# Application of PIV technique to spray behavior characteristics study in evaporative field
# 증발 분무 거동특성 연구에 있어서 PIV 기법의 적용

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**Key Words** : 枝狀구조(Branch-like Structure), 증발디젤분무(Evaporative Diesel Spray), Mie산란법(Mie Scattering Method), 화상상관법(PIV Technique), 와(Vortex)

**Abstract** : 디젤기관의 경우는 종래부터 직분식이 주류를 이루었고, 근래에는 분사압력의 고압화가 진행 중이다. 분사압력의 고압화에 의해 연소효율의 향상 및 배출가스중의 입자상물질(PM:Particulate Matter)의 저감을 유도하고 있으나, 연소가스의 고온화로 인해 질소산화물(NOx:Nitrogen Oxides)은 증가한다. 따라서, 분사기간의 지연(Retard)이나 파일럿분사(Pilot injection)등의 혼합기제어에 의해 질소산화물의 저감을 꾀하고 있다. 이와 같이 디젤기관에 있어서도 혼합기 형성의 최적화에 의한 연소제어를 시도하는 수법이 중시되고 있고, 이를 위해서는 디젤분무 구조에 기초한 혼합기의 형성기구에 대한 규명이 매우 중요하다. 그러므로 본 연구에서는 보다 고도의 혼합기형성 제어를 위한 기초연구로서 고온·고압장에서의 증발디젤자유분무구조를 해석하였으며, 계측영역은 연료와 주위기체와의 혼합이 활발히 진행되는 분무의 하류영역으로 설정하고, 입자화상속도측정법(Particle Image Velocimetry:PIV)[1]을 이용한 분무의 유동해석을 기초로 증발 디젤분무의 구조 해석을 행하였다. 실험조건으로서 분사압력을 72MPa, 112 MPa로 각각 변화시켰다.

## 1. Introduction

Reduction of harmful gases in the emission is necessary to guarantee the preservation of diesel engines, and the methods of reduction include the injection control and the combustion control. Presently the studies on purification of diesel engines by injection control technologies such as suppression of soot by high fuel spray pressure[2] and the simultaneous reduction of NOx, PM(particulate matter) and the fuel ratio through stratified fuel and water injection are the hot topics of research[3]. On the other hand, to find active method of spray control using fuel design, Senda et al.[4] are conducting a study on trade-off between NOx and PM through injection of mixed fuel(fuel + $CO_2$). Also in case of multi-stage diesel combustion( MULDIC)[5] using multiple injection nozzles, the improvement in the fuel ratio and PM is being promoted while maintaining low NOx by freely controlling the spatial and the temporal distribution of fuel injected to the combustion chamber. In addition, the spray-control study with premixed lean diesel combustion system(PREDIC) was conducted in the field of uniform mixture formed by early injection of fuel[6]. In this study, while paying special attention to the method of spray control, the behavior of the diesel spray depending on the changes in the experimental conditions is observed and analyzed. In the spray control method, the most important task is to examine the interaction between spray formed by the injected fuel and the surrounding gas and the mixing process. Therefore in this study, evaporative diesel free spray structure under high temperature and high pressure is analyzed as a basic study for more advanced control of mixture

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formation. The measurement region is configured as downstream region of spray in which mixing of fuel with surrounding gas is being actively processed. Structural analysis of evaporative diesel spray is performed based on the flow analysis of the spray using particle image velocimetry(PIV)[1]. Although many studies have been conducted using PIV method until now, however, most of them dealt with fluid flow in-cylinder or non-evaporating spray without phase change[7-12]. The behavior of a non-evaporating spray is different compared to a real spray in actual engine. The spray behavior study is done to get more detailed information in evaporative field. Injection pressure is varied as an experimental variable.

## 2. Experimental apparatus and method

### 2.1 Experimental apparatus

Figure 1 shows the outline of high temperature and high pressure chamber used in the experiment. Table 1 shows specifications of the chamber. Visual window was manufactured using synthetic quartz to achieve transmittance of ultraviolet rays and more thermal resistance. It was coated with anti-reflection coating to prevent attenuation of entering laser. Since the chamber volume is much larger than the volume of spray injected, the effect of chamber wall on the spray can be neglected.

