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Conference Paper

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Publication date:
2018-10-05

Permanent link:
https://doi.org/10.3929/ethz-b-000279157

FAST RESPONSE PRESSURE SENSITIVE PAINT MEASUREMENT ON A HYPERSONIC COMPRESSION CORNER

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KEYWORDS:
Main subjects: unsteady flow, flow visualization
Fluid:hypersonic flows
Visualization method(s): Pressure Sensitive Paint, Schlieren
Other keywords: Fast response, luminescence,

ABSTRACT: *Porous fast response Pressure Sensitive Paint (PSP) was studied to develop the capability of making global pressure measurements in unsteady and short duration flow conditions. By using the fast response PSP, unsteady flow field can be accurately measured. Dynamic calibration devices were developed to test the response time of PSP. As our PSP formulations continuous development, the stability and emission intensity are enhanced. The typical response time of fast response PSP is 0.2ms. The experiment frame rate was 2000 fps. In this paper, fast response PSP was applied to investigate the unsteady flow on a hypersonic compression corner. The emission from the PSP was detected by high-speed camera with a frame rate 2000fps. A detailed pressure distribution pattern of complex flow phenomena including shock/shock interactions, flow separation were clearly captured. Unsteady flow phenomena were shown as time-series images. Comparison between the PSP results and pressure transducers were also described.*

1 Introduction

A global surface pressure measurement using pressure-sensitive paint (PSP) has now been widely applied in aerodynamic testing[1,2]. Many aerodynamic phenomena and test facilities are inherently unsteady, requiring a fast response pressure measurement system. Facilities such as short-duration wind tunnels and shock tubes require a paint formulation that will reach a steady-state indicated value within the duration of the test. Similarly, unsteady aerodynamic phenomena in hypersonic, acoustic, and turbo-machinery testing require fast response instrument. Thus, the conventional steady PSP were insufficient for many of these tests. This deficiency has motivated the development of fast response PSP for unsteady testing.

Fast response PSP measurement method is basically the same with conventional steady PSP measurement method , however there are several differences, e.g. usage of a fast-response PSP and a high-speed camera. Compared with a conventional high frequency pressure transducer, data accuracy of fast response PSP measurement needs to be improve, however, it has advantage of high spatial resolution and high time resolution due to the large number of pixels and high frame rate of high-speed camera.

There are some fast response PSP applications from low speed[3] to hypersonic[4]. One of the most important applications of fast PSP is to study flow mechanism in hypersonic, such as shock/shock and shock/boundary layer interactions, flow separation, boundary layer transition[5]. Some researchers utilized Anodized Aluminum(AA) PSP to capture the complex hypersonic flow structure[6,7]. Nevertheless there are still rare to see the time resolved PSP measurement in hypersonic flow. CAAA has developed high porosity paints where the luminescent dyes can be incorporated into a highly porous polymer. Unlike AA PSP the polymer based paint can be sprayed onto any model surface. As our PSP formulations continuous development, the stability and emission intensity are enhanced. Due to this, the experiment frame rate increase from 250fps[8] to 2000 fps. In this paper, fast response PSP was applied to investigate the unsteady flow on a compression corner. Unsteady flow phenomena were shown as time-series images. Quantitative evaluation of fast response PSP measurement compared with Kulite transducer was also conducted. The PSP coating, experiment setup, calibration device, and PSP data processing method were introduced.

2 Experimental Setup

2.1 Wind Tunnel and Experiment Model

The experiment was conducted in FD-03 hypersonic wind tunnel in China Academy of Aerospace Aerodynamics (CAAA). This wind tunnel is transient, and blow down free jet one whose nozzle outlet diameter is 170m mx170mm. The Mach number extends from 5 to10, every Mach number has a corresponding nozzle that can be changed to change the Mach numbers.
Figure 1 shows a schematic and a photograph of compression corner. The span-wise length of the model is 80mm, the stream-wise length of the upstream plane is 40mm and the downstream plane is 40 mm. the ramp angle can be changed from 15° to 30° as shown in Figure 1. There are five pressure taps along the central line in order to install kulite pressure transducers, these sensors are used as reference and making in-situ calibration.

