DETECTION ANGLE CALIBRATION OF PRESSURE-SENSITIVE PAINTS

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Luminescent paint, pressure-sensitive paint, calibration, turbomachinery, oblique viewing

ABSTRACT

Uses of the pressure-sensitive paint (PSP) techniques in areas other than external aerodynamics continue to expand. The NASA Glenn Research Center has become a leader in the application of the global technique to non-conventional aeropropulsion applications including turbomachinery testing. The use of the global PSP technique in turbomachinery applications often requires detection of the luminescent paint in confined areas. With the limited viewing usually available, highly oblique illumination and detection angles are common in the confined areas in these applications. This paper will describe the results of pressure, viewing and excitation angle dependence calibrations using three popular PSP formulations to get a better understanding of the errors associated with these non-traditional views.

INTRODUCTION

Global measurement techniques have dramatically increased the amount of information realized during a wind tunnel test compared to point measurements. The additional information leads to an increased understanding of the flow physics around an aerospace vehicle thus decreasing its design cycle time. One of these widely accepted techniques is the measurement of surface pressures using pressure-sensitive paints [1-2]. The pressure-sensitive paint (PSP) technique has become a useful tool in quantitatively determining the pressure on the exterior of aerodynamic surfaces. The trend of extending global instrumentation techniques to more challenging applications is constantly expanding. This PSP technique has experienced similar expansion. The use of PSP to measure the pressure on turbomachinery components is still relatively new and has several obstacles to overcome including limited views, high-speed surfaces and flows, and high temperatures. Even so, PSP has been used to successfully measure steady state pressures on the suction side of high-speed fan blades by imaging methods and laser scanning techniques[3-5]. The desire to use this technique on internal components such as high-speed fan stators has yielded limited results[6]. The initial tests have yielded serious problems with adhesion of the paint because of the highly turbulent flow just downstream of the rotor. The accuracy of the pressure measurements was lower than desired even after modifications of the operational procedure of the rig were made in order to allow the paint to stick. The temperature sensitivity of the PSP is a known source of error in these applications. The highly compacted vane spacing led to severely limited optical access. The errors associated with these highly oblique viewing angles were not known and were perceived to be significant. Research is being conducted at Glenn Research Center to solve the problems of PSP applications with highly oblique viewing and limited optical access. The calibration of the "intensity technique" to acquire PSP data in these highly oblique viewing angle applications is the subject of this paper.

The need to measure the surface pressure at highly obtuse angles from the surface normal is common when using pressure and temperature-sensitive paints (TSP). Some examples of test article areas that experience steep angle of illumination and detection are: the leading edge of wings, aircraft fuselage and canopy areas, engine nacelles, turbomachinery components and ice accretions. Many of these applications have limited viewing options because of optical access from the test facility or internal flow surfaces. A significant practical problem, for instance, is knowing how far around the leading edge of a wing the PSP data is valid. Many things affect this problem. The viewing angle and surface curvature are significant, but so are registration errors for model motion and deformation between wind-on and wind-off images, reflections and self-illumination. The calibrations described in this paper will account for model motion between wind-off and wind-on images and reflections due to neighboring surfaces and windows, to realistically model actual test conditions.

PAINT BASICS

Pressure-sensitive paints are comprised of a luminescent compound (luminophore) or dye that is quenched by oxygen and is dispersed in an oxygen permeable polymeric binder. The luminescence is induced by the excitation of the dye at its absorption wavelength. The emitted intensity of the PSP is inversely proportional to the partial pressure of oxygen.

Photoluminescence is a radiative process that occurs when a luminescent molecule is stimulated by the absorption of light. When the molecule absorbs a photon, its electrons can be excited to a higher energy state. From this excited state, the luminescence process competes with non-radiative processes such as oxygen quenching to return the excited electrons to the initial ground state. The energy change for absorption is greater than for the emission process, therefore the mean wavelength for absorption is shorter than the mean wavelength of emission. The spectral separation of the excitation and emitted light allows the emitted light to be recorded without interference from the excitation source. It is essential that the camera record only the emission spectra. Therefore the excitation must be filtered sufficiently so that it emits no light in the emission band. Similarly, the detection system must be filtered to ensure the camera only records the emission band of the PSP.

