

# Simultaneous measurement of velocity and oxygen distributions using PIV-PSP hybrid system

by

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## ABSTRACT

A simultaneous measurement technique for the velocity distributions and scholar distributions, e.g., pressure, temperature, and so on, has been proposed. It visualized the spatial distribution using the multi-purpose particles, which has been coated with pressure-sensitive dye. The proposed particle technique, called the PSParticle method, is a hybrid system combining the technologies of pressure-sensitive paint (PSP) and particle image velocimetry (PIV) and allows the particle velocity and oxygen distribution to be measured simultaneously. A luminescence lifetime-based imaging technique involving double frame imaging is introduced. The system is calibrated and demonstrated in application to measurement of the oxygen distribution in an air jet. The velocity distributions are measured using the PSParticle movement (PIV). Simultaneously, the oxygen fraction distributions are measured using the PSParticle intensity lifetime (PSP).

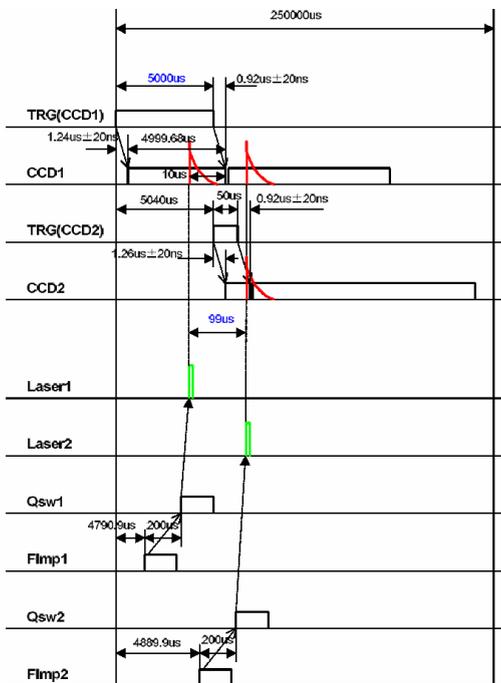


Fig. 1. Timing chart for PSP/PIV Hybrid image.

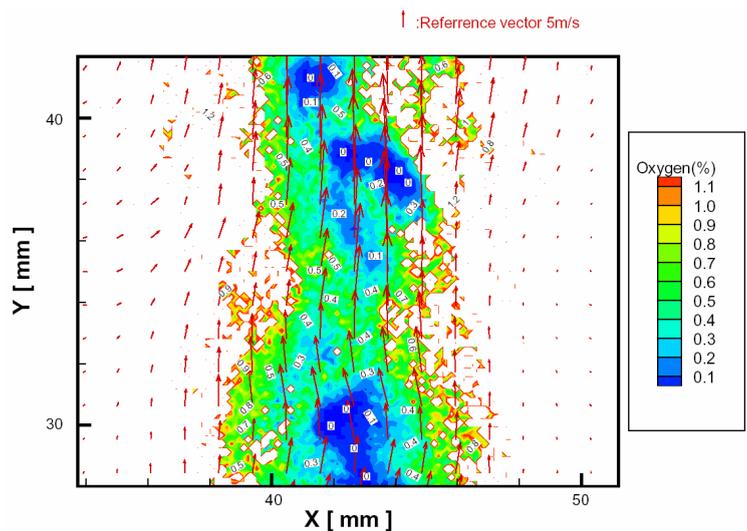


Fig.2 Example of measured data.

(velocity and oxygen mole-fraction)

## 1. INTRODUCTION

PSP (Pressure Sensitive Paint) measurement technique is a method to obtain oxygen distribution on a surface. This technique uses special chemical dyes. (McLachlan and Bell, 1995, Liu et al., 1997) The basis of this technique is using of luminescence quenching phenomena by oxygen. The PSP dye emits luminescence when it is excited by specific wavelength light. And the emitted light intensity is influenced by oxygen concentration. Therefore, The PSP technique is a method that gives a relationship between luminescence intensity and oxygen concentration. The information of oxygen distribution can easily change to pressure value information.

