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CALIBRATION AND USE OF PRESSURE SENSITIVE PAINT (PSP) FOR A TRANSONIC FLOW APPLICATION

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ABSTRACT

In this paper we demonstrate an application of pressure sensitive paint where the aim is to obtain quantitative results in a transonic flow application over a bump. We describe techniques for illumination and calibration of the model as well as results for the pressure distribution over the bump, with and without shock induced boundary layer separation. Qualitative results are in good agreement with standard pressure measurements however so far there are still fairly large quantitative differences.

INTRODUCTION

Pressure sensitive paint (PSP) is an interesting technique both for qualitative and quantitative determination of the pressure field in complex flow configurations. As a qualitative tool it may enable the experimentalist to obtain an overall view of the flow field as well as to detect details such a three dimensional effects, separation and shock wave/boundary layer interaction. It has an even larger potential for quantitative measurements since it would allow a spatial resolution comparable to that of numerical simulations. In practice, however, it has so far not come to much use for quantitative measurements since several practical problems have to be overcome. For a extensive review of PSP see ref. [1].

In the present paper we demonstrate some of the problems associated with PSP and possible solutions and we show our results regarding quantitative pressure measurements in a transonic flow application, where we have flow over a two-dimensional bump which separates on the downstream side due to shock-boundary layer interaction.

BACKGROUND TO PSP

Pressure sensitive paint is based on that oxygen sensitive luminophore molecules in a binder are deposited on a surface, much in the same way as an ordinary paint is applied (see figure 1). The thickness of the paint layer should be thin and the binder should be permeable to oxygen. Exposed to light the luminophore molecules are excited at a rate of i_e (exited molecules per volume paint and unit time) by light quanta with a frequency ν_1. The excitation is described by

$$L_0 + h\nu_1 \rightarrow L^*$$

where L_0 is the ground state of the luminophore, h is the Planck constant and * denotes an excited state. Three different processes may be responsible for the deactivation, one of which is determined by the oxygen concentration ($[\mathrm{O}_2]$) in the binder. The three processes are

- Radiative process: $L^* \rightarrow L_0 + h\nu_2$, rate constant k_r
- Oxygen quenching: $L^* + \mathrm{O}_2 \rightarrow L_0 + \mathrm{O}_2^*$, rate constant $k_q = \kappa_q[\mathrm{O}_2]$
- Non-radiative process: $L^* \rightarrow L_0$ + heat, rate constant k_{nr}

It should be noted that the luminophore is excited at a frequency range around ν_1 and emits its light at a lower frequency band around ν_2. The rate of the emitted light quanta, given by $i = [L^*]k_r$, at frequency ν_2 is reduced due to the oxygen quenching, because some of the excited molecules are deactivated through an interaction with the oxygen molecules, i.e. the higher the oxygen concentration the less emitted light at frequency ν_2. At

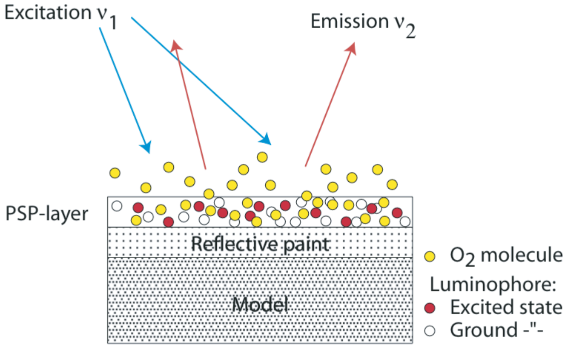

Fig. 1 Principle of pressure sensitive paint

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steady state the excitation rate (i_e) is the same as the deactivation rate and we can write

$$i_e = (k_r + \kappa_q[\mathrm{O}_2] + k_{nr})[L^*]$$

As the excitation and emission rates are proportional to the respective light intensity, I_e and I the ratio between the light intensities

$$\frac{I}{I_e} \propto \frac{k_r}{k_r + k_{nr} + [\mathrm{O}_2]\kappa_q}$$

Now the assumption is that the pressure is proportional to the oxygen molecule concentration in the binder

$$p \propto [O_2]$$

so we can therefore write

$$I^{-1} = C_0 + C_1 p$$

EXPERIMENTAL SET UP

The experimental set-up is the VM-100 tunnel at KTH Energy technology. The test section has a cross section of 120×100 mm^2 (height×width) and an interchangeable tunnel floor where the bump model is mounted (for the geometry of the model see figure 2). The maximum height of the bump is 11 mm. With an incoming flow Mach number slightly below 0.7 the flow becomes transonic and a shock is formed on the downward sloping side.

