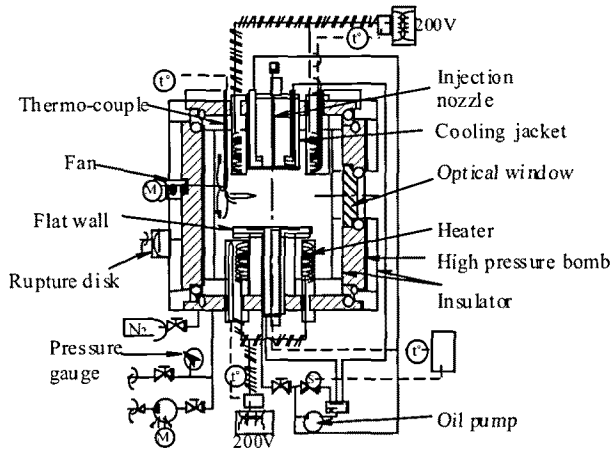E-mail : laser355@dau.ac.kr, Tel : 051-200-7640
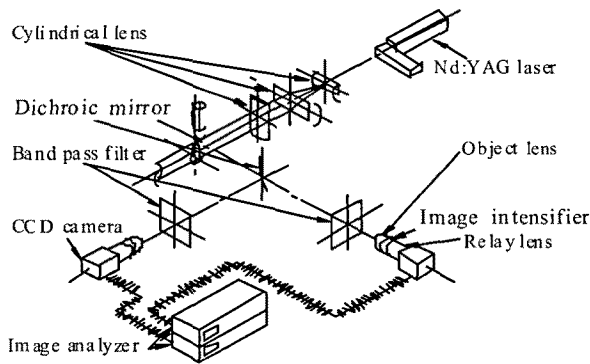
Fig. 1 Experimental apparatus

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

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]	1.04, 1.70, 2.55
Ambient density	ρ_a	[kg/m3]	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
Impingement distance	Z_v	[mm]	40
Wall temperature	T_w	[K]	550

injector. 9% in mass of naphthalene and 1% in that of TMPD (N,N,N',N' tetramethyl-p-phenylene diamine) 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) proposed by Denso Co., Ltd. was used in this study. The diameter and the length of nozzle were 0.2mm and 1.0mm, respectively. The ambient gas pressure was varied in the range from 1.04MPa to 2.55MPa by the change in the ambient density. The injection pressure and the fuel injection quantity were kept constantly as 72MPa and 12.0mg, respectively. Table 1 shows the experimental conditions.

Figure 2 shows a schematic of the optical system. The light source was the third harmonic of an Nd:YAG laser at 355nm (power 60mJ/pulse, pulse width : 8nsec., maximum frequency : 10Hz, beam diameter : 6.4mm, beam shape : doughnut type). The detailed explanation for the experimental method is also found in Yeom et al.[4].
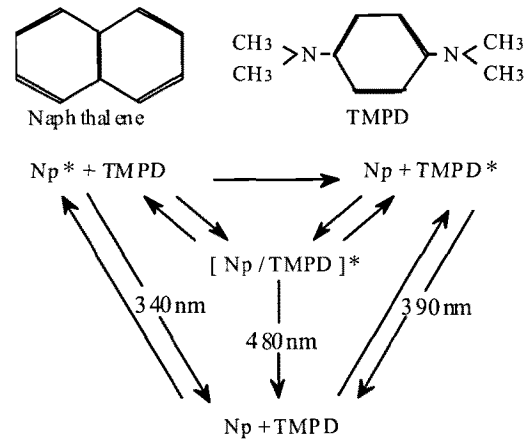

Fig. 3 Schematic summary of naphthalene and TMPD exciplex system

Figure 3 shows a schematic summary of the photophysics of the naphthalene/TMPD exciplex fluorescence system[5].

