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PSP Visualization Studies on a Convergent Nozzle with an Ejector System

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Abstract: An in-house Pressure Sensitive Paint (PSP) formulation has been developed at the Aero-Physics Laboratory at the University of Manchester. The PSP uses Bathophenanthroline Ruthenium as the luminophore molecule and is incorporated in a sol-gel matrix. Excitation occurs at *400-500 nm* and emission at *550-650 nm*. The Stern-Volmer plot of the PSP reveals small temperature dependence, which has always been an intrinsic drawback of PSPs. As a baseline experiment the PSP has been applied to examine the side-wall pressure field of the flow through a convergent nozzle with an ejector, at fully expanded Mach numbers in the range $M_j = 0.52\text{-}1.36$. Simultaneous static pressure measurements were also conducted to ascertain the accuracy of the PSP results. The paint has demonstrated satisfactory capabilities in not only measuring static pressures but also in visualizing key physical elements of the flow, such as the location of the expansion and oblique shock waves present in such flows.

Keywords: PSP, Supersonic Jet, Nozzle Flow, Oblique Shock Wave.

1. Introduction

Supersonic underexpanded free jets are found in many applications involving jet and rocket propulsion, thrust vectoring, fuel injectors for supersonic combustion, etc. The major structure of supersonic jets is determined by nozzle pressure ratio and nozzle configuration (Love et al., 1959 and Kweon et al., 2006).

One way of incorporating the benefits of air breathing into rocket-based launch vehicles is through the use of an ejector system. Ejectors are fluid pumps that are used to entrain secondary flows using a primary flow. For propulsion applications, this entrainment can augment thrust compared to that generated by the primary flow alone and thereby increase performance. Of course high thrust augmentation is only achievable once the gas-dynamics and the flow interactions are understood. This idea is central to the development of rocket-based combined cycle (RBCC) engines, in which it is the ejector effect that is primarily responsible for any increased performance over traditional rocket systems during the initial phases of launch (Etele et al., 2007).

Information about the fluid dynamic quantities of these jets has compelled comparisons of CFD results with schlieren visualization which is qualitative at best. Insertion of any intrusive probe, such as static and total pressure tubes or a hot-wire probe, changes the shock structures present in these flows significantly (Panda and Seasholtz, 1999). The Pressure-Sensitive Paint (PSP) technique offers the advantage of non-intrusive global mapping of the surface pressure (Liu and Sullivan 2005, Bell et al., 2001, Moshasrov et al., 1998).

Using a PSP obtained from McDonnell Douglas Aerospace (MDA PF2B), Taghavi et al., 2002 and 1999, obtained pressure data for a multi-jet supersonic ejector and were able to capture key flow properties such as bubbles of separated flow, and the shock cells within the flow and hence, confirmed the efficacy of the aforementioned PSP formulation. Huang et al., 2007, used PSP to study shock structures on the micro-scale. These are but two examples of many in the literature where detailed shock structures are visualized. The PSP formulation developed in-house at the Aero-Physics Laboratory, exhibits relatively low temperature sensitivity which has always been an intrinsic drawback of the PSP technique, forcing researchers to use a combination of PSP along with a Temperature Sensitive Paint (TSP) or numerous temperature sensors to correct for temperature variations along the model surface (Taghavi et al., 2002). Combined with the *in-situ* calibration procedure we aim to provide an accurate measurement of the surface pressure in a two-dimensional supersonic air-ejector system.

Methyl triethoxysilane (MTEOS) was used as the sol-gel precursor since under optimum conditions it creates a smooth coating with good adhesion (Basu 2007). Ruthenium bathophenanthroline perchlorate was chosen as the luminophore as it has been repeatedly demonstrated to exhibit significant oxygen sensitivity in its luminescence (Tang, et al., 2003, O'keeffe et al., 1995). The formulation consisted of: Ruthenium, MTEOS, ethanol and hydrochloric acid (0.1M).

2. Setup

2.1 A-Priori Calibration

A-priori calibration was employed to determine the pressure sensitivity of the PSP formulation. This was carried out in a pressure/temperature controlled chamber where the pressure was varied between *0* and *4.5 bar* and the temperature could be controlled between *270K* and *330K*. The temperature of the paint sample was controlled using a Peltier heater/cooler and monitored by a thermocouple. The peltier heater used for calibration purposes was manufactured by *Greenweld*. The heater was capable of producing sub-zero temperatures as low as *258 K*, with a maximum working temperature of *343 K*, the dimensions were *30 × 30 × 4.7 mm*. An aluminum test sample measuring approximately *30 × 30 × 3 mm* was initially spray coated with *2-3* layers of matte white paint *24 hours* prior to the application of the PSP and allowed to dry. Once the sample was ready it was spray-coated with *9* layers of PSP and cured at *343 K* for *7 hours*.

