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Pressure Field Visualization on the Surface of a Square Cylinder with Pressure Sensitive Paints

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Abstract

Pressure Sensitive Paints (PSP) are one of the breakthrough technologies for the measurement of aerodynamic sound from automobiles. Potential problems in applying Pressure Sensitive Paints to automobiles are low time resolution and less accuracy in the low-speed flow field. In this investigation, we attempted to improve the accuracy of PSP in a low-speed flow. A suction-type wind tunnel, which has a square test section of 75 mm by 150 mm, was developed to remove the influence of temperature differences during the wind tunnel experiments. A carefully selected array of ultraviolet LEDs was utilised as a lighting system to match the effective excitation wavelength of the developed PSP (390 nm). The surface pressure of a square cylinder was measured at velocity range from 35 m/s to 75 m/s with PSP and a conventional pressure sensor. The experimental data were compared with the results of conventional pressure measurements and numerical simulations. The experimental results showed that the accuracy of the PSP was about 10% at the velocities of 65 m/s or higher. The pressure profiles can be clearly observed at the uniform velocity of 75 m/s. Conversely, accuracy within the 35 m/s to 55 m/s velocity range was not high enough because of insufficient CCD camera resolution. Despite large error values, the colour depths of the luminescence image were almost identical for the same experimental conditions. This indicated that the calibration coefficients of the Stern-Volmer relation were almost constant during the experiments. It revealed that the suction-type wind tunnel is suitable for PSP measurements.

Introduction

Recently, Pressure Sensitive Paints (PSP) has been developed as a breakthrough technology enabling flow measurements [1][2]. Time-series Particle Image Velocimetory and PSP have been developed following advantages in chemical science and optical technologies. Two or three dimensional flow-field measurements are now possible utilising these new technologies The flow-field data help us to understand flow structures and details of the complicated flows, such as flow separations.

The information obtained from pressure measurements is important to industries keen to improve the product performance. For example, in the case of drag reduction in automobiles, fine details of pressure profiles on body surface are usually measured using the piezoresistive pressure sensors. A large number of pressure sensors are required. Moreover, conventional pressures measurements also require pressure ports or taps on the surface of model. The data acquire is limited only at the fixed point. The pressure distributions on the surface are then estimated by the point-source measurements. The quality of such experiments is dependent upon the predesign of the pressure port distribution.

Since the PSP is coating sensors with luminescence molecules, the pressure ports or taps are not required to measure the surface pressure profiles. PSP based on the oxygen quenching process of the luminescence molecules, gives a much higher range of pressure measurements than the dynamic pressure range of conventional measurements in automobile industries. The pressure range is suitable for measuring high-speed flow such as the supersonic flow around an aircraft. Since the PSP is the absolute pressure sensor, measurements of the low-pressure regions such as the flow around automobiles are quite difficult to obtain. In this paper, we attempted to improve the PSP measurements at the low-speed region with a low-temperature drift wind tunnel and array of ultra violet LED as the lighting system for the PSP.

Experimental Methods

Wind tunnel

Since the accuracy of PSP depends upon temperatures as well as pressure, the temperature drift of wind tunnels should be minimised. For this reason, a suction-type wind tunnel, which has square test section of 75 mm and 150 mm, was developed to remove temperature difference trends during the wind tunnel experiments. Figure 1 shows the low-temperature drift wind tunnel. The temperature difference was only 0.2 degrees during the experiments at the flow velocity of 75 m/s. This small temperature drift eliminated the temperature sensitivity of the PSP measurements. As a result, the experimental conditions and calibration coefficients were kept constant in the experiments.

The air leak from the insertion sensors of the test section is known to be a drawback of suction-type wind tunnel. However, in the case of PSP measurements, insertion sensors are not required. The suction-type wind tunnel is therefore suitable for PSP measurements. The non uniformity of the uniform flow was less than 0.1% and the intensity of turbulence was less than 0.7% at a uniform velocity of 75 m/s.

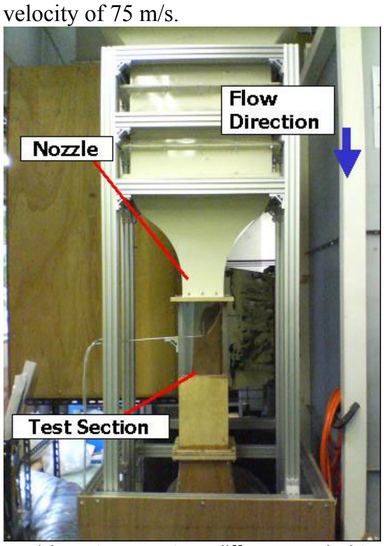


Figure 1 Low-temperature difference wind tunnel

The experiments were conducted from uniform velocities of 35 m/s to 75 m/s. The surface pressure was also measured by conventional piezoresistive pressure sensors with pressure ports mounted on the surface of the experimental model.

