Measurements of Pressure and Temperature in a Short Duration Turbine Facility

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Abstract

Experimental validation of turbine performance can be a challenging task. The high temperatures, scale of the hardware, and gas composition rend taking these measurements in a real turbine virtuously impossible. Facilities such as the Air Force's Turbine Research Facility enable acquiring this data through the use of simulating the turbine environment. The Turbine Research Facility is a blow down facility for testing full scale turbine hardware that allows control of the gas temperature and composition as well as matches the Reynolds number, pressure ratio, corrected speed, and temperature ratios in a more benign environment. The facility has been instrumented with thermocouples, heat flux gauges, and pressure taps for collecting experimental data. These are typically high frequency response measurements but at particular static locations making for low spatial resolution. These measurement have recently been supplemented with Temperature and Pressure-Sensitive Paints which provide high spatial resolution measurements at low frequency. This report details a test program that acquired temperature, pressure, and heat flux measurements using traditional gauges and temperature and pressure using Temperature and Pressure-sensitive paints at a range of flow conditions. Comparisons between the measurements indicated that the paints provided similar mean results. This suggests that Temperature and Pressure-Sensitive paints can be implemented into the Turbine Research Facility and provide high spatial resolution data with reasonable accuracy at moderate temperatures.

Introduction

Traditional techniques for acquiring measurements of surface temperature and pressure on wind tunnel models have utilized embedded arrays of thermocouples, heat flux gauges, and pressure taps. This approach requires significant model construction and setup time while producing data with limited spatial resolution. Furthermore, physical constraints such as mechanical movement, section thickness, and wiring access can preclude the use of thermocouples and pressure taps in certain regions of a model. These limitations makes it difficult to accurately determine a loading curve or resolve the film cooling flow distribution behind a coolant hole among other items of potential interest to the turbine designer. An alternative approach that has received considerable attention over the past 15 years is the use of luminescent probes that are sensitive to temperature and pressure. These techniques, known as Temperature and Pressure-Sensitive Paint[1] (TSP and PSP), have resulted in high spatial resolution measurements of temperature and pressure on surfaces that have proven in the past to be inaccessible. In fact measurements of temperature and pressure have been demonstrated on first stage compressor blades using TSP and PSP by several teams[2] [3] [4]. This type of data is of particular value at the Turbine Research Facility (TRF) where full scale turbine hardware is characterized including full film cooling. Gaining the details of the flow along the airfoil surface

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is of significant interest in determining shock locations, separation regions, and film distributions. Exact locations of these types of spatial dependant measurements are almost impossible to obtain from embedded or surface mounted hardware. Effective implementation of PSP and TSP would provide an effective supplement to the current TRF instrumentation as well as other similar facilities.

Pressure-Sensitive Paint

A typical pressure sensitive paint is composed of two main parts, an oxygen-sensitive fluorescent molecule, and an oxygen permeable binder. The pressure sensitive paint method is based on the sensitivity of certain luminescent molecules to the presence of oxygen. When a luminescent molecule absorbs a photon, it transitions to an excited singlet energy state. The molecule then typically recovers to the ground state by the emission of a photon of a longer wavelength. In some materials oxygen can interact with the molecule such that the transition to the ground state is non-radiative, this process is known as oxygen quenching. The rate at which these two processes compete is dependent on the partial pressure of oxygen present, with a higher oxygen pressure quenching the molecule more, thus giving off a lower intensity of light. Intensity based pressure measurements using PSP are accomplished by coating the model surface with the paint and illuminating the surface with light of the appropriate wavelength to excite the luminescent molecule. Luminescence from the surface is collected through a long-pass filter to separate the luminescent signal from the excitation light and the luminescent signal is recorded. A schematic of the basic equipment and methodology is shown in Figure 1. Unfortunately, the luminescent signal from the paint is not only a function of pressure. The luminescence varies with illumination intensity, probe concentration, paint layer thickness, and detector sensitivity. These spatial variations result in a non-uniform luminescent signal from the painted surface. The spatial variations are eliminated by taking the ratio of the luminescent intensity of the paint at an unknown test condition, *I*, with the luminescent intensity of the paint at a known reference condition, I_o. Using this *wind-on wind-off* ratio, the response of the system can be modeled using a modification of the Stern-Volmer equation.