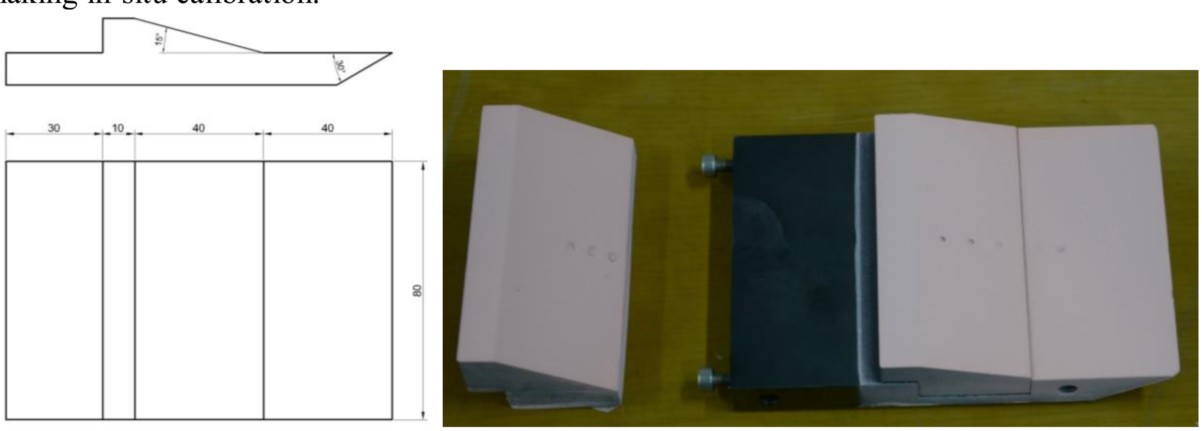


Figure 1. Compression corner

2.2 Instruments

A high-speed camera - Photron SA5 was used to capture PSP images. This camera has 12bit depth A/D resolution. Its ISO photosensitivity was 4000 on catalogue. High-photosensitivity of the high-speed camera is great merit for short exposure measurements like unsteady PSP measurement. The Photron SA5's maximum spatial resolution is 1024×1024 pixels at 7k (fps) frame rate. The measurement

configuration in this study was 1024×1024 pixels spatial resolution at 2000 fps with 0.5 ms exposure time. In this study, 50 wind-off and 1,000 wind-on images were captured for each test case. Measured images were firstly stored in the camera memory and then transferred to control PC. Data transfer used the 1GB Ethernet. Meanwhile, test using kulite pressure transducers were conducted.
The camera lens, Nikon 50mm F1.4S, was installed at the high-speed camera. Its aperture was set open to collect largest PSP luminescence. One bandpass optical filter was set in front of the camera lens to get the PSP signal from 640nm to 660nm and cut the illumination light component of UV light.
To compensate small exposure time, high-power illumination light source was one of the key components to increase PSP luminescence. A high-power UV light, INTELLIRAY 400, was used as the light source in this experiment. Its wavelength is from 300nm to 500nm, hence a filter was used to get 365nm UV light. Its total illumination power is 400W at maximum. The intensity can be adjusted from 50% to 100%. Its typical unstability is less than 1%, and it is air cooling.

2.3 Pressure Sensitive Paint

PSP is a molecular sensor based on oxygen quenching of its luminescence. Luminescence intensity from luminophore is varied by the environmental oxygen partial pressure. Conventional PSP, which consist of luminophore and polymer binder, have their typical response time of order 1 second. For unsteady PSP measurement, it is necessary to use much faster PSP.
Various PSP formulations are under continuous development in cooperation between CAAA and Institute of Chemistry, Chinese Academy of Science. CAAA has developed high porosity paints where the luminescent dyes can be incorporated into a highly porous polymer. The emission spectrum of the fast response PSP is shown in Figure 2. This paint uses PtTFPP as luminophore, which. is relatively photo-stable: the decay of luminescent intensity with continuous illumination is 1.5 percent/h. This paint is sprayable on any model surfaces. It is durable enough to withstand the aerodynamic forces. The response time of the high porosity paint is less than 0.2 milliseconds.

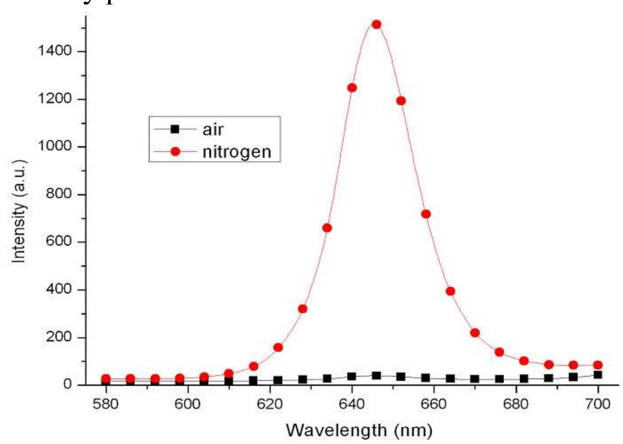


Figure 2. Emission spectra of the fast response PSP(excitation light 365nm)

2.4 Pressure sensitivity calibration

The static calibration device is shown in Figure 3above. Porous PSP samples were installed in a pressure chamber in which both the pressure and temperature can be set. The sample was excited by UV light and its photoluminescence was detected by a CCD digital camera. Pressure range was 10-100 KPa and calibration temperature are 25°C,30°C and 35°C. As we can see from Figure 4, PSP characteristic tend to have nonlinear pressure sensitivity. Polynomial expression was used to describe the relationship between pressure and luminescence intensity.

