

# Flow Characteristics inside Liquid Phase in an Evaporating Spray by Means of PIV

by

H. Fujimoto, T. Tanaka, K. Ashida, J.-K. Yeom and J. Senda

Doshisha University

Department of Mechanical Engineering

Kyotanabe, Kyoto 610-0321; Japan

## ABSTRACT

It is very significant to detect the flow characteristics inside diesel spray for understanding its mixing process between itself and its surroundings. It is capable of catching 2-D image of them only by use of PIV method not LDV technique. One of authors presented the characteristics of a non-evaporating spray of JIS-second class gas oil under the elevated pressure by applying this method in the other paper. This paper describes the case of an evaporating diesel spray under the quiescent atmosphere with high temperature at high pressure. 2-D image of Mie scattering of the unsteady spray was taken by a thin sheet of laser light passing through the cross sectional area including the spray axis. The distribution of velocity and that of vorticity were calculated by the application of the cross-correlation method as PIV technique to 2-D images. Figure 1 shows one of examples of the velocity distribution. Comparing with such results of evaporating spray and those of non-evaporating spray, the flow characteristics inside the former one are almost the same as those inside the latter one.

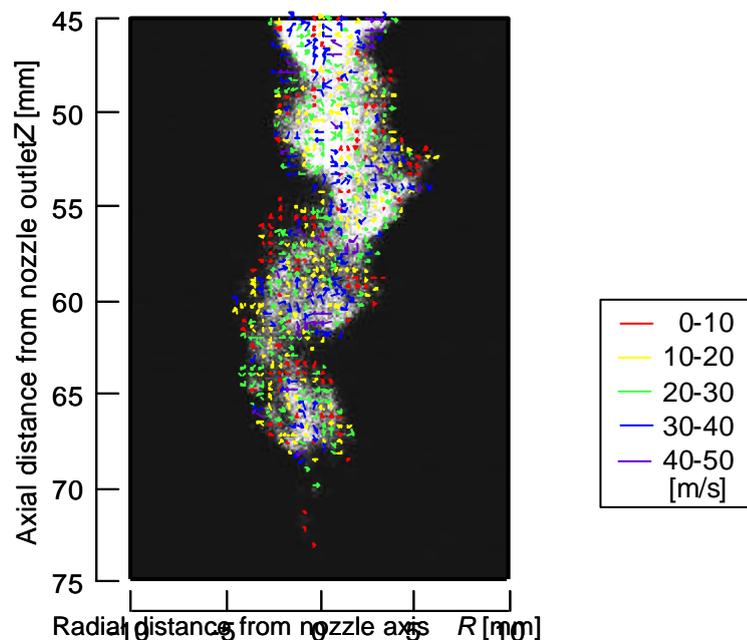


Fig. 1 One of examples of velocity distribution inside evaporating diesel spray ( $t=1.12$  [ms],  $t_{inj}=1.54$  [ms])

## 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 large. The injection pressure is very high, that is, over 100 Mpa, and the injection duration is very short, that is, 10 [ms] at most. The vaporization of spray, the diffusion and the mixing between the spray and its surroundings break out simultaneously just after injection start. Thereafter, the combustible mixture is formed and the combustion is promoting. Namely, it is very significant to detect the flow characteristics inside diesel spray for understanding its mixing process between itself and its surroundings.

The air motion around a diesel spray was investigated by one of the authors [1]. The motion was taken by the high-speed photography using the smoke wire method. The results are that the air is 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, the diesel spray has vortices with large scale in which many vortices with small scale are existent. These vortices are caused by the spray motion itself and the mutual interaction between it 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 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 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. 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 a 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 532 [nm] of the second harmonics. The power of light is 400 [mJ/pulse], the dimension of round is 10.0 [mm] in diameter, the pulse interval is 8 [ns] and the maximum oscillation frequency is 10 [Hz]. The light is passing through a pinhole to change its diameter from 10 [mm] to 5 [mm] and it is going to two sets of cylindrical lenses whose optical length are 15 [mm] and 1000 [mm], 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 the power of light. Then, a thin sheet of light whose thickness is 0.2 [mm] and width is 100.0 [mm] 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,  $f = 60$  [mm]) and a band pass filter (center wave length: 531.7 [nm], half width: 1 [nm], 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 0.06 [ $\mu\text{m}$ ]. 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.