PSP Technique

PSP is chemical sensor in a chemical sensor operating through oxygen quenching of luminescence molecules. The PSP is constructed of luminescence molecules held in a polymer binder as shown in figure 2. When the luminescence molecules are exited with an ultraviolet LED or Blue LED, the energy state of the molecules rises. To return to the original energy state, the luminophores are emitted from the luminescence molecules. The wavelength of the emission is longer than that of the excitation. Therefore, the intensity of the emission and excitation light can be measured independently. The intensity of the emission depends on the intensity of the excitation and the effect of oxygen quenching. Since the excited energy of the luminescence molecules is transferred to surrounding oxygen, the intensity of the emission is reduced. This phenomenon is known as the oxygen quenching process. If the intensity of excitation is constant, the intensity of the emission depends on the oxygen concentration, or the oxygen partial pressure. This is the principle of the static pressure measurement of the PSP.

The relationship between the intensity of luminescence and static pressure of the air (oxygen) can be formulated by the Stern-Volmer equation as follows;

$$\frac{I(P_{ref},T)}{I(P,T)} = A(T) + B(T)\frac{P}{P_{ref}}, \qquad (1)$$

where the I denotes the intensity of the emission, P denotes the static pressure and T denotes the temperature. The subscript of '*ref* denotes the reference condition. $A(T)$ and $B(T)$ are calibration constants with the function of temperature.

The calibration coefficients, A and B, strongly depend on the temperature. Therefore, the temperature correction is necessary when the temperature is not constant during the wind tunnel experiments. In this investigation, we used a low-temperature drift wind tunnel to avoid temperature drift as shown in Figure 1.

Since the effective excitation wavelength of the present PSP was 390 nm, the LED array of ultraviolet rays (UV-LED) was utilised as a lighting system. However, as the intensity of the UV-LED was not so high, LED array of blue light (wavelength 470 nm, BLUE-LED) was also used as an excitation source. Figure 3 shows the UV-LED and BLUE-LED. The intensity of LED depends upon the electric current of the circuit of the lighting system. To keep the electric current constant, a constant current power supply was used and the lighting systems were cooled with axial fans.

PtTFPP was used for the luminescence sensor of the PSP and Poly-IBM-co-TFEM was used for the binder. The PtTFPP and Poly-IBM-co-TFEM were mixed using toluene.

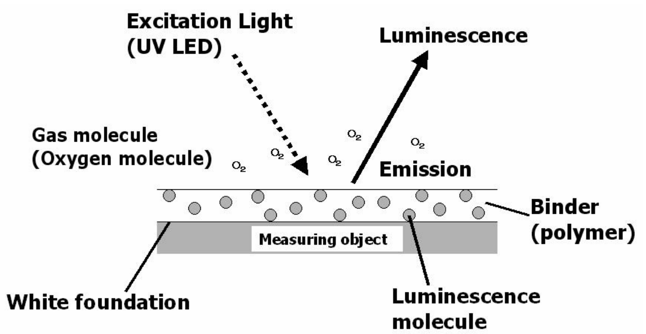


Figure 2 Schematic diagram of PSP measurements

In order to obtain a luminescence image of the PSP, a 10-bit CCD camera (SONY SharpVision) was utilised. The spatial resolution was 1024 × 1024 pixels. Since the effective wavelength of emission of the present PSP was 650 nm, the band-pass filter (λ = 650 ± 20 nm) was installed. The ensemble average was 32.

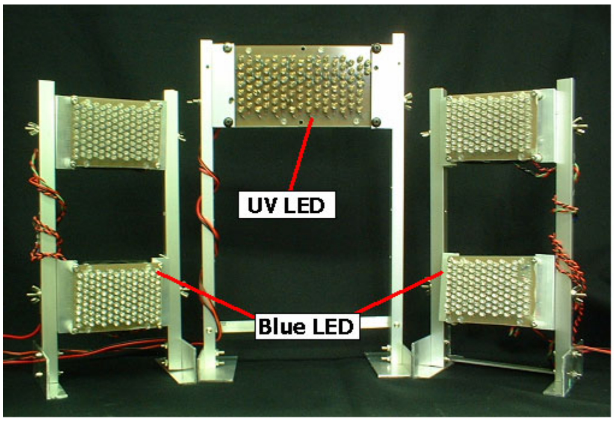


Figure 3 Ultraviolet LED array (wavelength = 375nm) and BLUE LED array (wavelength = 470nm)

Experimental Setup

Figure 4 shows experimental setup for PSP measurements. The square cylinder with a diameter, D = 20 mm, was placed in the test section of wind tunnel. The origin of the coordinate system was set at the centre of the square cylinder and the flow direction is as shown in Figure 4.