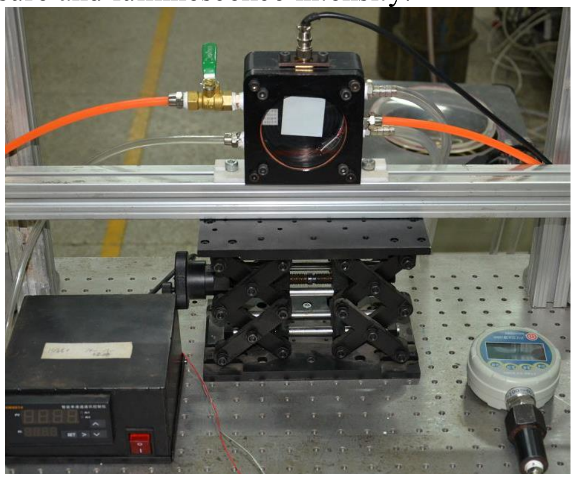


Figure 3. Static calibration device

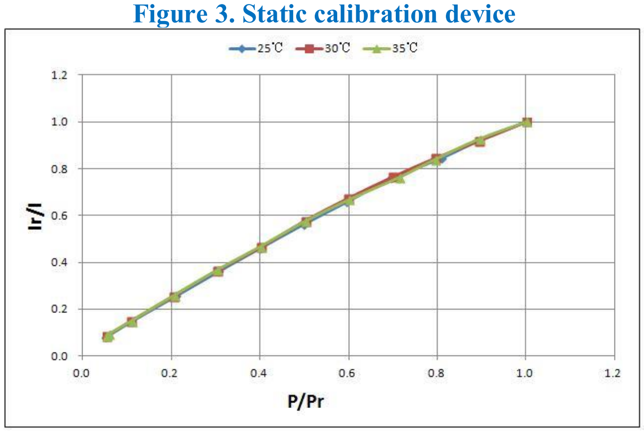


Figure 4. Calibration curves at different temperature

2.5 Dynamic-response Calibration

With the development of porous PSP, there has been a need for accurate characterization of the response times of PSP. Dynamic calibration methods have been developed to meet this need. Response times of PSP were measured from a step change of pressure created by Solenoid valve and pulsating jet. Two dynamic calibration device were developed to test the response time of PSP. The unsteady calibration device are shown in Figure 5 and Figure 6. For unsteady calibration the paint was sprayed onto 20 mm × 20 mm aluminum plates.

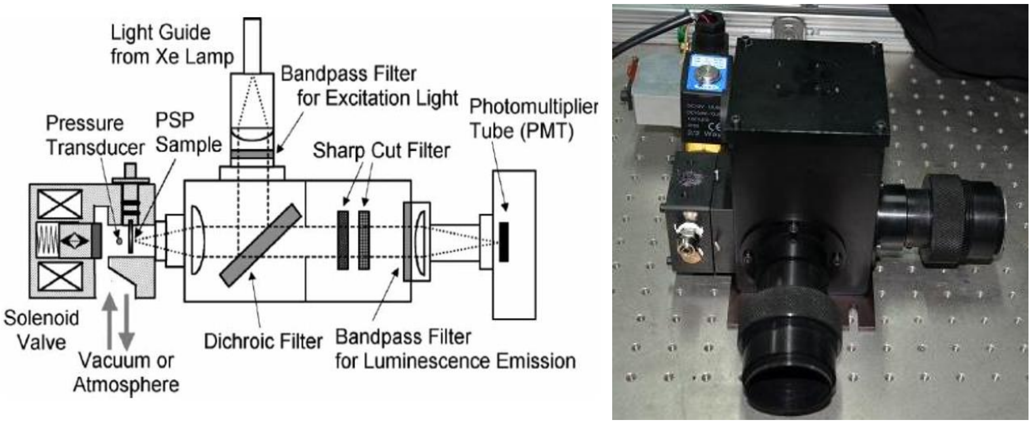


Figure 5. Schematic & solenoid valve dynamic calibration device (pressure chamber)

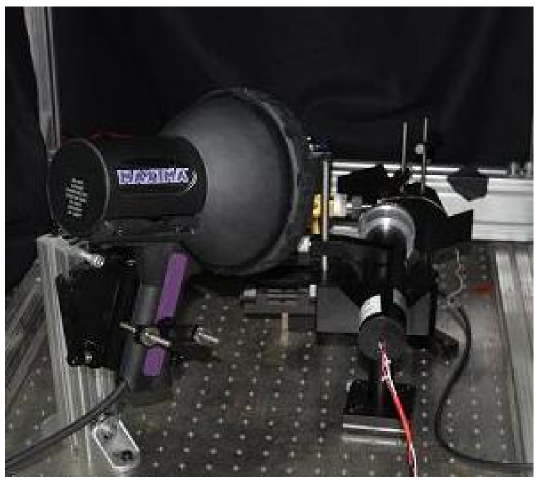


Figure 6. Pulsating jet dynamic calibration device

Several fast response PSP formulations was developed and tested. The typical response time of porous PSP is less than 0.2ms as shown in Figure 7.

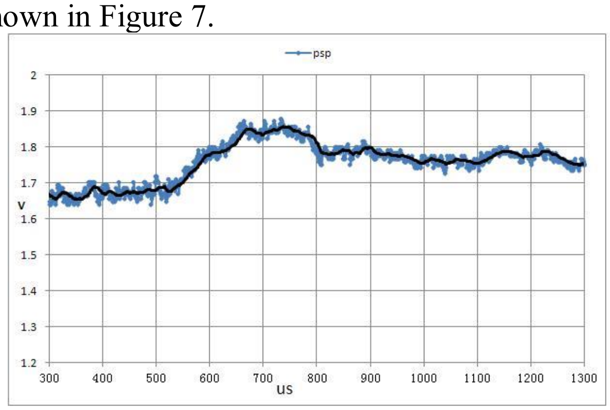


Figure 7. Response time of porous PSP

2.6 Experimental setup

Painted compression corner was mounted in the hypersonic wind tunnel as shown in Figure 8. Optical access was gained through a 200-mm-diameter observation window on the ceiling. A 450 Watt xenon lamp with bandpass filter (365±10 nm) was used as excitation light. The emission from the PSP was detected by Photron SA5 with 12-bit intensity resolution. A bandpass filter (650±10 nm) was installed in front of the camera lens. Maximum frame rate is limited by the intensity of the emission light, so the illumination light was set to maximum state, 2 kfps was the highest frame rate for the illumination light source. A synchronizer was designed to trigger the camera and amplifier. 5 kulite pressure transducers and the camera can acquire data at the same rate. Three PT100 temperature transducers was used to measure the model temperature during the wind tunnel test. It's accuracy is ± 0.2%F.S.

