PRESSURE SENSITIVE PAINT (PSP) EXPERIMENT AND COMPARISON WITH CFD VISUALIZATION OF JET FLOWS OVER A PLATE

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The paper describes the recent effort at the Institute of Space and Astronautical Science to better understand the flow fields created by the jet impingement over an inclined flat plate. The experiments and the computational analysis are conducted in parallel. The research is divided into three steps. First, conducting the PSP experiment and make the experiment quantitatively reliable by choosing adequate molecular sensors and binders. Second, evaluation of the experimental results. Comparison among the PSP data, pressure sensors, Schlieren pictures and CFD simulations results are conducted. Third, by validating the computer simulation results by comparison with the PSP experiment in the second step, CFD simulation data obtained for the flow field is used to discuss the detailed structure of the flow field. These three steps show the flow mechanism of the jet impingement over the flat plate and the locations of maximum pressure and maximum heat can be determined, which is important in many engineering problems.

INTRODUCTION

Problems created by the impingement of supersonic jets on solid objects arise in a wide variety of situations in the area of space transportation systems. Examples can be found in plume-wall interaction during the rocket launch, multi-stage rocket separation, attitude-control thruster operation and many more. The impingement flows are generally extremely complex. They contain mixed subsonic and supersonic regions, shock/shock or shock/expansion interaction, contact discontinuities, and instability inside the turbulent shear layer. Although there can be found a number of papers in the literature, and a background of understanding is gradually increasing[1,2], there still lacks a systematic study of the flow field.

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PSP EXPERIMENT & RESULTS

The experiment is carried out using the small induction-type wind tunnel (Fig. 1). The test section shown in the middle of the figure is connected to the large low-pressure chamber (in the left) and air is sucked into the test section when the valve becomes open. The duration time is roughly 10 –15 seconds for a typical supersonic external flow experiment, but can be much longer in the present experiment as a small sonic nozzle with the diameter 5 mm induces much smaller mass flow into the test section. Figure 2 shows the view inside the test section. The location and the angle of the flat plate can be changed, but only the result for the 45 degrees angle with the distance of 10 mm is shown in this abstract. The final paper will include the other results.

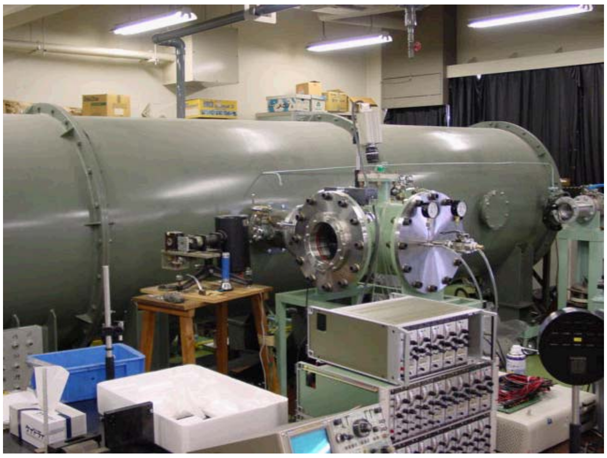


Fig. 1 Experimental Apparatus

Figure 3 shows the schematic picture showing the experimental set-up for the PSP (pressure-sensitive paint) measurement. The mechanism of the PSP is well known[3-5] and therefore only briefly described in this abstract. Pressure-sensitive paints are comprised of a luminescent compound or dye that is quenched by oxygen and is dispersed in an oxygen permeable polymeric binder. The luminescence is induced by the excitation of the dye at its absorption wave length. The emitted intensity of the PSP is inversely proportional to the partial pressure of oxygen. The relationship between the intensity of the luminescence and the partial pressure of oxygen can be expressed in terms of the Stern-Volmer relation with which pressure data can be obtained by the measurement of luminescence intensity, in other words, picture images taken by a CCD camera. In the present experiment, PSP date on the flat plate is acquired using a 12-bit CCD camera system illuminated with 779 blue LED arrays. The blue LED has a narrow wavelength range around 460nm, and is adequate for the paint of Ruthenium complexes having around 460 nm excitation wavelength. The Ruthenium complexes emit 620 nm luminescence and the images are acquired using a CCD camera.

