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Pressure sensitive paint measurements at high Mach numbers

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Depending on the case study examined, different PSPs may be used, each applied using a different method onto the model. For polymer PSP the paint is sprayed on. In contrast, the model may first be anodised or covered with a thin-layer chromatography plate and then dipped in PSP. The objective of the present study is to analyse the characteristics of different PSP substrates at high Mach numbers which use two well-known PSP molecules: (i) tris-Bathophenanthroline Ruthenium (II) Perchlorate and (ii) Platinum-tetrakis (pentafluorophenyl) Porphyrin. Using a double ramp geometry under a Mach 5 hypersonic flow the feasibility of applying each of the aforementioned PSP methods is investigated and compared to discrete pressure measurements. The flow over a 3D bump under a Mach 1.3 flow is also studied to give a broader Mach number range. In the hypersonic tunnel, all PSP techniques and formulations were able to capture the complex flowfield with the results quantitatively agreeing with the discrete measurements. For the transonic bumps however, it was found that the polymer based Platinum PSP could map the flowfield more accurately.

1. Introduction

The pressure-sensitive paint technique has the capability of providing a global quantitative, non-intrusive measurement of the pressure distribution over large surfaces. Detailed description of the principles of operation of PSP along with its merits over conventional pressure measurement techniques is well documented in the literature [1–4]. Conventional PSP contains luminescent molecules distributed in an oxygen-permeable polymer binder, which is sprayed or painted on the model surface. To increase the emission signal level, a base coat is usually added on the model surface underneath the PSP layer. The polymer based PSP has been successfully applied in low speed [5,6], transonic [7–10], supersonic [11–14], and hypersonic flows [15–17].

Additionally, porous PSP techniques are also available which increase the response time due to a greater surface area available that increases the chance of interaction of the oxygen molecules in the flow with the PSP molecules [18]. Generally, the thin-layer chromatography (TLC) and anodised aluminium seem to be the most frequently used porous binder for PSP applications in high speed flows. The micropores on the porous binder absorb the luminophore molecules via the internal-molecule force [16]. The open structure of the support matrix makes the oxygen molecule interact with the luminophores easier. Therefore, fast response time and high pressure sensitivity can be obtained by these paints.

The idea of anodised aluminium PSP (AA-PSP) was initially suggested by Asai et al. [19] and further developed by Sakaue and Sullivan [20]. The luminophore molecules are absorbed into the porous binder structure and interact with the oxygen molecules more easily. The improvement of response time and pressure sensitivity has been successfully recorded at Mach 10.4 flow in a shock tunnel by Nakakita et al. [8,9]. Complex flow structures consisting of flow separation, re-attachment, and shock-shock interactions were readily captured using the AA-PSP method. A scramjet inlet model coated with AA-PSP was tested in a Mach 4 short duration Ludwieg tube by Sakaue et al. [11]. The surface pressure was in the order of hundreds of Pascals and the test duration was around 100 ms. The AA-PSP captured the surface pressure change well and the results agreed with the CFD findings.

Although AA-PSP has been successfully used in the short duration hypersonic tunnels, there are still several limitations of AA-PSP. The model material is limited to pure aluminium or aluminium alloys with small dimensions. For large models with complicated sensor inside, it is difficult or even impossible to immerse the model in the sulphuric acid solvent for anodisation [21]. Mérienne et al. [12] applied an anodised aluminium tape as the PSP binder in the transonic tunnel, where the tape was glued on the model. The fast response is comparable to the Kulite pressure transducers. This is a good idea but it is limited only to 2D geometries, the thickness of the tape must also be taken into account.

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Another type of porous material used in PSP research is TLC plates. Baron et al. [13] applied TLC as the binder of PSP in a solenoid valve with a pressure jump. The response time of the TLC-PSP can be as low as 10 μs. Sakamura et al. [22] used the TLC-PSP in the shock tube and Laval nozzle testing. The porous PSP captured the shock wave motion in the order of kilohertz during the starting process of the supersonic nozzle in a qualitative manner. TLC-PSP was also applied in the shock tube by Gongora-Orozco et al. [15]. The greatest drawback of TLC plates is their fragile surface texture which makes them susceptible to strong interactions and difficult to apply to curved surfaces.

The present study aims to provide a comparison of the changes and differences observed when using the various permutations of the PSP techniques, under high Mach numbers, by applying them to hypersonic and transonic flows. This work builds upon the static tests of Quinn et al. [18].

2. PSP samples tests

The PSP luminophores employed in the present study are the tris-Bathophenanthroline Ruthenium Perchlorate (referred to here as $Ru(dpp)_3$) and the Platinum tetrakis (pentafluorophenyl) Porphyrin (referred to here as PtTFPP).