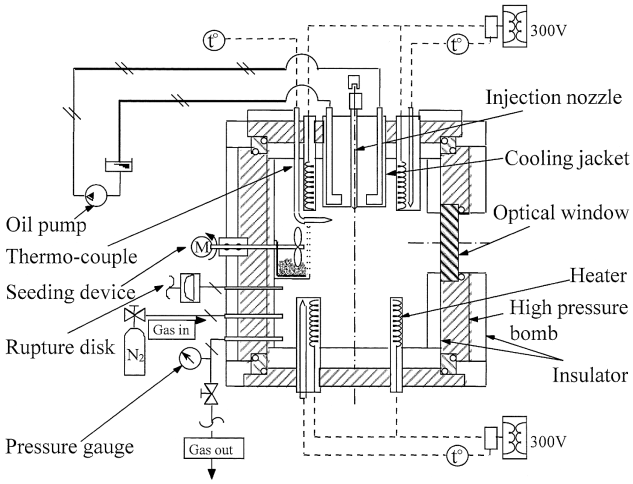


Fig. 1 Schematic diagram of experimental apparatus[13)]

Table 1 Specifications of the apparatus chamber

| | |
|---|---|
| Material | SS440 |
| Design pressure of chamber [MPa] | 3.4 |
| Maximum pressure of chamber [MPa] | 3.0 |
| Diameter of visual glass window [mm] | 120 |
| Thickness of visual glass window [mm] | 45 |

As a tracer for observing the flow of surrounding gas, seed particles(lumilight pigment: red, average diameter 2~8mm, specific gravity 4, heat resisting temperature 1023K) were mixed with gas using an agitation fan before fuel injection. Uniform distribution of seed particles in the measurement region of the chamber was verified through PIV image.

### 2.2 Experimental conditions

Table 2 presents the experimental conditions. The ambient pressure and the temperature inside the cylinder are high at the initial injection of high speed diesel engine with direct injection system. In addition, the injection system used in this experiment showed a square shaped injection rate, and the injection quantity for each capture time(i.e., 2/4, 3/4 and 4/4 $t/t_{inj}$, dimensionless time) was kept same. Prior to conducting the actual experiment, the reproducibility of the injected fuel spray was fully confirmed.

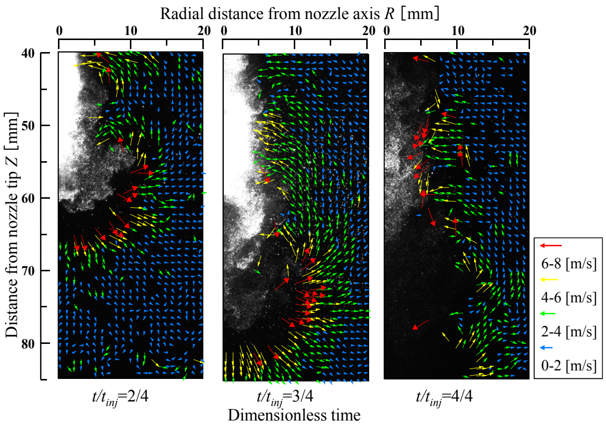
Table 2 Experimental conditions

| | |
|---|---|
| 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 $\rho_a$ [kg/m$^3$] | 12.3 |
| Injection pressure $p_{inj}$ [MPa] | 72, 112 |
| Injection quantity $Q_{inj}$ [mg] | 12.0 |
| Injection duration $t_{inj}$ [ms] | 1.54, 1.20 |

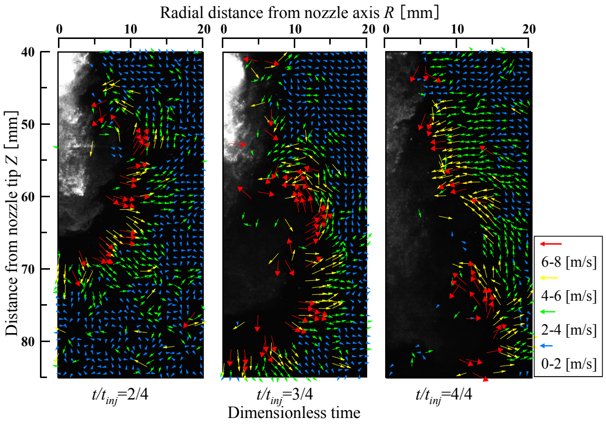
## 3. Experimental results and discussion