The sample was illuminated by a pair of LED arrays with a peak wavelength of $\lambda = 470nm$, and the luminescent emission was captured by a camera (LaVision Image Intense). A pair of LED panels were employed so that in any setup the camera could be positioned normal to the test section with an LED panel exciting the PSP from each side, leading to uniform illumination. The main advantage of placing the camera normal to the test section is that it reduces the danger of surface contamination due to internal reflections. A combination of two filters was used to capture the emitted light. The first, an orange long-pass filter, only allowing the transmission of light with $\lambda > 600\ nm$ and the second filter was an Infra-Red (IR) cut-off filter, preventing the transmission of light with $\lambda > 700\ nm$. From the plot of I_{ref}/I vs. P/P_{ref}, where I_{ref} and P_{ref} correspond to the no flow state, the pressure sensitivity of the paint defined as $PS = \Delta(I_{ref}/I)/\Delta(P/P_{ref})$ was determined. This plot, commonly known as the Stern-Volmer plot, is presented in Fig. 1.

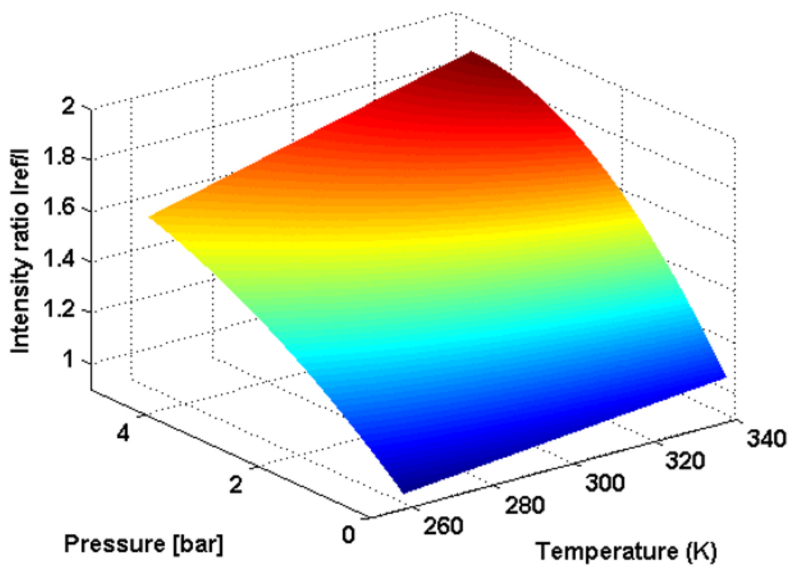

Fig. 1. Stern-Volmer plot.

By taking the ratio of wind-off (I_{ref}) to wind-on (I), the effect of paint thickness and luminophore concentration could be eliminated. The temperature sensitivity of the PSP for different pressures tested is presented in Fig. 2. The maximum temperature sensitivity of the paint (($\Delta I_{ref}/I$)/ΔT) was estimated as 0.46%/^{o}K. The temperature sensitivity of the PSP formulation used in the current investigation is smaller than the PSP recipe of the University of Washington and also that of the Arnold Engineering Development Centre (AEDC) (Moshasrov et al., 1998).

