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Basic study on the Behavior Characteristics of Liquid-phase Spray with Phase Change
상변화를 동반한 액상분무의 거동 특성에 관한 기초 연구

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주요용어 : 분무구조(Spray Structure), 혼합기형성(Mixture Formation), 증발디젤분무(Evaporative Diesel Spray), 와(Vortex), 화상상관법(PIV Technique)

요 약 : 분사연료의 혼합기형성과정 최적화를 통한 연소제어 기술은 디젤기관의 기관운전 및 배기특성을 향상시키기 위하여 매우 중요하다. 또한 분무의 혼합기형성 최적화를 위해서는 분사된 연료와 주위기체와의 혼합과정에 영향을 미치는 분무내부의 유동특성에 대한 연구는 필수 불가결하다. 따라서 본 연구에서는 고온・고압의 증발장에서 분무의 액상 거동에 주목하고, 그 거동특성을 통하여 증발디젤분무의 혼합기형성을 해석한다. 비정상 증발분무의 중심축에 레이저 시트광을 입사한 후, 액상분무 액적의 Mie 산란광에 의한 2차원 화상을 획득하여 증발분무 액상의 속도분포 및 와도(vorticity) 등을 구하였다. 분무의 속도분포 및 와도는 2차원 화상에 PIV법을 적용하여 계산하였다. 그림 1에 본 연구에서 구한 속도분포의 일례를 보인다. 본 연구의 결과로 상변화를 동반하는 비정상 증발장에서 구한 분무액상의 거동 특성은 상변화가 일어나지 않는 비증발장에 있어서의 분무거동특성과 유사함을 확인하였다.

1. Introduction

An unsteady spray, that is, a diesel spray used in a DI diesel engine is injected into a combustion chamber with small space whose pressure and temperature are very high. While the injection pressure is very high, that is, over 100MPa, but the injection duration is very short, that is, 10ms at most. The vaporization of spray, the diffusion and the mixing between the spray and its surroundings break out simultaneously just after fuel injection start. Thereafter, the combustible mixture is formed and the combustion is promoting. Namely, it is very significant to detect the flow characteristics inside the diesel spray for understanding its mixing process between itself and its surroundings. The air motion around a diesel spay was investigated by one of the authors[1]. The motion was taken by the high-speed photography using the smoke wire method. The results were that the air was entrained at normal angle into the spray at its conical part and is pushed aside at the spray tip region. At that time, it was not able to catch the flow inside spray. After long time they applied the technique of a thin sheet of laser light[2]. Owing to the detailed observation, it was found that the diesel spray had vortices with large scale in which many vortices with small scale were existent. These vortices are caused by the spray motion itself and the mutual interaction between itself and its surroundings, and it seems that they affect the flow characteristics inside the diesel spray and its combustion processes. The Christmas tree structure or the fish born structure of this spray taken on the still photograph is caused by the existence of these vortices. It is unable to presume precisely the internal flow characteristics not only in the case

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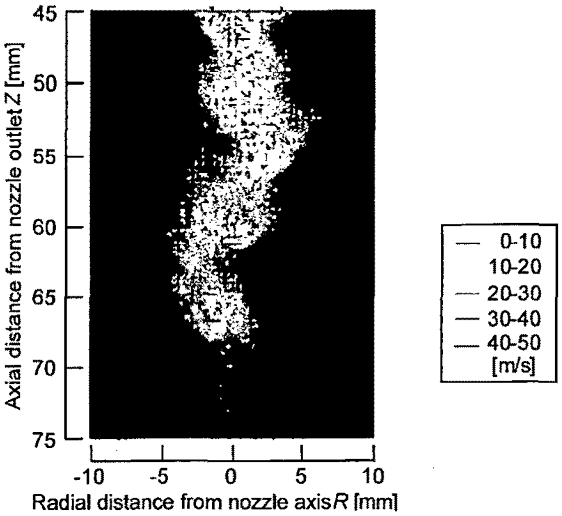


