METHODOLOGY TO IMPLEMENT PSP TECHNIQUE IN A TRANSIENT FACILITY

J. Michalek, G. Paniagua, M. Vergalla, N. Zerelli, M. Tulkens
Turbomachinery and Propulsion Department
von Karman Institute for Fluid Dynamics
Chaussée de Waterloo 72
B1640 – Rhode Saint Genèse, Belgium.
paniagua@vki.ac.be

INTRODUCTION

Accurate pressure measurement on a test model is an important goal during the design phase or numerical code validation. A tremendous gain in a spatial resolution is obtained by using Pressure Sensitive Paint techniques (PSP) in a comparison with conventional pressure measurements (pressure taps on model surface, etc.); however; this technique requires delicate treatments. The benefit of global 2-D measurement is obvious, but is limited by image acquisition system capabilities as well (CCD camera, light source, etc.).

The emphasis of presented work was put on the feasibility of using PSP technique at VKI's transient facilities (CT3). The test duration time of such facilities is about 500 ms, which is considerable shorter than the time response of a polymer binder PSP formula used during this study. The time response of a conventional PSP obeys two different time scales. The first is the luminescent lifetime of PSP that represents the physical limit for an achievable temporal resolution of PSP formulas. The second is the time scale of oxygen diffusion across the paint layer. In the case of a polymer binder PSP, the oxygen diffusion is much larger and therefore determines the time response of the PSP itself.

A compensated slow response conventional probes have been already successfully used in transient facilities. The same concept seems to be achievable even for PSP technique. Unfortunately, common PSP formulas are not only sensitive to pressure but also suffer of the temperature dependence. This unfavorable aspect was overcame by pressure and temperature calibration for steady test measurements. In the case of transient phenomena, compensation of the signal was assumed as a *Linear Invariant System* (*LTI*), where temporal effects of pressure and temperature signal components were simply superimposed. Decoupled step tests for pressure and temperature were performed, in order to obtain a transformation functions for further final pressure estimation. An intensity based data processing method has been applied during the study.

STEADY-STATE PERFORMANCE

During the entire test campaign platinum porphyrins luminescent dye (PtTFPP) in a polymer binder (FIB) was used. Before an active layer was applied, a white base primer was sprayed on the surface of the model in each test case.

Steady-state paint calibration is necessary for a quantitative estimation of pressure from the emitted luminiscence signal. Obtained linear relation is described by Stern-Volmer eq.1.

$$I_{ref} / I = A(T) + B(T)\, p / p_{ref} \qquad (1)$$

The aim of the procedure was to obtain Stern-Volmer coefficients A and B considering different temperature levels. During the calibration process, pressure and temperature were controlled. A signal from the reference pressure gauge was recorded as multiple intensity images was acquired for consequential averaging. Case the temperature was held constant while the pressure was adjusted in a certain range of interest for each calibration. This procedure was repeated for a required range of temperatures. More details about data processing can be found in [7].

Setup

The experimental setup used during calibration is shown in fig. 2. A PSP sample (30 x 30 x 6 mm) was placed in a calibration chamber furnished with an optical access. Illumination of the test coupon was provided by a field of blue LED's (470 nm) located inside the chamber. Emitted light was acquired through the long-pass optical filter (600 nm) by the 12-bit grayscale CCD camera. Pressure inside of the chamber was controlled by a system of manual valves and a vacuum pump. Temperature of the sample has been adjusted by means of a Peltiere circuit. Temperature was monitored by a flat thermocouple placed directly on the painted surface.

