Journal of Visualization, Vol. 5, No. 1 (2002) 45-50

Application of Pressure Sensitive Paint Measurement to a Low-Solidity Cascade Diffuser of a Transonic Centrifugal Compressor

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Received 30 July 2001.
Revised 1 November 2001.

***Abstract*:** A pressure sensitive paint (PSP) measurement has been known as a pressure field measurement technique based on the oxygen quenching phenomenon of luminescence of specific luminophores. A PSP measurement was applied for pressure field measurement in a low-solidity circular cascade diffuser of a single-stage transonic centrifugal compressor with 5 in pressure ratio for HFC134a gas. The oxygen concentration was about 500 ppm. Ru (bath-phen) was adsorbed on a silica-gel thin-layer chromatography sheet, and the sheet was pasted onto the side-wall between the cascade vanes. A drastic change in luminescent intensity was recognized during a surge condition. Also the pressure variations based on luminescent intensity agreed well with the pressure fluctuations measured using a semiconductor pressure sensor with high-frequency-response. It was shown that a PSP measurement worked well to investigate the unsteady pressure fields in a circular cascade diffuser of a transonic centrifugal compressor. Moreover, the time response of PSP becomes clear as a problem to be overcome for the present.

***Keywords*:** pressure sensitive paint, pressure field measurement, transonic centrifugal compressor, low-solidity circular cascade diffuser, surge.

1. Introduction

In a single-stage high-pressure-ratio centrifugal compressor, the relative velocity to the impeller and the absolute velocity to the diffuser usually exceed the velocity of sound. Since a conventional vaned diffuser is sensitive to the angle of incidence, especially at such a supersonic condition, the flow range of high pressure-ratio compressors with a vaned diffuser is usually very narrow. The maximum flow is specified by the choked flow rate due to either the inducer of the impeller or the throat of the diffuser. On the other hand, the minimum flow is specified by a surge. The surge is an unstable phenomenon of a compressor system including the whole piping configuration, and it causes an intense pressure fluctuation, a noise, a backward flow, and so on. Therefore, the researches on the cause of a surge, its mechanism and detecting methods are needed.

In a preceding paper (Hayami et al., 1990), a low-solidity circular cascade was successfully applied as a part of a diffuser system to a transonic centrifugal compressor. A wider flow range as well as a higher pressure ratio and a higher efficiency, superior to those of a conventional vaneless diffuser, were obtained, although the maximum flow rate was limited by choking of the impeller. To investigate the surging phenomenon, pressure fluctuations were measured using semiconductor pressure sensors with high-frequency-response mounted on the side-wall of a circular cascade diffuser (Hayami et al., 1997; Hayami and Fukuuchi, 1999).

A pressure sensitive paint (PSP) measurement has been known as a pressure field measurement technique based on the oxygen quenching phenomenon of luminescence of specific luminophores (Liu et al., 1997). In the present paper, a PSP measurement was applied for pressure field measurement in a low-solidity circular cascade diffuser of a transonic centrifugal compressor during a surge condition. The variation of luminescent intensity was evaluated on the basis of pressure fluctuation measured using a semiconductor pressure sensor with high-frequency- response. Some problems to be overcome are also discussed.

2. Experimental Apparatus and Procedure

A high-pressure-ratio centrifugal compressor was tested in a closed loop with HFC134a gas. Figure 1 shows the meridional profile of the test compressor and measurement system. The diameter of the impeller was 280 mm and the exit blade height was 8.9 mm. The open shroud impeller with 40 deg in backswept angle had 15 main blades and 15 splitter blades. The diffuser consisted of a cascade and two parallel walls with a space of 9.4 mm. A linear cascade with 0.69 in solidity and 69 in stagger angle was conformally transformed to the circular cascade with eleven vanes. The radius ratio of the circular cascade to the impeller was 1.1 at the leading edges, and 1.26 at the trailing edges. An airfoil of NACA66-066 with 10 deg in blade turning angle was adopted as the original airfoil section of the linear cascade.