Fig. 1 One of examples of velocity distribution inside evaporating diesel spray (t=1.12 [ms], tinj=1.54[ms])

of a non-evaporating spray but also in that of an evaporating spray by use of these results. It is very difficult to catch the flow characteristics inside a diesel spray directly as the droplets density is very dense and the velocity of droplets passing through a unit volume of the spray is very fast. Then, the PIV method proposed by Adrian[3] is only one technique for detection of 2-D characteristics in such complex flow because LDV technique can detect only the pinpoint information. One of authors presented previously the internal flow characteristics in a transient gas jet[4]. It seems that there is the capability of the analogy of the characteristics between the jet and the spray because the characteristics of entrained air of the flat spray, the transient water jet injected into water, and the diesel spray injected into the atmosphere with high pressure at room temperature are almost the same with each other[5]. Recently, they described 2-D characteristics of internal flow in the case of a non-evaporating spray at the elevated pressure just at the end of injection and after the injection period applying the PIV technique.[6] It is unable to detect the flow during the injection duration because the droplets density is too dense. Accordingly, they proposed the model of this case. The objective this research is to detect the flow characteristics inside an evaporating spray injected into the quiescent atmosphere with high temperature at high pressure applying the PIV technique as well. It was able to detect the characteristics of the liquid phase and it was unable to catch the information of the vapor.

2. Optical setup, experimental procedure and conditions

2.1 Optical setup

Figure 2 displays a schematic diagram of optical and photography system for Mie scattering image. The two lines of light oscillated from two sets of Nd:YAG lasers (Spectra-Physics : GCR170) which are installed in an Nd:YAG laser (Spectra-Physics : PIV400) are combined into one line by a beam combiner. This light is incident into a high frequency generator (Quanta-Ray : HG-2) and it adjusts the light to its wavelength of 532nm of the second harmonics. The power of light is 400mJ/pulse, the dimension of round is 10.0mm in diameter, the pulse interval is 8ns and the maximum oscillation frequency is 10Hz. The light is passing through a pinhole to change its diameter from 10mm to 5mm and it is going to two sets of cylindrical lenses whose optical length are 15mm and 1000mm, respectively. The lenses were made of optical quarts in order to have the sufficient transmittance and they were given non-reflection coating to avoid the distinction of

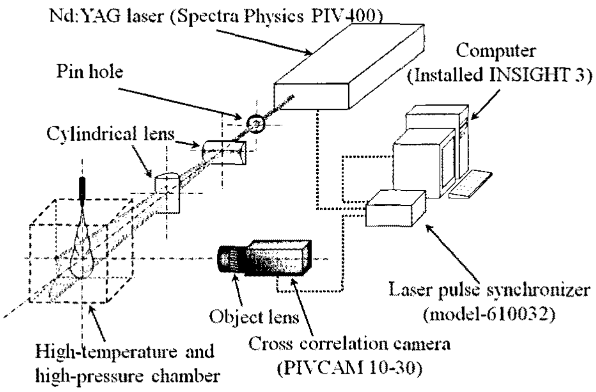


Fig. 2 Schematic diagram of optical and photography system for Mie scattering image

the power of light. Then, a thin sheet of light whose thickness is 0.2mm and width is 100.0mm is incident to the spray perpendicularly to its axis. A cross-correlation camera (TSI: PIVCAM10-30) is equipped with an objective lens (Nippon Kogaku: Micronikkor, f = 60mm) and a band pass filter (center wave length: 531.7nm, half width: 1nm, maximum transmittance: 47.8%). The camera is a digital camera with high resolution and it can take two sheets of 2-D sequential images of Mie scattering with short time interval. Its number of pixels is 1000 in width and 1012 in height; in other words, its spatial resolution is 0.06mm. The center wavelength of the filter is almost the same as that of the laser to eliminate the images through the other wavelengths. A laser pulse synchronizer (TSI:Model-610032) is controlled by software for PIV (TSI: INSIGHT3), which is installed in a personal computer, and it synchronizes the timing of the oscillation of the laser and that of photography at arbitrary timing. The distribution of velocity inside the spray is calculated by the software, which is based on the cross-correlation method. The image was digitalized 256 gradations.