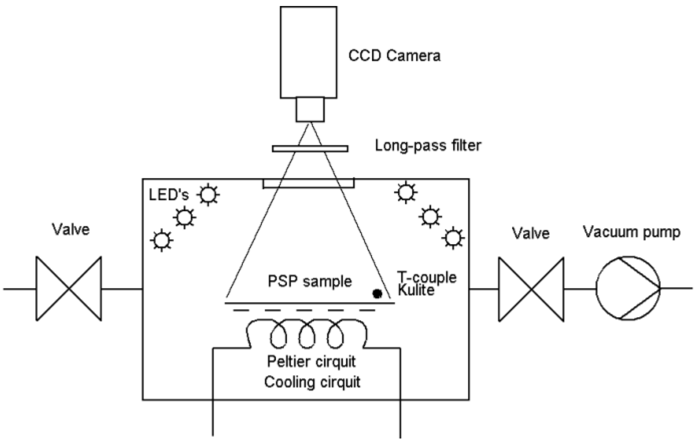

Figure 2: Steady-state calibration setup

Results

Before the calibration results were used for quantitative estimation of pressure, some basic characteristics were gathered in order to better understanding of the paint performance. Stern-Volmer coefficients for an arbitrary pixel at different temperature levels were obtained and pressure and temperature sensitivity information could be extracted from data.

Unfortunately, extensive dispersion of estimated values was observed and thus prompted a conclusion of a poor performance by the paint. Even though temperature sensitivity was in a good agreement with manufactures given parameters, pressure sensitivity was found to be significantly lower. This observation can be related to a change in the paint properties due to the expiration of the paint and thus changes in properties of used PSP formula. Pixel by pixel calibration proves to be unconditional for accurate qualitative result estimations. Finally, pressure and temperature sensitivity data were compared with literature data [8], fig. 3. The effect of different binders is clearly evident. The deviation of pressure sensitivity of study paint formula (marked as FIB study) is also significant.

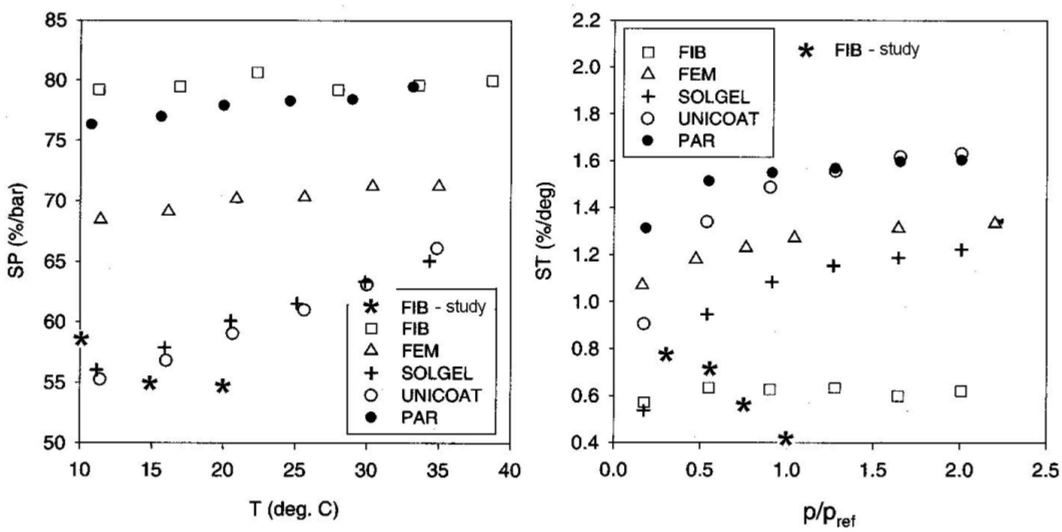

Figure 3: Comparison of pressure and temperature sensitivity from Lachendro (2000), study data added (PtTFPP in five different polymer binders; P_{ref} = 1 bar, T_{ref} = 283 K)

TRANSIENT PERFORMANCE

The behavior of tested PSP formula exposed to transient conditions was also study. The aim was to investigate the paint time response related to pressure and temperature change (step tests), and to describe the system behavior using appropriate transformation functions (TF). If TFs exists, compensation of the delayed PSP signal might be obtained. Thus an assumption of a Linear Time-Invariant (LTI) system allows us to simply superimpose separated components of paint time response (pressure and temperature) on each other.

Setup

The similar setup for steady calibration was used also in this case of pressure step tests (Fig. 2). The opening valve was refurnished by a manual fast valve to enable a shorten transient time; however, due to the small inner diameter of the chamber opening, a transient time of about 350 ms was usually reached. Pressure measurement was performed by the Kulite sensor placed close to the painted coupon. Temperature was also monitored by a thermocouple, in the same manner as the case of steady–state calibration. The signal from the sensors has been triggered by camera's TTL pulses and acquired by data acquisition system.