When this technique applies to surface pressure measurement, the PSP dye paints on a target surface using the special binder that is diffused oxygen molecules in it well. Recently, this technique has developed rapidly and applied to many applications widely. For example, surface pressure distribution measurement on airplane model, on turbine blade and analysis of any basic fluid dynamics phenomena etc. But, at the moment the PSP technique are used on a surface measurement only.

PIV (Particle Image Velocimetry) measurement technique is a velocity measurement by particle tracing on image. This technique can obtain instantaneous two-dimensional velocity distribution by non-contact way and applies to a lot of studies about fluid dynamics as a powerful measurement tool. (Adrian, 1991) Recently, Not only velocity measurement but some simultaneous measurement has been developed using other specific measurement technique which are LIF (Laser Induced Fluorescence), TLC (Thermo-chromic liquid crystal) etc. Simultaneous measurement of PIV with other technique must be given much effective information rather than each single measurement. (Sakakibara and Adrian, 1998, Hishida and Sakakibara, 2000)

The authors report a new technique for measuring oxygen density distribution in space using PSP technique (Abe et al., 2004). In order to measure the oxygen density distribution in space, instead of on a surface, the PSParticle (Pressure Sensitive Particle) for seeding in gas was developed. It is the particle with PSP dye. Such kind of tracer particle was named PSParticle to distinguish with conventional PSP. The particle is so-called the multi-purpose particles, which indicate the velocity and pressure distributions.

In the usual PSP system, the continuous light illumination system is used. Pressure, i.e., oxygen mole fraction, has been detected with the intensity distributions of PSP dye. However, to measure the PIV simultaneously, the pulsed laser illumination should be used. When the PSP dye is excited by the pulsed illumination, the luminescence intensity raises sharply and then decay due to influence by oxygen. The lifetime is a function of oxygen mole-fraction. With measuring the intensity itself, the intensity value may have a function of oxygen mole-fraction. However, it does have an effect of pulse laser intensity. Also, the intensity is affected by the concentration of PSP dye itself. When the PSP dye is stuck on the surface, the PSP dye concentration has a constant value; therefore, it can be canceled out using the calibration images. While, in the PSParticle case, the particle does move in the space, because it should follow the flow velocity. Therefore, the PSP dye concentration in space does change with time. This means that the intensity of the PSParticle image is not only a function of oxygen mole-fraction, but also the function of PSParticle concentration, (distribution of PSParticle). We should cancel out the effects of the PSParticle concentration in space.

In order to overcome above the problem, the double frame method was developed. Furthermore, The method, which uses PSParticle, can be obtained the velocity information as the PIV technique at the same time. The two double-shutter cameras and double pulse laser for PIV had been applied to develop the PSP/PIV hybrid system.

## 2. PSParticle Methods

### 2.1 Lifetime

The PSP measurement technique applies the luminescence quenching phenomena by oxygen. The lifetime of the fluorescence is usually pico to nano seconds order. Another path is through the intersystem crossing and excited triplet state. The energy level of PSP molecule on the triplet state return to the ground state by internal conversion and emits phosphorescence. The intersystem crossing by the electron spin-flip gives long lifetime for luminescence as phosphorescence. Normally, cause of this, the lifetime of phosphorescence continues micro to milli seconds order.

When the PSP molecules are surrounded by oxygen containing gas, oxygen molecule quenches the phosphorescence emission energy cause of oxygen molecule is on the same excited triplet state and lifts up its energy level. It means the energy can easily transfer between same energy level and phosphorescence from PSP molecules is quenched by oxygen efficiently. Thus, when oxygen concentration is smaller the luminescence lifetime becomes to longer and on the other hand the oxygen concentration is larger the rate of luminescence intensity decay becomes faster. Figure 1 shows the experimental data of the decay curve of the PSP dye with the pulsed laser illumination. The pulse width of the laser is 7ns, which is short enough for the measurement of the decay. The lower the oxygen mole-fraction is, the faster the decay is, as shown in Fig.1. The lifetime is a function of oxygen mole-fraction. The decay curve of the intensity of the luminescence is schematically expressed as follows,