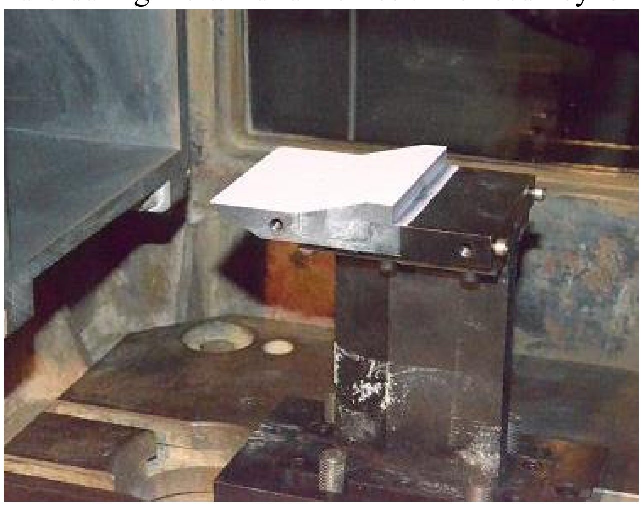


Figure 8. Painted compression corner mounted in wind tunnel

2.7 Data Processing

As the pressure calculation process of PSP measurement, there are two types of acquired images, reference and wind-on ones, which are time-series images acquired by a high-speed camera. Reference images are PSP intensity images under atmospheric pressure around 100 KPa. Wind-on images are test data. Both images are subtracted dark component. Then, reference images are averaged to single reference image, Iref. Wind-on images keep time-series images. Time series Iref/I ratio images are calculated using the reference image and time-series wind-on images. The test model stand still while wind-on, image registration between reference and wind-on image was not necessary on present data processing. Finally, Iref/I ratio images are processed to time-series pressure images using the relation between Iref/I and pressure and PSP characteristics provided from calibration. Theoretically the relation between Iref/I and pressure is represented by following Stern-Volmer relation;

$$\frac{I_{ref}}{I} = A + B\frac{P}{P_{ref}} \tag{1}$$

In this study, the second order expression as following was appropriate to fit the relationship between pressure and luminescence intensity.

$$\frac{I_{ref}}{I} = A + B\frac{P}{P_{ref}} + C(\frac{P}{P_{ref}})^2 \tag{2}$$

A,B,C are the constant and decided through calibration process described in part B. The quantitative pressure value was calculated using this equation(2) in this study.

3 Results and Discussion

Figure 9 shows the sketch of the flow structure around the compression corner model. Color schlieren images of 0°, 5° and 10° angle of attack were captured after PSP experiment, they are compared to PSP pressure distribution as shown in Figure 10 - Figure 13. The shock wave angle and strength relates to the model angle. The leading edge shock, weak separation shock, reattachment shock, separation region, and the thicker boundary layer in the rear of the reattachment line are identifiable from the schlieren images.

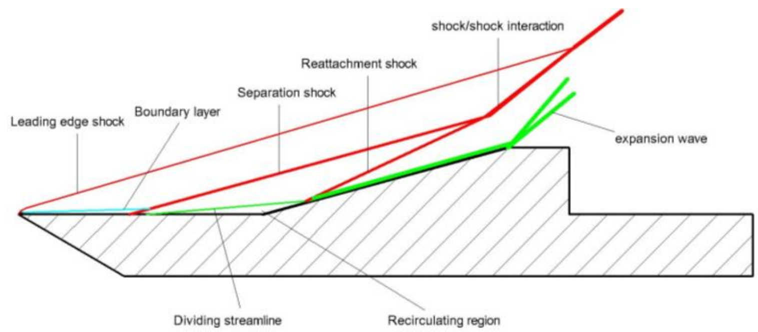


Figure 9 . Schematic of the flow structure

A separation region is formed around the corner junction due to the adverse pressure gradient imposed by the ramp surface. A separation shock wave is created in front of the separation region. Boundary layer is clearly visible after separation shock wave. The yellow color of the schlieren image on the ramp also clearly shows the thicker boundary layer, this might suggest boundary layer transition due to flow reattachment. A Prandtl-Meyer expansion fan forms on the shoulder to guide the flow parallel to the model surface whilst accelerating it.

PSP images (see Figure 14-17) show the highest pressure value along ramp surface. This is because the flow in this region has been compressed three times, firstly by the leading edge shock and then by the separation shock and finally by the reattachment shock. As the ramp angle increase, separation region increase, the intensity of reattachment and main shock increase. The lowest pressure is along the shoulder due to the acceleration of the flow across the expansion fan. This pressure distribution agrees with theory prediction.

At AoA=00 and 50, we can see a curved separation zone before the corner. The high pressure flow over the plate spills to the sides, which is the free stream flow at a relatively lower pressure. This three-dimensional effect occurs because the model does not have side walls, giving rise to the low pressure regions on each side of model surface on plate.

