VERMESSUNG DER STRÖMUNGEN AUS HYPERSCHALLDÜSEN MIT PIV

FLOW-FIELD MEASUREMENTS BY PIV IN HYPERSONIC FLOWS

P. Gnemmi, C. Rey, J. Srulijes, F. Seiler, J. Haertig
French-German Research Institute of Saint-Louis (ISL), Boite Postale 70034, 68301 Saint-Louis Cedex, France

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Abstract

Experiments in the high-energy shock-tunnels of ISL were carried out in order to validate the hypersonic nozzle flow field for a Mach number of 8.0 (≈ 2500 m/s). The validation consisted in measuring the velocity flow field behind the nozzle for that Mach number by using Particle Image Velocimetry systems. Al_2O_3 microparticles mixed with Aerosil were seeded in the flow and illuminated two times by a very small laser-light sheet. For each laser-light sheet pulse the reflected light of the particles is recorded by a CCD camera on a particle image. The pair of particle images separated by some tenths of microsecond is analyzed by an inter-correlation method of the images in order to obtain the displacement of the particles in the flow. At the end, the complete 2D velocity flow field is measured and compared with other measurements coming from the Pitot-pressure measurement method.

Introduction

At ISL, since a few years, there is an increase in studies of supersonic and hypersonic flows around projectiles, missiles and space vehicles. The shock-tube laboratory has to design nozzles for such studies and the flow field generated by the nozzle geometry must be analyzed and qualified in order to know the characteristics of such flow fields before performing experiments around models. The flow-field validation consists on the one hand in measuring the Pitot pressure in the flow field and on the other hand the PIV (Particle Image Velocimetry) velocity field at the end of the shaped nozzles. Pitot-pressure measurements were made for several Mach-number nozzles by Srulijes, 2009. Velocity-field measurements are complementary to the Pitot-pressure measurements and are the main topic of the present paper.

Velocity measurements are a difficult task in shock-tunnel flows because strong spatial and temporal flow gradients occur in short testing times of typically milliseconds. Additionally, the high-energy flows produced in shock tunnels require the use of non-intrusive measurement techniques due to the formation of shock waves with non-equilibrium zones in front of probes. The short measuring times and the high velocity range make the application of well-established measurement techniques like Laser Doppler Anemometry (LDA) nearly impossible. Therefore, a particular laser Doppler velocimeter based on a Michelson interferometer was designed at ISL more than 20 years ago by Smeets and George (1978). This kind of velocimeter allows accurate velocity measurements even in short-duration high-speed flows.

Its single-point measuring character makes systematic flow-field measurements very time- and cost-consuming. The PIV technique allows an instantaneous and 2D-component measurement of the velocity field, which makes it ideally suited for shock-tunnel flows. High-speed PIV measurements are rarely found in the literature. First PIV measurements performed at the ISL were presented by Haertig 1986. Then, PIV has been applied to blow-down or continuously running wind tunnels with low stagnation states (Johé 1996), which implies relatively low velocities even for high Mach numbers (velocities smaller than 1 km/s for Mach 6, Humphreys 1993). Only recently PIV has been successfully applied to shock-tunnel flows for the first time worldwide at the ISL (Haertig 2001). Freestream velocities of 1.5 km/s in a Mach-4.5 flow and up to 1.8 km/s in a Mach-6.0 flow were measured with a high accuracy (Havermann 2002). The velocity jump across shock waves was studied using wedges and blunt bodies and the seeding particle performance was found to be consistent with theoretical estimations (Havermann 2002).

Based on the experience and results obtained at ISL during 10 years and particularly for supersonic flows at Mach numbers of 4.5 and 6.0, both the analysis and the qualifying of the nozzle flow-field at Mach number 8.0 are presented in the paper.

ISL Shock-Tunnel Facilities

A shock tunnel is a short-time-duration wind-tunnel consisting of a shock tube connected to a supersonic nozzle and a test chamber (Fig. 1). The ISL shock tube has an inner diameter of 100 mm and is divided into a 2.7-m-long high-pressure driver tube and an 18.4-m-long low-pressure driven tube. The driver gas is a mixture of hydrogen and nitrogen at a pressure of up to 45 MPa, whereas the driven or test gas consists of pure nitrogen at a pressure of up to 0.5 MPa. The two sections are separated by a steel diaphragm with a thickness of up to 5 mm. After pumping up the high-pressure driver tube, the diaphragm bursts and a shock wave is formed. The shock wave propagates at a supersonic speed into the low-pressure test gas, which is consequently heated and pressurized. At the end of the driven tube, the shock wave is reflected at the beginning of the convergent entrance section of the nozzle. The shock travels back through the accelerated test gas, which is decelerated and further heated and pressurized. As a result, a highly heated and compressed stagnation gas volume is created at the nozzle entrance for some milliseconds. This gas is then expanded in the convergent-divergent nozzle to supersonic or hypersonic speed. The flow is stationary during the test time of approximately 2 milliseconds.