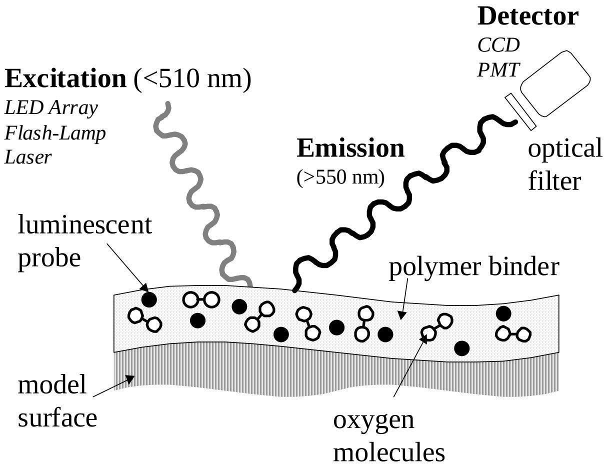

Figure 1 Basic Pressure-Sensitive Paint system.

$$\frac{I_o}{I} = A(T) + B(T)\frac{P}{P_o} \qquad (1)$$

Sources of uncertainty for PSP measurements have been investigated and modeled by Liu[5]. These error sources include temperature, illumination, model displacement/deformation, sedimentation, photo-degradation, and shot noise. Liu concluded that the major sources of error are temperature and illumination. Note in equation 1 that the Stern-Volmer coefficients, A(T) and B(T) are functions of temperature. The Stern-Volmer coefficients are temperature dependent because temperature affects both non-radiative deactivation and oxygen diffusion in a polymer. In fact, the temperature dependence of A(T) is due to thermal quenching while the temperature dependence of B(T) is related to the diffusivity of oxygen in a polymer binder.

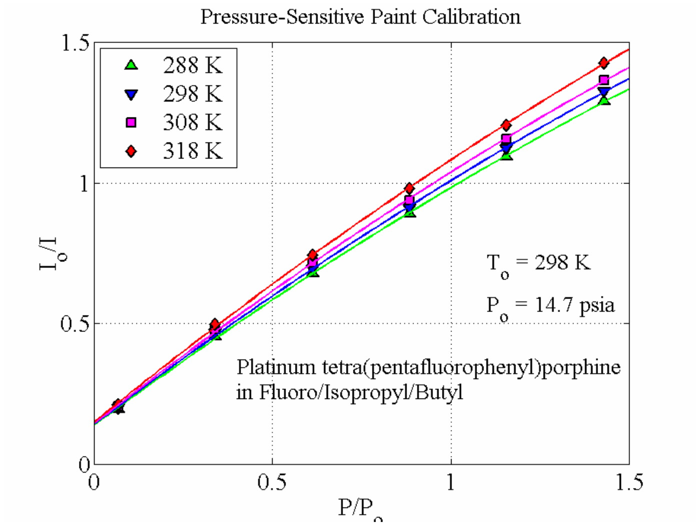

Figure 2 Calibration of PtTFPP in FIB.

Temperature sensitivity can lead to errors in converting the intensity distributions to pressure. This is demonstrated by considering a calibration of a PSP composed of Platinum tetra(pentafluorophenyl)porphine (PtTFPP) in Fluoro/Isopropyl/Butyl (FIB), shown in Figure 2. The quantity I_o/I is a monotonic function of pressure along each isotherm. The *wind-on* and *wind-off* data however, must be acquired at the same temperature if the conversion to pressure is to be free from temperature errors. A second temperature related issue is the slope of the curve along each isotherm. For most PSP's, the slope of the sensitivity curve is a function of temperature. An accurate measurement of the absolute temperature is necessary to correctly convert the intensity ratio to pressure. An important property of the PtTFPP/FIB paint is the property of ideality[6]. For an ideal paint, the slope of the sensitivity curve is independent of temperature. This property is of significant value for minimizing temperature errors in PSP measurements.