3. Experimental results and discussion

Figure 4 shows the two-dimensional images of impinging spray at various ambient gas densities which were obtained by the exciplex fluorescence method.
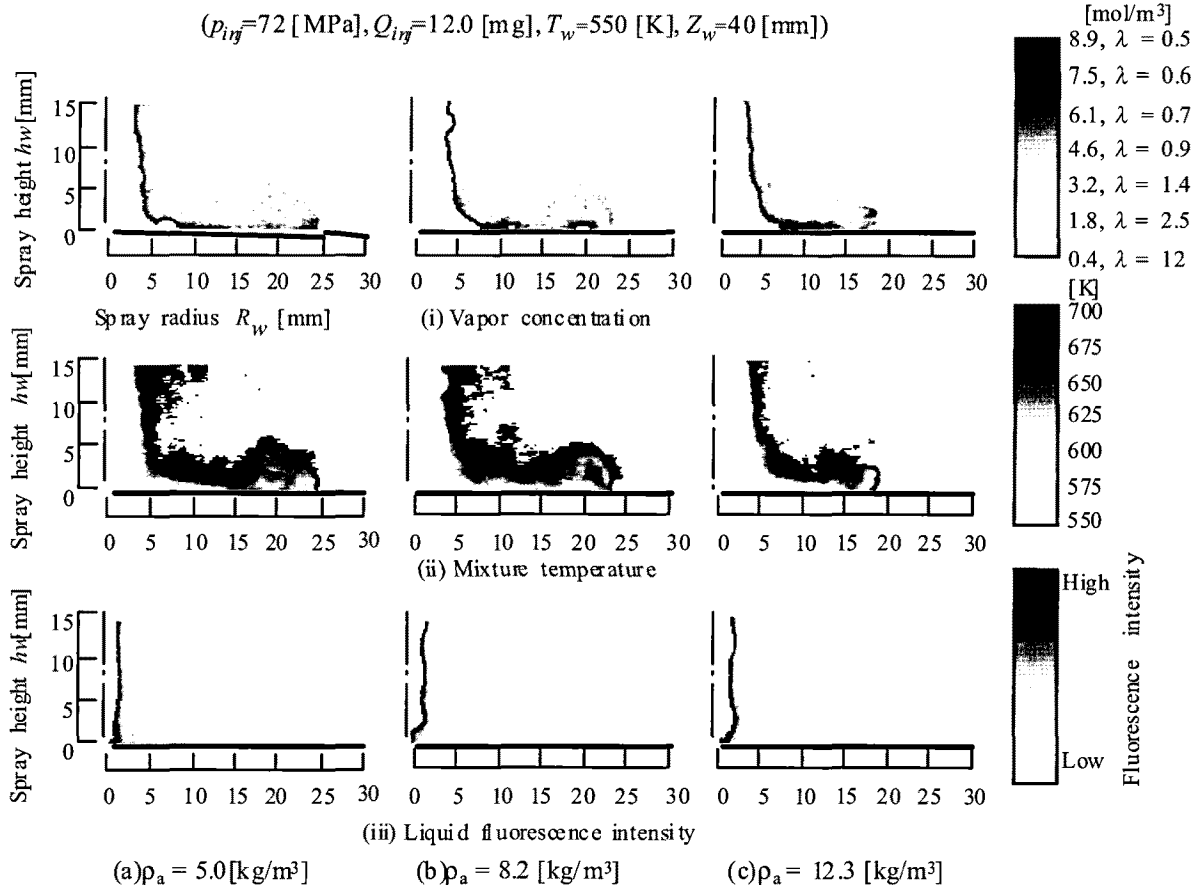
Fig. 4 Temporal change in impinging spray image with exciplex fluorescence method at t=1.10ms from injection start

3.1 Behavior study of the liquid phase fuel

From each image of the Fig. 4-(iii), in the impinging wall surface, the liquid phase fuel spreads in radial direction, with decreasing ambient gas density. In the case of ambient gas density r_a=5.0kg/m^3, the high fluorescence intensity of free spray region of the liquid phase fuel reaches to the impinging wall surface. In the liquid phase fuel, with decreasing ambient gas density, the distance between central spray axis and spray periphery decreases due to increase in drag force from ambient gas. This result corresponds with spray angle decreasing in non-evaporating diesel free spray[6].

3.2 Behavior study of the vapor phase fuel

For the vapor phase of the Fig. 4-(i), the lean mixture is formed over the central spray axis to the spray tip region at the impinging wall surface