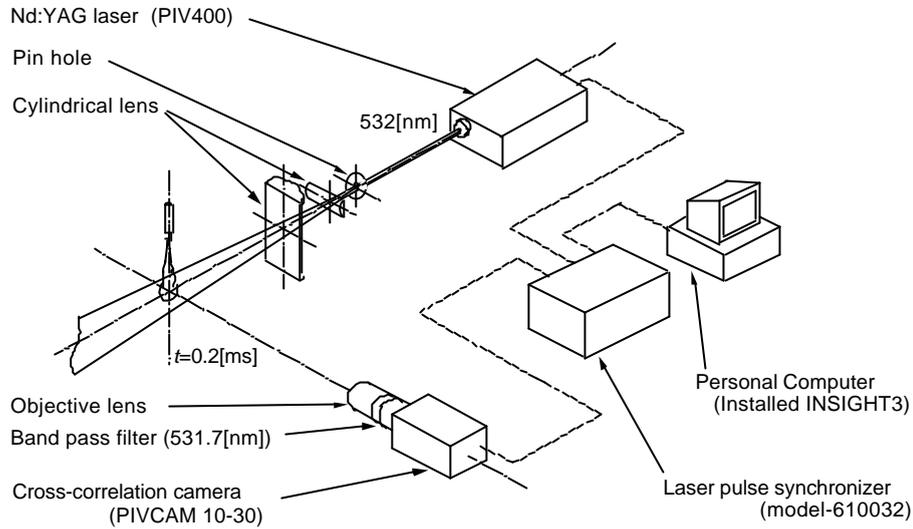


Fig. 2 Schematic diagram of optical and photography system for Mie scattering image

## 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: 0.2 [mm], hole length: 1.0 [mm]) 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 700 [K], the ambient pressure  $p_a$  was 2.55 [MPa] constant and the charge density  $r_a$  was 12.3 [ $\text{kg}/\text{m}^3$ ]. 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 72 [MPa], the injection duration  $t_{inj}$  was 1.54 [ms] constant and the injection quantity  $Q_{inj}$  was 12.0 [mg]. 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 <sub>2</sub> gas
Ambient temperature	$T_a$ [K]	700
Ambient pressure	$p_a$ [MPa]	2.55
Ambient density	$r_a$ [ $\text{kg}/\text{m}^3$ ]	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  $t = 1.12$  [ms] 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 40 [m/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 to the lost of their momentum. It is notable that the vortex with large scale exists corresponding to the meandering motion. The vorticity distributes at all the region observed, 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].

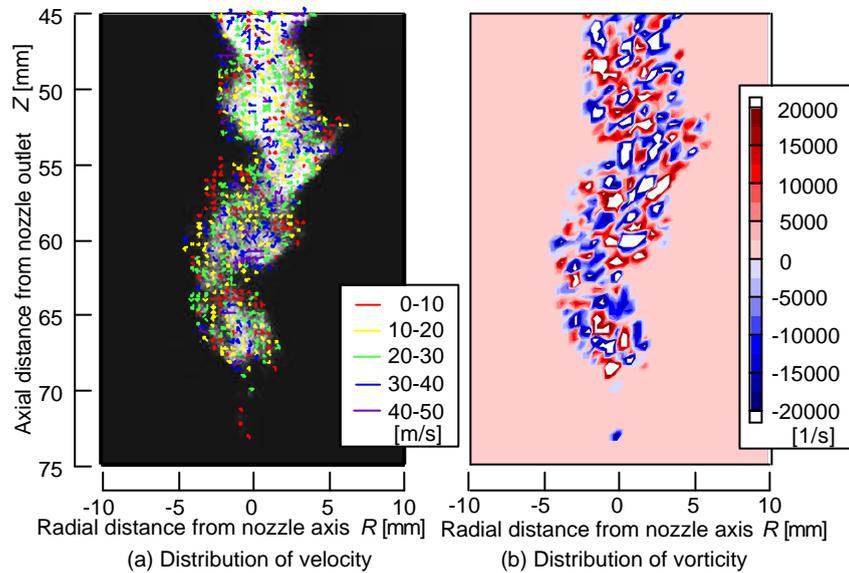


Fig. 3 Distributions of velocity and vorticity ( $t=1.12$  [ms])

Figure 4 demonstrates the same distributions as that of figure 3 at  $t = 1.54$  [ms] 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.