For radiometric PSP, errors in pressure measurements due to temperature are largely the result of changes in the temperature of the model surface between the acquisition of the *wind-off* and *wind-on* data. However, any temperature gradient on the model surface will still result in a temperature-induced error in the pressure measurements. Any temperature difference between the vane and the free stream fluid will result in a heat flux at the surface of the vanes and thus, the temperature of the painted surface could be changing throughout the run. The TRF is a blow down facility so the total temperature of the flow is dynamic throughout the run and therefore, the issue of temperature errors is difficult to avoid. In fact, this effect is most apparent during the heated runs.

The relationship between surface illumination and paint luminescence is linear; therefore, any change in surface illumination will result in an equal change in paint luminescence. Errors in pressure measurements caused by variations in surface illumination can stem from several sources such as displacement or deformation of the model. The construction of the TRF is such that this type of error is of minor importance. Another source of illumination errors is the temporal stability of the illumination source. Any variation of the intensity of the illumination source between the *wind-off* and *wind-on* images will register as an error in illumination. The illumination source utilized here is a solid state laser. The quoted stability of the laser is better than one-tenth of a percent per hour. This is sufficiently stable for these measurements. Finally, uncertainty in PSP measurements is a function of the ratio of the *wind-off* pressure to the *wind-on* pressure. Care must be taken to ensure that the *wind-off* data is acquired at a condition near the anticipated *wind-on* conditions to minimize this uncertainty.

The experimental approach during the first TRF entry envisioned using a vane painted with a TSP to measure and compensate for temperature errors from the PSP vane. This approach was not effective and will be discussed in more detail later. During the first entry it became apparent that both the TSP and PSP data should be acquired simultaneously from a single vane using a single paint. A means of accomplishing this goal on future test is to embed a second probe into the PSP that is sensitive to temperature but not pressure. This is generally known as a binary paint and several groups have successfully demonstrated this approach[7 8 9]. One limitation to these techniques is the need to view the signal and reference probes independently and this is generally accomplished by using a filter switch or two detectors. Due to physical constraints in the TRF these approaches are not desirable, the binary paint must be implemented using a single detector and acquire data from both channels simultaneously. A new technique that offers a potential solution is the Temporally Resolved[10] [11] or Dual Lifetime[12] approach. This approach will be utilized on future entries.

Experimental Facility

The Turbine Research Facility (TRF), shown in Figure 3 is a blow down facility for testing full scale turbine hardware. The system is composed of a supply tank and a pair of vacuum tanks with the turbine hardware residing in the middle. Both upstream and downstream of the test article is a set of traversing rings. These rings provides a means of rotating probes, such as total pressure rakes, relative to the turbine hardware during a blow down. To perform a test, the supply tank is filled with gas (usually nitrogen) and pressurized and heated to an aerothermodynamic match point. That is one that matches the Reynolds number and temperature ratio for the turbine. An isolation valve acts as a choke for the system and controls the pressure ratio. Facility startup is initiated by opening the main valve, which starts the blow down process as well as the data acquisition and traversing system. Flow proceeds through the test article and past the isolation valve into the initially evacuated dump tanks. The total run time is about five seconds and this can be repeated one to five times a day depending on the run conditions.