$$I_{dye} = I_0(C_{dye}) \cdot f(O_2) \quad \text{for PSP (Paint)} \quad (1)$$

$$I_{particle} = I_0(C_{particle}(x, y, t)) \cdot f(O_2) \quad \text{for PSParticle} \quad (2)$$

where,  $I_0$  is the initial peak intensity. In the Pressure Sensitive Paint (PSP) case, the concentration of PSP dye is always constant because the dye is painted on the surface. However, in the PSParticle case, the  $I_0$  is a function of oxygen mole-fraction and the concentration of PSP dye, i.e., concentration of PSParticle. The PSParticle move in the space with the flow. This means the  $I_0$  is a function of location and time. The intensity data cannot be used for the oxygen mole-fraction measurement.

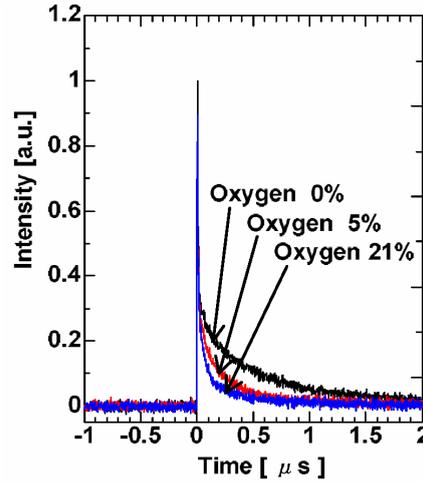


Fig.1 Decay profiles of PSP

## 2.2 Double Frame Imaging

Figure 2 schematically shows the intensity decay of the luminescence by oxygen. Initially, the luminescence of dye has a peak value  $I_0$  with the laser pulse illumination, then it decays. The decay curve has been divided into two parts; first half which consists of the initial peak  $I_0$ , and second half which consists of the intensity decay with oxygen. These two parts are measured using the CCD camera, which accumulates the light during the shutter period. The first half is recorded onto Image A, then second half does onto Image B. The accumulated lights for both images are assumed to be,

$$I_A = \int_A I dt = a I_0 \quad (3)$$

$$I_B = \int_B I dt = b I_0 \cdot g(O_2) \quad (4)$$

$I_A$  is the function of  $I_0$ , while,  $I_B$  is a function of  $I_0$  and decay curve, i.e. Oxygen mole-fraction. Then, let's take the ratio of  $I_A$  to  $I_B$ . The effect of the initial peak  $I_0$  has been cancel out in  $I_A/I_B$ , as shown in Equation (5), The  $I_A/I_B$  does only be a function of oxygen mole-fraction.