A pressure step was obtained by vacuuming the test chamber to the minimum level and followed by a sudden opening of the valve. The pressure change inside the chamber was reached within transient time of t = 350 ms going from initial pressure P_{ini} = 0.2 bar to ambient pressure. A non-ideal pressure step was accepted considering the slow response of the paint estimated during preliminary measurements. Temperature was kept same for the test coupon as the ambient one. During the pressure step, a slight temperature increase of about 4 K was observed due to the compression effect. Complete decoupling of pressure and temperature in the present facility is difficult; however, the temperature change was not enormous and it was not considered hereafter. The camera frame rate (FPS) has been adjusted by exposure time (t_{exp} = 0.001 s) to a value of ~ 39 FPS.

Results

Fig. 4 refers to the results of three different step test measurements. The reference Kulite's pressure signal is depicted by the solid line. Test case #1 is related to the step test for conditions as mentioned in the text above. Test case #2 was performed with same PSP sample for higher initial pressure (p_{ini} = 0.5 bar) inside the chamber. A slight signal deviation can be noticed during the initial phase. This result could be related to the non-linear behavior of the paint and this observation also pointed out conclusions of previous studies [3], [6]. In the last test case, marked as #3 the effect of temperature is shown at glance. The test piece was kept at higher temperature value than ambient temperature by means of a Peltiere circuit. The effect of temperature is obvious during the tests initial phase. After initial steep increased of the signal caused by the pressure, intensity signal drops off caused by cooling effect . After that the signal starts to rise again because of oxygen diffusion across the layer. This described phenomenon gives an insight of transient behavior of the temperature effects at glance. More details are listed in the text below.

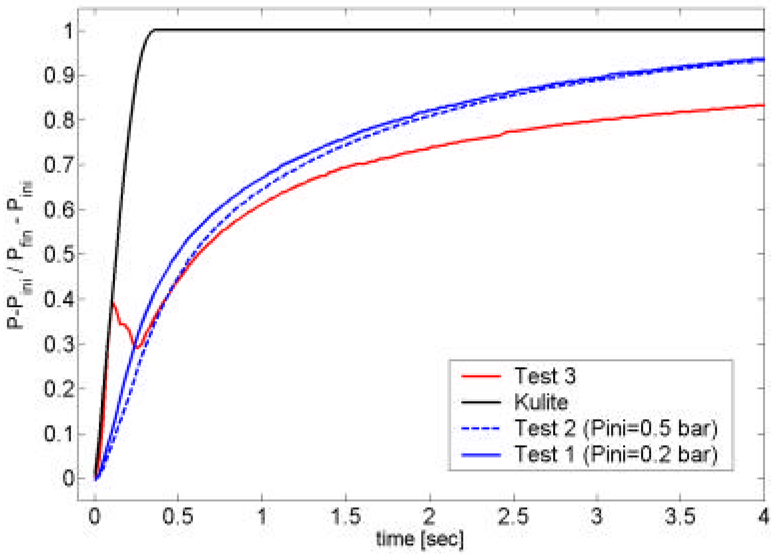

Figure 4: Pressure step test results

The influence of paint thickness was also noticed from observations. Unfortunately, there were not reliable means to measure the layer thickness,; thus it was established as either ``thick'' or ``thin'' coatings, controlled only by the number of layers sprayed during painting. As expected, SNR decrease was disproportional to a coating thickness. The time constant was determined from measurements varying from 3 - 6 s. Contrary to these conclusions, the manufacturer of the PSP states values of about 0.3 s. This discrepancy points out again the poor performance of PSP formula and probable ageing of key luminophores components. As mentioned in previous text, it can be caused by dissolving of PSP ingredients a long time before application. For future work it is strongly recommended that the preparation of a required paint amount is done just before utilization.