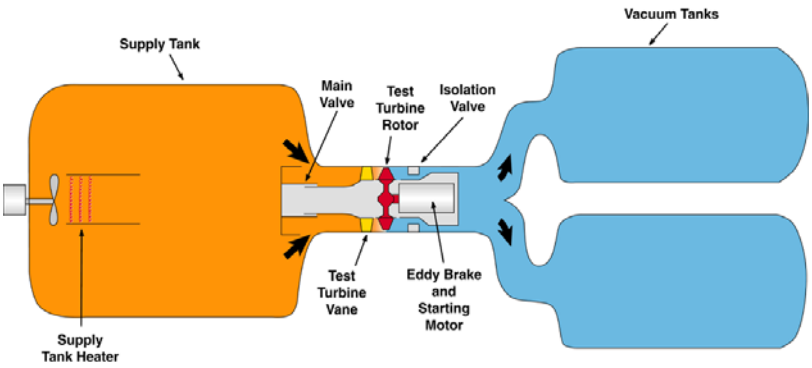

Figure 3 Block diagram of the Turbine Research Facility.

The TRF is instrumented with an array of pressure taps, pressure rakes, thermocouples and heat flux gauges. This instrumentation is installed at fixed axial and radial locations on the vanes and the rotor. This yields high frequency response needed for many uses such as vane /rotor interactions and turbulence structure resolution. The ability to supplement this capability with measurements of pressure and temperature at any location on the vanes and rotor blades would be of significant value (even at lower frequency response). Optical techniques, known as temperature and pressure-sensitive paint (TSP/PSP), for measurements of temperature and pressure based on luminescent probes have been demonstrated on turbomachinery[13] before and can provide this needed information.

In this study the aft section of the suction surface of an uncooled high pressure turbine vane was studied. This vane had multiple pieces of static instrumentation, but in particular has three flush mounted Kulite pressure transducers in the region of interest mounted at nominally 50% span. These transducers are located at 0.25, 0.65, 0.90 x/x_{ac} (where x is the axial distance and x_{ac} is the axial chord). Also, thin film heat flux gauges were applied to another vane at 50% span. These gauges are located at 0.25, 0.40, 0.65, 0.80, and 0.90 x/x_{ac}. These gauged served as the reference measurements to compare the results of the TSP and PSP in this investigation.

Experimental Setup

Three separate paints were applied to three individual vanes in the TRF in one quadrant of the facility. Two vanes were coated with pressure-sensitive paint (UniCoat and UniFIB) and one vane was coated with temperature-sensitive paint (UniT-01). UniCoat is a latex based paint that can be easily dispensed from an Aerosol can and thus offers a simple application process.

UniFIB is a high performance paint that offers low temperature sensitivity and high pressure sensitivity. UniFIB must be sprayed using an AirBrush and cured using heat treatment, this results in a more labor intensive application process. UniT-01 is a temperature sensitive paint which like UniCoat is dispensed from an Aerosol can. The role of the TSP in this test is to monitor any temperature changes that occur between the pre-run scan and run as well as detect temperature gradients on the vane surface during the run. These paints were chosen for this first investigation because they are all compatible with the chosen 532-nm excitation source thus simplifying the data acquisition system. The vanes were cleaned with alcohol to remove any oil and then painted prior to closing up of the facility. Since the TRF is an enclosed facility, no photo-degradation of the paint was expected over time as the paint was only exposed to light during the test runs.

In the TRF there was no direct optical access to the vane hardware. To deliver the needed excitation to the PSP/TSP paint a fiber optic system was developed utilizing the existing downstream traversing ring. This data acquisition system, shown in Figure 4, is a scanned point system. A 532-nm laser was used as the excitation source for this experiment. The laser was coupled into a fiber-optic and the fiber-optic was fed through the bulkhead of the TRF using an SMA to SMA connector. Once inside the bulkhead, a second fiber-optic was used to carry the beam to a set of collimating optics that were coupled to a Pyrex tube. The Pyrex tube was embedded in a modified downstream rake. A prism on the end of the Pyrex tube turned the light onto the vane providing a spot on the painted surface. Luminescence from the vane was collected through a second port in the rake. This Pyrex tube had a pair of prisms for steering the fluorescence into a liquid light guide. The light guide carried the fluorescence back to the bulkhead where a compression fitting was used to feed the end of the light guide through the bulkhead. The fluorescence was passed through a 610 nm long-pass filter and collected by an avalanche photo-diode. The avalanche photo-diode signal was detected and demodulated by a lock-in amplifier. Finally, scanning the point across the surface of the vanes was accomplished by rotating the ring mechanism rake past several vanes during the run.