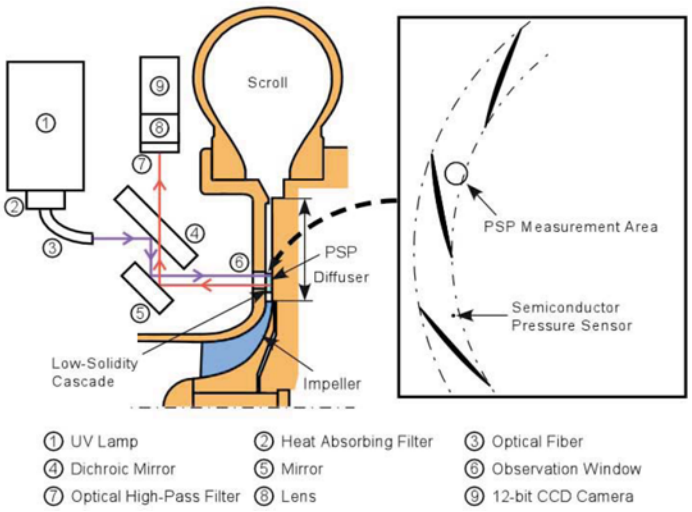

Fig. 1. Meridional profile of the test compressor and measurement system.

A PSP consists of a luminophore with oxygen sensitivity and a binder with oxygen permeability. Ru (bath-phen) (GFS Chemical Bathophenanthroline Ruthenium Chloride) was used as a luminophore, and a thin-layer chromatography (TLC) sheet (Merck Silica-Gel 60, 0.5 mm thick) was used as a binder. The luminophore was dissolved in dichloromethane as a solvent, and the TLC sheet was dipped in the dichloromethane solution. The TLC sheet was pasted onto the hub side-wall between the circular cascade vanes shown in Fig. 1. The absorption and emission wavelengths of the PSP were 470 nm and 620 nm, respectively.

In the present measurement, a UV lamp (HAMAMATSU L5662-01) equipped with a heat absorbing filter (HAMAMATSU A6562-03) was used to excite the PSP. The excitation light was drawn to the PSP by an optical fiber (HAMAMATSU A4831) through a dichroic mirror and a mirror due to structural restrictions of the test compressor. The images of luminescent intensity passed through an observation window mounted on the shroud casing. And then the images were captured using a 12-bit CCD camera (HAMAMATSU C4742-95-12NR) equipped with a lens (NIKON Micro Nikkor 105 mm f/2.8) and an optical high-pass filter (SIGMA KOKI SCF-50S-58O) with 580 nm in cut-off wavelength. The diameter of the observation window was 13.5 mm. A PC was used to control the CCD camera and to store the images.

Temporal variation of static pressure was simultaneously measured using a semiconductor pressure sensor (Kulite XCS-062-15G) with high-frequency-response to compare with variation of PSP pressure and also to calibrate the pressure level. The semiconductor pressure sensor was located on the shroud side-wall between neighboring cascade vanes of the PSP measurement location as shown in Fig. 1. The natural frequency of the semiconductor pressure sensor was 250 kHz, and the diameter of pressure sensitive area was 0.71 mm. The sampling rate was 150 kHz.

3. Theory of Pressure Sensitive Paint Measurement

When PSP is excited by the light of a specific wavelength, it emits luminescence. The oxygen quenching phenomenon of luminescence results from collision deactivation by oxygen in the process of emission. Thus the luminescent intensity is inversely proportional to oxygen concentration. Since the oxygen concentration is proportional to the oxygen partial pressure, the oxygen quenching phenomenon can be described by the following simple equation.

$$\frac{I_{ref}}{I} = A + B \cdot \left(\frac{p}{p_{ref}} \right) \tag{1}$$

Where I is luminescent intensity, p is pressure, coefficients A and B are constant, and I_{ref} is luminescent intensity at a reference pressure p_{ref}. Equation (1) was proposed as the form of the Stern-Volmer relation to map the measured luminescent intensity field into the pressure field (McLachlan et al., 1993). Instead of Eq. (1), the following polynomial equation may be used due to the non-linearity. Here C is a constant coefficient.

$$\frac{I_{ref}}{I} = A + B \cdot \left(\frac{p}{p_{ref}} \right) + C \cdot \left(\frac{p}{p_{ref}} \right)^2 \tag{2}$$

4. Experimental Results and Discussions

The characteristic curves of the compressor are shown in Fig. 2. The ordinate P_4/P_0 is the total pressure ratio, and the abscissa G/G^* is the ratio of the mass flow rate to the choked flow rate in the suction pipe. The parameter M_t is the corrected speed or the nominal Mach number based on inducer tip speed and inlet stagnation temperature. The PSP measurement was performed in the surge condition of M_t = 1.041. The rotor speed was 17,800 rpm. The temperature at the measurement area was about 324 K. The compressor fell into surge by closing the delivery valve gradually. Oxygen concentration was about 500 ppm based on the measured velocity of sound of the working fluid.