2.2 Experimental procedure and conditions

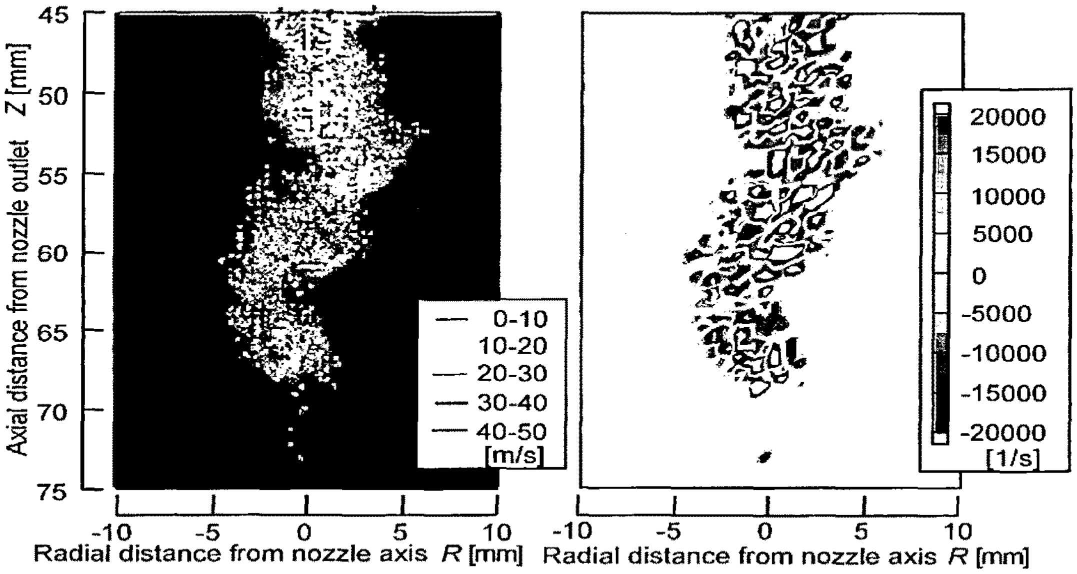
Table 1 summarizes the experimental conditions. The fuel oil of n-tridecane (purity: 99%) as the reference of JIS second-class gas oil for a high-speed diesel engine was injected through a hole nozzle having a single hole (hole diameter: 0.2mm, hole length: 1.0mm) into a chamber where nitrogen gas (purity: 99.9%) was charged to avoid the ignition. The volume of chamber was large and its wall had no effect on the growth of spray. The ambient temperature T_a was kept constant at 700K, the ambient pressure p_a was 2.55MPa constant and the charge density r_a was 12.3kg/m^3. The atmospheric conditions are the same as that at the timing of injection start in a usual high-speed DI diesel engine, and these are the smallest when the normal burning of diffusion flame is promoting in the combustion chamber, that is, the shape of flame is almost the same as that of spray. The injection pressure p_{inj} was kept constant 72MPa, the injection duration t_{inj} was 1.54ms constant and the injection quantity Q_{inj} was 12.0mg. The reproducibility of injection was confirmed before experiments. The location of photography located at the downstream of spray not at the upstream region. The PIV technique could not be applied to the latter region where the droplets density was too large. However, the flow characteristics can be catching during the injection period because the droplets density becomes sparse due to the promotion of vaporization.

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/m^3]	12.3
Injection pressure	p_{inj} [MPa]	72
Injection quantity	Q_{inj} [mg]	12.0
Injection duration	t_{inj} [ms]	1.54