The relationship between the intensity of the luminescence and the partial pressure of oxygen can be expressed in terms of the Stern Volmer relation given by

$$\frac{I_0}{I_{O_2}} = 1 + K_{SV} P_{O_2} \qquad (1)$$

where:
Po_2 = Partial pressure of oxygen

I_0 = luminescent intensity at zero oxygen pressure
I_{O_2} = luminescent intensity at partial pressure of oxygen P_{O_2}
K_{SV} = Stern Volmer constant.
In general it is not practical or even feasible to measure I_0 in a wind tunnel environment. By using Henry's Law that linearly relates the ambient pressure P to the partial pressure of oxygen in air, equation 1 can be rewritten using the popular intensity ratio based form

$$\frac{P}{P_{REF}} = A + B\frac{I_{REF}}{I} \qquad (2)$$

where:
I_{REF} = "wind-off" intensity at constant pressure P_{REF}
I = "wind-on" intensity at pressure P.

It should be noted that both A and B in equation 2 are temperature dependent. The temperature sensitivity of a typical PSP is in the range of 0.6 to 1.5% per °C[7].

The intensity technique requires two data points to be acquired, I_{REF} and I, to determine the unknown pressure P. The technique holds true whether the acquired intensity data is from a single point detector or two dimensional intensities from a CCD camera. Since all the data used in this paper were acquired with a cooled CCD camera, the data points will be referred to as images. The reference image is acquired at a constant known pressure usually at ambient conditions, and is commonly referred to as the "wind-off" image. The image of the unknown pressure at test conditions is referred to as the "wind-on" image.

DESCRIPTION OF EXPERIMENTS

The test specimens were placed in a glass vacuum calibration cell providing a full 360°optical access to the test specimen as shown in figure 1. This calibration cell is limited to a pressure range between 0 and 1 atmosphere since the top is not restrained for pressures above atmospheric pressure. The current cell configuration does not support simultaneous temperature dependence calibration of PSP test samples. The purpose of this cell is to allow three-dimensional specimens to be calibrated for pressure, unlike most PSP calibration chambers that support only flat metal coupons. The cylindrical glass chamber simulates the shape of windows typically used in turbomachinery applications for other flow measurement techniques such as laser doppler velocimetry (LDV) or particle imaging velocimetry (PIV). This portable chamber allows pressure calibrations on actual test articles including non-conventional applications like PSP on ice accretions in a cold room environment.

The detection angle calibration test consisted of three different test articles. A 50.8 mm diameter stainless steel cylinder was used to determine illumination and detection angle effects on surfaces with high curvature. A 76.2 by 63.5 mm flat coupon was used to determine the effects of viewing at various angles. (The detection angle of the coupon was varied from 45° from the surface normal down to highly oblique angles of 5° off the surface plane.) The third test article consisted of two sections of stator vanes nominally 96 by 55 mm from a turbomachinery application. This test specimen was included to determine the error that may be expected for a curved surface viewed at fairly steep angles using an actual test hardware configuration with confined areas caused by an adjacent vane.

The test cell was mounted on a system that allowed the cell to be manually rotated and translated. The cell pressure was then controlled by an electronic regulator and monitored with a precision transducer with an accuracy of 0.02% of full scale (250kPa). The PSP data was acquired using a cooled 16-bit back illuminated CCD camera system illuminated with blue LED arrays[8]. Data was acquired using the intensity method of obtaining a wind-off reference at atmospheric pressure and wind-on images at varying pressures. The test article was moved laterally 1mm after acquiring the reference image using the translational mounting stage for every calibration sequence that was tested. The 1mm movement of the test sample represents approximately a five pixel shift in the image x direction and a one pixel shift in the image y-direction. The shifting of the data images was done to more realistically simulate the conditions that occur during actual testing. The wind-off is never completely registered to the wind-on images when using the intensity technique. The simplest registration that can occur is that the two images are a simple x-y pixel shift or x-y shift and rotation between the reference and data images as was intentionally applied to this calibration.

The optical setup of the cylinder is shown in figure 2a. In this setup a single blue light emitting diode (LED) excitation source was placed in one of the two locations. The first was directly next to the detector. This excitation /detection setup is similar to a case where optical access is limited to one location or window. The second location was 45° from the detector. This type of illumination is typical when there is ample optical access and multiple excitation sources are used to illuminate a complex geometry test article such as an aircraft fuselage. Figure 2b illustrates the setup for the flat coupon. Again this test was conducted using a single illumination source located at one of the two shown locations.