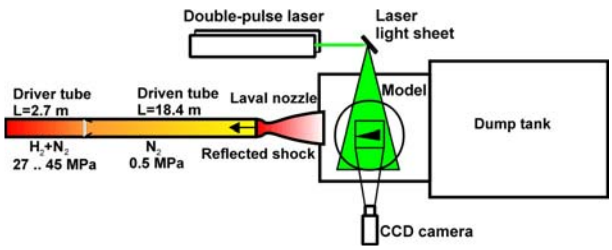


Fig. 1: ISL shock-tunnel facility

Three contoured Laval nozzles with an exit diameter ranging from 220 mm to 380 mm and nominal Mach numbers of 4.5, 6.0 and 8.0 are available now. Shock Tunnel STA is used for Mach numbers of 4.5 and 6.0 and the shock tunnel STB is employed for the Mach number of 8.0. The test chamber contains the models to be studied and catches the shock-tube gases after the experiment. Additionally, the test chamber has optical access from three sides to apply particular flow visualization methods. After each shot, the freestream flow conditions are recalculated using a one-dimensional shock-tube code, which requires the measured shock wave speed in the driven tube as an input. By varying the tube pressure, the freestream flow can be adjusted to duplicate flow conditions present in the atmosphere down to 2.5-km-altitude for the Mach-4.5 nozzle, down to 13-km-altitude for Mach-6.0 and down to the 26-km-altitude for Mach-8.0. At these heights, the corresponding flow velocity is about 1.5 km/s, 1.8 km/s and 2.5 km/s, respectively.

Particle Image Velocimetry System

A double-frame/single-exposure digital PIV system was installed at the ISL shock tunnel STB. The light source consisted of a frequency-doubled Nd:YAG double-pulse laser (Quantel CFR Ultra 200) with a nominal pulse energy of 200 mJ each and a pulse duration of about 5 ns. The vertical laser-light sheet (140 mm wide, 0.2 mm thick) perpendicular to the nozzle axis was created by means of a TSI light arm. The use of the light arm considerably simplifies the optical setup of the PIV system compared to the one handled in the previous experiments.
The CCD camera was mounted on the horizontal axis to view the illuminated flow field behind the nozzle axis and it can acquire two images within a pulse delay of 0.3 µs. The experiments were carried out with a PowerView Plus 4MP PIV camera distributed by TSI. Figure 2 depicts the laser pair in the foreground, the light arm, the CCD camera and in the background a spherical model in the shock-tunnel test section.

Fig. 2: ISL shock-tunnel facility STB with the PIV system for Mach number 8.0 investigations

The camera spatial resolution is of 2048 pixels x 2048 pixels which is about 4 times higher than the one used in previous Mach-4.5 and Mach-6.0 nozzle experiments. The PIV images were analyzed after the experiment by an inter-correlation algorithm included in the ISL software (Haertig 2005, 2008).
The width and height of the correlation windows can be chosen between 16 and 128 pixels. The inter-correlation function is calculated by Fourier transform. An automatic filtering allows the increase of the function quality. A quality index (named “flag”) based on the signal-noise ratio (SNR) and on the adequately of the inter-correlation peak with a Gaussian curve is affected to each measurement. The best quality corresponds to a flag equal zero, however the measurement is considered to be valid for a flag lower than 6. The uncertainty on the displacement measurement is evaluated to 0.015•flag (in pixel). The software allows the examination of “difficult” zones of the flow field in detail.
An iterative process allows the correlation windows to be shifted and the decrease of the window dimensions. A series of files is then obtained for each image pairs containing the flag for each measurement. A sorting is performed among all velocity fields obtained by imposing a minimum quality (maximum accepted flag) and by giving a priority to measurements found

with the smallest inter-correlation windows (Scarano 2003 and Haertig 2008). The efficiency of that process has been demonstrated in previous studies at Mach 6.0 (Haertig 2005 and Havermann 2008).

