PRESSURE SENSITIVE PAINT FOR ANALYSIS OF FILM-COOLING EFFECTS ON A GAS TURBINE BLADE TIP

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Abstract

This paper deals with the implementation of Pressure Sensitive Paints (PSP) in turbomachinery and other aero-thermal research studies. A specific calibration setup developed at the Pennsylvania State University and the applications of PSP are discussed in detail. PSP is an experimental technique for mapping pressure distributions on any aerodynamic body. It requires coating the surface of the body with a special paint that exhibits luminescence when it is exposed to light of appropriate frequency. The intensity of the exposed light is then used as a measure of the pressure at that point. In order to draw up a reference criteria, calibration of the paint was carried out in a specially designed chamber. The paper provides details about the calibration procedure as well as the setup. Although in the recent years PSP has been used for the investigation of high speed flows, its low-speed applications are also being investigated. The current effort aims at using PSP technology in exploring film-cooling effectiveness and the pressure loss characteristics associated with the use of flat as well as squealer tip rotor blades in an axial flow turbine. In conclusion, this paper attempts at establishing PSP as a simple, cost effective and highly efficient means of experimental verification of computational results along with proposing this technique as a substitute for the expensive wind tunnel testing of various aerodynamic bodies.

Introduction

Any increase in the thermal efficiency of a gas turbine engine is contingent on a corresponding increase in the turbine inlet temperature. However, at the same time an increased turbine inlet temperature leads to enhanced heat transfer and thermal stresses on the blade surface. In order for the blade to withstand such adverse environment and avoid any material failure, it becomes essential to provide an arrangement for cooling the system. Of the various cooling mechanism available, film-cooling has come to be widely accepted as one of the more useful active cooling methods. In case of film-cooling, relatively cooler air is passed through several small discreet holes onto the surface of the blade. This generates a protective film between the hot mainstream flow and the blade surface which protects the surface of the blade by keeping it at a lower temperature. The coolant used in film cooling is actually bled air from the compressor. Hence, although it protects the turbine components and allows for an increased turbine inlet temperature, excessive use of the coolant leads to a decrease in the overall thermal efficiency of the system as we have a higher percentage of compressor air being bled and greater mixing of cooler air into the hot mainstream air taking place. Thus the best configuration would have to be the one yielding the maximum increase in the turbine inlet temperature with the expense of least coolant possible. Many research efforts have been directed towards a better understanding of the phenomenon of film cooling and devising new and efficient configurations that can provide the maximum increase in the efficiency.

The current effort also aims at explaining the above mentioned phenomenon but with the help of a recently developed experimental tool: Pressure Sensitive Paint. The main advantage of using this technique as against the more widely used conventional means, is that this can provide an accurate and spatially continuous pressure map of the whole surface whereas with the other means only a certain percentage of the whole surface is available for analysis. Conventional means of pressure measurement mainly include discrete pressure taps and electronically scanned transducers. Although these methods are also capable of providing accurate pressure data, this data is only limited to certain discrete points. In addition to this, the various mounted pressure taps lead to a compromise in the structural integrity and tend to disturb the actual flow. Moreover, their installation over the blade surface generally proves time consuming and expensive. For these reasons, improved techniques for the measurement of surface pressure on the turbine blade have continuously been explored and pressure sensitive paint is one of the results of these efforts.

In the recent years a lot of work has been done on the development of pressure sensitive paint (PSP) and its use for various aerodynamic applications. McLachlan and Bell (1995) provided an initial review of this technology with experiments focused on the aircraft development wind tunnel testing.. Many researchers have also been using PSP for pressure mapping in high speed (transonic) flows for example Liu et al (1997, 2002) and Gruber et al (1997). PSP applications in advanced turbomachinery components have also been investigated (Navarra et al (2001)). In particular, the use of PSP has greatly assisted in the understanding of film-cooling in turbine blades. Zhang et al (1999, 2001) have used this technique to investigate the turbine nozzle film cooling. This has also been used by Ahn et al (2004a,b) for determining film-cooling effectiveness over the leading edge and blade tip region.