### 3.1 Flow analysis of surrounding gas by PIV

Figure 2 shows the velocity distribution of surrounding gas obtained by 2-dimensional section image of spray in liquid phase and PIV. The y-axis represents the distance from injection nozzle in the Z direction and the x-axis represents distance R in the radial direction. Although scattering signal of particles is used as a tracer in this study, the scattering signal of liquid droplets in the spray in addition to seed particles is also measured. However, the velocity Vm/s of the liquid-droplets in the spray was high compared to the surrounding gas velocity. Therefore, $V \geq 8.0$m/s was range cut by considering the velocity difference between liquid spray and surrounding gas. Figure 2-(b) shows the velocity distribution for high injection pressure, and there is a gap between the image of liquid spray and the velocity vector. This is thought to be the region of vapor spray with weak scattering optical density. The gap is broader in Fig. 2-(b) compared to Fig. 2-(a). The scattering optical density of overall liquid phase is low, and the difference becomes significant in the boundary of liquid phase spray. Atomization of liquid droplets is accelerated by high pressure injection and evaporation, and spreading of spray is actively performed by the vortex motion caused by shear action with surrounding gas. Branch-like structure15) found in non-evaporative spray, or asperity of spray boundary is formed by initial perturbation due to the interaction between the spray and the surrounding gas in the upstream part of the spray. Such branch-like structure causes non-uniformity of mixture in the spray and decides mixture formation characteristics of diesel spray in the downstream part of spray. Flow of seed particles mixed with surrounding gas is observed as they flow towards the spray in the upstream and in the direction of growth of spray at the downstream, with liquid phase length of spray as the boundary at t/tinj=2/4, 3/4. Therefore, with the entrainment of surrounding gas into the spray in the upstream region, the spray velocity is increased causing the vortex motion. On one hand, there is a vector with large velocity in the direction of growth of spray in the length part. Also in the length part of the spray, the flow velocity is in the direction of radius, because of the resistance offered by the surrounding gas. Local increase in pressure occurs at the tip of the spray, is caused by the inertia of the spray injected at high velocity into the gas. A relative pressure decay results in the boundary surface because of the entrance of surrounding gas. Thus, pressure gradient that occurs in the continuous space within the chamber controls the flow of surrounding gas. As a result, macroscopically in the regions away from liquid phase of spray in Figs. 2-(a) and (b), a large scale vortex flow of surrounding gas seems to occur while moving from the tip to the upstream.



(a) $p_{inj}$=72[MPa], $t_{inj}$=1.54[ms]



(b) $p_{inj}$=112[MPa], $t_{inj}$=1.20[ms]

Fig. 2 Temporal change in ambient gas velocity taken by PIV method[14)]

### 3.2 Flow analysis of surrounding gas by statistical method

Figure 3 shows the average velocity V of surrounding gas, calculated from second power average of data. In the lateral axis, measurement position was divided by the spray tip distance $L_{liq}$ in order to examine the correlation with the tip. According to Takahashi et al.[16], tip distance does not depend on injection pressure if mass of fuel in the spray is kept constant under the same ambient conditions. However, due to sudden change in scattering luminance in this study, it is difficult to measure the spray tip distance of liquid phase. The liquid phase tip distance $L_{liq}$ was taken from the experimental results of exciplex fluorescence method performed by Takahashi et al.[9]. The length, are $L_{liq}$= 65.05mm at $t/t_{inj}$= 2/4, $L_{liq}$= 74.81mm at $t/t_{inj}$= 3/4, and $L_{liq}$= 82.66mm at $t/t_{inj}$= 4/4. As shown in the figure, the motion of surrounding gas that receives the momentum from the injected fuel becomes active with the progress of time. Also, when the injection pressure is low, the flow of surrounding gas maintain relatively smooth changes in the velocity for long time in the region $Z/L_{liq}$= 1.0. When the injection pressure is high, change in velocity becomes rapid and flow becomes more complicated. Here, the change in the velocity of surrounding gas is correlated with the size of the flow, and the sample displacement coefficient[17] that shows the change in velocity is applied to average velocity in Fig. 2.