Figure 3 shows a typical example of time sequence of visualized luminescent intensity images for 1.66 s during a surge. The camera exposure time was 2.163 ms, and the sampling rate was 18 Hz. The time was

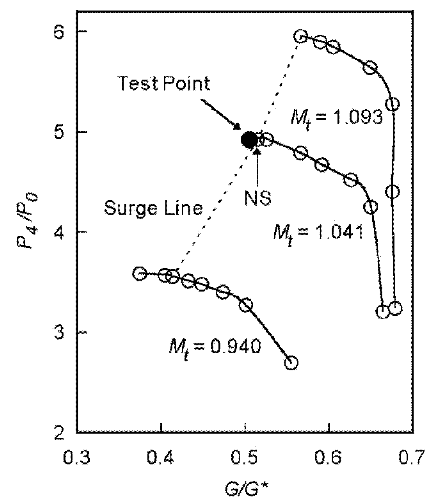

Fig. 2. Compressor characteristics.

normalized with the periodic time of surge. The geometrical relationship between the images and the circular cascade vanes corresponds with Fig. 1. Here colors in the images indicate the reciprocal of luminescent intensity I_{ref}/I. The time t = 0 s corresponds to the onset of surge. The effective measurement area was within a circle of 340 pixels in diameter. The spatial resolution of the images was 40 μm/pixel. In order to reduce the readout noise of the CCD camera, a spatial filtering of 3 × 3 pixels was performed to the images. A drastic change in luminescent intensity was recognized. However, luminescent intensity was almost fixed in the upper part of every image. This was because the excitation light did not pass through the window straight and did not hit the upper PSP due to the thick and small window. Any strong pressure gradient was not observed clearly in the images to show the existence of a shock wave.

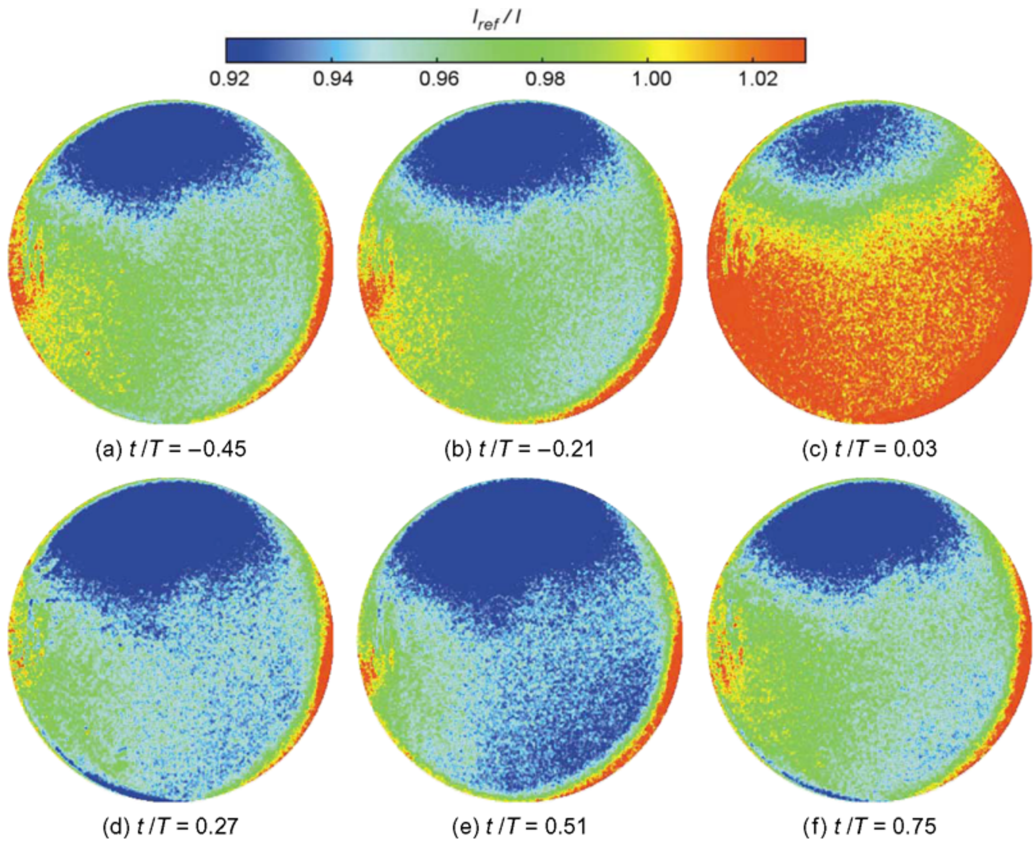

Fig. 3. Time sequence of luminescent intensity images.