A problem with PSP is that its luminosity is temperature sensitive. The model surface temperature is therefore monitored during the runs with a thermocouple mounted upstream the bump and flush with the surface. In our experiment the model increases its temperature as compared to the wind off situation. Therefore a heating foil is glued underneath the model and during calibration the model is heated and the surface is held at the same temperature as during runs. Typically a temperature increase of 5 degrees above room temperature is needed. Figure 2b shows the backside of the bump model with the heating foil, thermocouple as well as three pressure tap ports.

The paint used in the present experiments is the UNIFIB paint from Innovative Scientific Solutions Inc. First the model is sprayed with a white non-reflective paint which is allowed to dry for 24 hours. Thereafter the UNIFIB paint is sprayed in nine layers and thereafter cured at an elevated temperature.

To be able to achieve quantitative results it is necessary to have a sufficiently strong, and homogeneous illumination of the test surface. Here we use 200 blue light emitting diodes, arranged in 4 linear arrays in a frame (see figure 3) attached to the tunnel window at each side of the test section . A ground glass plate diffusing the light and a blue filter suppressing longer wavelengths are placed between the window and the diode arrays. The emission frequency band given by the manufacturer of the LEDs is shown in figure 4a as well as the transmission characteristics of the blue filter. As can be seen the blue filter transmission overlaps nicely with the emission

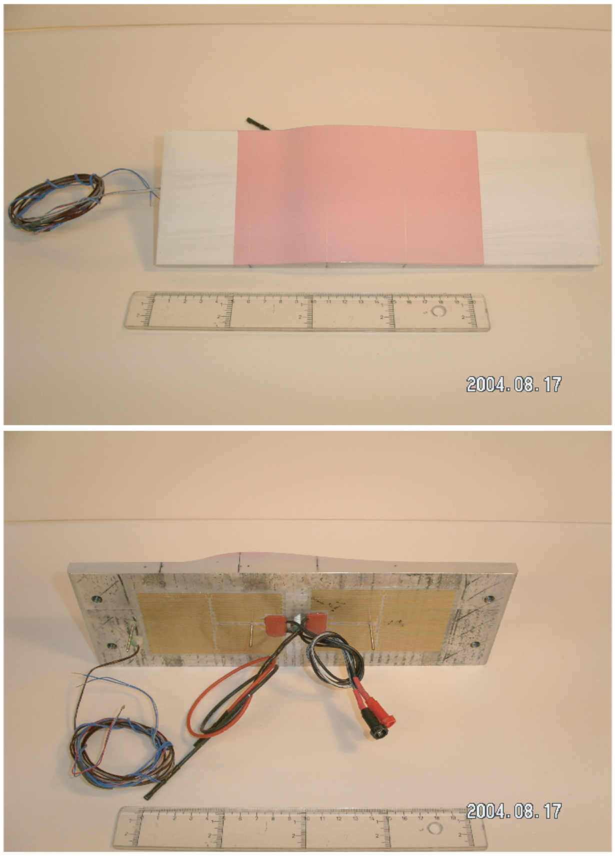

Fig. 2 a) Bump model with painted surface shown, b) Backside of bump model showing heating foil and instrumentation.

Fig. 3 LED-panel light source showing 4 rows of 25 diodes in each.