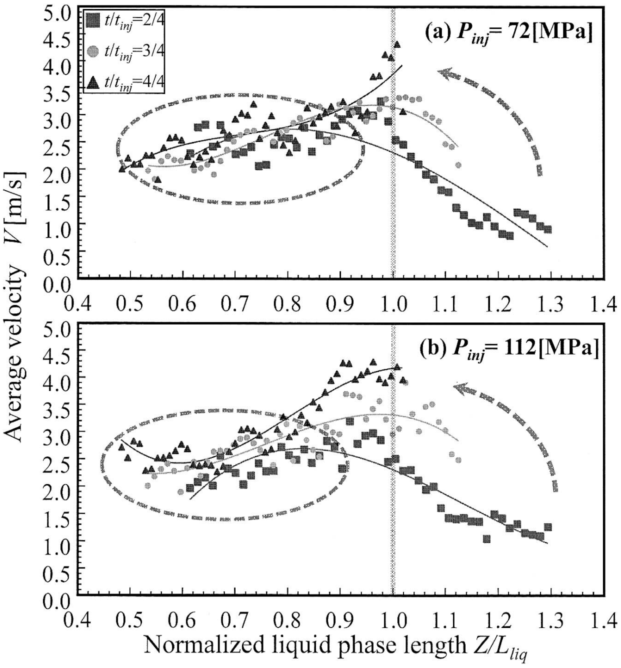


Fig. 3 Temporal change in average velocity

Figure 4 quantitatively shows the change in average velocity caused by injection pressure. In addition, (a), (b) and (c) in the figure each represent the sample displacement coefficients of

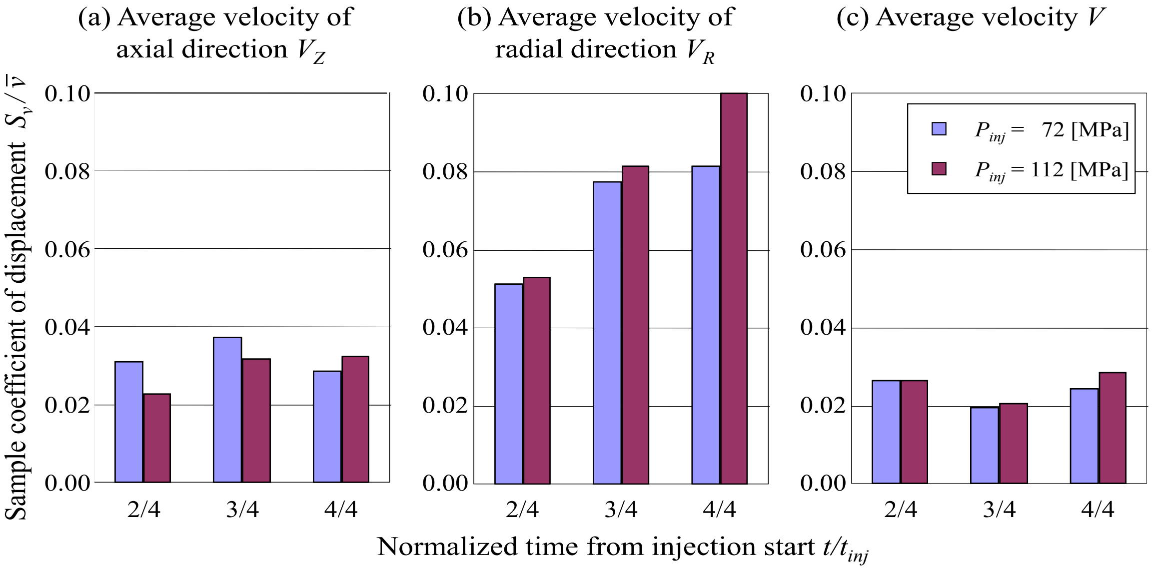
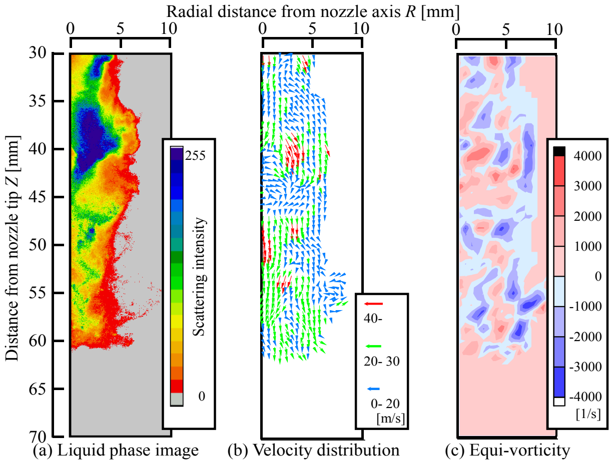