An amplitude attenuation and phase lag were also estimated. Bode diagram of the step test signal is shown in fig. 5. The cut-off frequency corresponding to signal attenuation of -3 dB was determined at F_{cutoff}= 0.1 Hz. From the Bode plot one can conclude that pressure fluctuations higher then the cut-off frequency lead to significant signal distortion and consequential compensation has to be performed.

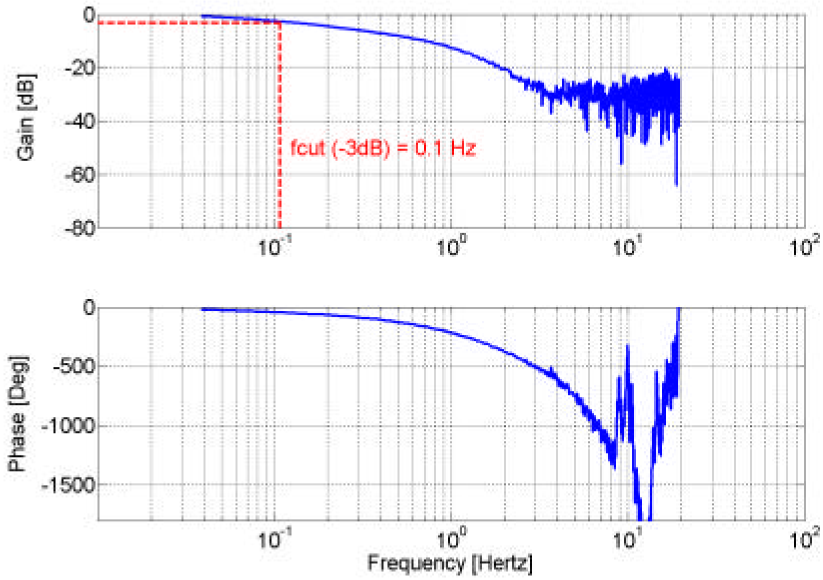

Figure 5: Bode plot of pressure step signal

PSP paint is not only sensitive to pressure but unfortunately to temperature as well; therefore, an investigation of paint during temperature transient is required. For these reason intermittent hot jet test was undertaken. The aim of these test was to describe the time response with respect to temperature and to learn of paint behavior through extensive data processing. The assumption of a LTI system should be later verified by comparing superimposed pressure and temperature step results with the incorporated test outcomes.

The arrangement of the intermittent hot jet case is demonstrated in fig. 6. The sample with PSP was located on a vertical platform surrounded by illumination lights. The axis of convergent nozzle was inclined with respect to normal of the platform. The outlet diameter of the nozzle was D = 10 mm and distance between coupon and exit of nozzle was about L = 120 mm. Just downstream of the convergent nozzle outlet a miniature Pitot and temperature probe was placed. For comparison, probes in the settling chamber of the nozzle provided total pressure and temperature readings. A manual shutter was positioned further downstream. CCD camera with an optical filter was situated out of the jet axis.

The nozzle was powered by a 7 bar air line and passed through heat exchanger before reaching the outlet. Total pressure was controlled by a regulator. Kulite sensor was replaced by a pressure tap in the middle of the test piece. Readings from the pressure tap was used as a trigger. The delay between Kulite sensor and pressure port reading was about 5 ms. The pressure step duration was about 20 ms.

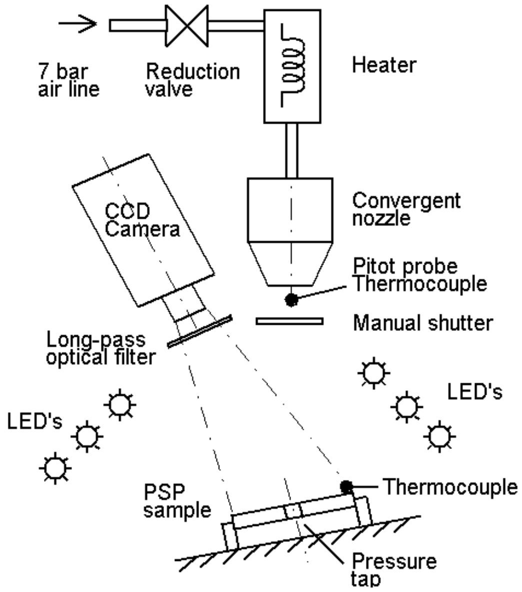

Figure 6: Temperature step test – intermittent hot jet

In the case of the intermittent hot jet an ideal temperature step was assumed. Jet was operated on low subsonic velocities ~0.1 M to avoid significant distortion of the output signal due to the pressure. Because the jet was discharged to atmospheric conditions, the SNR of paint signal is rather low. The free jet that impinged on the surface of the sample caused turbulent flow structure that contributed to the already noisy signal. Thus, the pressure reading from the PSP sample was blurred and it was further neglected.