$$\frac{I_A}{I_B} = \frac{bI_0 \cdot g(O_2)}{aI_0} = g \cdot g(O_2) \quad (5)$$

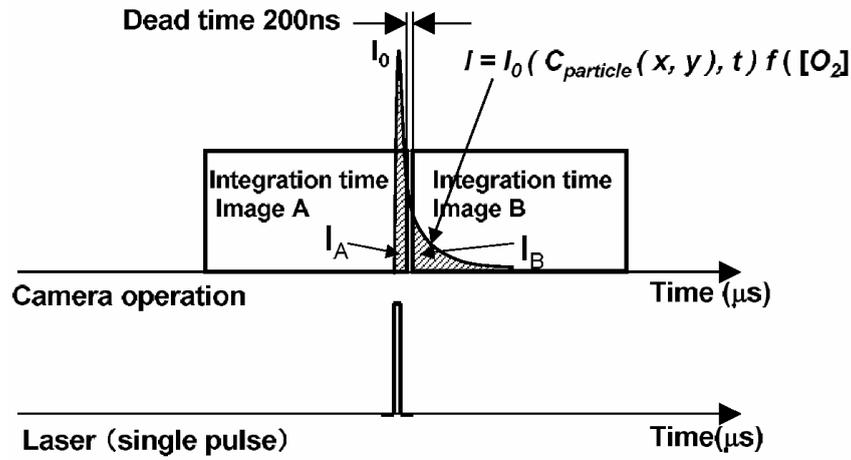


Fig.2 Schematic Image of Double Frame Imaging

### 2.3 PSParticle

The PSParticle is made with a God Ball (Suzuki Yushi Kougyo, B-25C). It is a micro-balloon made of silicon dioxide. Shape is hollow porous globular particle. The diameter is 0.5 to 25  $\mu\text{m}$ , with about 13  $\mu\text{m}$  in average. True density and bulk densities are 2.1  $\text{g}/\text{m}^3$  and 0.22 ~ 0.40  $\text{g}/\text{m}^3$ . The God Ball is widely used as the tracer particle for air flows. The porous medium has an advantage to capture the PSP dye on the medium. No binder is needed. Also, the dye has direct contact with the air. As the PSP dye, ruthenium complex ( $\text{Ru}(\text{pby})_3^{2+}$ ) is used. The solution of mixing 0.10mg of ruthenium complex ( $\text{Ru}(\text{bpy})_3^{2+}$ ) in 100ml of ethyl alcohol is prepared. The dye concentration is 0.0013 mol/L. Then the particle is dipped in the ruthenium complex solution. The sediment is dried and crushed well. The ethyl alcohol does not react to silicon dioxide chemically. Consequently the pressure sensitive dye invaded into the porous holes of the God Ball to be a PSParticle. The emission wave length of the PSParticle is 600nm.

### 2.4 Calibration

Using the Double Frame Imaging technique, the calibration curve should be obtained. The PSParticle has been set on the glass plate inside the gas chamber. The oxygen mole-fraction of the gas chamber has been controlled by the oxygen and nitrogen flow rate and monitored by the Galvano meter. The PSParticle is illuminated by the pulsed laser with 532nm or 355nm. The images are captured by the double shutter camera (PCO Sensicam). The double shutter mode enables the very short dead time for two sequential images. The dead time for the camera is only 200ns. Therefore, the intensity variations with the lifetime of around 500ns can be captured. Figure 3 shows the calibration system.

Figure 4 shows the obtained calibration curve for the PSParticle with 532nm excitation. The vertical axis denotes the measured intensity ratio  $I_A/I_B$ . For the calculation of the  $I_A$  or  $I_B$ , the background intensity has been substituted. The line inside the figure shows the obtained calibration curve, with fitting the data. Using the relationship, the oxygen mole-fraction can be obtained from the intensity ratio  $I_A/I_B$ . The curve shows that the measurable range is less than 3%. When the oxygen mole-fraction is larger than 3%, the ratio almost has no dependency because of the higher S/N ratio.