The high-speed fan stator calibration setup is shown in figure 2c. The use of two illumination sources was required to uniformly illuminate the vane since the curved surface and confined area caused by the adjacent vane prohibited the source from being placed closer to the surface normal. The illumination field of the painted vane was adjusted using the iris feature on the front of the LED sources to provide a near uniform emitted intensity at the detector.

RESULTS AND DISCUSSION

Cylinder Calibration

The cylinder calibration results at a pressure of 86.2 kPa are shown in figure 3 for the three PSP's tested with a single excitation source located at the 45° location as shown in figure 2a. The three paint formulations are; a silicone based Ruthenium complex paint, a sol-gel based fluorinated platinum porphyrin Pt(TfPP) paint and Pt(TfPP) within a fluoroacrylic copolymer (FIB) binder. The data is shown plotted as pixel location around the cylinder against normalized intensity. The pixel locations are also labeled with the viewing angle with respect to the camera. The 90° point on the cylinder is the surface normal that points at the camera. The image data was averaged over a given column or angular view to achieve the single curve from the intensity ratio image. The data shows that the intensity ratio stays nearly constant until you reach an angle of approximately 15°. Beyond 15° the intensity ratio increases rapidly. At this point making further paint measurements was clearly unreliable. The divergence of the three curves as the viewing angle became smaller was repeated with a sample painted a second time to confirm these trends. The repeated test yielded similar results.

A critical property of any PSP system is the selection of excitation and detection filters. Four filters were used here. For the camera, both a long-pass color glass detection filter and a narrow band-pass interference filter were used. For the source, a short pass gel filter and a narrow band-pass interference filter were used in conjunction with a short-pass interference filter for the LED source. Table 1 shows the four filter combinations used. The intensity ratio variation with observed angle for each of the four filter sets is shown in figure 4 at a constant pressure of 44.8 kPa. The hump in the filter combination 1 line reveals a spectral leakage through the filters from a specular reflection off the surface of the silicone-based paint. The color glass filters allow a wider spectral band of light in to the detector by allowing the longer wavelengths to pass that the interference filter rejects. These slight differences are one reason why the test acquisition hardware should be used in the calibration especially when an a-priori PSP calibration is required. Even though the specular reflection from the surface shows no spectral leakage in filter sets 2,3 and 4, the proximity of the test article to the glass surface caused reflections or self illumination that required adjusting the placement of the test article in the calibration cell to minimize this effect.

Table 1. Detection and excitation filter combinations used for the Ruthenium silicone paint in the cylinder calibration as reference to in figure 4.

Excitation Filter Detection Filter	500nm Short Pass + Short Pass Gel $\lambda_C = 500nm$	500nm Short Pass + Interference $\lambda_0 = 450nm$ $\Delta\lambda = 40nm$
Color Glass Long Pass $\lambda_C = 530nm$	1	2
Interference $\lambda_0 = 550nm$ $\Delta\lambda = 40nm$	3	4

Flat Coupon Calibration

The calibration of a flat coupon was performed using the Pt(TfPP) in FIB sprayed over a FIB white basecoat on to an aluminum coupon with a combined coating thickness of 12-18μm. A single excitation source was placed at two locations with respect to the detection camera and coupon as in the cylinder calibration previously shown. This calibration was performed to determine the errors associated with making PSP measurements on flat test articles at very oblique viewing angles where surface curvature is not a factor. An example of this test configuration is viewing into a wind tunnel aircraft model inlet from an upstream window in the test section wall. Optical access is limited because interference with the flow field around the model can not be tolerated. A plot of the intensity ratio difference between the coupon at 45° and at shallower detection angles is shown in figure 5. The data labeled as modified (Mod) is for the lights at the 45° location. The plotted data is a region of interest average over the center section of the coupon. The difference is the same for the two excitation angles until the detection angle moves to the extreme at 5°. The difference of the 5° data from the 45° reference case more than doubles when the illumination is close to the camera but when the excitation source is moved to a location 45° (5° Mod plot data) from the camera, the difference falls within the range of the other data. This data shows that PSP data can be accurately achieved at highly oblique detection and excitation angles when the painted surface is flat. The major drawback of using this technique at these angles is the loss of spatial resolution because of projected area at high incidence angle where the projected area decreases by the cosine of the viewing angle from the surface normal.