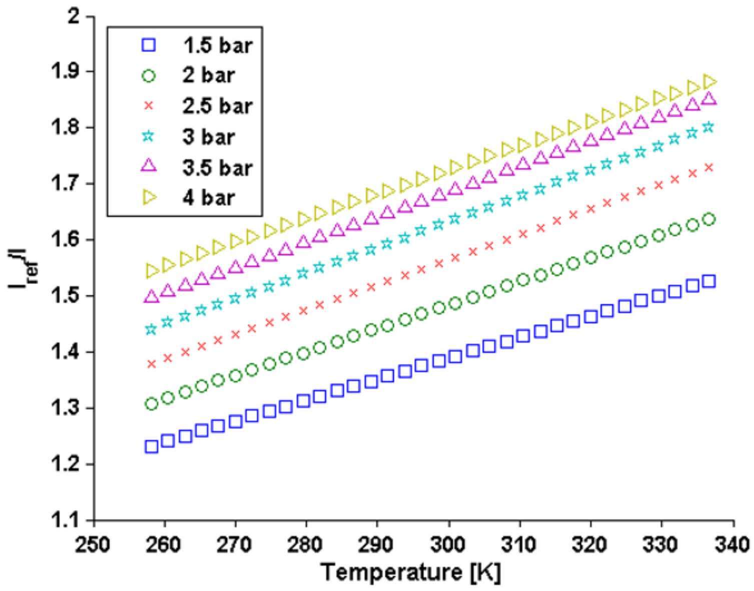

Fig. 2. Temperature sensitivity of PSP at various pressures.

2.2 Nozzle

The nozzle shown in Fig. 3 was cut from the same piece of steel. This material was used because it has uniform thickness, nominally *19.05 mm*, and is stress free and, therefore, does not warp when cut (Eustace 1969). The nozzle has a contraction ratio of *6:1* and a throat height of *9.6 mm*. The ejector (mixing tube) side walls were milled to shape and are bolted directly to the outer frame. The ejector side walls become parallel to the centre line at the plane of the nozzle exit with a distance of *45 mm* between the upper and lower walls. The total length of the test section was 307 *mm* with a height of *209 mm*. For the PSP experiments, one side of the nozzle is covered using an aluminum plate coated with the PSP while the other side is covered with optical grade perspex.

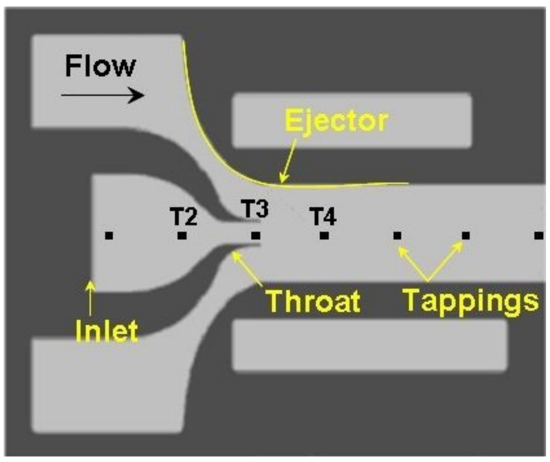

Fig. 3. Schematic of the test section.

To provide a good seal between the test section and the two joining side walls a thin layer of the *Hermatite* instant gasket was applied. Since the seal is very flexible, when the side walls are screwed on it has negligible thickness. This provides a good seal for high pressures and because it is only a very thin layer it does not alter the thickness of the test section, ensuring a truly two-dimensional geometry. A rubber gasket was also thought to be used but because of the very delicate shape and thickness of the nozzle, especially at the exit of the convergent section, this idea was not approved. Figure 3 also shows the location of the pressure tappings on the side wall, marked out with black squares.

The plate coated with PSP was initially covered with *2 - 3* layers of primer to give a uniform background. Matte white paint was used as the primer. The plate was allowed to dry. Afterwards, the PSP was spray-painted using an air-brush and the plate was heat treated at *343K* for approximately *7 hours*. This procedure is identical to the preparation of the sample used for *a-priori* calibration. Once the plate was ready it was fastened on to the nozzle with screws and the side with the perspex was covered with a black piece of cardboard to cut out any light shining on the PSP surface with the exception of just before and during image acquisition to reduce effects of photodegradation. The exposure time was *0.9 seconds*.

The inlet pressure was varied between the range *1.2-3.0 bar*, with ambient pressure taken as *1 bar*. This corresponds to a fully expanded Mach number range $0.52 \leq M_j \leq 1.36$ (White, 2003). The "fully expanded Mach number," M_j, is the ideal Mach number achievable by isentropically expanding the plenum pressure to the ambient value. For each pressure setting a wind-off image was obtained just before and immediately after the flow was introduced and the average of the two wind-offs was used as I_{ref}. Using the average wind-off image reduces bias errors due to long-term drift in the voltage out of the measurement system caused by changes in illumination intensity and photo-degradation of the PSP luminophores (Raju and Viswanath, (2005) and Carroll et al., (1996)).