Unlike PSP, film-cooling has been a topic of research for several years. Despite this, the experimental results for investigation of film-cooling near a blade tip are very limited. Most recently, Kwak and Han (2002a,b) had used the transient liquid crystal technique for studying cooling effectiveness for plane and squealer blade tips. Using a 5-blade linear cascade, they experimented with different blowing ratios for the coolant at different tip gap clearances. Their results proved that the squealer tip geometry for the blade tip was better than the flat tip in terms of cooling effectiveness as well as heat transfer coefficients.

Heat transfer coefficients in the blade tip region which form an essential part of any film-cooling related study, have been researched over by many research groups. One of the earliest works in this direction was done by Metzger et al (1991), who used heat flux sensors to measure the heat transfer coefficients on the blade tip and near tip region. Bunker et al (2000 a,b) used liquid crystal technique to determine the effect of tip gap clearance on local heat transfer distributions over the blade. Alternate tip geometries are also being continuously researched. Azad et al(2002) and Kwak et al(2002) experimented with different squealer geometries and both concluded the same result that the suction side squealer tip gave the lowest heat transfer among all the test cases. Saxena et al (2003) experimented on a scaled up HP turbine blade in a low-speed wind tunnel facility. They found that of all the various tip sealing geometries, the one having trip strips placed against the tip leakage flow yielded the lowest heat transfer on the tips. Ahn et al (2004 b) used PSP to investigate the cooling effectiveness on the flat as well as squealer tips in a 5-blade linear cascade.

The main goal of this effort is to study the effects of various parameters like blowing ratio, tip geometry etc on the coolant effectiveness and eventually come up with an optimum solution to the problem of excessive heat transfer in the tip region of the blade. Although similar efforts have also been done using liquid crystal techniques, they all suffer from the inherent problem of huge conduction errors on sharp edges (like film-cooling holes). The initial time required to achieve steady state also creates errors due to a false initial tip temperature. PSP, on the other hand is based on oxygen quenching by the mainstream flow and being a dynamic measurement tool it is independent of initial temperature. Although the study by Ahn et al (2004 b) yields reliable results but it does not include the effects of rotation of the machinery on output of PSP. In the current effort experiments would be carried out in the "Axial Flow Turbine Research Facility" (AFTRF) of the Pennsylvania State University. This cold turbine facility houses a test section with a single turbine stage. Details about the facility have been provided in Lakshminarayana et al. (1992). This paper intends to present the current status of this complete research effort. Before the PSP can be applied to any application, it needs to be calibrated. Therefore, the first step was to calibrate the paint that we intend to use. This was done in a specially designed calibration chamber. The results of this process have been presented. The next step would be to verify these calibration results by evaluating the performance of PSP on an aerodynamic body under dynamic conditions. Finally, the paint would be used in the turbine facility.

Pressure sensitive paint: theory and analysis

PSP is a technique in which the measurements are made using oxygen sensitive molecules embedded in the paint solution using a polymer binder. Based on the luminescence behavior of these molecules the oxygen concentration of the atmosphere can be determined which in turn can be related to the partial pressure of air at that temperature. In order to measure the pressure distribution over any aerodynamic body, the paint is first applied to its surface in the form of a coating of appropriate thickness. On incidence of a light of certain frequency on the paint, electrons in the oxygen sensitive molecules get excited to higher energy levels. On returning back to their original energy states, these electrons emit light of frequency different from the incident one. However, the emission of this light depends upon the oxygen concentration around the molecules. This is because of a phenomenon called oxygen quenching. Under the effect of pressure, oxygen molecules would always be in a state of constant random motion. This kind of motion coupled with their affinity for the sensitive molecules causes the oxygen molecules to collide with the excited electrons and deactivate them to yield stable electrons in the ground state. Therefore this is basically a dynamic non-radiative process which competes with the radiative deactivation of electrons. Hence, in the absence (or lack) of oxygen quenchers almost all the deactivation occurs through radiative process, generating the highest levels of intensity. Navarra (1997) provides further details of the process of oxygen quenching in her elaborate treatise on PSP.