Stator Vane Calibration

The stator vane calibration used the Pt(TfPP) in FIB sprayed over a FIB white basecoat at a total measured coating thickness of 14-20μm. The PSP coated vane was attached to a second vane to form a confined channel as it is installed in the rig as shown in figure 6. The adjacent vane and all surrounding areas were coated with a flat black paint to reduce reflections in the tight channel approximately 22 mm wide. The calibration procedure consisted of taking a wind-off reference at atmospheric pressure and then shifting the sample 0.1 mm by means of the translating stage. The pressure was varied between 0 and 1 atmosphere. The image intensity ratio was computed after image registration and statistical information over the entire vane surface was calculated. The plot of standard deviation for different pressure levels over the vane surface is shown in figure 7. This plot shows the standard deviation slowly declining with decreasing pressure but the deviation as expressed as a percentage of the average intensity ratio reading nearly doubles from 0.79% at 1 atm to 1.4% at a pressure of 0.14 atm. The image in Figure 8 shows the variation in the intensity ratio image at a P/P_0 of 0.36 and a mean intensity ratio of 0.558 having a standard deviation of 1.02%.

The camera-viewing angle was estimated to be between 18 and 30° with respect to the stator vane surface. The curvature of the vane and the view blocked by the adjacent vane limits the range of viewing angle experienced. The standard deviation was calculated for the cylinder calibration image data for the same paint with the excitation source mounted close to the camera in an attempt to compare the errors associated with a curved surface at highly oblique viewing angles. The calculations were made for the region of the cylinder that corresponds to the vane viewing angle with respect to the detector. For the cylinder, a mean intensity ratio of 0.5679 and standard deviation of 0.75% of I_0/I were computed for a P/P_0 of 0.37, which are similar conditions as those presented in figure 8. The difference between the cylinder and vane deviation data can be attributed to two areas. First, the small region comprising the 18 to 30° view of the cylinder surface is simple compared to complex geometry of the vane. Secondly, even though steps were taken to prevent reflections in the channel between the vanes, the emitted light from the PSP is not totally absorbed by the black surface of the adjacent vane.

Several factors contributing to errors associated with the geometry of the acquisition setup have been discussed. Another is the choice of PSP. The grazing incidence of the excitation and emitted luminescence is dependent on the diffuse reflection properties of the PSP. All three paints are near ideal Lambertian emitters, that is their radiance is independent of the viewing angle. This property starts to break down at low incidence angles where the surface properties have an effect. By visual inspection, the RTV based PSP has the highest specular reflection characteristics, or in more common words, has the highest gloss. The sol-gel and FIB paint by contrast would be considered matte or flat type paints.

CONCLUSIONS

Several important conclusions have been learned from this series of calibration experiments. The data shows that making PSP measurements at very high angles from the surface normal is possible. Surface curvature errors stay less than 2% for the surface normals perpendicular to the detector out to ±75° from the camera. The data shows that the detector angle makes little difference when measuring flat surfaces over a wide range of angles. Errors remained less than 0.4% for the detector angle ranging from 5° to 45°. Finally, a complex surface within a confined passage with a simulated registration error was shown to have intensity ratio errors ranging from 0.8 to 1.4% over the pressure range of 0.14 to 1.0 atmosphere. This error is less than errors caused by temperature variations typically encountered in turbomachinery applications. Therefore, in turbomachinery applications such as a stator vane downstream of a high-speed fan, temperature effects have more of an influence on the measurement than the geometry.

Another major observation is the spectral rejection of the excitation and detection filter combination. The filter combinations that were typically used for the ruthenium-based paints were inadequate on surfaces that have a specular reflection regardless of where the excitation sources are placed, as is the case with the cylinder. The addition of complementary filters added to the LED sources eliminated this filter leakage.

The stator vane calibration test was used to simulate a typical experiment at high oblique viewing angles in a confined channel. This experiment showed that significant care must be used in applying an absorptive paint on all surfaces in and near the PSP coated surface. Though all surfaces were coated with a flat black paint not all the emitted radiation is absorbed by the surrounding surfaces and led to gradients in the intensity ratio images. These errors while limited exclusively to the variation in pressure, emitted radiation and sample movement can be a significant source of error (as high as 1.4% of the reading at low pressures). This error is usually overshadowed by the temperature sensitivity of the PSP where a temperature gradient of several degrees centigrade can achieve the same error as was achieved at the lowest pressures tested.