3. Results

The *in-situ* calibration was applied to the experimental results of steady flow through the nozzle. The benefit of *in-situ* calibration is that it eliminates the dependency of the Stern-Volmer constants, obtained from *a-priori* calibration, to the setup. This involves the location of the different apparatus, such as the camera and light source, relative to each other. It is believed that the effects of temperature changes were minimized by the use of *in-situ* calibration using the wall static taps. This is because the model surface temperature is different during the wind-off and wind-on cases; therefore, the intensities obtained during an experimental run provide a more accurate means of calibration since the intensities take into account the changes in surface temperature (Liu and Sullivan 2003, Taghavi et al., 2002). Pressures obtained from transducer 2 (T2 in Fig. 3) were used for in-situ calibration, since it recorded the largest variation in pressure and would therefore provide a better curve fit.

To examine the accuracy of the results PSP results, simultaneous pressure measurements were conducted on the side wall of the test section using a number of pressure transducers. Figure 4 presents the pressure profile along the nozzle centerline obtained from PSP measurements with the discrete measurement results, shown by square blocks, for various inlet pressures. The transducers correspond to T2, T3, and T4 in Fig. 3. The pressure along the y-axis is non-dimensionlised with the corresponding inlet pressure (P_{inlet}), and the x-axis is non-dimensionlised with the inlet height of the nozzle (h). The rms error was calculated as 3.15%. The rms error was obtained by taking the difference between PSP and "true" static pressure tap values at each of the pressure tap locations and calculating a root mean square (expressed as a percent of the true value) (Taghavi et al., 1999).

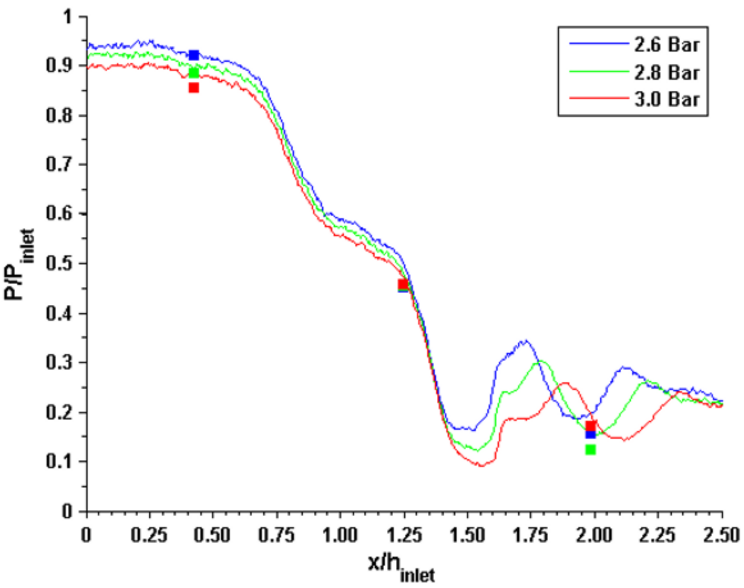

Fig. 4. Comparison between discrete measurements and PSP results for various inlet pressures.

Figure 5 represents the PSP results obtained for inlet pressures varying from *1.4-2.4 bar*. As the flow is introduced at low pressures we begin to notice the rise in pressure in the convergent portion the nozzle and the decrease at the exit of the uniform area section due to the acceleration of the flow (Fig. 5(a)). If the pressure difference is further increased the stronger pressure ratio between the inlet and exit accelerates the flow and the variations of subsonic Mach number and static pressure through the duct will be larger.