A few test cases were undertaken. The samples were prepared with two different types of base materials. The aim of this was to investigate differences in thermal conductivity of the base materials affecting the signal output reading. Aluminum and Plexiglas pieces were used for this reason. Then each material were furnished by ``thick" and ``thin" layer of paint. Measurements were conducted with two final temperature levels. One step was marked as ``low" and other as ``high" ranging from ambient temperature ~295 K to ~330 K and from ambient temperature to ~350 K respectively. Figure 8 presents results of measurements.

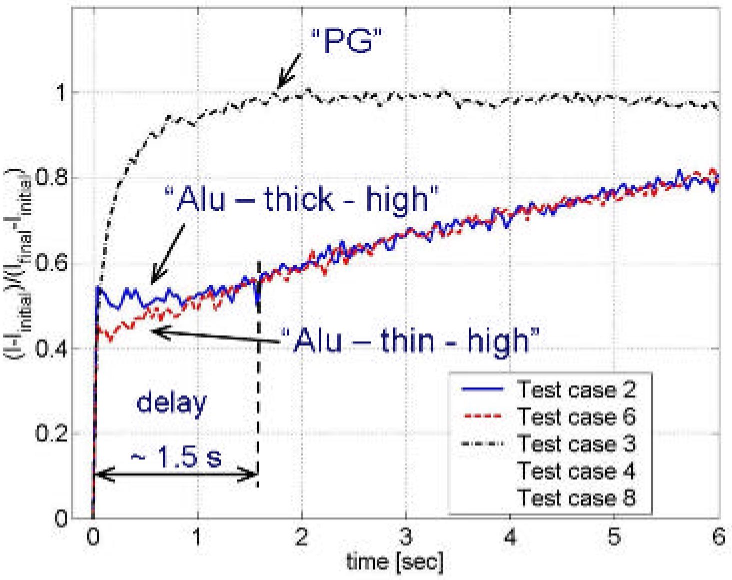

Figure 8: Temperature response – intermittent jet

The increase of PSP signal was steep and temperature effects took place without any time delay. Further development of the output signal depends mainly on base material used for the test sample. No significant difference between two levels of temperatures of Plexiglas pieces was noticed. In the case of the ``lower" step for aluminum test pieces, high thermal conductivity of base material resulted in a non-distinguishable output readings from before and after measurements. Test cases 2 and 6 show the time response of the aluminum sample. Again, after the initial step, thermal conductivity damped the developing signal output. Also a difference between ``thick" and ``thin" paint layers was observed. Because of the inertia of the paint coating and thermal diffusivity, signal remains almost constant during the initial phase in a case of ``thick" layer. For ``thin" coating a continuous increase of signal was observed.

Signal output in the case of Plexiglas was affected by the insulating properties of this material. Even in this case the initial temperature step was obvious; however, the signal increased continuously and more rapidly then in the case of aluminum piece. Only one measurement with Plexiglas is plotted in fig. 8 since the output from all others cases with this material were almost identical.

From the previous observations, one can conclude that the type of base material together with thickness of the paint play significant roles on paints time response. There is no doubt about the importance of monitoring temperature during measurements. One could eventually gain from the fact that for certain arrangements (type of base material, paint thickness) the temperature remains almost constant within particular time. This can be utilized during data processing, when only one constant value of temperature can be considered and simple compensation can be performed; nevertheless, achieving such a precise certain setup could prove to be rather complex.