The test cylinder was made of aluminium and six pressure holes were fabricated on the surface of the cylinder. These pressure holes and piezoresistive pressure sensors were connected with pressure tubes. The surface of the test cylinder was also coated uniformly by the developed PSP.

The surface pressure was measured with PSP and compared with conventional, piezoresistive sensors. The experimental results were also compared with results of the numerical simulation. The simulation was calculated using an incompressible Navier-Stokes equation and the sub-grid scale model for turbulence.

The experiments were conducted at velocity ranges from 35 m/s to 75 m/s. The angle of attack of the square cylinder was set from 0 degrees to 45 degrees.

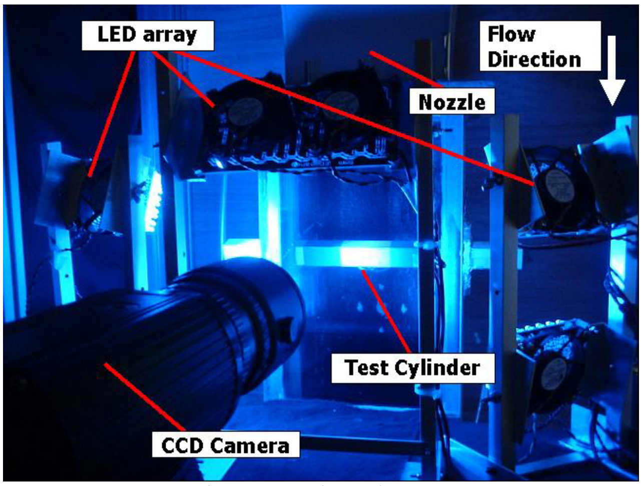


Figure 4 Experimental setup

Experimental Results

Figure 5 shows the intensity of luminescence images on the surface of the square cylinder placed in the uniform flow at velocity ranges of 35 m/s to 75 m/s. The colour of the upstream region (the upper side in the picture) was changed from light green to orange with increasing uniform velocity. On the downstream region (the lower side in the picture), the colour was green. The colour differences in the image data of the low-speed region were weak. However, its intensity changed slightly. The errors within the PSP measurements are shown in Figure 6. In the case of the low-speed region, at velocity ranges from 35 m/s to 45 m/s, surface pressure cannot be measured by the PSP utilised here. In the case of 55 m/s velocity, the measurement error was about 80 %. One of the reasons for this range error seems to be insufficient camera resolution. The resolution of the CCD camera was only 10 bit. This is not enough to capture the detail and subtle differences among luminescence images resulting from small pressure differences. On the other hand, in the case of higher velocity ranges (from 65 m/s to 75 m/s), the error was about 10 %. The pressure profiles can be captured as shown in Figure 7 and 8. The discrepancy among pressure profiles at different angles of attack can be seen in these figures.

The PSP results obtained from the higher velocity regions were in agreement with conventional measurements and the results of the numerical simulation.

Discussions

The pressure distributions of the average velosity ranges of automobile are too low to be measured by the PSP system utilised here due to high error values. Sufficient resolution can only be obtained at velocities ranges over 65 m/s (234 km/h). In commercial automobile development, velocity ranges from 60 km/h to 120 km/h are important. The dynamic pressures are less than 700 Pa. The accuracy of the PSP was almost of the same order obtained utilising a 16 bit CCD camera. Therefore, measurements of these low pressures are difficult to achieve.

In our experiments, pressure measurements could not be obtained successfully in the low-speed region. However, reliable reproduction of images was obtained. This indicated that the calibration coefficient of the Stern-Volmer relation was almost constant during the experiments. The temperature difference of the wind tunnel was kept constant (within 0.2 degrees). This low temperature drift improved the PSP measurements. In the case of the velocity ranges from 65 m/s to 75 m/s, the error was about 10%. The pressure profiles on the surface of the square cylinder were reasonably well in agreement with those of the conventional measurements and the numerical simulation.

These results revealed that the suction-type wind tunnels are suitable for the PSP measurements. Moreover, a 16 bit CCD camera is required to measure the low-speed flow with the PSP.