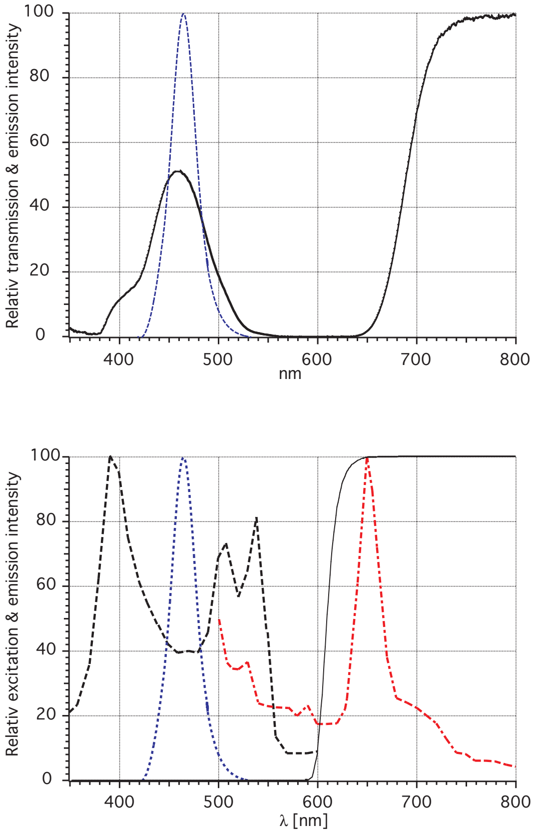

Fig. 4 a)Diagram showing the frequency of the LEDs (- - - -) and the transmission spectrum (——) of the blue filter which is placed in front of the LEDs. b) Diagram showing the frequency of the LEDs (·····), the excitation response of the PSP (- - - -), the emitting frequency of the PSP (· — · — ·) and the characteristics of the red-filter (——).

of the LEDs. In figure 4b the excitation and emission bands of the PSP are shown as given by the manufacturer together with the emission curve of the LEDs. Also the characteristics of a red-filter (long-pass filter) which is placed in front of the camera is shown.

It was essential to make the pressure calibration in situ. To obtain a closed chamber two blockage doors with expandable silicon sealing were inserted into the channel upstream and downstream of the test section. The doors had a black non-reflective facing surface in order to simulate the light reflection of the open channel. The pressure in the test section could then easily be set above (using the high pressure system of the lab) or below (using a vacuum pump) the ambient pressure. The model in position with illumination (with the window open) can be seen in figure 5.

The PSP was monitored using a digital PCO SensiCam CCD camera mounted on top of the test section. In front of the camera lens a long-pass filter with a rather sharp characteristic was placed in order for the camera to receive only the emitted light (ν_2).

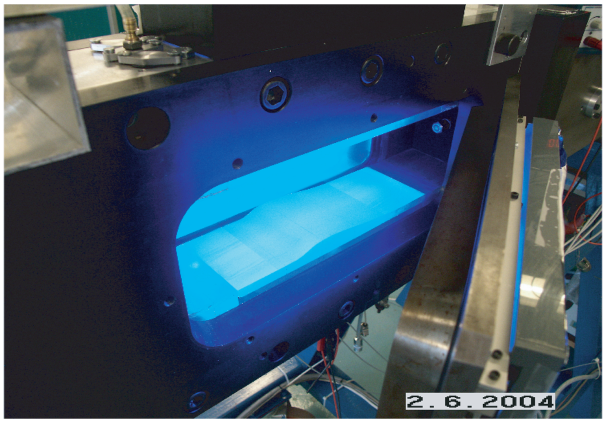

Fig. 5 Illuminated bump model set-up for calibration. The downstream blockage door is seen inside the test section.

Each PSP picture is an average of 128 frames taken at a rate of 15 Hz and exposure time of 1 ms. The grey images were transformed from 12 bit PCO format to 16 bit TIF format on the PC connected to the camera. The images were finally processed using Matlab software on a Macintosh computer.

In figure 6a we have a typical picture of the bump model at at pressure $p = 68$ kPa taken with an exposure time of 1 ms. The camera was programmed to take 128 pictures and then automatically takes the average. In the picture the intensity goes from black to white, however this is because the picture is dynamically expanded. The intensity variation of the light over the bump is mainly caused by the variations of the thickness of the paint and non-homogeneous illumination.