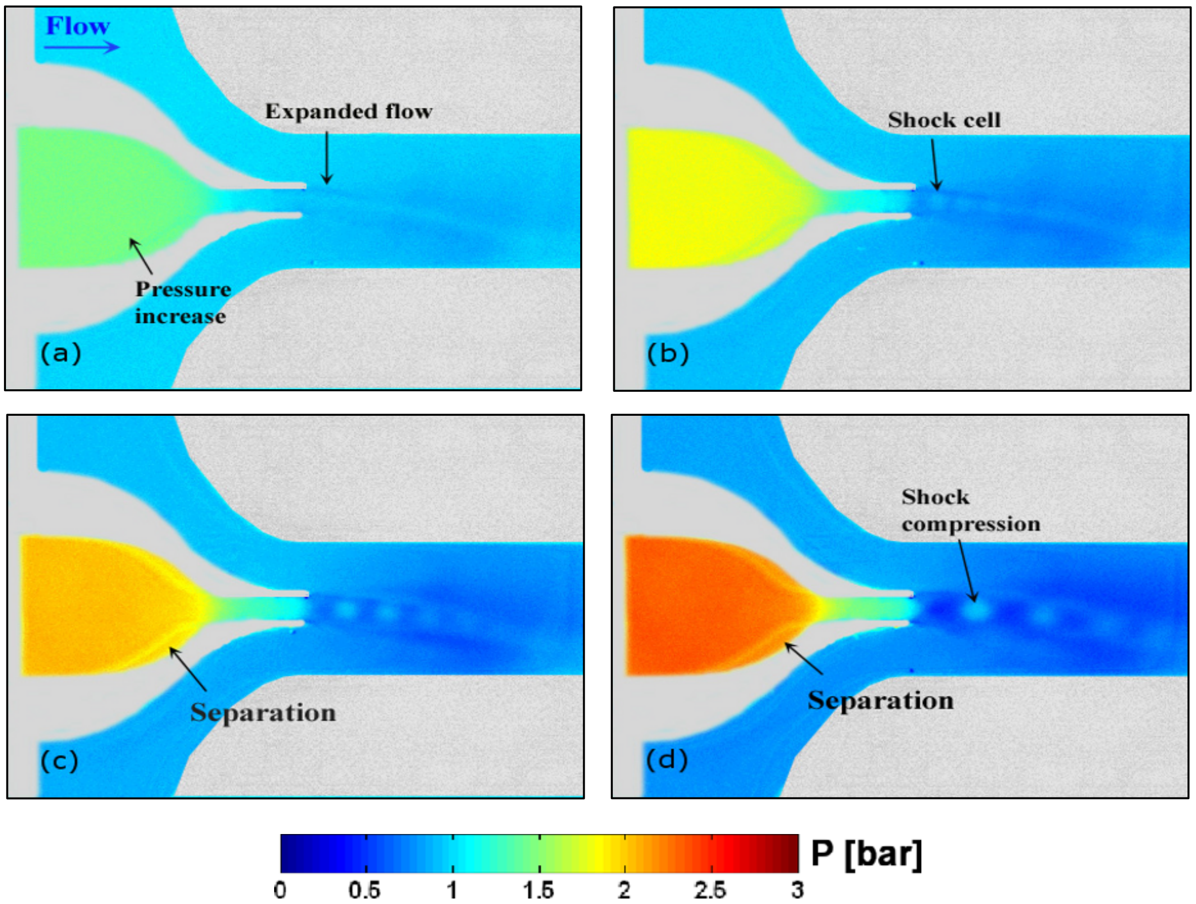

Fig. 5. PSP images for P_{inlet} = (a) 1.4 bar, (b) 1.8 bar, (c) 2.0 bar, (d) 2.4 bar.

With further increase of the inlet pressure, the Mach number at the throat cannot increase beyond $M=1$. This is dictated by the area Mach number relation. Hence, the flow properties at the throat and indeed throughout the entire subsonic section of the duct become frozen and the mass flow remains constant. This condition after sonic flow is attained at the throat corresponds to the choked flow condition. As the plenum pressure is increased beyond the choked flow condition, a series of shock cells form in the jet plume, as it can be seen in Fig. 5(b). Figures 5(c) and 5(d), exhibit properties of underexpanded jets since the flow is capable of additional expansion. An underexpanded jet starts with an expansion process where pressure progressively decreases until the shock compression region (Fig. 5(d)) is encountered where pressure jumps to a higher value. Equilibrium of the flow takes place across expansion waves outside the duct, since across the expansion fan the pressure decreases and thus the sudden acceleration of the flow is communicated to the surrounding flow. The supersonic flow is decelerated and the wall static pressure increases through a shock train region.

The separation of the flow along converging portion of the nozzle causes the static pressure to decrease. The regions of flow separation are identified in Figs. 5(c) and 5(d).

Close-ups of the flow corresponding to inlet pressures of *1.8 bar* and *2.4 bar* (similar to Figs. 5(b) and 5(d)) are presented in Fig. 6. The colourbar is adjusted such that the shock structures are easier to discern. Increasing the inlet pressure causes the pressure through the throat to gradually increase; this terminates at the nozzle exit with the formation of expansion fans and consequent shock cells. In Fig. 6(a) we can see three compression zones in full and half of the fourth compression zone, whereas in Fig. 6(b) only one compression zone exists. Due to the increase in flow Mach number through the throat, the inclination of the last running expansion fan (relative to the vertical) is greater (Fig. 6(b)).