Data processing – signal compensation

As presented in the previous section, the PSP signal acquired during transient measurement must be compensated. Both pressure and temperature compensation must be applied before proper conversion from intensity signal to pressure can occur. Signal compensation is achieved by using a TF. Many techniques suitable for this type of processing exist and each one offers specific advantages. During the work, parametric and non-parametric methods were applied and these results are presented below. More details about signal compensation can be found in literature [9]. Non-parametric methods don't suffer as much by insufficient number of points; however, in some cases relatively a big error of the compensated signal is introduced. Linear differential equation eq. 4 was used for compensation. It describes differential equation of discrete model by means of differences. For details see [9].

$$y_k = \sum_{i=0}^{m} b_i i_{k-i-d} - \sum_{i=1}^{m} a_i y_{k-1} \qquad (4)$$

Figure 10 depicts the results of parametric method. A differential equation of 5th order with 1 step delay was performed. This equation was used for the final signal processing. However further effort to find more suitable TF is suggested. From the presented results it is evident, that a tremendous error is introduced by improper compensation. The error can be as high as ten percent of the signal range.

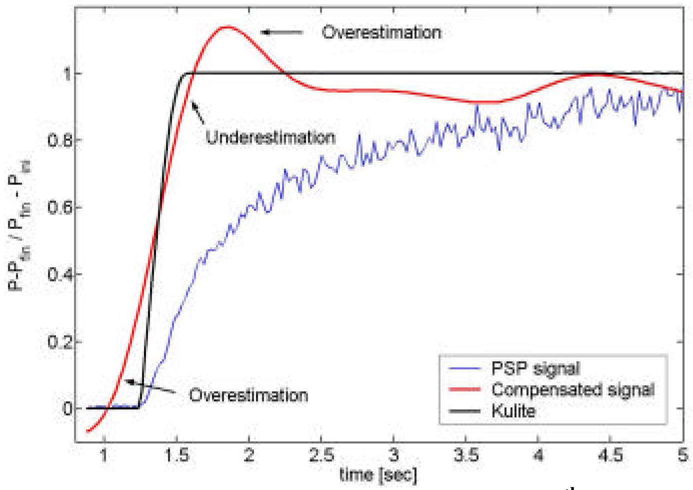

Figure 10: Compensated signal by linear differential eq., 5th order, 1 step delay

VALIDATION EXPERIMENTS

Setup

A final test case was performed to verify the ability of reconstructing the signal acquired during transient condition. An under-expanded jet was placed so that it impinged on a flat plate painted with PSP. This was done to prove that the proposed methodology is feasible. The goal of this test was to obtain pressure distribution on impinged surface from the intensity signal taken within transient conditions.

Figure 11 shows the arrangement used in a verification test. A convergent nozzle with diameter D_n = 5 mm was used to produce an under-expanded jet impinging on a flat plate. An aluminum test sample coated with PSP was used as the impingement plate surface. The incidence angle of the jet axis with respect to the horizontal direction was about θ = 10 deg. Dimensions of the test plate were identical to earlier tests (30x30x6 mm). The sample was furnished with seven uniformly spaced pressure taps located along the centerline. These tapings serve as a reference for final comparison with the pressure distribution estimated by PSP. The second pressure tap downstream of the nozzle worked equally as a trigger to highlight the origin of the test and compensation. Two fast miniature thermocouples were glued on top of the painted test plate. These sensors were located between the 2nd and 3rd and the 6th and 7th pressure taps respectively. Compressed air was supplied to the nozzle from a 7 bar line and reduced by a regulator for the required pressure. Illumination LED's were positioned in suitable locations around the test sample. A CCD camera was placed directly above the arrangement.