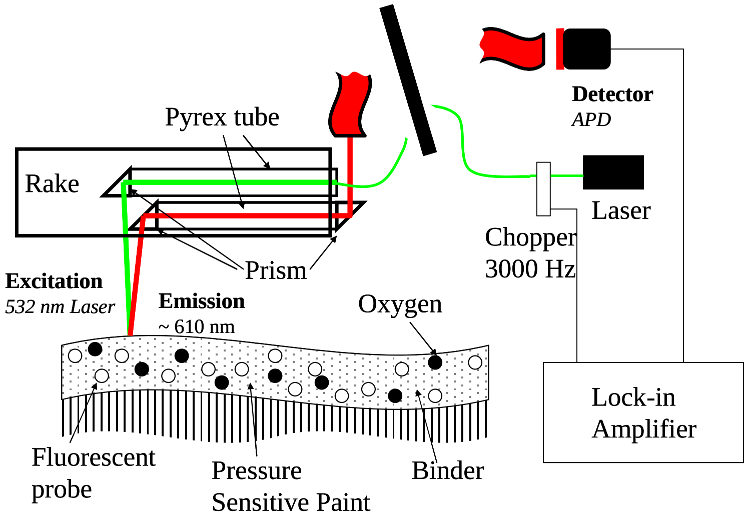

Figure 4 Data acquisition system.

The composition of the gas in the supply tank for the TRF facility can be controlled by the user. This feature was used to set the partial pressure of oxygen at each test condition to an optimized level. Most of these runs were performed between 30 and 75 psia initial supply tank pressure. The signal to noise ratio of this pressure-sensitive paint system was optimum when the partial pressure of oxygen was near 1 psia. therefore the composition of the supply tank was set between two and six percent oxygen for this series of tests. This was accomplished by filling the tank with nitrogen and then adding air until the desired O_2 concentration was achieved.

Paint data was reduced by ratioing the data obtained during a run against a similar traverse performed at a steady pressure and known O_2 concentration. This creates the *wind-on* and *wind-off* conditions described previously. These two traverses were lined up utilizing the sharp change in signal that occurred as the scan passed the vane trailing edges along with two markers at known locations on one vane. Once this ratio was obtained, short time windows of 10-ms length were created and the average intensity ratio was converted to pressure using the appropriate paint

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calibration. This is in essence a spatial average of the pressure over the portion of the vane that was traversed during the 10-ms window. The spatial resolution thus was about 1% chord for this investigation which corresponded to 50 measurements over the last 60% of the vane suction surface.

One issue of concern for this test was with the stability of both temperature and pressure sensitive paints during the experimental campaign. Contaminants in the TRF could damage the luminescent probes or poison the binders in which they reside. The issue of paint stability was investigated by performing a series of in-situ calibrations of the paints over the course of the two-week campaign. The static pressure inside the test section of the TRF can be controlled, therefore the pressure was set at several different levels and a *wind-off* scan of the vane was performed. This in-situ calibration was repeated three times over the course of the two-week test program. A plot of both intensity ratio and lifetime as a function of pressure for UniFib is shown in Figure 5. Investigation Figure 5 indicates that the calibration of UniFib does not change significantly over the course of the tests. Similar stability in the calibration of the other two paints was observed. We conclude therefore that the TRF environment does not contain contaminants that damage the performance of the paints.