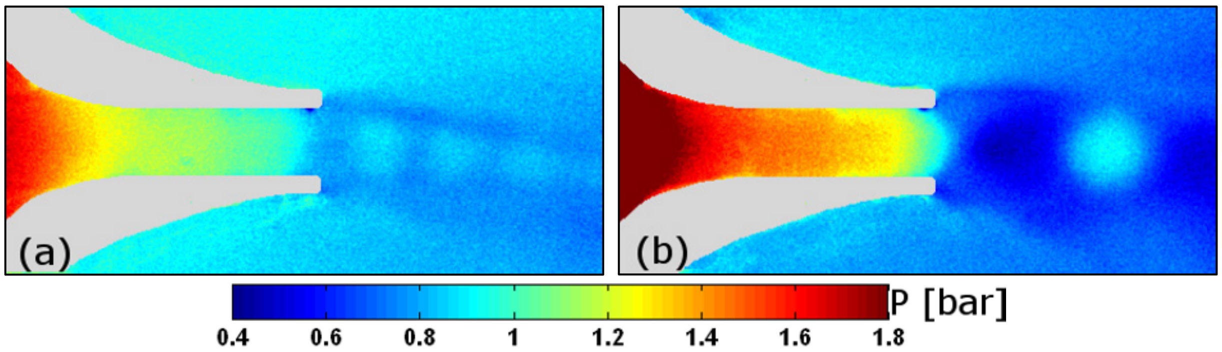

Fig. 6. Close-up of throat section for P_{inlet} = (a) 1.8 bar, (b) 2.4 bar.

With increase in plenum pressure, the static pressure along the converging entrance of the nozzle continues to increase. Observing the PSP images of events taking place in Fig. 7, the expansion zones are relatively longer with the pressure within the convergent section continuing to increase. The decrease in wall static pressure is reminiscent of the acceleration of the flow exiting the nozzle. Examining closely Figs. 7(a) and 7(b) we can see how the deflection of the last expansion fan increases relative to the normal with increasing flow Mach number, tending to become parallel to the free stream at higher Mach numbers.

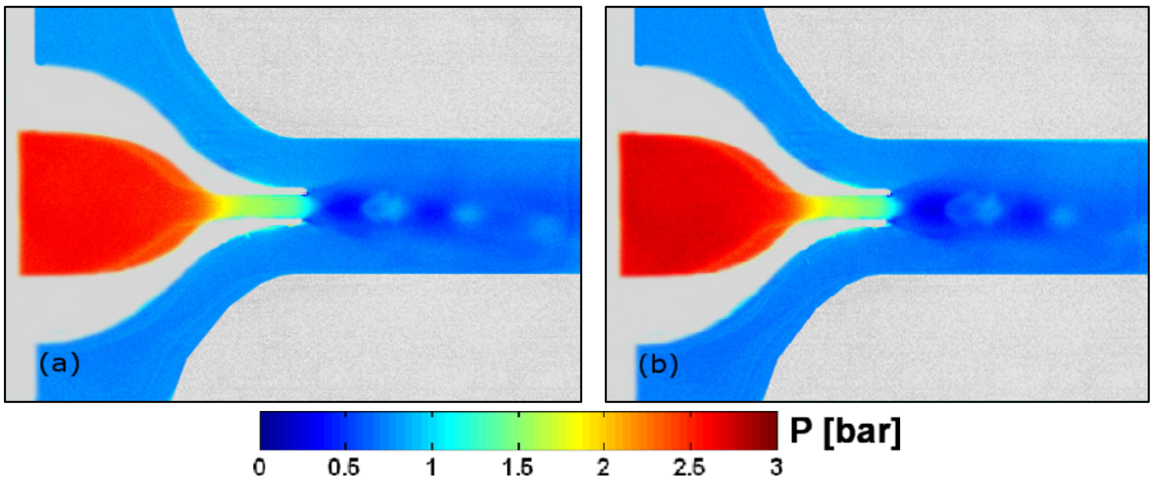

Fig. 7. PSP images for P_{inlet} = (a) 2.8 bar, (b) 3.0 bar.

4. Conclusions

The present study has involved the application of an in-house developed pressure sensitive paint (PSP) formulation, incorporating Bathophenanthroline Ruthenium as the luminophore molecules into a sol-gel matrix, to a two-dimensional convergent nozzle with an ejector system. Excitation took place at *400-500 nm* and the emission was captured at *550-650 nm*.