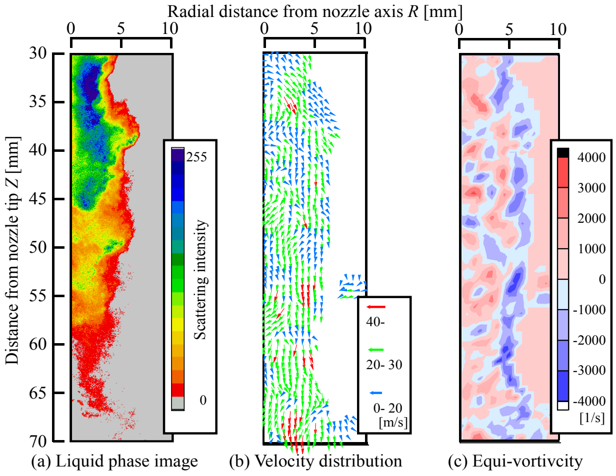
Fig. 4 Temporal change in sample displacement coefficient under injection pressure variation

velocity in the lateral direction $V_R$, velocity in the radial direction $V_Z$, and velocity of surrounding gas V. In terms of lateral direction velocity in (a), change in velocity is small until $t/t_{inj}=2/4$, 3/4 and the injection pressure is high($p_{inj}$=112MPa). However, change in radial velocity is large when injection pressure is high for each filming time of (b). This result is the opposite of lateral speed in (a). The magnitude of velocity in the radial direction in (b) is larger, and the change in velocity is also larger than lateral direction. Diffusion is divided into molecular diffusion by thermal motions and vortex diffusion by the vortex flow[18], but the vortex diffusion is important in the diffusion of spray. The vortex diffusion refers to the phenomenon in which the property moves in the direction of flow and in the perpendicular direction by the movement of vortex included in the flow. Velocity in the direction perpendicular to flow, or in the radial direction, is related to vortex diffusion. As a result, increased injection pressure seems to increase the vortex motion of the surrounding gas.



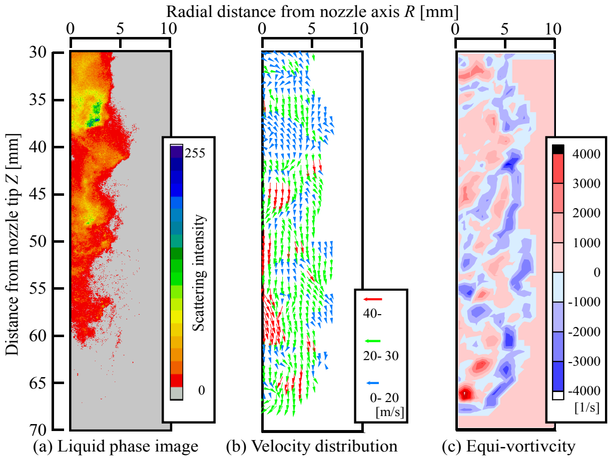
(a) Liquid phase image (b) Velocity distribution (c) Equi-vorticity