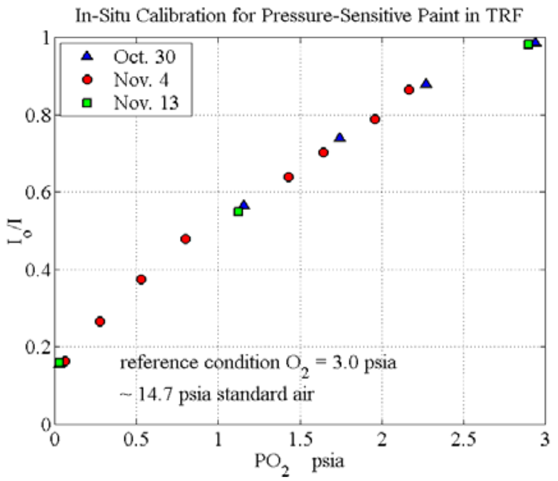

Figure 5 In-situ calibration demonstrating PSP stability over the two week test campaign.

Results

The first issue of concern was to verify that the PSP system performance was repeatable and independent of oxygen concentration. First two experiments were performed with the tank pressure near 40 psia, tank temperature at 316 K, and oxygen concentrations of 3.2% and 6.2%. The results for these two runs are have been normalized by the upstream pressure and these results are shown in Figure 6. First note that the PSP measurements are in good agreement with the measurements of the pressure taps near this span on the vane. There was a slight difference in the supply tank pressure between these two cases and this is manifested in the small shift that is evident in both the PSP and the Kulite measurements. However, normalization of this data by its supply tank pressure results in agreement of the data for these two

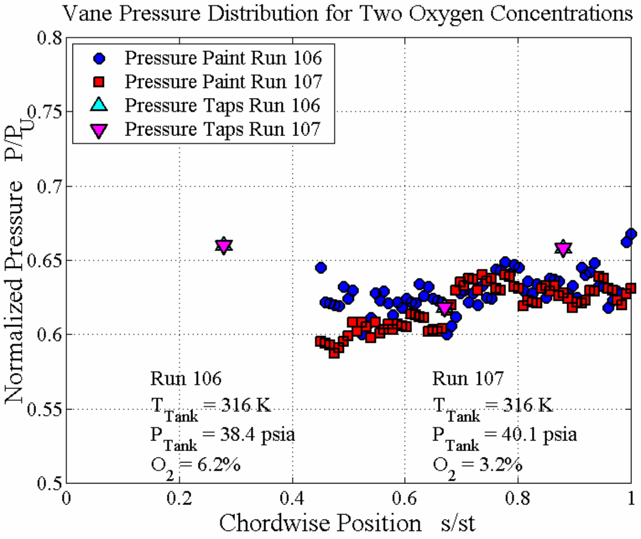

Figure 6 Normalized pressure near 50% span for two O_2 concentrations.

tests to within the uncertainty of these measurements and thus confirms that the data acquisition system is not dependant on oxygen concentration. The uncertainty is a function of the partial pressure of oxygen since this is the component that the system is sensitive to. It is estimated that the uncertainty is approximately 0.05 psi of O_2. The repeatability of the PSP measurements was confirmed by performing a third test using a tank pressure near 40 psia, tank temperature of 316 K, and again an oxygen concentration of 6.2%. The data was again in good agreement with the preceding run and thus the repeatability of the PSP system was demonstrated.