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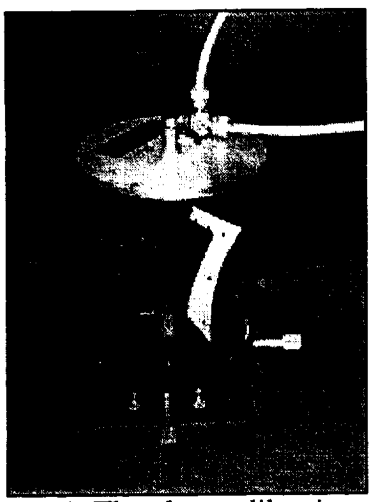
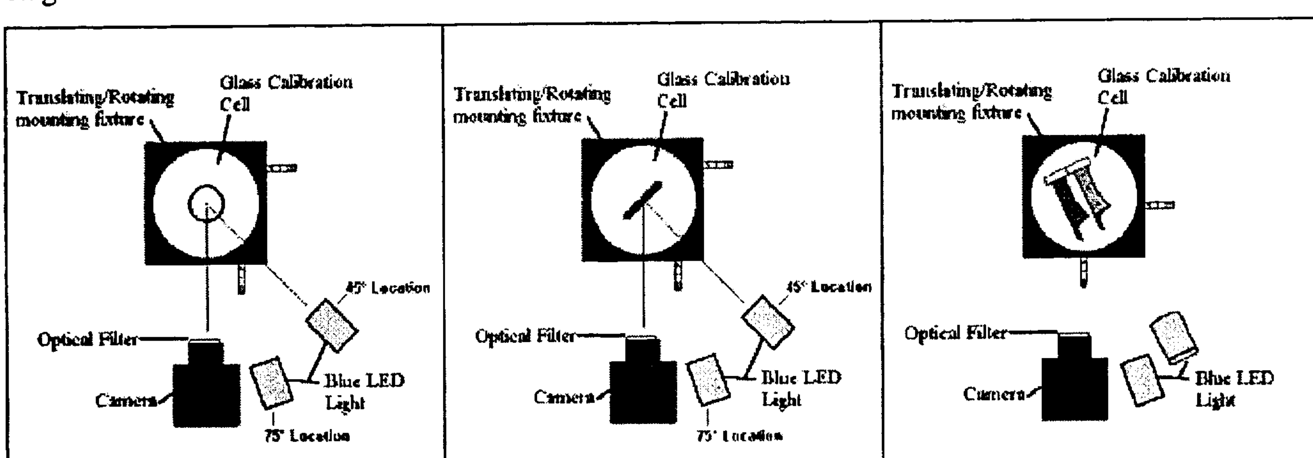


Figure 1. The clear calibration cell with the stator vane installed mounted on the translating stage.



(a) (b) (c)

Figure 2. The calibration experimental setups for the 50.8 mm diameter cylinder (a), the 76.2 by 63.5 mm flat coupon (b), and the stator vane channel (c).

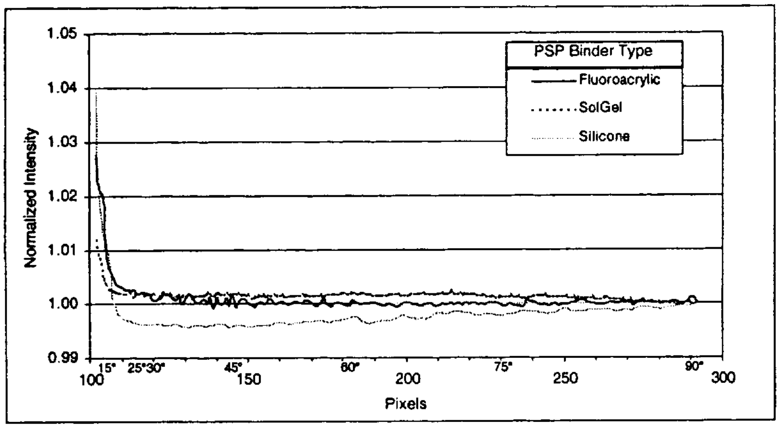


Figure 3. Cylinder calibration using 3 different types of paint with illumination next to the camera.