2.1. Polymer PSP

The polymer paint is an in-house developed formulation consisting of Methyl Triethoxysilane (MTEOS), ethanol, and hydrochloric acid (HCl), where MTEOS is the sol–gel binder and ethanol and HCl are the solvents [23]. The polymer-based samples are prepared on 10 × 10 mm square aluminium plates with a thickness of 1 mm. The samples are first sprayed with a base coat using a white acrylic paint (Ambersil matt Ral9010) with 3 layers. The white base coat reflects the emission and increases the signal level. The polymer paint is applied on the sample surface using an air brush. The samples are coated with a total of 16 layers. Afterwards, the samples are cured in an oven at 70° for 7 h to evaporate the solvent in order to obtain a uniform layer of PSP coating.

2.2. Anodised Aluminium PSP (AA-PSP)

AA-PSP samples are prepared by the anodisation procedure proposed by Sakaue [17] with a slight modification. A 1 mm thick aluminium sheet with a length of 150 mm is dipped in a sulphuric acid solution with 1 M concentration at room temperature, instead of the constant low temperature as recommended by Sakaue [17] and Kameda et al. [24]. The obtained anodised sheet is then dried and cut into 10 × 10 mm square samples.

After anodisation the sample is dipped in the porous luminophore solution with a concentration of 0.3 mM/L with respect to the volume of solvent as suggested by Gregory et al. [16]. In the case of AA-PSP, dichloromethane (DCM) is used as the solvent.

2.3. TLC plate

TLC plates consist of a thin layer of adsorbent material applied over a flat carrier sheet. They are typically used to separate mixtures using the capillary action. Their porous surface provides an ideal environment for the PSP luminophores, increasing the probability of oxygen quenching occurring. A 10 × 10 mm sample is cut from the TLC silica gel aluminium plate (MERCK Chemicals International). The sample is dipped in the same luminophore solution used in the preparation of AA-PSP.

2.4. PSP calibration statistics

All the static samples (no flow) were simultaneously tested in a sealed calibration chamber by Quinn et al. [18] where pressure and temperature can be controlled; some of their findings are presented here for completeness. A total of six samples were placed in the calibration chamber: the PtTFPP-polymer, PtTFPP-AA-PSP, and PtTFPP-TLC, $Ru(dpp)_3$-polymer, $Ru(dpp)_3$-AA-PSP, and $Ru(dpp)_3$-TLC. According to the findings of Quinn et al. [18] the polymer based paints gave the strongest signal followed by the TLC plate. The AA-PSP signal was the lowest. This is mainly due to the higher concentration of luminophore accumulated on the model surface for the polymer based PSP, compared to the AA-PSP that is dipped. Additionally, it appears that the TLC plate is a stronger adsorbent than the AA-PSP, therefore more luminophores adhere to the surface. Compared to the PtTFPP luminophore, the $Ru(dpp)_3$ was found to give a higher signal output. The reason for this behaviour is attributed to the higher quantum yield of $Ru(dpp)_3$ compared to PtTFPP.

Generally, it was found that the porous PSP samples (TLC and AA-PSPs) showed a non-linear relationship with pressure change across the sub-atmospheric pressure regime. At the sub-atmospheric pressure conditions, the pressure-sensitivity was the highest showing the suitability of applying porous PSP techniques in supersonic or hypersonic flow conditions where low freestream pressures are encountered. Comparing the two different luminophores, the polymer PtTFPP was found to show a higher pressure sensitivity than the polymer $Ru(dpp)_3$.

3. Wind tunnel tests

3.1. Hypersonic tunnel

The hypersonic facility used is an intermittent blow-down tunnel having a test time of 7.5 s, capable of generating flows with a range of Mach numbers from 4 to 6. For the present study a Mach 5 contoured nozzle with an exit diameter of 152 mm is used. The wind tunnel test section is free-jet type having dimensions of 325 × 325 × 900 mm (height × width × length). Two 195 mm diameter Quartz windows are installed at the two sides of the test section to provide optical access for flow visualisation.

Unit Reynolds numbers of $4.5 \times 10^6\ m^{-1}$ to $13.5 \times 10^6\ m^{-1}$ can be obtained by varying the supply pressure and heater temperature. The wind tunnel was calibrated and the variation of Mach number and Unit Reynolds number were found to be ±0.4% and ±(3.7–3.9)%, respectively. The total pressure and the total temperature are monitored using a pitot tube and a thermocouple in the setting chamber upstream of a honeycomb. The outputs from the pressure transducers and thermocouple are recorded using a National Instruments (NI) SXCI-1000 unit and PCI-6251 acquisition card which is controlled using LabVIEW. Further details of the facility and testing instruments, used in this investigation, have been reported elsewhere [26,27].

The feasibility and characteristics of the PSP techniques are investigated over a double ramp model in the hypersonic tunnel. The significantly low pressures of the freestream and the relatively large pressure changes expected over the double ramp, due to the compression shocks, are believed to provide a suitable testing case for the PSP techniques.

The dimensions of the aluminium double ramp model investigated are shown in Fig. 1. The angle of the first ramp is 12° and the second ramp is 22° relative to the horizontal. The ramp is followed by a 40 mm long flat shoulder with a height of 23.5 mm. Eight pressure taps are incorporated along the model centreline with their locations from the leading edge shown in the figure.