and the spray tip proceeds to radial direction. In the region between stagnation point(spray radius, R_w=0) and the spray tip region(spray radius, 0<R_w), the spray structure can be divided into two regions of fuel rich region near the impinging wall and the fuel lean region in spray periphery as shown in Fig. 4. In the case of vapor phase fuel, the height from the impinging wall surface of the rich concentration region decreases, with decreasing ambient gas density and the lean concentration region of the vapor phase fuel becomes wider. Furthermore, in case of ambient gas density 8.2kg/m^3, the rich concentration region of vapor phase fuel near the impinging wall surface is similar to that of ambient gas density r_a=12.3kg/m^3, however, the lean concentration region of vapor phase fuel is similar to that of ambient gas density 5.0kg/m^3 in spray periphery.
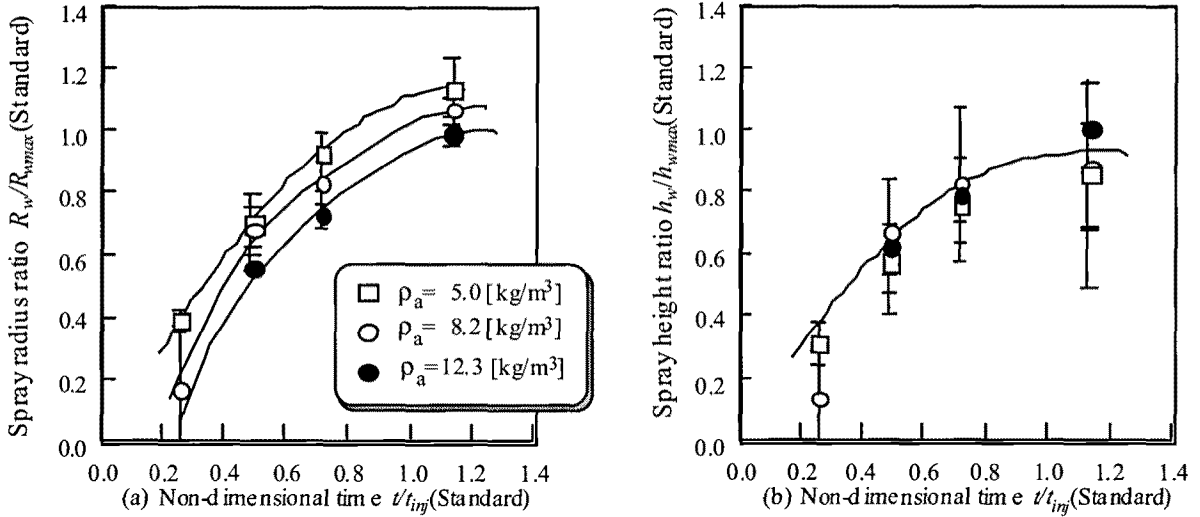
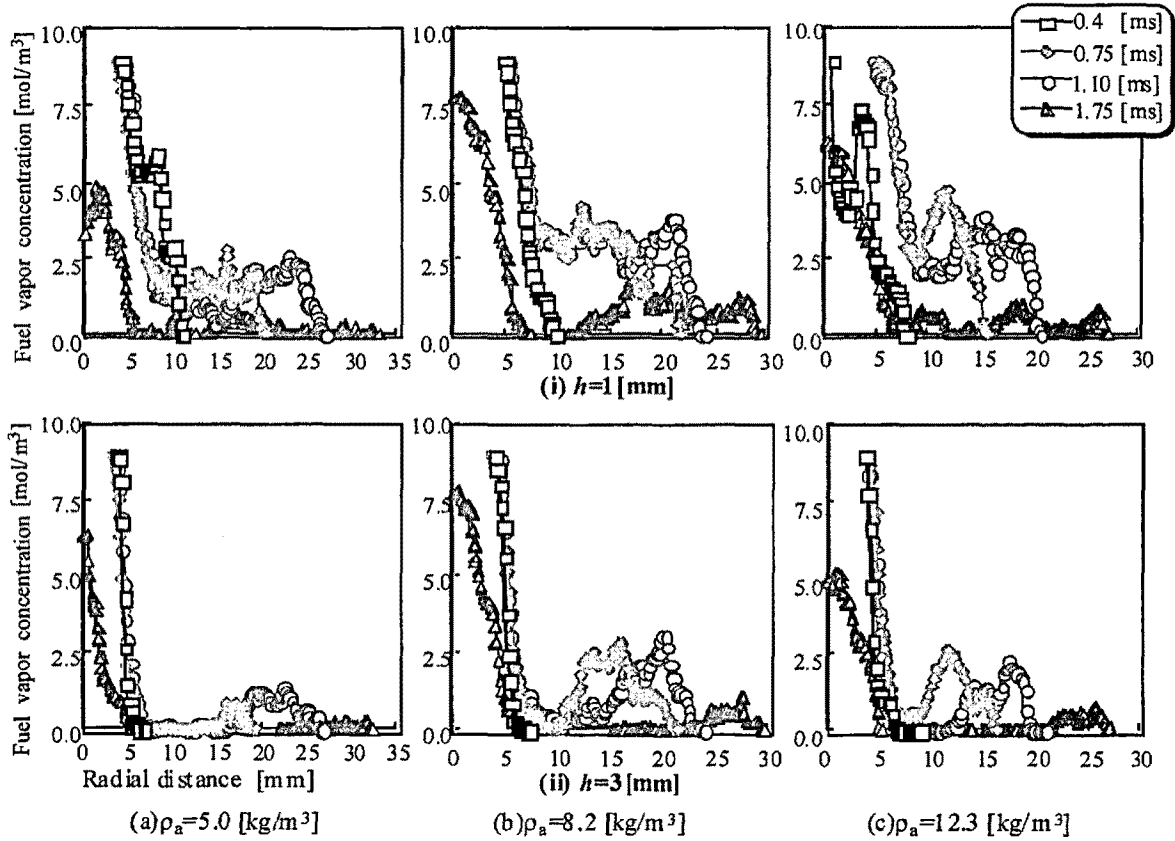Fig. 5 Temporal change in spray radius R_w and height h_w(p_{inj}=72MPa, Q_{inj}=12.0mg, T_w=550K, Z_w=40mm)