Figure 4 shows the calibration curve based on Eq. (2). The calibration curve was generated from the pressure measured using the semiconductor pressure sensor. The luminescent intensity of PSP is affected by not only pressure but also temperature (Schanze et al., 1997). The effect of temperature was included in Eq. (2).

Figure 5 shows the histories of pressure fluctuation based on luminescent intensity compared with the pressure variation simultaneously measured using a semiconductor pressure sensor shown in Fig. 1. The camera exposure time was 16 ms, and the sampling rate was 25.6 Hz. The pressure resolution of the PSP was 190 Pa, while that of the semiconductor pressure sensor was 49 Pa. In order to match both data conditions, the PSP pressure was an integrated value in the same area with the pressure sensitive area of the semiconductor pressure sensor. The pressure of the semiconductor pressure sensor was a moving-averaged value for the camera exposure time for the PSP measurement. The variations of pressure agreed well with each other. The pressure level also agreed with each other, because the calibration curve was based on the steady-part pressure in Fig. 5. However, there are some problems in time response during the step-down change in pressure. The time constant for the PSP measurement was 75.2 ms at the step-down change, which was very large in comparison with that of other researches (Sakaue and Sullivan, 2000). Here, there are more problems such as the temperature effect and the differences in the measurement locations of side-wall and passage, but these effects are considered in Eq. (2) for the present. That is, the improvement of time response is one problem to be overcome.

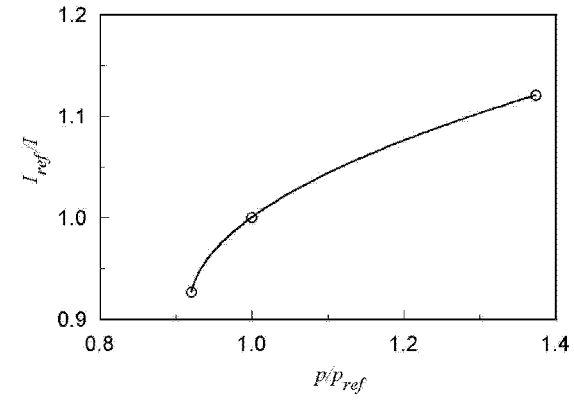

Fig. 4. Calibration curve (p_{ref} = 63 kPa).

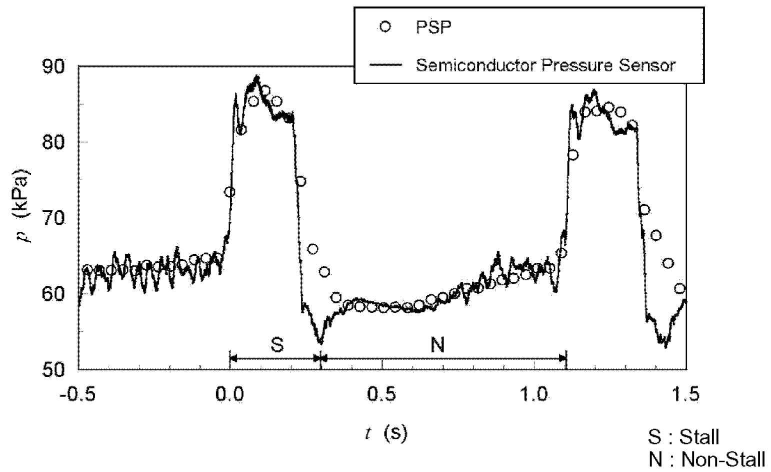

Fig. 5. Histories of pressure fluctuation.

5. Conclusion

A PSP measurement technique was applied for pressure field measurement in a low-solidity circular cascade diffuser of a transonic centrifugal compressor. A drastic change in luminescent intensity was recognized during a surge. The temporal pressure variation agreed well with the pressure variation measured using the semiconductor pressure sensor with high-frequency-response. Moreover, the time response of PSP becomes clear as a problem to be overcome for the present.

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