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 50.5 [mm] to 55.1 [mm] and that the radial distance from the nozzle axis  $R$  from 1.4 [mm] to 6.0 [mm]. The region locates at the right hand side of the spray periphery. (b) is the region of  $Z$  from 53.1 [mm] to 57.7 [mm] and that of  $R$  from  $-2.3$  [mm] to 2.3 [mm]. The region is at the left hand side. (c) is the region of  $Z$  from 55.4 [mm] to 62.3 [mm] and that of  $R$  from  $-2.4$  [mm] to 4.5 [mm]. The region covers the spray itself and the surroundings. The three small figures are expressed the luminosity by 8 bits gradation.

Figure 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 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.

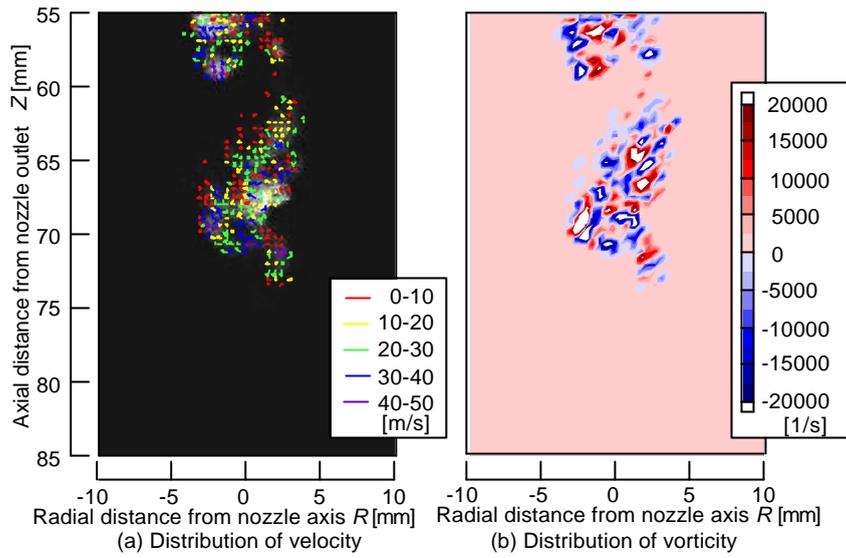


Fig. 4 Distributions of velocity and vorticity ( $t=1.54$  [ms])

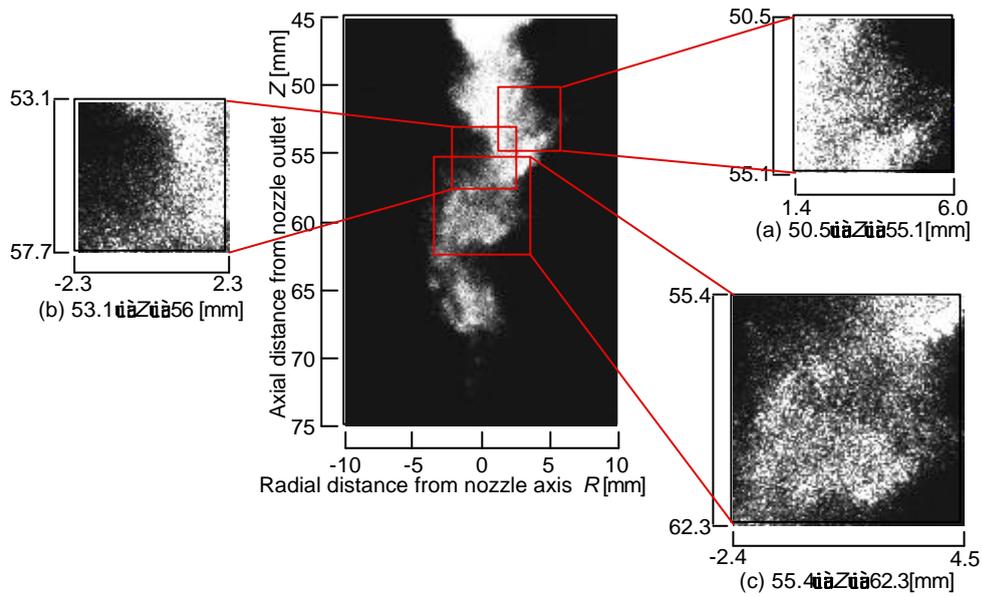


Fig. 5 Given three different small local areas applied to PIV technique ( $t=1.12$  [ms])

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.