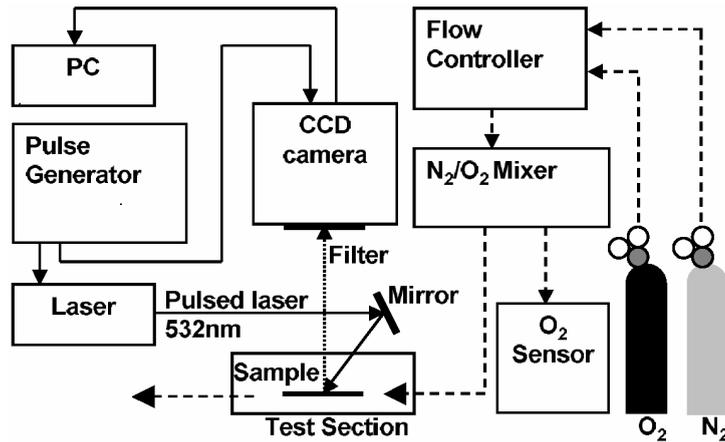


Fig.3 Schematic Image of acquisition system for Calibration curve

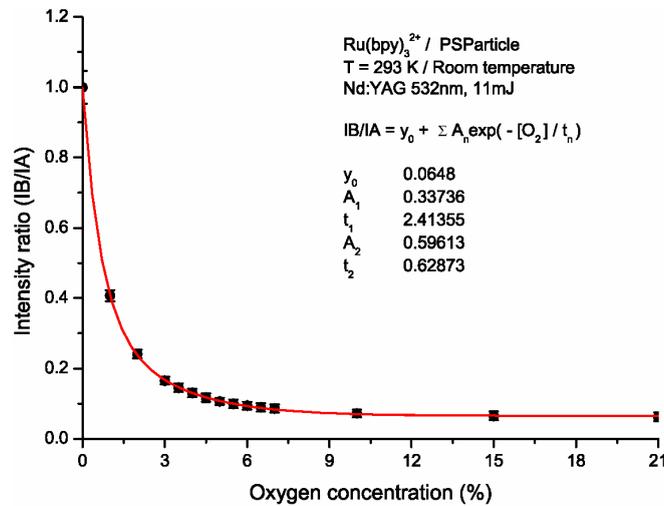


Fig.4 Calibration curve Intensity ratio vs. Oxygen concentration

### 3. PIV-PSP HYBRID SYSTEM

#### 3.1 System Configuration

The PSParticle shows the oxygen mole-fraction with its lifetime, i.e. image intensity ratio  $I_A/I_B$ . It also shows the velocity distributions with analyzing PIV technique. The time scale of PSP is about 500ns. While the time scale of PIV depends on the velocity. When the velocity is around several meter per seconds (~m/s), the time interval between two images are about 0.1ms, which is much bigger than the time scale of PSP. To measure the PSP and PIV image simultaneously, two PCO Sensicam cameras have been used. Figure 5 shows the schematic diagram of the measurement system. One camera captures the PSP signal, and the other does the PIV signal. As discussed above, the time scale of PSP is much faster than that of PIV. Double pulse laser will be used for PIV. One pulse of the double laser pulse will be used for PSP measurement. The timing chart of the PIV/PSP Hybrid system is shown in Fig. 6. For the PIV camera, the double frame image captures individual laser pulse images. The time interval between the double pulses is 99 $\mu$ s, which is long enough comparing with the lifetime of PSParticle. The images will be analyzed to detect the displacement of the image pattern to measure the velocity distributions. On the other hand, the PSP camera operates with double shutter mode with different timing. The 1st frame will start capturing the image after the 1st laser pulse, so that the 1st laser image may not be recorded on to the 1st frame. Then using the 2nd laser pulse, the double frame imaging technique is carried out to detect the oxygen mole-fraction. The timing of the double frame imaging with the 2nd pulse is the same timing with the previous section. The images will be analyzed to detect the oxygen mole-fraction. The timing of the cameras and lasers is controlled precisely with the timing generators. The PCO camera can capture the 4 image pairs in one second. Since the PIV camera and PSP camera captures the same plain from the other direction, the image for the one camera should be reversed to show the same image. The calibration for the location of the two cameras should be carried out

precisely. For this purpose, the images of the 2nd pulse PIV and PSP are correlated to detect the location bias errors. Then, the location has been precisely matched.