Conclusions

In order improve the accuracy of Pressure Sensitive Paints (PSP) at the low-speed flow, a suction-type, low-temperature drift wind tunnel and array of ultraviolet LEDs were developed. The pressure distributions of the square cylinder were measured at the velocity ranges from 35 m/s to 75 m/s. The experimental results showed that changes in the PSP utilised here could not be measure accurately in the low-speed region. However, the reproduction of images produced was fine. The calibration coefficients were almost constant during the experiments. The error of the pressure measurements at velocities of 65 m/s and 75 m/s was about 10%. The pressure profiles on the surface were in agreement with that of the conventional measurements and the numerical simulations.

Results indicated that the calibration coefficients of the Stern-Volmer relation were the almost constant during the experiments. They revealed that the suction-type wind tunnel ias suitable for PSP measurements.

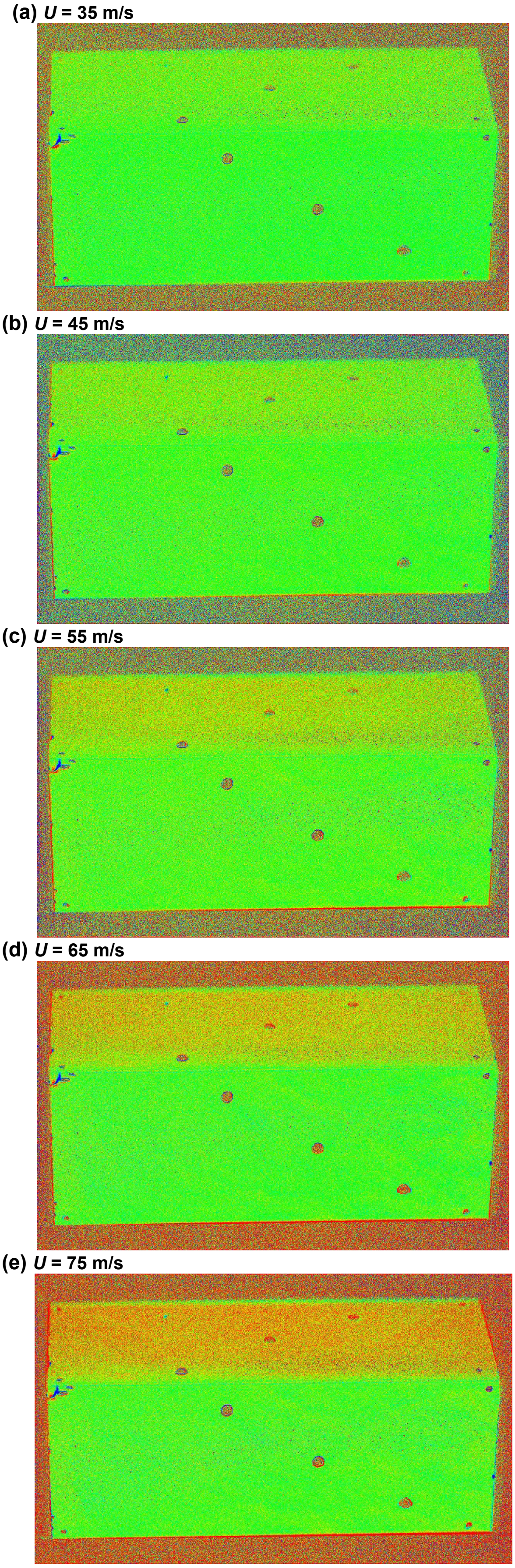


Figure 5 Pressure distribution on a surface of square cylinder placed in uniform flow (PSP measurement)

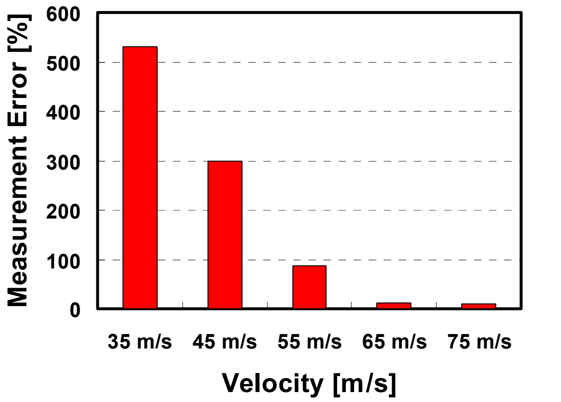
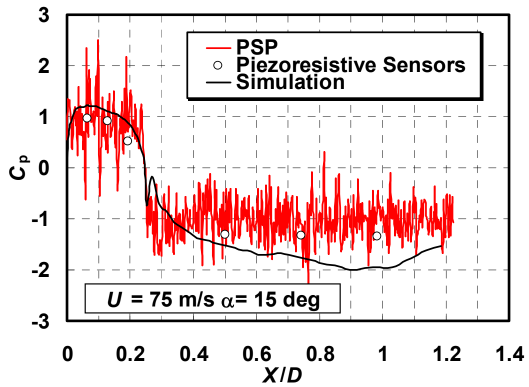
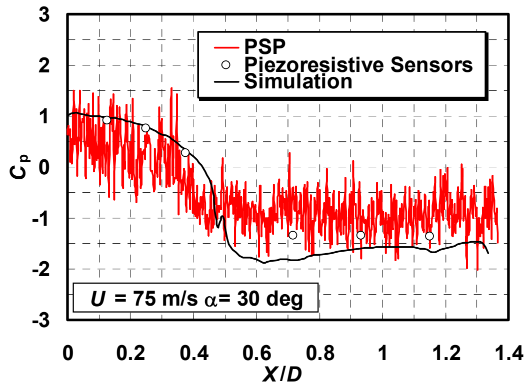