Navarra (1997) and Navarra et al (2001) present a mathematical formulation based on the Stern-Volmer framework to relate the emitted intensity to the ambient pressure. A brief description of this formulation is provided here. The modified Stern-Volmer equation for the intensity ratio is as follows,

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

here, I_{ref}, P_{ref} and I, P represent the intensity and pressure at the reference condition and the variable condition, respectively. A and B are calibration coefficients determined experimentally for different paint formulations and temperatures. Such a temperature dependence of intensity can be attributed to the effect that temperature has on the random motion of oxygen (quencher) molecules. The present set of experiments also utilizes the Stern-Volmer equation but after modifying it suitably to eliminate the temperature dependence. In order to do this the reference values are taken at the same temperature as are the variable values. This yields separate equations for different temperatures. Incidentally, all these equations were observed to be the same (or similar). An important point to note here is that the emitted intensity is captured by the imaging device on a pixel-by-pixel basis. Hence, the use of a high resolution digital camera can yield an equally high spatial resolution of the pressure distribution over the test surface.

At a later stage, it is planned to use the calibration results for the determination of pressure distribution over the turbine blade tip. Two separate sets of experiments will be conducted using two different coolants i.e. air and air/nitrogen mixture. Partial pressures of oxygen would be calculated in both the cases using the experimentally determined Stern-Volmer equation. Han et al (2000, book) explain the mass transfer analogy which provides a relationship between the partial pressures of oxygen in both the cases and the coolant effectiveness. It is reproduced here as follows

$$\eta = \frac{Co_{air} - Co_{mix}}{Co_{air}} = \frac{\left(P_{O_2}\right)_{air} - \left(P_{O_2}\right)_{mix}}{\left(P_{O_2}\right)_{air}}$$

where Co_{air} and Co_{mix} are the oxygen concentrations of mainstream air and air/nitrogen mixture respectively. By assuming the molecular weights of air and nitrogen as same, effectiveness can be expressed as a ratio of partial pressures of oxygen due to proportionality between concentration and partial pressure.

Experimental Setup

Fig 1a shows details of the calibration chamber and the associated instrumentation used in calibrating the paint. The chamber was made out of a small piece of a large diameter aluminum pipe, closed at one end and open at the other. The chamber was made pressure tight by closing its open end with the help of a removable thick plexi-glass cover. A vacuum pump was connected to the chamber through a pressure control valve. The temperature of the paint was controlled using a pelteir thermoelectric cooling/heating device attached to the closed end of the chamber from outside. This cooler/heater was supplied with a 12 V DC supply which served as a means of varying the operating temperature of the device. The temperature and the pressure over the paint were monitored using a pair of K-type thermocouples and a pressure barometer, respectively. The paint sample was sprayed over a small region of a thin aluminum coupon attached to the base of the chamber.

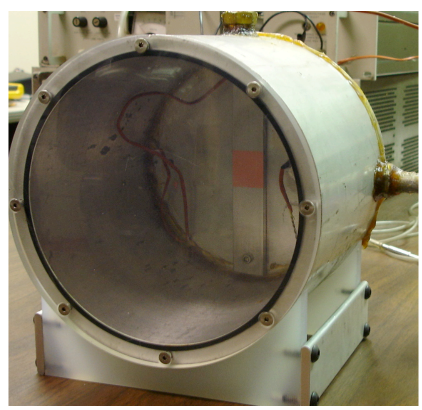

Fig 1a Calibration chamber

The imaging system consisted of an 8-bit digital video recorder connected to a monitor screen. The paint coupon was illuminated using a xenon arc lamp. As the paint responds to light of only a certain frequency, a blue colored bandpass filter was used infront of the light source. Similarly, in order to capture the correct emitted frequency in the image, a red colored longpass filter was used infront of the camera. Fig 1b shows the complete setup for calibration.