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

The effects of ambient gas density on the spray height(h) and the spray radius(R) are shown in Fig. 5. In the figure, the h_{wmax}(Standard) and R_{wmax}(Standard) are maximum height and radius in ambient gas density r_a=12.3kg/m³,

respectively. From the Fig. 5, spray radius increases with decreasing ambient gas density, because drag force from ambient gas decreases at spray tip.

Figure 6 shows distribution of fuel vapor

concentration in the spray. In Fig. 6-(i), the distributions concentration of the vapor phase fuel at r_a=12.3 kg/m^3 and r_a=8.2kg/m^3 are higher than that of the case at r_a=5.0kg/m^3 at the distance from impinging wall surface, h=1mm. Figure 6-(ii) shows the vapor-phase concentration distribution at h=3mm and the tendency of concentration distribution is nearly similar to that for h=1mm. 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 impinging wall surface and the lean concentration region of vapor phase fuel increases in spray periphery.
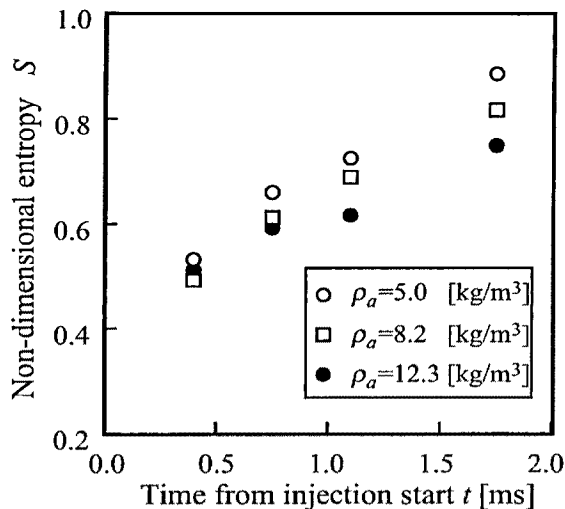

Fig. 7 Temporal change in dimensionless entropy

Figure 7 is dimensionless entropy change found from Figure 4. A detailed explain about the entropy analysis can be found in Yeom[7]. As in the results of Figure 7, entropy of vapor phase fuel decreases with increase of the density of ambient gases. This means that in case of high ambient density, diffusion of spray vapor phase fuel is suppressed by increase in drag force of ambient gases against developing spray. Therefore, increase in the density of ambient gases limits uniform mixture formation of evaporative spray and reduces entropy. According to above results, application of entropy theory based on diffusion theory of molecules to

interpretation of evaporative spray development process has enough validity.

4. Conclusions

In this study, an experimental study was performed for evaporative impinging spray. In order to measure images of the vapor and liquid phase of the fuel, the exciplex fluorescence method was used. The following conclusions are drawn from this study.

1) With increasing ambient gas density, the penetration tip region of impinging spray decreases due to increase in the drag force of ambient gas.

2) 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.

3) If density of ambient gases is low (e.g. r_a=5.0kg/m^3, r_a=8.2kg/m^3), larger dimensionless entropy is obtained in comparison to lower density. Low density allows easier growth of spray in axial and radial directions and contributes to formation of a more uniform mixture.

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