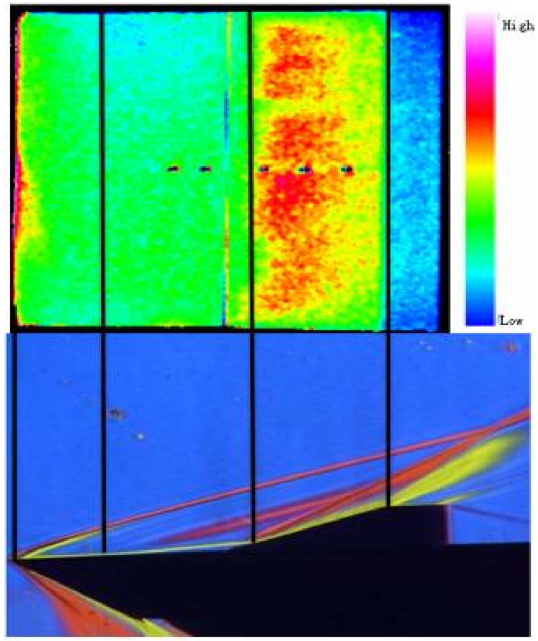


Figure 10 . AOA=0deg, PSP pressure and schlieren images ,ramp angle=15deg

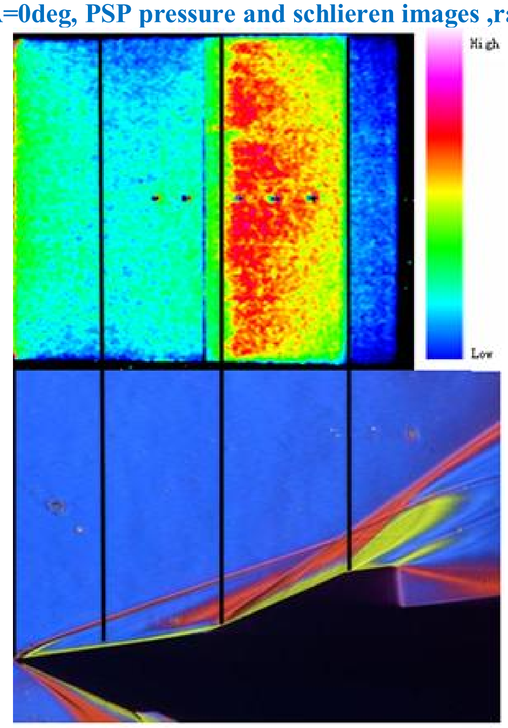


Figure 11 . AOA=5deg, PSP pressure and schlieren images ,ramp angle=15deg

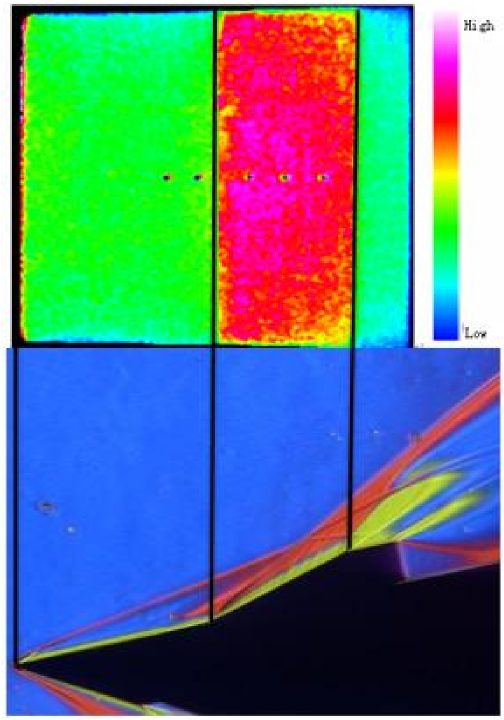


Figure 12 . AOA=10deg, PSP pressure and schlieren images ,ramp angle=15deg

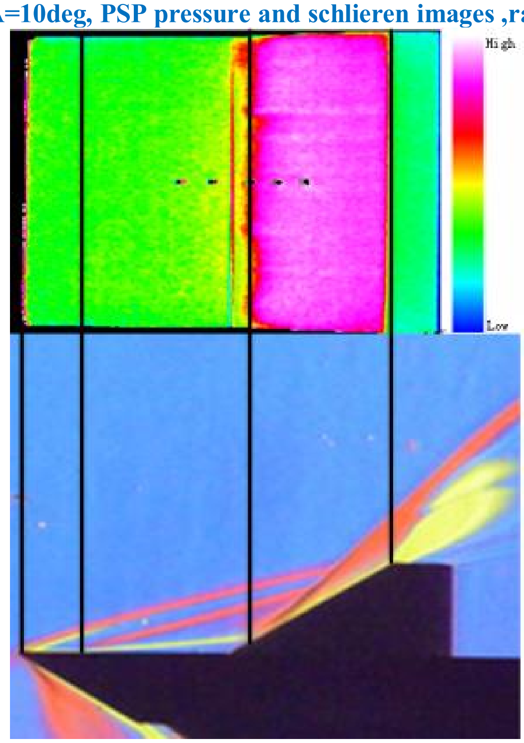


Figure 13. AOA=0deg, PSP pressure and schlieren images ,ramp angle=30deg

Time series unsteady pressure images on compression corner measured by the fast response PSP are shown in Figure 14-Figure 16. PSP measurement frame rate was 2kfps and all frames of PSP results are possible to see as movie. The Pressure distribution results are shown every 0.5ms. As the angle of attack increasing, separation region decrease, reattachment shock line moved forward, until there is no more separation. The pressure increase in the separation region, and highly increase in reattachment region.