Fig 1b Calibration setup

Results

The xenon arc lamp was tested for stability of the output intensity that it provided. The test consisted of taking an image of the light emitted by the lamp at small intervals of time. It corroborated the assumption that there were no fluctuations in the intensity levels due to the temperature of the arc. It was necessary to ensure that the recorded image had light only due to the emission by the paint and none due to reflection of the incident light. In order to confirm this, an image was taken in the absence of the PSP sample, with the rest of the whole imaging system switched on. This image showed zero intensity (black), which validated our choice of filters.

The calibration of PSP was carried out at three different temperatures: $25°C$, $30°C$ and $35°C$, for a pressure range varying from 0 psi/ 0 atm (gauge) to -9 psi/ -0.6122 atm (gauge). For every temperature value, an image was taken at each 1 psi/ 0.068 atm change in pressure. Finally, a background image was taken with the light source switched off, after every set of experiments. This helped in accounting for the noise due to the camera and any stray lights incident on the sample. In the final analysis this background image is subtracted from both the reference (atmospheric) and the actual image. In order to obtain a reliable set of data, at every test condition a large number of images were averaged to yield a single image for that particular condition. A MATLAB code was generated to perform the various mathematical operations on the intensity of all the images. This code averaged the various images for the same test condition. From this averaged image it subtracted the background image. Finally, after doing the necessary ratio between the reference and the test image, the code provided an equation relating this ratio to the known pressure ratio. Such an equation for all the three temperatures was observed to be the same.

Fig 2: Images of the paint taken at the maximum vacuum (left) and atmospheric pressure (right)

Fig 2 shows final processed images taken for 35º C at maximum vacuum (left) and at the atmospheric pressure (right). The difference in intensities of the PSP sample can be clearly observed in both these images. Higher vacuum level leads to a lesser number of oxygen quencher molecules and hence the higher intensity.

Fig 3 shows the calibration results obtained for the PSP. Intensity ratios have been plotted against the corresponding pressure ratios for different temperatures. As can be seen from the plot, the intensity ratio variations for different temperatures follow the same trend. Based on this observation, a single Stern-Volmer equation for the paint was developed and the constants were obtained to be A= 0.4124 and B= 0.5897. The current set of results was also compared with that from Ahn et al (2004 b) who had used a similar paint formulation and it was found that both the results matched within the limits of experimental errors.

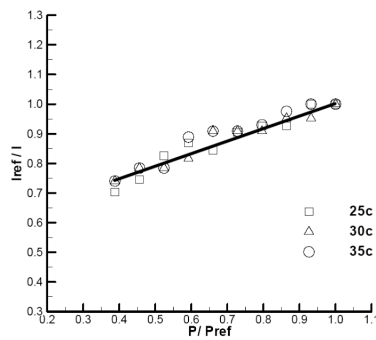

Fig 3: Calibration of the PSP

Conclusions

The most important conclusion at this stage of the project is that the PSP is calibrated and ready to be used for experimentation with the turbine. The calibration results were obtained as expected i.e. with an increase in the vacuum levels, the intensity of the image was observed to be increasing, or in other words, the intensity ratio with the reference image, which was taken at the atmospheric pressure, was decreasing. This also proves that the imaging system being used is also functioning properly. The next step would be to perform a similar calibration on a dynamic system, say a cylinder in cross-flow. The paint would then be applied to the turbine blade tip and the resulting PSP intensity would be imaged. Using the Stern-Volmer equation obtained through calibration, the pressure distribution from the image will be determined. This information would then be used for calculating the film-cooling effectiveness in the blade tip region.

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