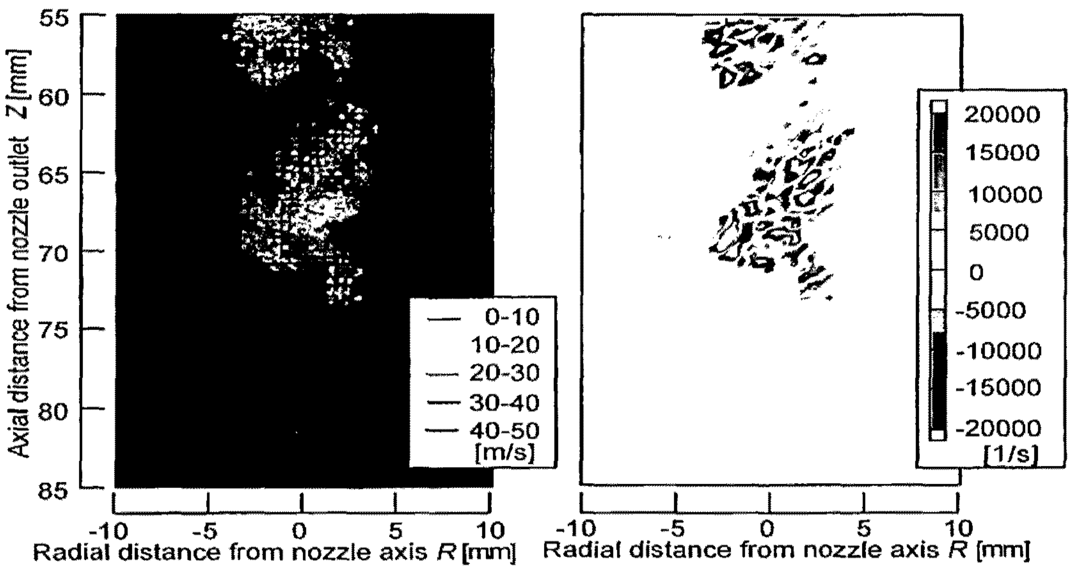
3. Experimental results

Figure 3 shows the distributions of the velocity and the vorticity at the time t= 1.12ms from the injection start, that is, during the injection duration, at the downstream region. (a) is the case of the velocity and (b) is that of the vorticity. It is marked matter that the meandering motion of the spray appears remarkably. The phenomenon becomes distinguished as the vaporization promotes. However, the fast velocity over 40m/s appears near at the central region where the droplets density and the droplet diameter are larger than that at the periphery region and the droplets keep their momentum. The velocity at the periphery region is slower than that at the central region because there is the shear between the surroundings and the spray envelope and small droplets follow the flow due



(a) Distribution of velocity (b) Distribution of vorticity

Fig. 3 Distributions of velocity and vorticity (t-1.12 [ms])



(a) Distribution of velocity (b) Distribution of vorticity

Fig. 4 Distributions of velocity and vorticity (t=1.54 [ms])

to the lost of their momentum. It is notable that the vortex with large scale exists corresponding to the meandering motion. The vorticity distributes observed at all the region, in other words, at the liquid phase of the evaporating spray. The positive vorticity and the negative one appear alternately, namely, the former exists neighboring the latter. It seems that many vortices with small scale exist inside a vortex with large scale. The tendencies of both quantities are almost the same as those of the non-evaporating spray(6).

Figure 4 demonstrates the same distributions as that of figure 3 at t = 1.54ms i.e., just at the injection end. (a) is the case of the velocity and (b) is that of the vorticity. The observed region becomes smaller than that of the case of figure 3 due to the promotion of the vaporization. However, the trend of velocity and that of vorticity are just same as those of the case of figure 3.