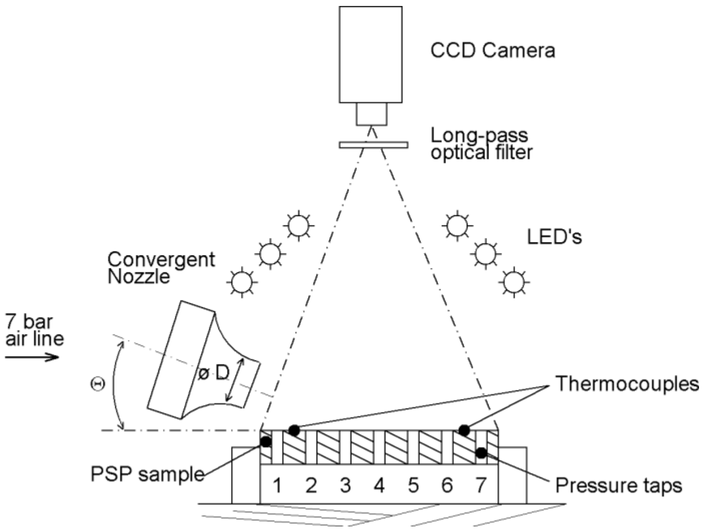

Figure 11: Scheme of impinging jet arrangement

Results

Prior to a test run, steady and transient *a priori* calibrations were completed. Both were performed by means of a vacuum chamber. Calibration points were acquired for prospective pressures ranges 0.6 …1 bar and temperatures 278, 283, 288 K. Reference conditions during the calibrations were p_{ref} = 99.5 kPa and T_{ref} = 295 K and were identical as for the validation test.

Since there was no technique for registration of acquired images at disposal at that time, only one Stern-Volmer relation (1) was used for the domain. That was evaluated by the averaging of slopes and intercepts across the entire domain; nevertheless, this limitation introduced certain error in the final pressure estimation. As for the previous case only one ``characteristic'' TF was implemented at each pixel in the domain. A linear differential equation of the 5^{th} order with one step delay was used as already mentioned above.

Shadowgraph picture was taken to investigate flow structure and to determine a suitable angle of the impinging jet. The complex flow structure produced by the under-expanded jet is presented in fig. 12. The nozzle was operated at ambient pressure p_{atm} = 0.995 bar, upstream total pressure of about p_{tot} = 3 bar and ambient temperature of T_{atm} = 295 K.

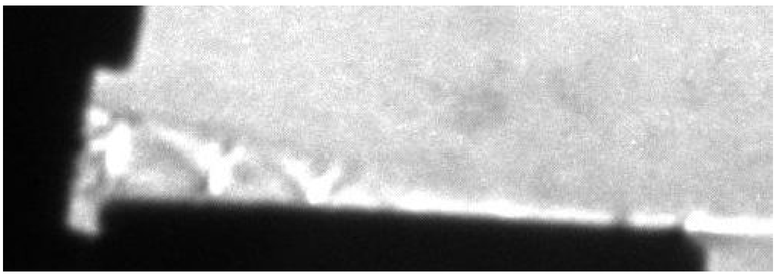

Figure 12: Shadowgraph of impinging under-expanded jet, Δp = 3 bar

Considering a slow paint response, measurement time window was established within 4 seconds. Frame rate used during acquisition was 25 *FPS*. It offered 100 images for signal compensation. Final value of each pixel was calculated by averaging lasts 20 reconstructed points. As mentioned above, only one characteristic TF was used for final pressure compensation at each pixel of a considering domain. Signal compensation respect of temperature drop was utilized based on results obtain by temperature step test. Gain from conclusions of this observation (aluminum coupon, ``thin'' paint layer), constant temperature was used for signal compensation. Linear relation between two measured temperatures on sample surface was assumed.

Figures 13 shows estimated pressure distribution on impingent plate for a steady conditions with resolution 128 by 128 points. Pressure drop on nozzle was Δp=~3 bar, reference pressure p_{ref} =0.995 bar. Pressure map is plotted in non-dimensional pressure scale with p/p_{ref} =1 corresponding to ambient pressure. Shock pattern caused on flat plate is clearly distinguishable.