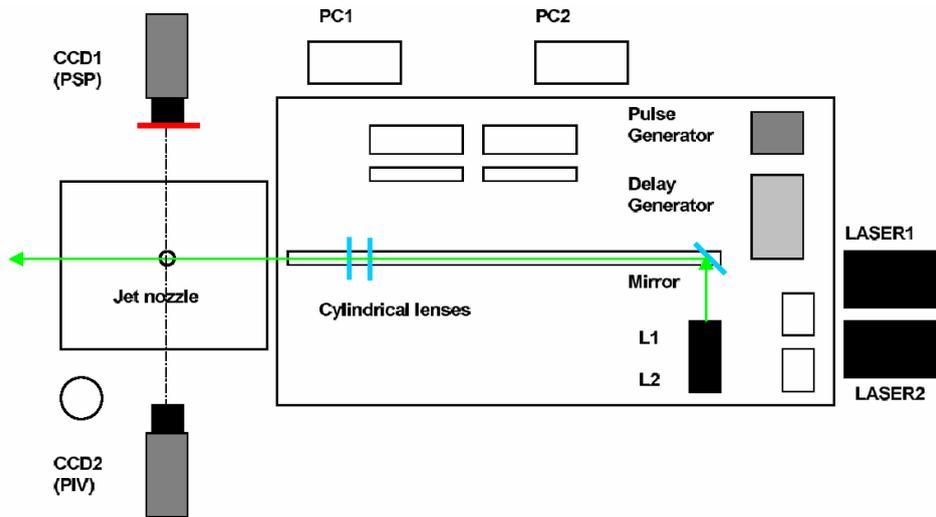


Fig. 5 The arrangements of two side camera PIV-PSP hybrid system

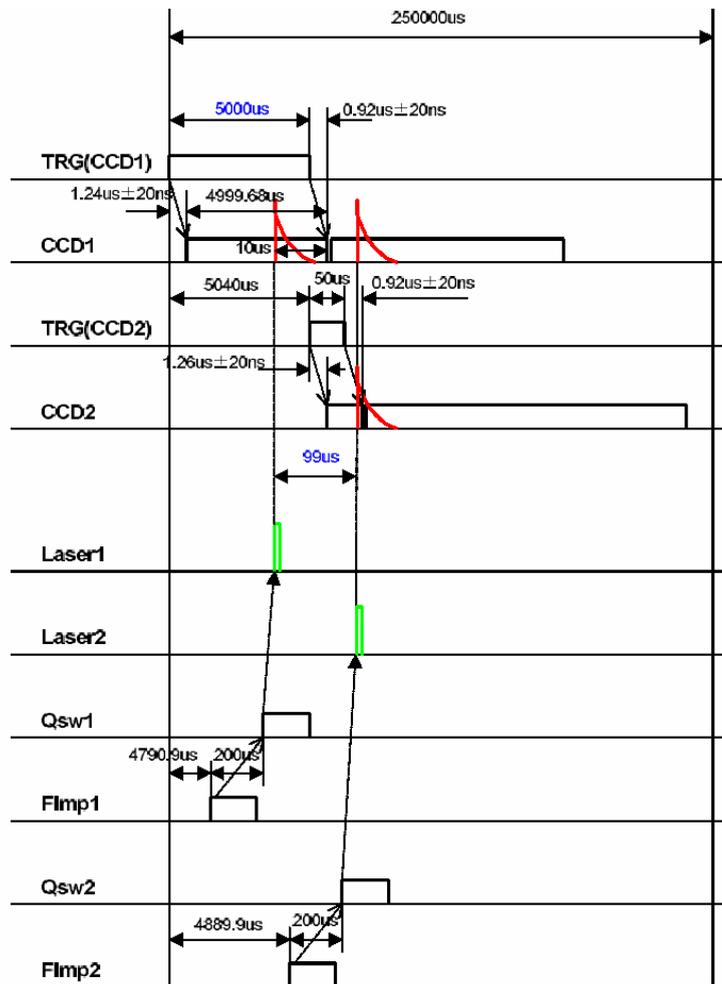


Fig. 6 The timing diagram of two side camera PIV-PSP hybrid system

### 3.2 Nitrogen gas jet experiment

Using the above mentioned PIV-PSP Hybrid system, the velocity distribution and oxygen mole-fraction distribution of the nitrogen gas jet has been measured. The diameter of the nozzle is 7.5mm, which is settled upward inside the air chamber. The PSParticle is set inside the nozzle, so that the PSParticle will flow with nitrogen gas jet. The average jet velocity is 7.55m/s. For the illumination, Nd:YAG laser 2nd harmonic beam (532nm) is used. The laser light sheet illuminates the center plain of the nozzle.

Figure 7 (a) and (b) shows the PIV image pair, which corresponds the 1st image and 2nd image, respectively. The time interval between the two images is 99 $\mu$ s. These image has been converted to the same directional image of PSP images. Figure 8 (a) and (b) shows the PSP image pair for the double frame imaging technique. The time interval between the two images is 200ns. The 2nd image ( $I_B$ ) shows the quenched images with oxygen. The edge area of the jet is darker than the center, because of the mixing with the oxygen.