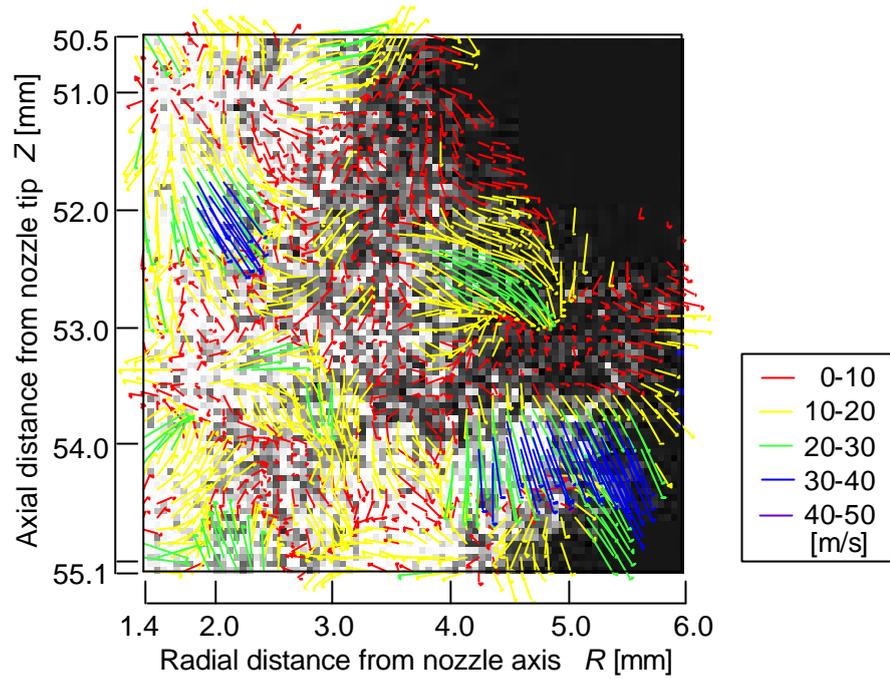


Fig. 6 Distribution of velocity at location (a) shown in Fig. 4 ( $t= 1.12$  [ms])

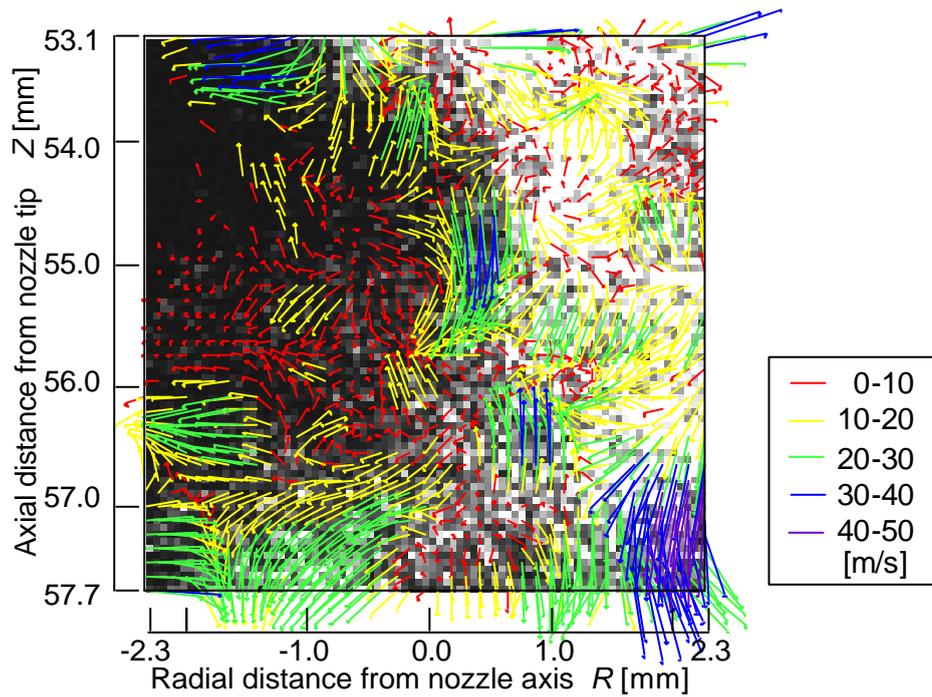


Fig. 7 Distribution of velocity at location (b) shown in Fig. 4 ( $t= 1.12$  [ms])

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.