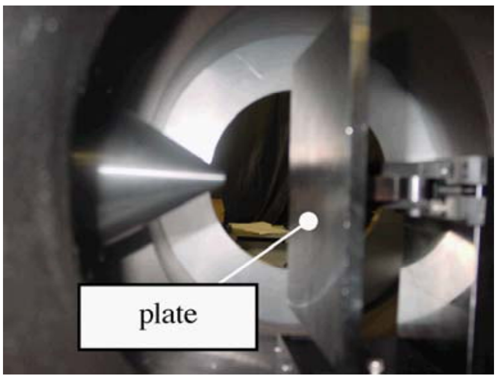


Fig. 2 Inside the test section - Sonic nozzle and the flat plate

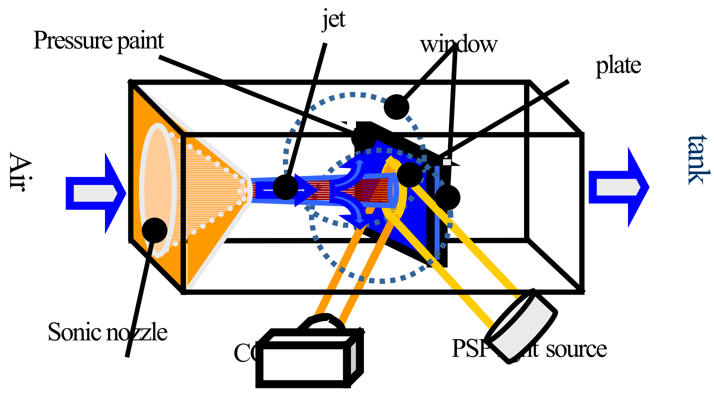


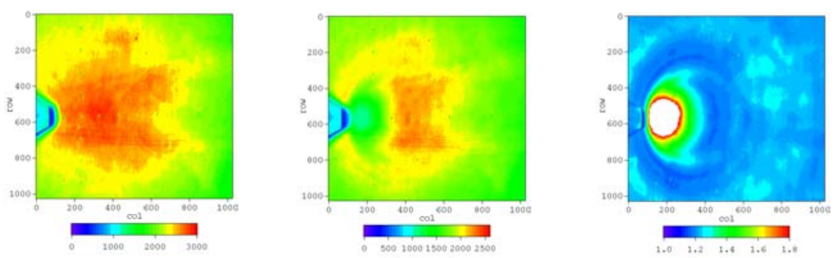
Fig. 3 Schematic picture of the experimental set-up

Two types of binders are tried; one is a silica-gel thin-layer chromatography (TLC) plate of 0.5 mm thick and the other is an anodized aluminum plate. Both show clear images of the jet impingement.. However, the result for the TLC plate shows a strong temperature-variation dependency and therefore an anodized aluminum plate is used. The ratio of the ambient pressure and the jet total pressure is varied by the control of the valve vane.

One of the resulting images is shown in Figs. 4(a)-4(c). Figure 4(a) showed the reference image (Iref) taken after the experiment. Figure 4(b) is the original image (I) taken in the experiment, and Fig. 4(c) shows the image of Iref/I. The nozzle can be recognized in the left. The subtracted final image shows the pressure field of the jet impingement over an inclined flat plate. Figures 5(a) shows the plot of the calibration curve that translates the image intensity to the quantitative pressure level. The curve is almost linear, with which the image of the pressure distributions over the flat plate is obtained as Fig. 5(b). Again, the ring-like structure, which is typical for the jet-plate interaction is observed. The post-processing software that plots the pressure distributions on any line drawn on this type of PSP picture image is under development. Figure 6(a) shows the side view of the jet by the Schlieren method and Figure 6(b) shows the pressure distributions obtained from the PSP image. The comparison of two images shows the correspondence of the shock wave and other flow characteristics. So far, the obtained PSP images look acceptable. Five test cases were done and the cases for smaller pressure ratios are underway. The final paper includes more results and the quantitative discussions of the PSP images. Also discussed are the problems in the PSP acquisition process. They are, for instance, temperature effect, humidity effect, filtering to reduce the noise in the obtained images, and else.