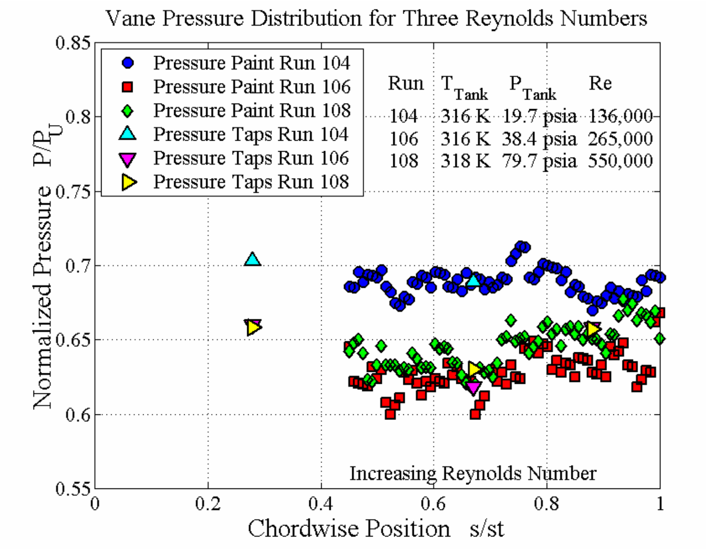

Figure 7 Pressure measurements at 50% span and three Reynolds Numbers.

Pressure distributions for three separate Reynolds numbers on the suction surface of the vane are shown in Figure 7. These Reynolds numbers were 136,000, 265,000. and 550,000 for these runs. As the Reynolds number was increased, the pressure on the suction surface decreases serving to increase the loading as expected. Again the PSP results matched up well with the static pressure taps for these three runs. More importantly is that the PSP resulted in over 50 data points compared to the three static taps. This provides more accurate resolution of the loading on this vane than the surface transducers can provide. Some of the variations plotted with span are real and of importance to the turbine designer. Some, though, are artifacts of higher noise level in the PSP measurements than expected. This is primarily the result of a low signal to noise ratio for the system as configured here. The signal to noise ratio can be improved by using a stronger excitation source and improving the design of the optical system in the rake. These modifications are currently being implemented and should yield a more accurate representation of the suction side loading.

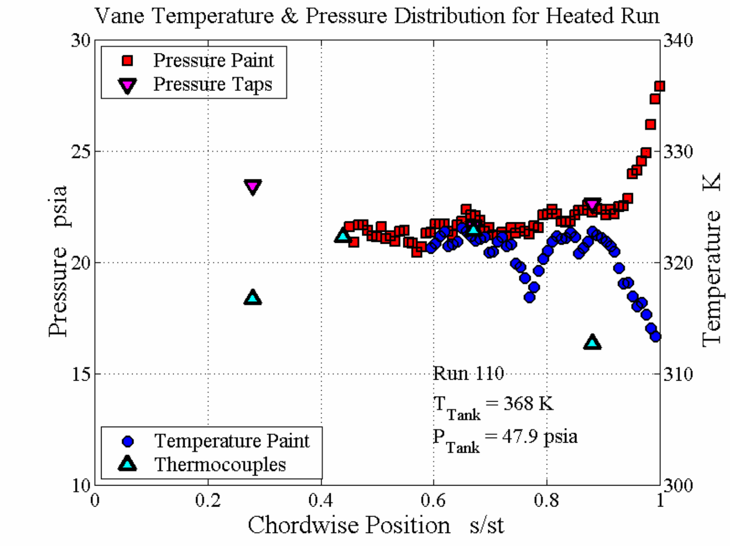

Figure 8 Pressure measurements at 50% span at elevated temperature.

One feature of the TRF that is of substantial interest is the ability to perform test with heated air. Several test were performed in this mode to evaluate the performance of the PSP measurements for heated runs. The tank pressure was set at 47 psia and the tank was heated to 368K. The PSP and TSP results are presented in Figure 8. First note that there is a significant deviation of the paint and the Kulite measurements, particularly