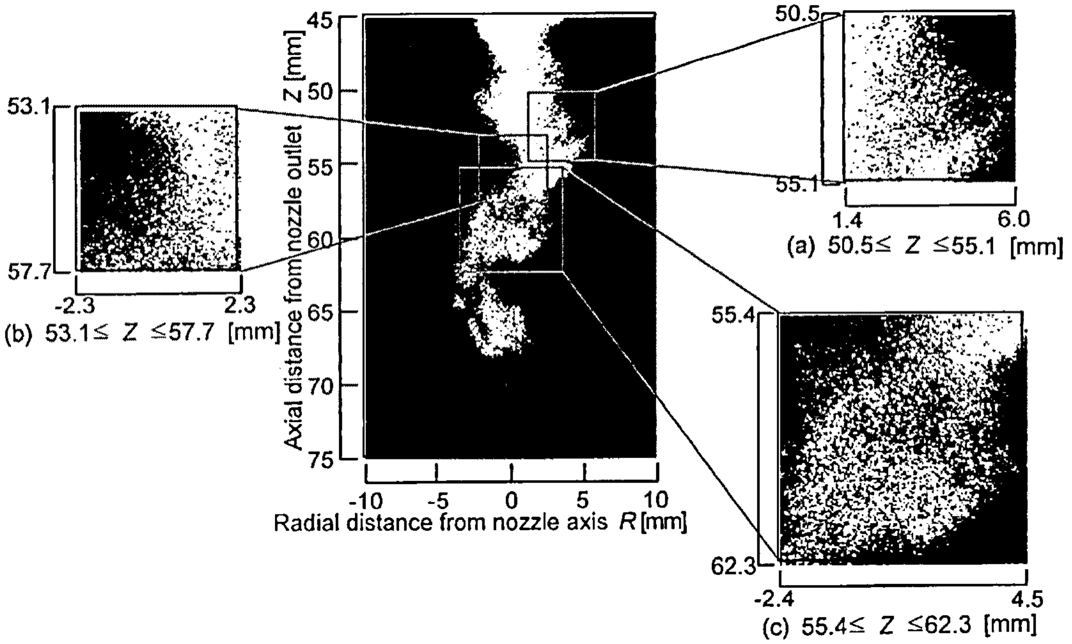


Fig. 5 Given three different small local areas applied to PIV technique (t=1.12 [ms])

To understand clearly the structure of vortex, PIV technique is applied to three different local areas picked up in figure 2, as shown in figure 5. (a) is the region of the axial distance from the nozzle outlet Z from 50.5mm to 55.1mm and that the radial distance from the nozzle axis R from 1.4mm to 6.0mm. The region locates at the right hand side of the spray periphery. (b) is the region of Z from 53.1mm to 57.7mm and that of R from -2.3mm to 2.3mm. The region is at the left hand side. (c) is the region of Z from 55.4mm to 62.3mm and that of R from -2.4mm to 4.5mm. The region covers the spray itself and the surroundings. The three small figures are expressed the luminosity by 8 bits gradation.

Figures 6, 7 and 8 show the distribution of velocity at the location presented in figure 4. At the waist region, the rotational motion with slow velocity appears in all the cases. The fast velocity exists in the vicinity of this region, that is, in the peninsular of the main flow region of the spray caused by the meandering motion. Inside the spray the large velocity and small velocity appear and they consist the vortex structure. The direction of vortex is reversing each other and its scale becomes large as the location goes near the spray tip region. From these tendencies, the

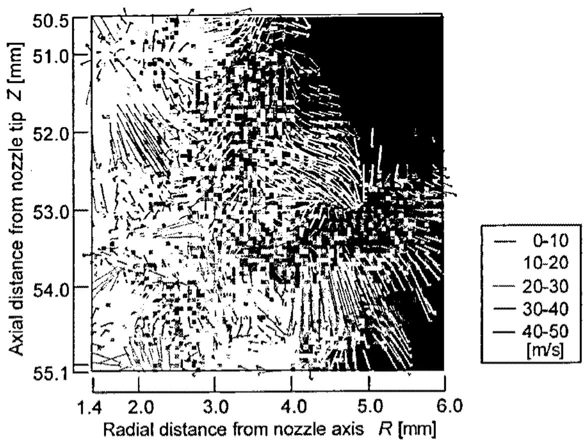


Fig. 6 Distribution of velocity at location (a) shown in Fig. 5 (t= 1.12 [ms])

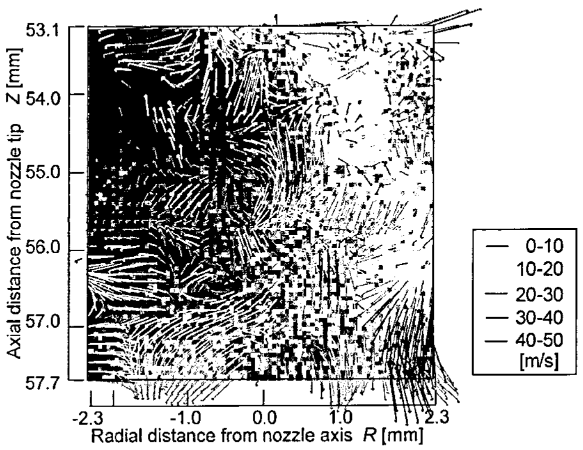


Fig. 7 Distribution of velocity at location (b) shown in Fig. 5 (t= 1.12 [ms])

spray engulfs the surroundings and it forms the vortices having reverse direction with its growth as well as the case of the non-evaporating spray.