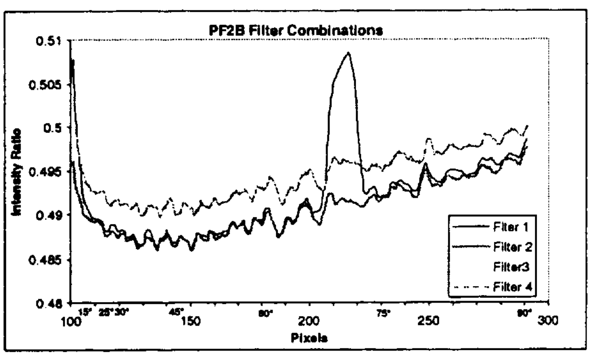


Figure 4. Plot of silicone based PSP on cylinder with 75° illumination showing the effects of excitation/detection filter combinations and spectral leakage.

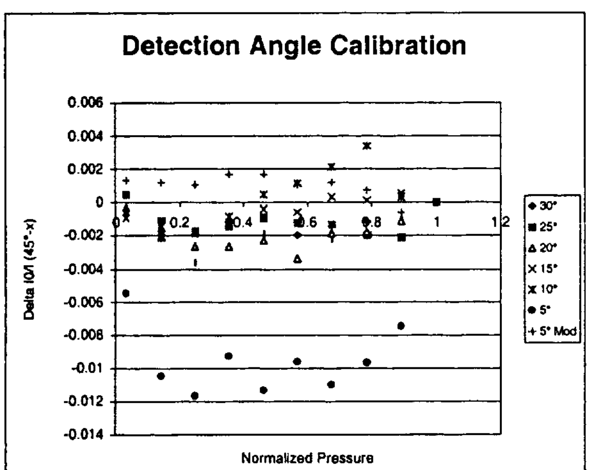


Figure 5. Plot of flat coupon calibration data using FIB showing the difference at various detection angles with respect to a 45°-detection angle. The illumination source was placed next to the camera except in the 5° Mod case where the excitation source is 45° to the camera.

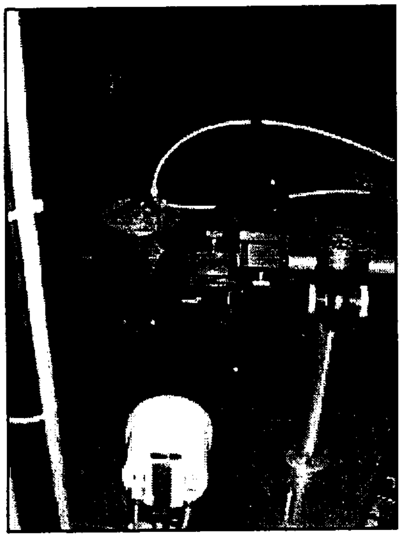


Figure 6. The calibration setup with stator vane install in the calibration cell. Two illumination sources were needed to uniformly illuminate the vane surface.

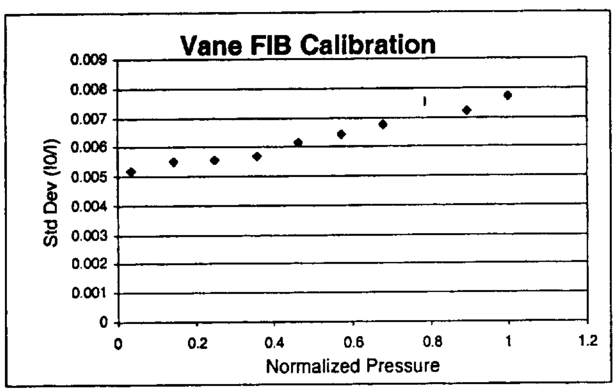


Figure 7. Plot of the intensity ratio image's standard deviation for different pressure levels. The sample was painted with FIB and excited with two sources.

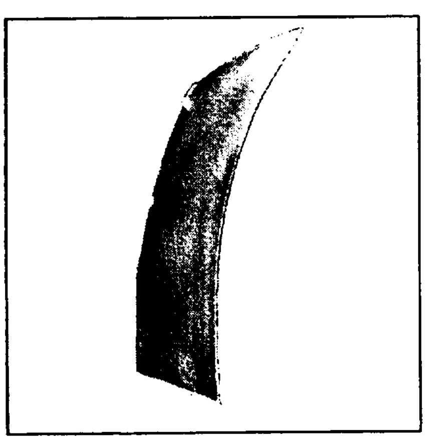


Figure 8. Confined channel stator vane intensity ratio image at constant normalized pressure of $P/P_0 = 0.37$ showing the variation of indicated pressure. (scale: 0.54 (black) to 0.57 (white))