The Stern-Volmer plot of the PSP showed relatively little temperature dependency which has always been a source of error in PSP measurements, forcing researchers to use Temperature Sensitive Paints (TSPs) or multiple thermocouple measurements to correct for the temperature variations on the model surface. This can be a very time consuming and expensive process, especially when some experiments have a low repeatability factor.

The results obtained from applying the PSP to a convergent nozzle with an ejector, were in good agreement with discrete pressure measurements carried out. Various flow features such as the location of the shock cells and the expansion and compression zones present in supersonic underexpanded jets have also been clearly identified using the current PSP formulation.

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References

Basu, B.J., Optical oxygen sensing based on luminescence quenching of platinum porphyrin dyes doped in ormosil coatings, Sensors and Actuators B, 123 (2007), 568-577.
Bell, J. H., Schairer, E. T., Hand, L. A. and Mehta, R. D., Surface pressure measurements using luminescent coatings, Annual Review of Fluid Mechanics, 33 (2001), 155-206.
Carroll, B. F., Abbitt, J. D., Lucas, E. W. and Morris, M. J., Step response of pressure-sensitive paints, AIAA Journal, 34 (1996), 521-526.
Etele, J., Parent, B. and Sislian, J. P., Analysis of increased compression through area constriction on ejector-rocket performance, J. Spacecraft and Rockets, 44 (2007), 355-364.
Eustace, V. A., A study of two-dimensional supersonic air ejector systems, PhD Thesis, The University of Manchester Institute of Science and Technology, 1969.
Huang, C.Y., Gregory, J.W., and Sullivan, J.P., Flow visualization and pressure measurement in micronozzles, J. Visualization, 10 (2007), 123-130.
Kweon, Y-H., Miyazato, Y., Aoki, T. and Kim, H-D., Experimental investigation of nozzle exit reflector effect on supersonic jet, Shock Waves, 15 (2006), 229-239.
Lepicovsky, J. and Bencic, T. J., Use of pressure-sensitive paint for diagnostics in turbo-machinery flows with shocks, Experiments in Fluids, 33 (2002), 531-538.
Liu, T. and Sullivan, J. P., Pressure and temperature sensitive paints (2005), Springer, Berlin.
Liu, T. and Sullivan, J. P., In situ calibration uncertainty of pressure-sensitive paint, AIAA Journal, 41 (2003), 2300-2302.
Love, E. S., Grigsby, C. E, Lee, L. P. and Woodling, M. J., Experimental and theoretical studies of axisymmetric free jets, NASA technical report, (1959), NASA TR R-6.
McLachlan, B.G., Bell, J.H., Park, H., Kennelly, R.A., Schreiner, J.A., Smith, S.C., Strong, J.M., Gallery, J. and Gouterman, M., Pressure-sensitive paint measurements on a supersonic high-sweep oblique wing model, Journal of Aircraft, 32 (1995), 217-227.
Moshasrov, V., Radchenko, V. and Fonov, S., Luminescent pressure sensors in aerodynamic experiments, (1998), Central Aerodynamic Institute (TsAGI).
O'keeffe, G., MacCraith, B. D., McEvoy. A. K., McDonaghk C. M. and McGilp, J.F., evelopment of a LED-based phase fluorimetric oxygen sensor using evanescent wave excitation of a sol-gel immobilized dye, Sensors and Actuators B 29 (1995), 226-230.
Panda, J. and Seasholtz, R. G., Measurement of shock structure and shock-vortex interaction in underexpanded jets using Rayleigh scattering, Physics of Fluids, 11 (1999), 3761-3777.
Raju, C. and Viswanath, P. R., Pressure-sensitive paint measurements in a blowdown wind tunnel, Journal of Aircraft, 42 (2005), 908-915.
Taghavi, R. R., Raman, G. and Bencic, T. J., Mixer-ejector wall pressure and temperature measurements based on photoluminescence, AIAA Journal, 40 (2002), 745-750.
Taghavi, R., Raman, G. and Bencic, T., Pressure sensitive paint demonstrates relationship between ejector wall pressure and aerodynamic performance, Exp. in Fluids, 26 (1999), 481-487.
Tang, Y., Tehan, E.C., Tao, Z. and Bright, F. V., Sol-gel-derived sensor materials that yield linear calibration plots, high sensitivity, and long-term stability, Analytical Chemistry 75 (2003), 2407-2413.
White, F. M., Fluid Mechanics, (2003), McGraw-Hill.

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