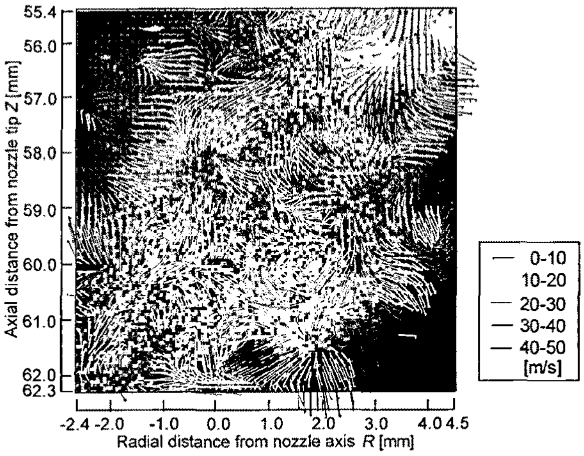


Fig. 8 Distribution of velocity at location (c) shown in Fig. 5 (t= 1.12 [ms])

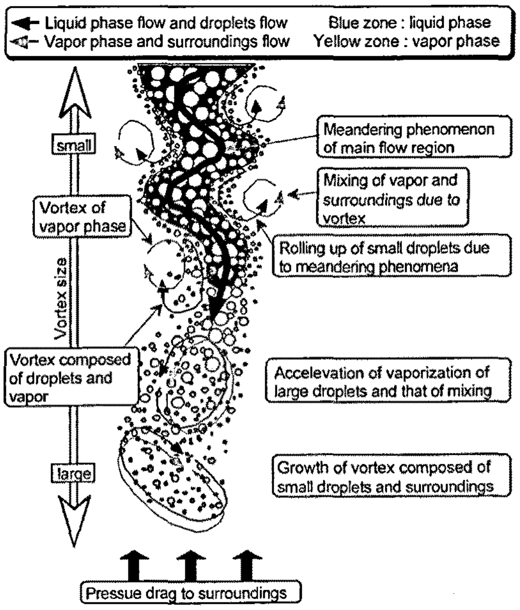


Fig. 9 Model of internal flow of evaporating spray and its surroundings

The model of the internal flow of the evaporating spray and its surroundings is constructing as shown in figure 9. This model is almost the same as that of the case of the non-evaporating spray [6]. Gray arrows express the flow of vapor phase and surroundings, and black ones show the flow of liquid phase and droplets. The blue zone is the region dominated by the liquid phase and the yellow zone is that dominated by the vapor phase.

The meandering phenomenon exists in the main flow region. Around of this region, small droplets roll up due to lost of their momentum, the vapor phase also rolls up in accompany with the droplets motion and vortices related to small droplets and vapor phase are formed. As a consequence, the mixing of vapor and surroundings is promoting. At the downstream of the main flow region, the phase composed of only the liquid becomes extinct and droplets are mixed in the vapor phase, the vaporization of pretty large droplets promotes and the mixing is accelerated. As the position locates farther from the nozzle exit, the vortex becomes larger and the mixing promotes more remarkably.

4. Conclusions

The following conclusions are drawn from the experiments:

1) The flow inside the evaporating diesel spray and that of its surroundings were almost the same as those of the non-evaporating spray.

2) The spray had vortices with large scale in which many small vortices exist.

3) The positive vorticities and the negative ones distributed alternately.

4) The scale of vortex became large as its location comes up to the spray tip region.

5) The model of internal flow of the evaporating diesel spray and its surroundings was constructed by use of the experimental results.

Acknowledgement

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