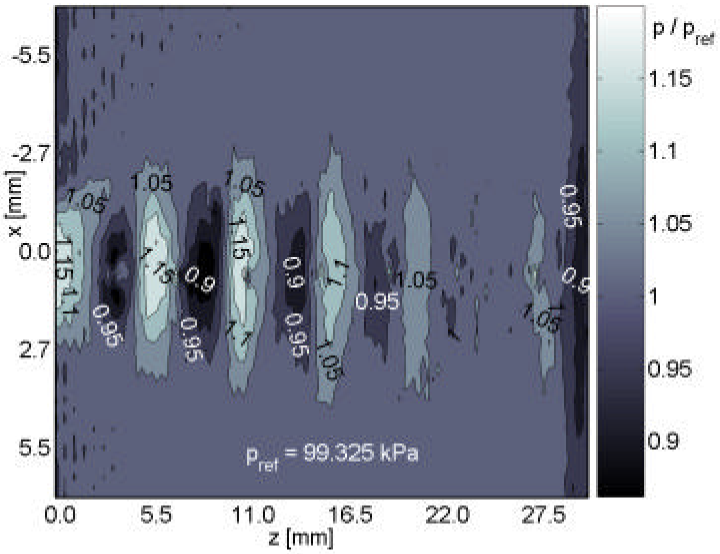

Figure 13: Pressure distribution obtained by PSP, impinging under-expanded jet, Δp = 3 bar

Comparison of pressure distribution along the plate axis is presented in fig. 14. Pressure reference values are plotted together with non-dimensional pressure obtained by compensated PSP signal and steady PSP signal. Considering all of the simplification introduced, the comparison of the reference pressure taps readings with compensated pressure is rather in a good agreement. All compared points are in error range of about 7 % of the reference signal, except of the one outstanding point of the pressure tap # 1.

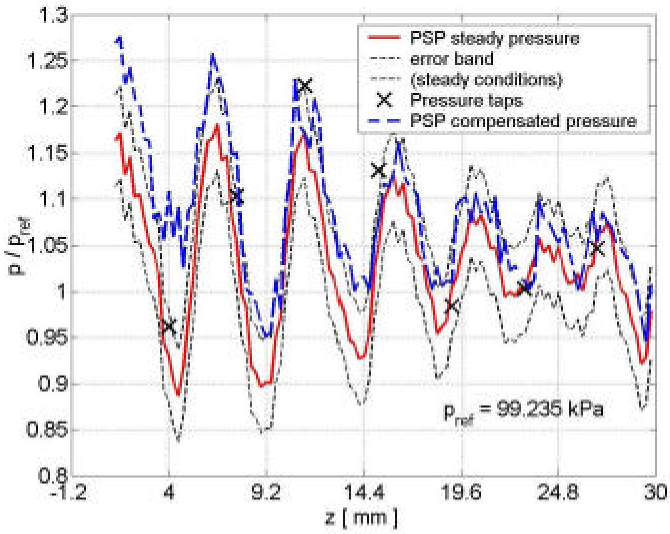

Figure 14: Comparison of pressure distribution along the plate axis, impinging under-expanded jet, Δp = 3 bar

CONCLUSIONS

Feasibility study of pressure sensitive paint for transient facilities is outlined in presented study. It has to be pointed out; that the results obtained in scope of this work is related to properties of used PSP formula. Some basic steady characteristics of the paint were measured. From the results obtained during steady state performance measurements was concluded, that some parameters significantly vary from the manufactures statement. Tangibly in case of pressure sensitivity, when values of about 20 % lower then stated were measured. This deviation was caused probably by long time dissolving of the paint ingredients and their ageing. The temperature sensitivity was recognized as similar values given by the producer.

Compensation of the transient intensity signal respective to pressure and temperature was performed in acceptable manner. Both the parametric and non-parametric method was applied. It was found out, that the parametric method could be more suitable in the case of lack of data points. Otherwise, non-parametric methods

(*FFT*) would be preferable, because of a lower ``dynamic" error was introduced. Good performance of a *CCD* camera is an imperative for utilizing this method.

A strong dependence of base materials on developing of the PSP signal was observed in temperature step test. For low thermal conductive materials, a fast increase of the signal was monitored. This leaded to earlier steady state signal establishment. For high conductive materials a certain time window with constant signal was observed. This fact can significantly simplified temperature compensation data processing.

The final test was performed to validate proposed procedure. Impinging jet on flat plate was used as a test case. The comparison with pressure taps reading along the axis of the impingement plate with reconstructed signal was done. Estimated values differs from reference pressure points in range of about 7 ... 9 % of the reference signal range.

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