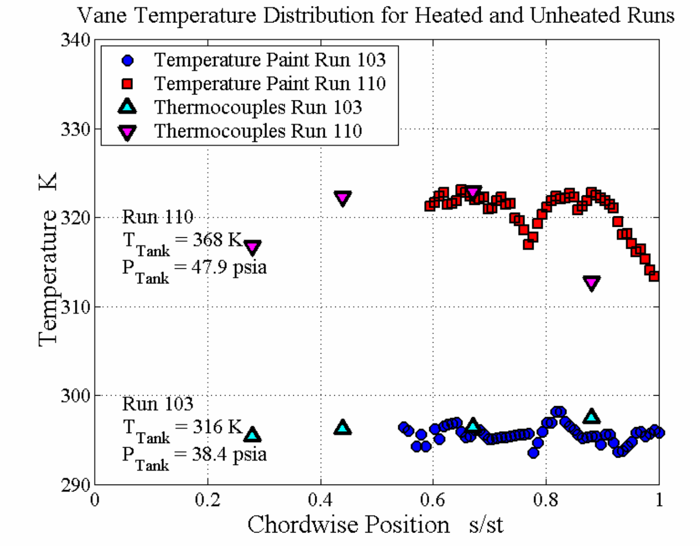

Figure 9 Temperature measurements at 50% span for heated and unheated runs.

at the aft portion of the vane. Also evident in Figure 8 is the presence of a chord wise temperature gradient on the vane. This temperature profile is evident in both the Thermocouples and the TSP data, the TSP data however is noisy. Regardless of the quality of the TSP data, it is evident that the aft portion of the blade has a lower temperature than the central portion. It also appears that there is a strong temperature gradient in this aft portion of the vane. The temperature sensitivity of PSP has been discussed previously. We note here that the lower temperatures on the aft portion of the vane should result in an apparent rise in pressure for the PSP, this is the trend that is displayed in Figure 8. One might wonder why this temperature issue was not apparent in the PSP data for the unheated runs. Some insight is gained by comparing the TSP and Thermocouple data for a heated and an unheated run shown in Figure 9. For the unheated runs the temperature of the vane is relatively constant over the entire chord, the PSP data therefore suffers little or no temperature error. The deviation in pressure on the aft portion of the vane in Figure 8 is attributed to the temperature distribution on the vane that resulted from the heated run condition.

One might be tempted to use the TSP or Thermocouple data to correct the PSP data for temperature effects. Unfortunately, this is not effective for several reasons. The TSP and PSP measurements were taken on a separate vanes, at separate times, and utilized different polymer binders. The issue of concern is the thermal history of the system. The temperature of the paint on the vane is a function of the heat flux to the vane and time. At a given location we must consider the heat transfer coefficient, the paint layer thickness and thermal conductivity, the thermal mass of the system, and the free stream temperature. Since this is a blowdown facility the free stream temperature is dropping throughout the run. The TSP and PSP utilize different polymer materials and have different thicknesses, and therefore present different boundary conditions for heat transfer. Finally, it is noted that the thin trailing edge of the vane appears to suffer the most significant temperature rise. This could be due to the smaller thermal mass of this portion of the vane. This higher heat flux presented by the heated runs will saturate this portion of the blade more quickly, and thus result in a higher temperature. Unfortunately, the temperature at any point on any painted surface will be a function of both time and the properties of the paint and vane at that point. It is necessary to measure both the temperature and pressure at each point simultaneously. Future plans include the use of a Temporally Resolved binary paint to improve the system accuracy. The binary paint will allow both PSP and TSP measurements on the same vane at the same time enabling compensation for any errors caused by temperature variation on the stator.

Conclusions

Measurements of pressure using pressure-sensitive paint have been conducted in the TRF. Optical access to the vanes has been gained using a fiber-optic and liquid light guide that have been integrated into an upstream rake on the traversing ring. Preliminary results indicate that the

TRF environment does not contaminate the paint. The complex optical system resulted in a significant loss of signal strength and thus a low signal to noise ratio for the initial measurements. Heated runs introduced a second source of error, a non-uniform temperature distribution on the vane. These noise sources resulted in data with a higher level of uncertainty than was anticipated. In spite of these issues the PSP results are consistent with the measurements of the in-situ pressure taps and provide the high-spatial resolution needed to supplement the high frequency response taps. Improvements to the system that should reduce the noise level in the measurements include a stronger excitation source and improved optical design. This coupled with a binary paint to compensate for temperature errors will drastically improve the accuracy of the system in future enties.

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