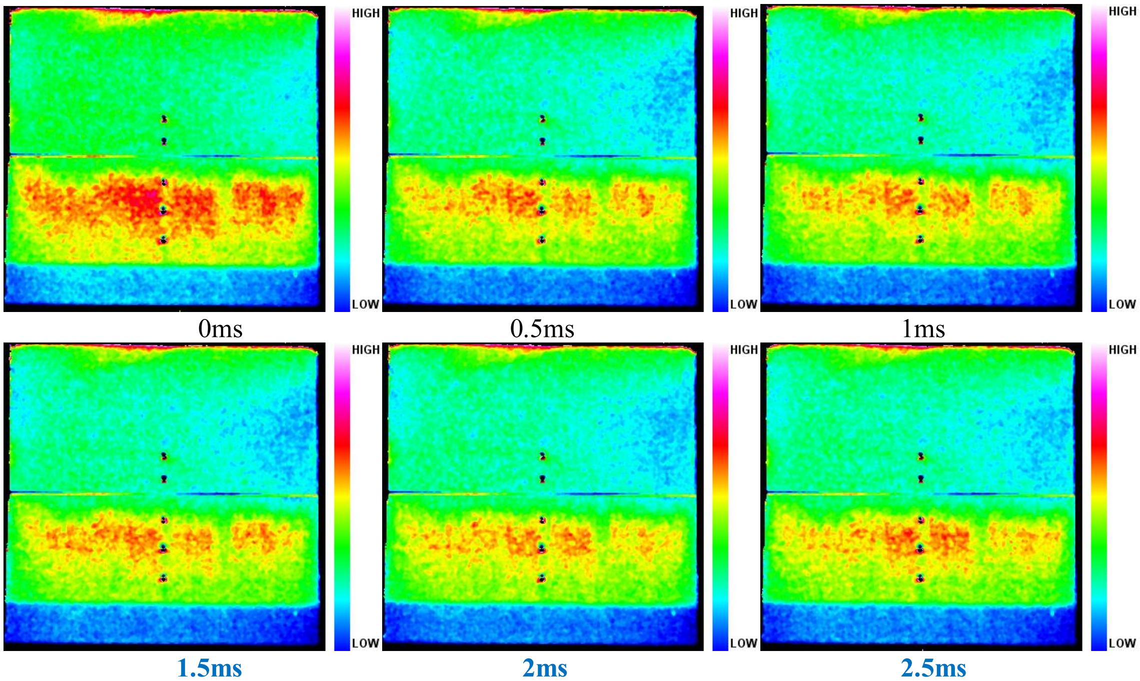


Figure 14. AOA=0deg, PSP pressure distribution on compression corner with 15°ramp, frame rate was 2000fps. Flow direction was from up to down on images.

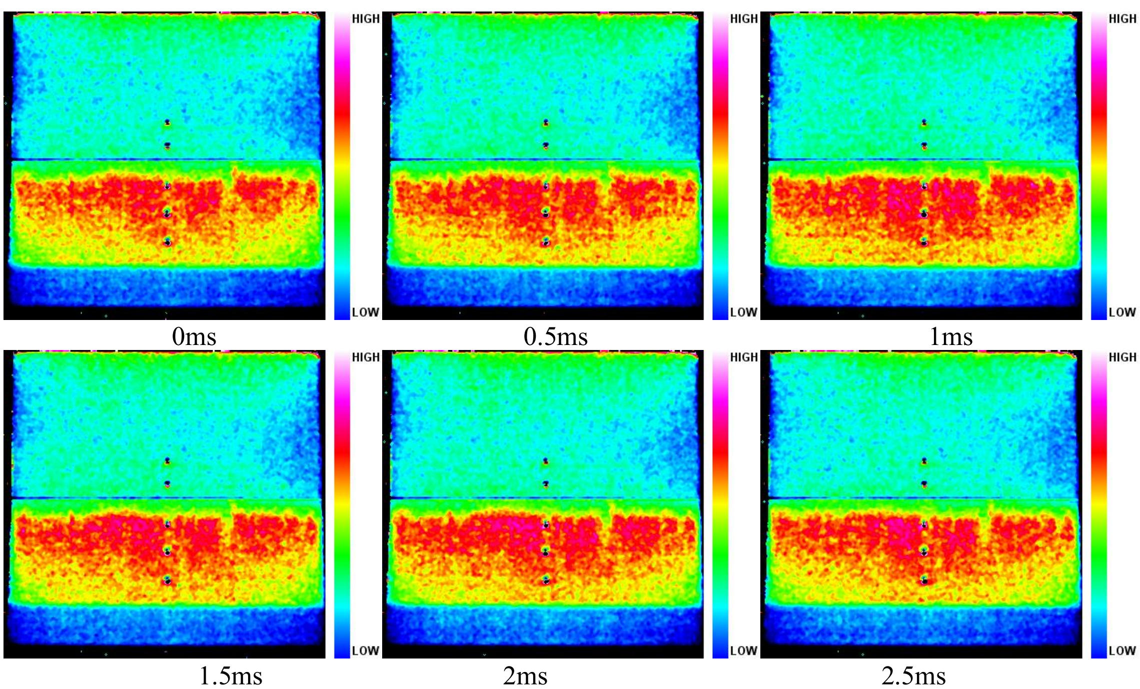


Figure 15. AOA=5deg, PSP pressure distribution on compression corner with 15°ramp, frame rate was 2000fps. Flow direction was from up to down on images.