Fig. 5 Calculated results taken by PIV at time from injection start, t/tinj=2/4



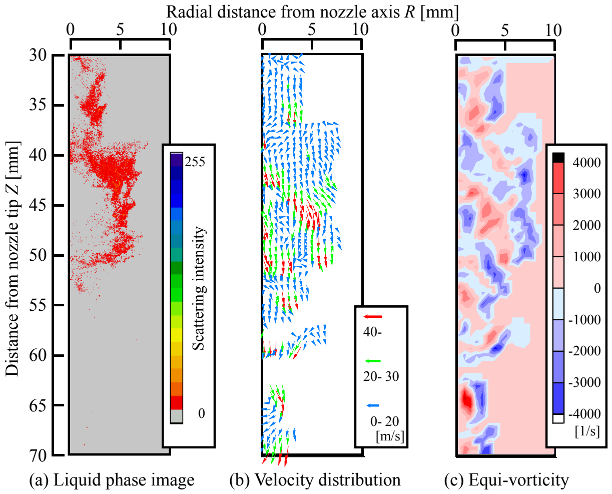
(a) Liquid phase image (b) Velocity distribution (c) Equi-vortivcity

Fig. 6 Calculated results taken by PIV at time from injection start, t/tinj=3/4



(a) Liquid phase image (b) Velocity distribution (c) Equi-vortivcity

Fig. 7 Calculated results taken by PIV at time from injection start, $t/t_{inj}=4/4$



(a) Liquid phase image (b) Velocity distribution (c) Equi-vorticity

Fig. 8 Calculated results taken by PIV at time from injection start, t/tinj=5/4

Figures 5~8 are the results obtained by PIV analysis using liquid Mie scattering signal as tracer. In each figure, (a) shows the image of scattering light in liquid spray, (b) the velocity vector distribution and (c) the vorticity distribution. Also, the time interval between the two images for PIV measurement was chosen as

Dt=5ms. The figures, (a) are converted from 8bit(256steps) black and white images to 20step color images in order to clearly show luminance change, distribution of liquid droplet diameter and density. Tanaka[19)] defines Z=56mm as the turning point of the liquid spray in the flow analysis of evaporative spray performed under identical conditions. Accordingly the mainstream region of liquid spray that separates vortex structure horizontally exists from the nozzle exit to until Z=56mm. In the downstream, separated vortex structures come together to form a complicated flow. Takahashi[16)] defines the region from nozzle exit to Z=38mm as liquid phase nucleus and argues that this is the region in which exchange of momentum with surrounding gas is active. In the liquid phase images of Figs. 5~8 (a), high luminance is continuously shown along the central axis of spray until Z=50mm. The change in luminance is significant in downstream region in the exterior of spray or below Z=50mm. Also looking at the velocity vector shown by (b), there is a vector with high velocity in the region of high scattering luminance. Change in velocity vector becomes remarkable in regions with rapid change in luminance and a local vortex flow is observed. From the vorticity distribution in (c), a strong vorticity of $w<-3000s^{-1}$ exists at the wall in the exterior of the spray. The vortex is formed on the exterior of spray and scattered by the shear action of the surrounding gas. The region with high vorticity is seen locally in the downstream of the spray. Liquid fuel droplet loses the momentum given during the injection and follows the flow of surrounding gas. After the injection, as illustrated in Fig. 8, liquid phase of spray is hardly observed and the flow becomes significantly turbulent. This is similar to the phenomenon at the tip of spray described above. Momentum of liquid fuel droplets is gradually lost and droplets are controlled by the flow of surrounding gas.

## 4. Conclusions

The focus of this study was placed on the analysis of the mixture formation process from structure characteristics of evaporative free diesel spray under high temperature and high pressure field. Particle image velocimetry was used as visual measurement method.

The following conclusions are drawn from the results of this study.

1) In the case of non-evaporative spray, a non-uniform distribution of liquid droplets in branch-like structure exists in evaporative spray, caused by the vortex motion which occurs due to the interaction between injected fuel and surrounding gas. As a result, a mixture of non-uniform concentration is formed in the branch-like structure.

2) For evaporative free diesel spray, the increase in the injection pressure turns the flow of surrounding gas in the radial direction($V_R$) with more irregular vortex diffusion. As a result, mixing of injected fuel and surrounding gas is accelerated.