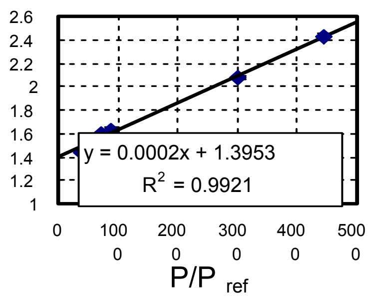
COMPUTATION RESULTS

The three-dimensional compressible Euler and Navier-Stokes equations are solved by the computer codes developed in house. Two computer codes using explicit and implicit time integration are used to see the unsteadiness of the flow field although an example in this abstract is essentially steady. There may occur unsteady features depending on the flow parameters (distance between the nozzle and the flat plate, inclined angle of the flat plate, pressure ratio…), and they will be discussed in the final paper.. The convective terms are discretized, by the so-called TVD upwind scheme. The viscous terms, when necessary, are evaluated by the central differencing. Baldwin-Lomax algebraic turbulence model[6] is mainly used in the Navier-Stokes equations for the viscous flow simulations. For the implicit time-integration code, the LU-ADI factorization algorithm5 is used. This computer code has been used for a wide variety of CFD applications and was validated by the comparison with experiments[7-9]. Only one result for the explicit code is shown here as an example. The case is: the distance/nozzle diameter =4.37, the inclined angle θ =45°.

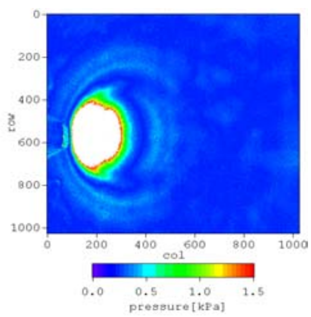


(a) I_{ref} (b) I (c) I_{ref}□I

Fig. 4 An example of the acquired PSP images



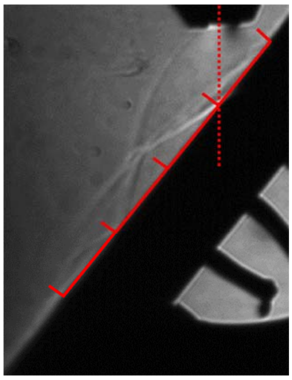
□a□calibration curve

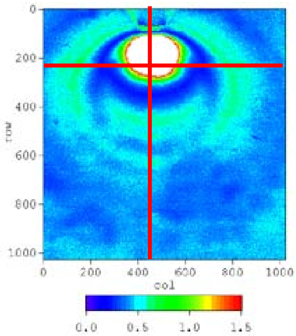


□b□pressure distributions

Fig. 5 Calibration curve and the pressure distributions over an inclined flat plate

Unfortunately, the case does not correspond to the experiment shown above, but such comparison will be done before the meeting. The flow structure such as plate shock wave and triple point is well captured. The cases that correspond to the PSP experiment will be included in the final paper.





(a) Schlieren picture –side (b) PSP image –top

Fig. 6 comparison of the Schlieren image and the PSP image

SUMMARY

The recent effort for better understanding of the flow fields created by the jet impingement over an inclined flat plate is described. The experiments and the computational analysis are being conducted in parallel. The research started recently and only the preliminary results are presented in this extended abstract. More results with important parameters changed will presented in the meeting with, the discussion of the flow fields.

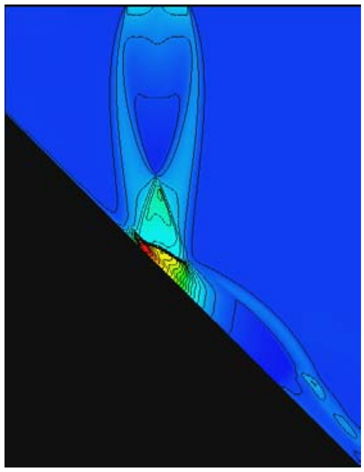


Fig. 7 Computed density contour plots in the symmetry plane

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