Using these 4 images (2 image pairs for PIV and PSP), the velocity and the mole-fraction distributions are calculated. Figure 9 shows the results of the measured data. The color indicates the oxygen mole-fraction whose range is 0 to 1.2%. The nozzle outlet has no oxygen. However, oxygen mole-fraction increases at the downstream region, because of the mixing with air. The vector denotes the velocity distributions. Since the PSParticle just exist around the jet, the information far from the nozzle cannot be captured. Figure 10 shows the magnified images of Fig.9. The oxygen mole-fraction distributions and velocity distributions clearly shows the interaction between the vortex and the mixing. It is confirmed that the simultaneous measurement for velocity and scholar distributions can be achievable using the PSParticle. The system will be improved to detect not only the oxygen mole-fraction, but also temperature, pressure and so on.

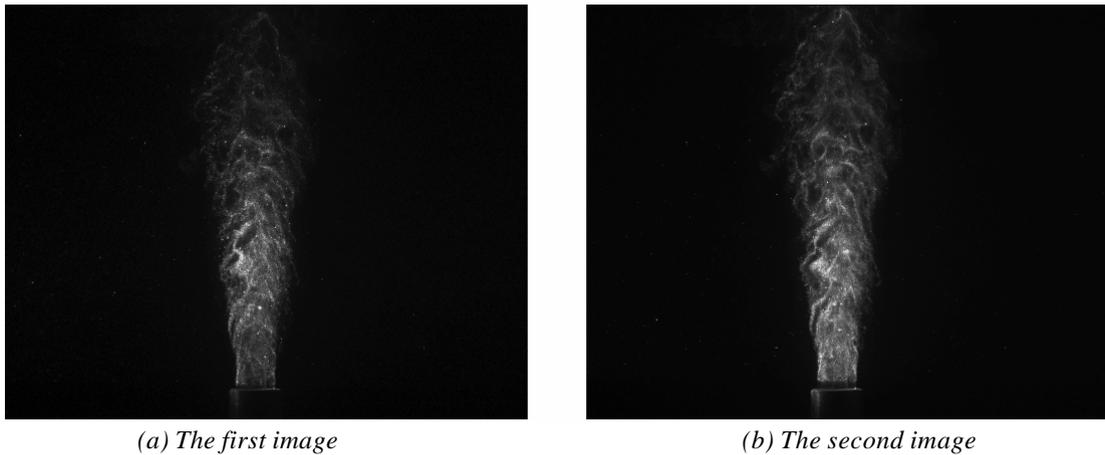


Fig.7 The images of PIV



Fig.8 The images of PSP

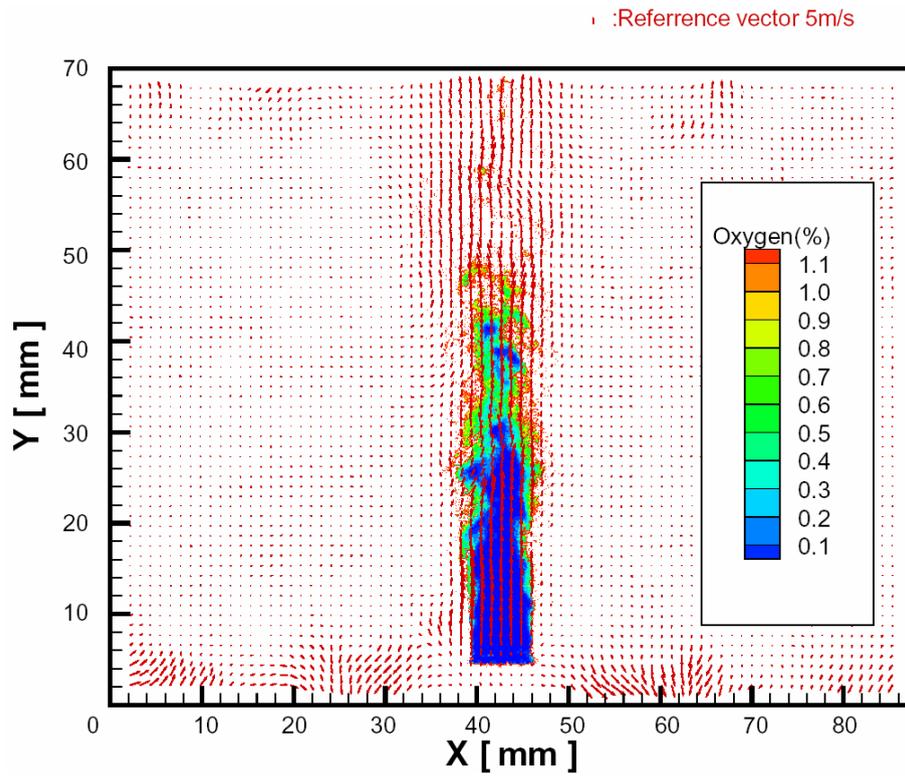


Fig.9 The result of simultaneous measurement by PIV-PSP hybrid system

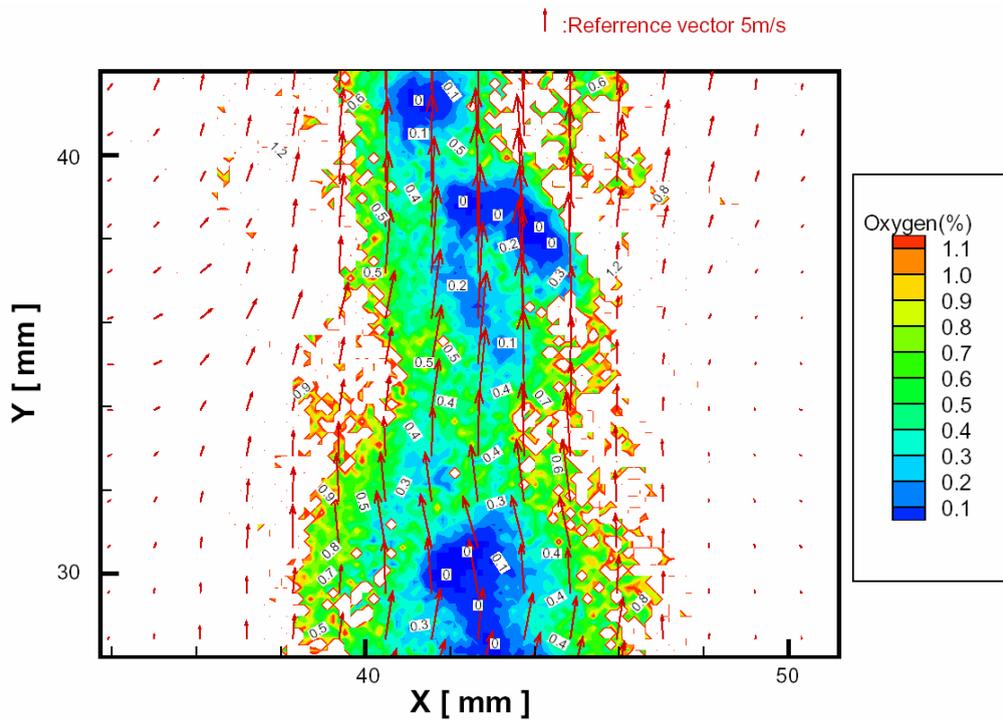


Fig.10 The magnification of Fig.9

#### 4. CONCLUSION

The PIV-PSP Hybrid system has been developed.

(1) The PSParticle is developed. The PSParticle contains the pressure sensitive dye.

(2) To measure the lifetime of the PSP dye, Double Frame Imaging technique has been proposed. The intensity variation caused the particle concentration distributions are canceled out by dividing the two serial images with very short interval. It can be applied to detect the moving surface.

(3) The technique has been applied to the nitrogen gas jet experiment showing the effectiveness of the present technique.

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