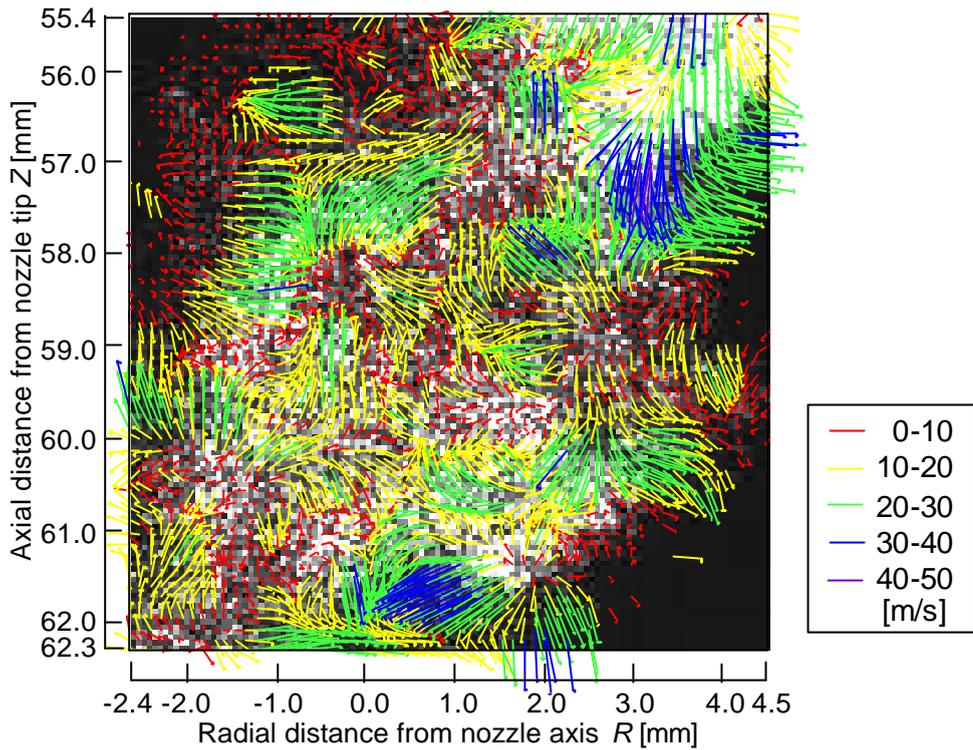


Fig. 8 Distribution of velocity at location (c) shown in Fig. 4 ( $t= 1.12$  [ms])

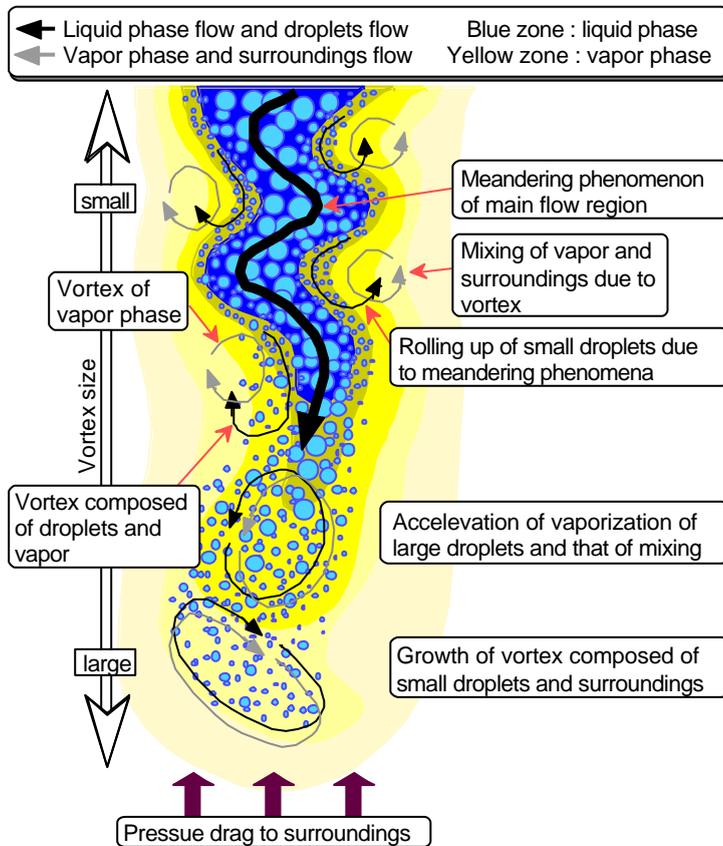


Fig.9 Model of internal flow of evaporating spray and its surroundings

#### **4. Conclusions**

The following conclusions are drawn from the experiments:

- (1) The flow inside the evaporating diesel spray and that of its surroundings are almost the same as those of the non-evaporating spray.
- (2) The spray has vortices with large scale in which many small vortices exist.
- (3) The positive vorticities and the negative ones distribute alternately.
- (4) The scale of vortex becomes 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 is constructed by use of the experimental results.

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