Figure 6b shows the light intensity (grey value) of the picture along the CCD camera line on the centreline at two different calibration pressures. The dips at x =60, 100 and 160 mm are markings in the paint in order to enable alignment of the photographs to the coordinate system. These lines are also clearly seen in the photograph. The bit resolution can be clearly seen in the pressure signatures and in this calibration it is only about 15 bits between the two pressures. Unfortunately when the camera makes the averaging it only takes the integer number and this gives rise to the bit noise in the representation of the light intensity. However the resolution can be significantly improved with a longer exposure time and probably also by doing the averaging in a different way.

Figure 7 shows a typical example of a greyscale photograph converted to a colour representation of the pressure.

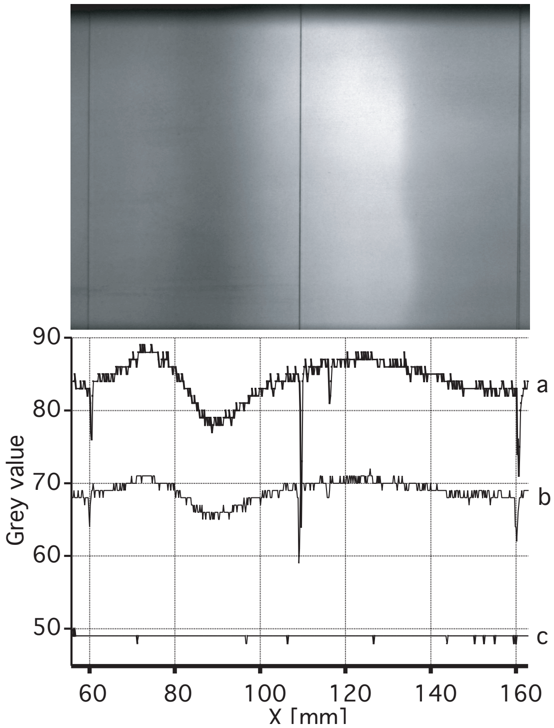

Fig. 6 Typical intensity photograph of the painted model during calibration. Below is the grey scale variation along the centreline taken at two different pressures (a) 68 and (b) 138 kPa. Also shown (c) is the noise level without illumination.

RESULTS

The measurements were made at incoming Mach numbers between 0.60 and 0.69. A compressor drives the wind tunnel and a by-pass valve together with a regulating valve and an evacuating fan placed at the outlet adjust the flow through the test section. This is done manually and in the present measurements we try to keep the stagnation pressure (measured in the stagnation chamber) constant independent of Mach number and varies the outlet pressure in order to change the inlet Mach number. The test section is choked for an inlet Mach number around 0.69 and a shock wave on the downstream side of the bump appears at a Mach number of around 0.65.

Figure 8 shows seven different cases where the Mach number varies from 0.60 to 0.69. The red region (high pressure) in front of the bump is similar for all cases, whereas the pressure decreases as the flow moves across the bump. The dark blue region is the region of lowest pressure and this region expands with decreasing outlet pressure. The rapid change from dark to light blue most probably signifies the location of the shock wave.

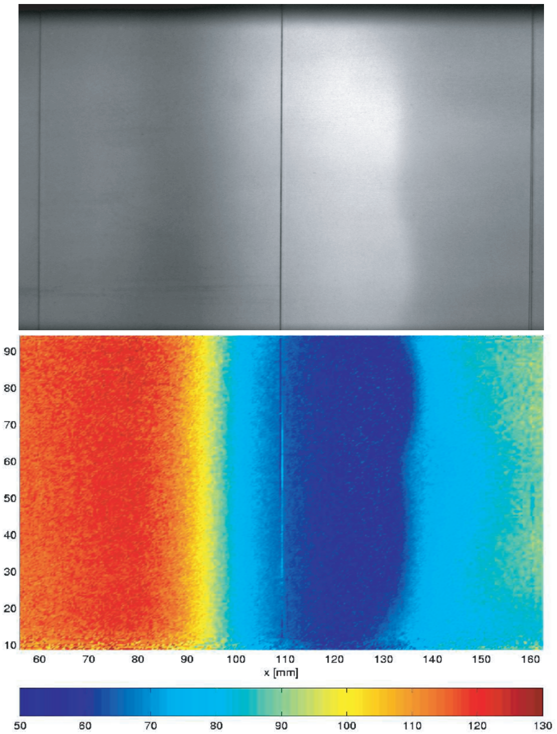

Fig. 7 a) Grey scale CCD image and corresponding picture converted to colour image. $M_{in} = 0.69, p_{outlet} = 106$ **kPa.**