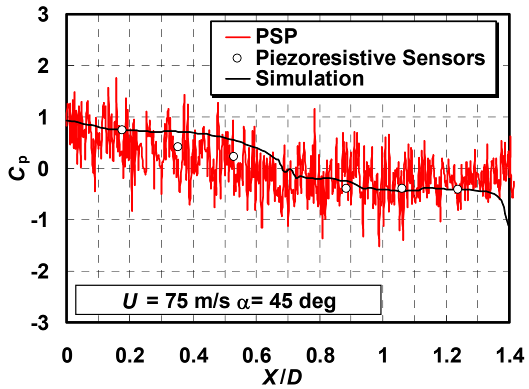
Figure 6 Relationship between uniform flow velocity and measurement error utilising PSP



(a) α=15 deg



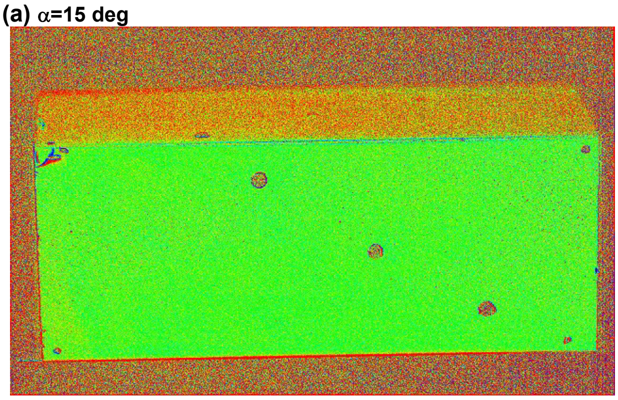
(b) α=30 deg



(c) α=45 deg

Figure 7 Comparison of conventional pressure measurements and PSP

(a) α=15 deg



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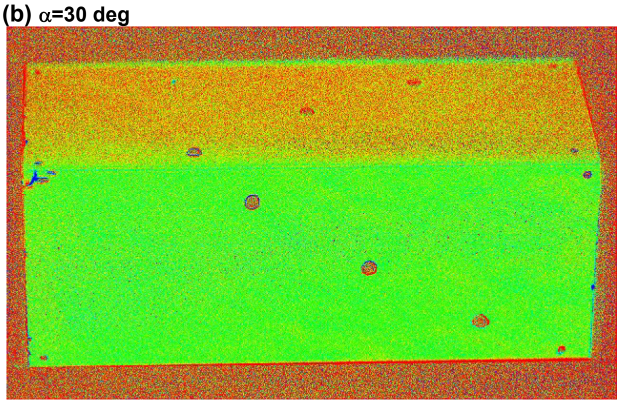

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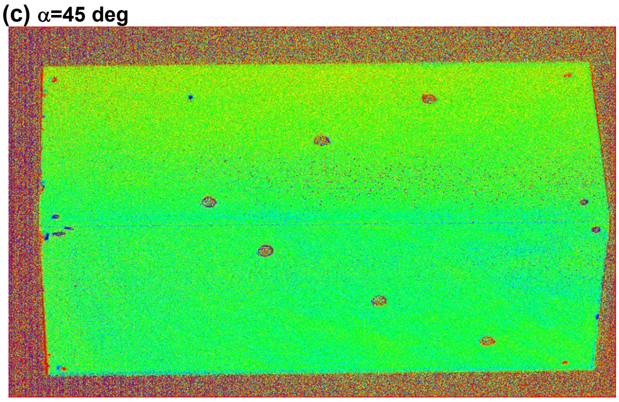

Figure 8 Comparison of pressure distributions and angle of attack of the square cylinder

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