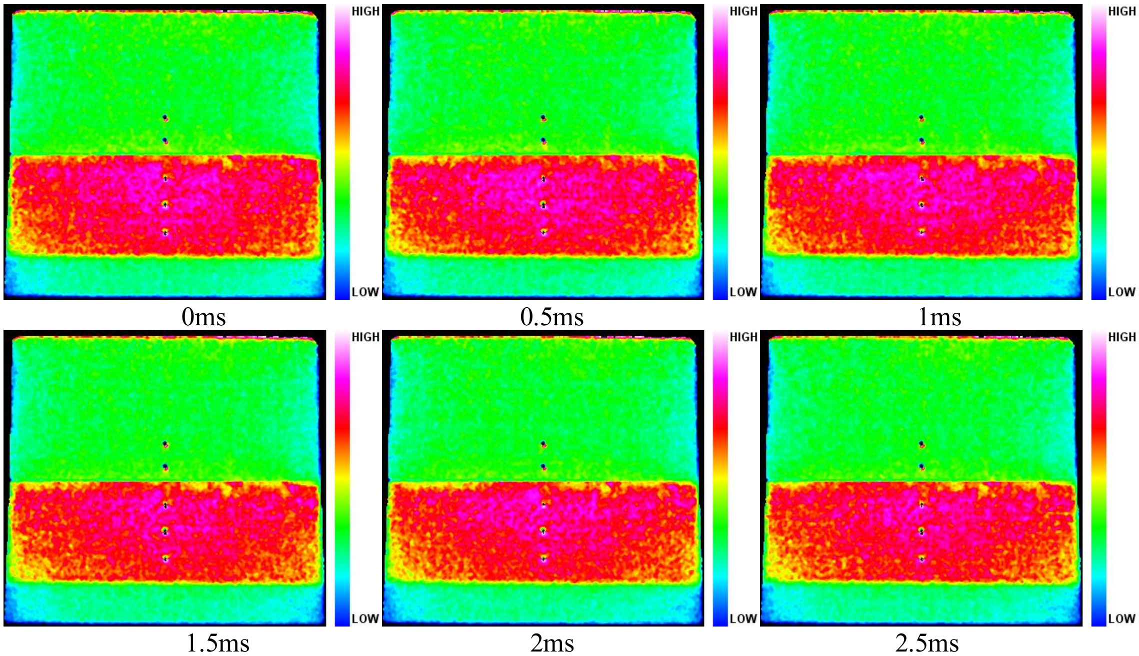


Figure 16. AOA=10deg,PSP pressure distribution on compression corner with 15°ramp, frame rate was 2000fps. Flow direction was from up to down on images.

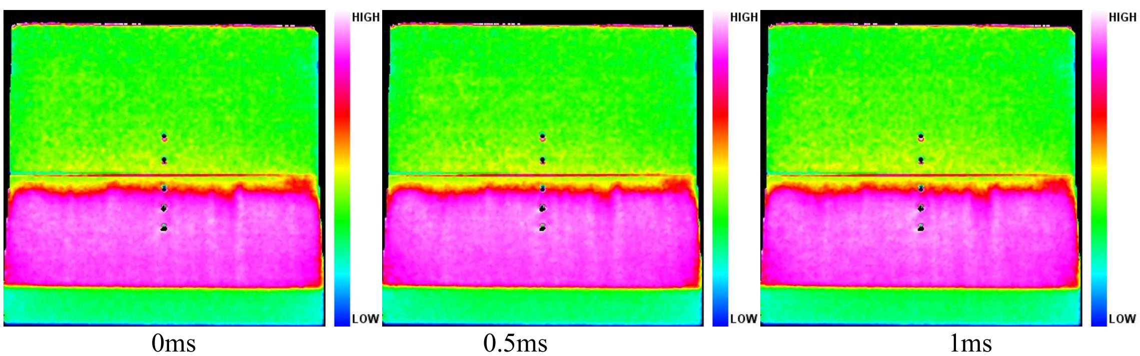


Figure 17. AOA=0deg,PSP pressure distribution on compression corner with 30° ramp, frame rate was 2000fps. Flow direction was from up to down on images.

Figure 17 shows the pressure distribution on 30°ramp. At the attachment line, some slight striations are observed which are believed to be caused by Görtler vortices due to the reattachment of the flow on the ramp.

There are four acting Kulite pressure transducers which measure the pressure at the same rate with PSP method. PSP pressure data are extracted almost along the pressure taps as shown in Figure 18. The time series contrast pressure curves are shown in Figure 19. Pressure data agree well and pressure deviation is less than 5% between Kulite transducer and PSP. This is caused by the temperature difference of the model between reference and win-on. To reduce the deviation, reducing PSP temperature dependency is necessary in future.