Figure 9 shows the pressure distribution for three different cases as well as comparisons with measurements by Bron [2] from a sliding bump model equipped with a row of pressure taps in the streamwise direction. The pressure signature from PSP was obtained by averaging the digital picture in the spanwise direction over a width of 9 pixels, corresponding to 2 mm. The two dips in the pressure curve correspond to two markings on the model in order to establish the geometrical scale and position. The symbols in the figure are pressure measurements taken simultaneously with the PSP measurements. As can be seen the inlet pressure were adjusted so as to be the same as the pressure obtained by [2].

For $M = 0.63$ (p_{outlet}=118 kPa) the flow is seen to accelerate across the bump (pressure decreases) and thereafter to return smoothly towards the outlet pressure. Here there are no indications of a shock wave. As can be seen the pressure profile obtained from PSP seems to be shifted downwards as compared to the measurements obtained in [2], whereas the span between the inlet and outlet pressures seems to be approximately the same.

For $M = 0.68$ (p_{outlet}=110 kPa) an abrupt increase in the pressure around x=125 mm signifies the existence of a shock wave and there is a fairly good agreement between the two different measurements.

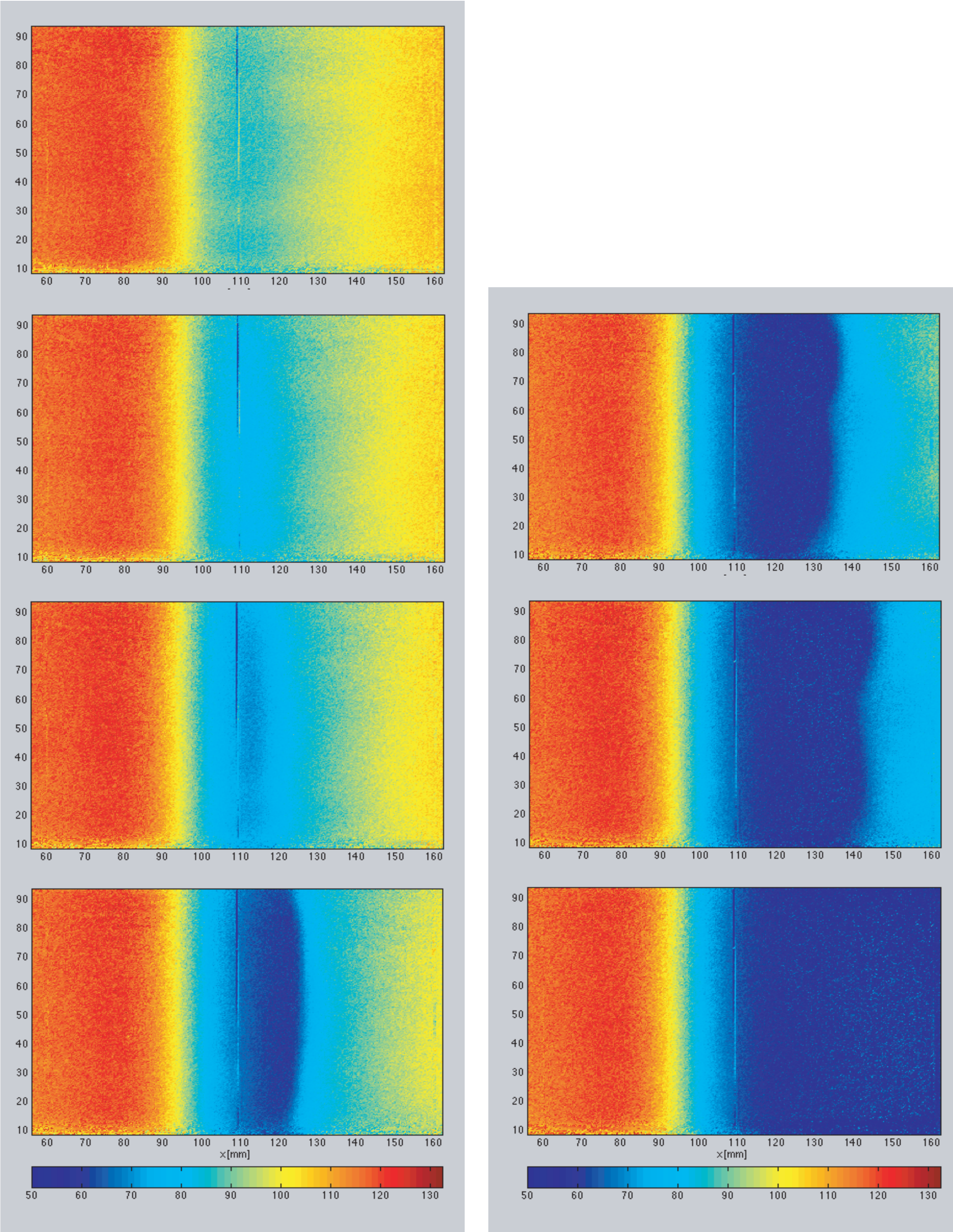

Fig. 8 Pressure distribution on the bump at varying outlet pressures (from top left to bottom right) [M_{inlet}=0.60, p_{outlet}=121 kPa], [0.63, 118], [0.65, 115], [0.68, 110], [0.69, 106], [0.69, 102], [0.69, 98]

Finally the curves for $M = 0.69$ (p_{outlet}=98 kPa) shows no shock in the region of the measurements. However the PSP pressure profile levels out at a constant value indicating a boundary separation not found in [2]. The difference in the boundary layer behaviour observed in the PSP experiment may be due to a small leakage in the gasket between model and side window.