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## References

1. Shioji, M., Kimoto, T., Okamoto, M. and Ikegami, M., 1998, “An Analysis of Diesel Flame by Picture Processing”, Transactions of the Japan Society of Mechanical Engineers Series B, Vol. 54, No. 504, pp. 2228-2235.
2. Ando, H., 2000, “Key Word for Power Train Development of the Future Car”, Journal of Society of Automotive Engineers of Japan, Vol. 54, No. 7, pp. 7-9.
3. Kohketsu, S., Mori, K., Sakai, K., Nakagawa, H. and Oda, Y., 1996, “Reduction of Exhaust Emission with Fuel-Water Stratified Injection System in a Diesel Engine”, The 13th Internal Combustion Engine Symposium pp.465-470(in Japanese).

4. Senda, J., Yokoyama, T., Ikeda, M. and Fujimoto, H., 1998, “Spray Combustion of Liquefied $CO_2$ Mixed Fuel for NO and soot Simultaneous Reduction”, International Symposium COMODIA 98(Kyoto), pp.117-122.
5. Takeda, Y. and Niimura, K., 1995 “Characteristics of Diesel Combustion and Emissions with a Multi-Injector System”, SAE Paper 952511.
6. Takeda, Y., 1995, “Reduction of NOx with Premixed Lean Diesel Combustion”, New-ACE Technical Paper, pp.89-92.
7. Lee, K. H., Lee, C. H. 2007, “Experimental Study on the Flow and Mixture Distribution in a Visualization Engine Using Digital Particle Image Velocimetry and Entropy Analysis”, IJAT, Vol. 8, No. 2 pp.127-135.
8. Ohm, I. Y. and Park, C. J., 2006, “In-Cylinder Compression Flow Characteristics According to Inlet Valve Angle”, Transactions of KSAE, Vol. 14, No. 4, pp.77-83.
9. Choi, K. H., Park, J. H. and Lee, N. H., 1998, “Analysis of Spray and Flow Fields for Development of Spark-ignited Direct Injection Engine”, Transactions of KSAE, Vol. 6, No. 6, pp.202-209.
10. An, Y. H., Lee, C. H., Lee, K. H. and Lee, C. S., 2004, “A Study on the Spray Characteristics of Swirl Injector for Use a HCCI Engine using Entropy Analysis and PIV Technique”, Transactions of KSAE, Vol. 12, No. 1, pp.39-47.
11. Lee, C. H., Lee, K. H. and Lee, C. S., 2005, “An Experimental Study on the Flow Characteristics and the Stratification Effects in Visualization Engine Using the DPIV and the Entropy Analysis″, Transactions of KSAE, Vol. 13, No. 1, pp.9-18.
12. Choi, W., Hong, C. H. and Choi, B. C., 2001, “Estimation on Air-entraining Tendency of a Transient High Pressure Diesel Spray”, Proceeding of KSAE Fall, Vol. 1, pp.311-317.
13. Yeom, J. K., 2010, “An Experimental Analysis on the Behavior Characteristics of Evaporative Impinging Spray″, KSPSE, Vol. 14. No. 2, pp.16-21.
14. Yeom, J. K., 2008, “Diagnosis of the Behavior Characteristics of the Evaporative Diesel Spray by Using Images Analysis”, KSME International Journal(JMST) Vol. 22, pp. 1785-1792.
15. Dan, T., 1996, “Turbulent Structure and Formation Mechanism of Diesel Sprays”, Doshisha University Doctoral Thesis, Japan.
16. Takahashi, T., 1999, “Analysis on the Vaporization, Dispersion and Mixing Process in Unsteady Diesel Spray”, Doshisha University Master’s Thesis, Japan.
17. Soeda, T., Ota, M. and Omatsu, S., 1992, “Fundamental and Application of Mathematical Statistics”, Nissin Publication, pp. 177-178.
18. Takarazawa, M., Toada, M., Kikuchi, K., Yonemoto, T. and Tsukada, T., 1996, “Diffusion and Transport Phenomena”, Baifukan, pp. 123-125.
19. Tanaka, T., 2000, “Analysis on Inner Structure and Mixture Formation Process in Unsteady Evaporating Diesel Sprays”, Doshisha University Master’s Thesis, Japan.