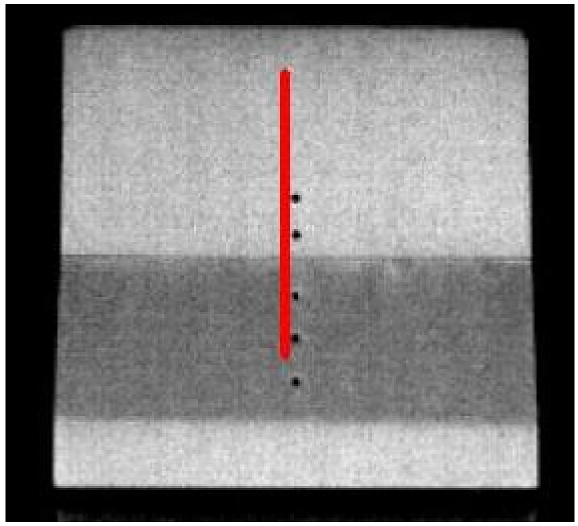
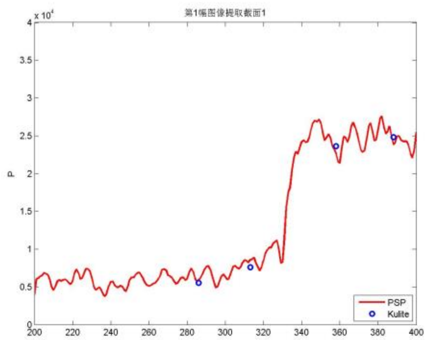
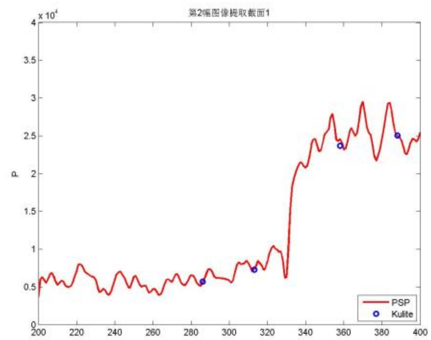


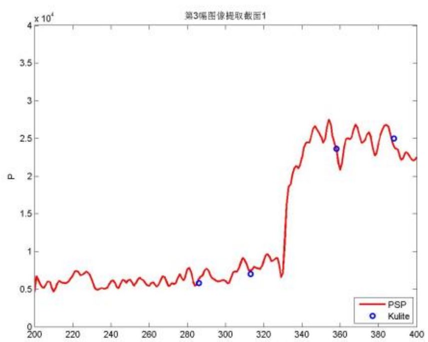
Figure 18 . Pressure section and Kulite transducer location



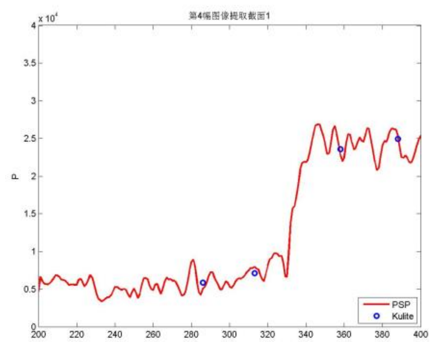
0ms



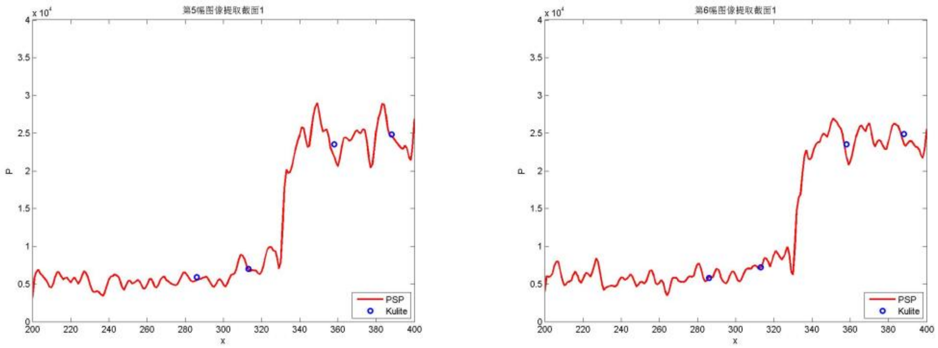
0.5ms



1ms



1.5ms



2ms **2.5ms**

Figure 19 . PSP data compare to Kulite data on section(AOA=0deg,ramp angle=15deg)

4 Conclusion

A polymer based porous PSP formulation has been developed in CAAA. This PSP formulation has a response time of 200 microseconds. Fast response PSP measurement was applied to a compression corner in hypersonic wind tunnel. Time-series pressure images were obtained from the PSP data measured by a high-speed camera involving pressure transducer data. M=5, AoA=0° were introduced as the typical case. Quantitative and time-series pressure images gave global pressure distribution and time series behavior of the unsteady flow field on the compression corner. Standard deviation of the pressure data of the fast PSP measurement compared with pressure transducer data were less than 5%. Application of fast response PSP on the compression corner captures the complicated flow regimes including separation zones, reattachment line, and three-dimensional effects which cannot easily obtained using the conventional discrete pressure taps. Fast response PSP measurement was confirmed as a powerful tool to investigate hypersonic and unsteady flow field. It could validate the unsteady CFD codes in combination of global unsteady PSP results and pressure transducer data.

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