The reason for the discrepancy between the standard pressure measurement results and those made with PSP is not clear at present. We have observed an aging effect of the paint itself that may affect the calibration. The calibration data should therefore preferably be taken both before and after the measurements. A second uncertainty is the temperature sensitivity. In the measurements we try to keep the temperature the same during calibration and measurements which requires the use of the heating foil. It is operated to give the same temperature at the thermocouple position but there may be variations along the model. Finally the resolution obtained in the present experiments was not very large, an increase of the exposure time and illumination would be a remedy for this.

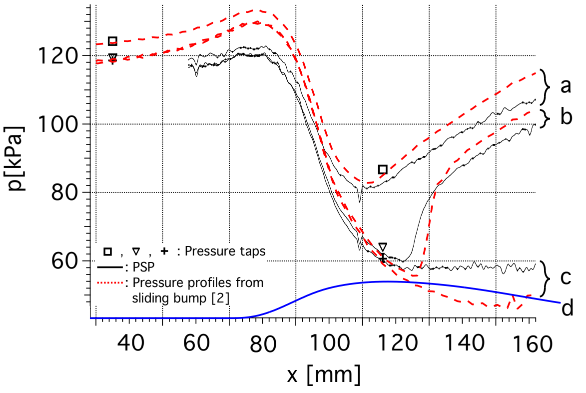

Fig. 9 Pressure distribution from PSP (——), pressure distribution from [2] (- - - -). (a) $M = 0.63$ **(**p_{outlet}**=118 kPa), (b)** $M = 0.68$ **(**p_{outlet}**=110 kPa), (c)** $M = 0.69$ **(**p_{outlet}**=98 kPa), (d) shape of bump.**

CONCLUSIONS

Pressure sensitive paint is an interesting technique to use in complex flow fields, especially where it is inconvenient to use pressure taps. However in order to achieve quantitative results many different difficulties have to be overcome. The sensitivity to illumination requires that calibration is performed in situ, the sensitivity to temperature requires heating of the model. The ageing of the paint is also a limitation. However as has been shown it is still possible to obtain good qualitative and acceptable quantitative results.

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