Nikon zoom objectives were mounted to the camera to change the field of view. The laser and the camera are synchronized and triggered by a heat-flux sensor in the shock-tube wall. The synchronizer separation time was checked by a fast-response photodiode and timing errors were found to be less than 1 %. Solid particles were chosen for the seeding because they had to withstand the high stagnation temperatures of about 2800 K after shock reflection at the nozzle entrance. For this reason, Al_2O_3 particles of a nominal diameter of 0.3 µm mixed with Aerosil dispersed by a fluidized-bed seeder were seeded into the low-pressure driven tube together with the nitrogen test gas before the experiment started.

Experimental Results

Freestream Mach-8.0 Nozzle Flow

Before performing experiments in which the flow field around models can be studied, it is of high importance to validate the flow structure produced by the nozzle of the shock tunnel. The Mach-8.0 nozzle should generate a parallel flow and the validation consists in measuring Pitot pressures in the flow field and the PIV velocity field at the end of the shaped nozzle.

Among four altitudes ranging from 30 to 60 km, the chosen shock tunnel conditions presented in the paper are those of the atmospheric altitude near 30 km. The Pitot-pressure measurements were carried out by using a rake equipped with 11 Kulite piezoresistive pressure transducers (Fig. 3 left). During the experiments the flow field around the Pitot-pressure transducers is visualized by grey patterns obtained by using the differential interferometry which provides the visualization of the density-gradient field (Fig. 3 right). The detailed description of the experiments and the complete set of results are reported by Srulijes 2009.

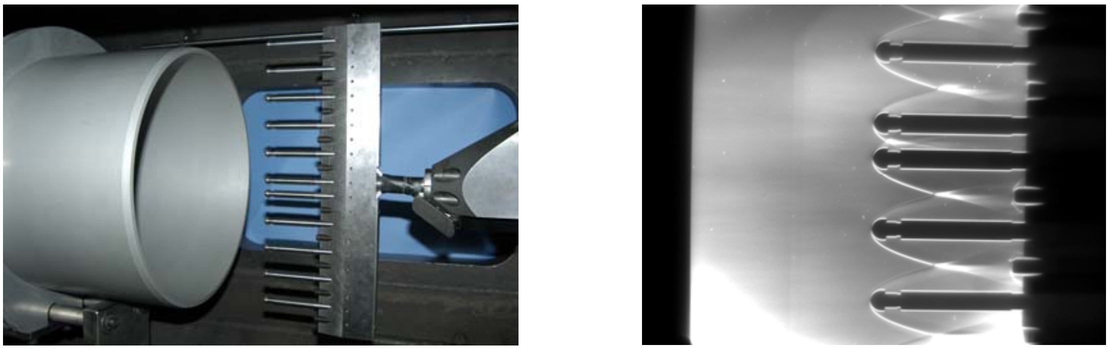
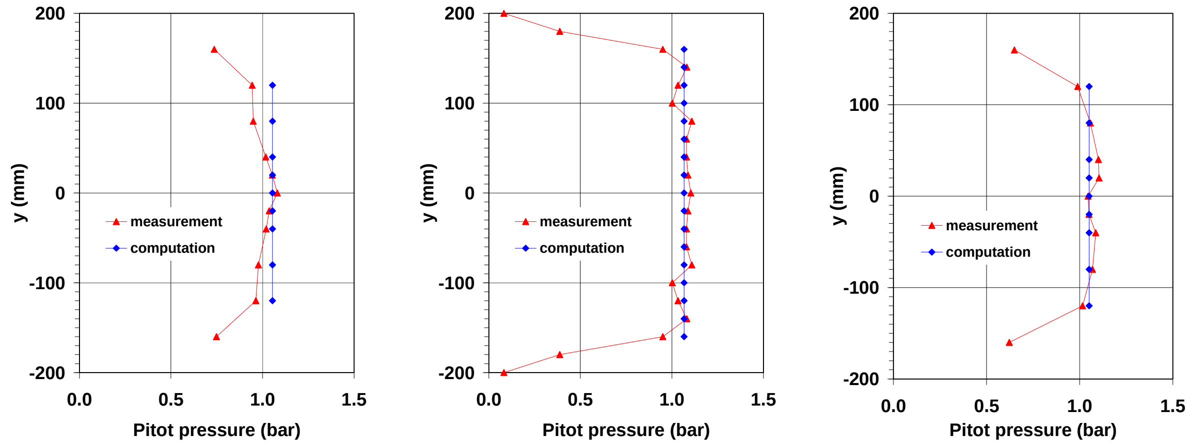


Fig. 3: Rake with Pitot-pressure transducers (left) located in front of the Mach-8.0 nozzle and interferogram picture taken during the experiment (right)

Figure 4 shows the Pitot pressure profiles measured and computed at different distances from the nozzle exit. The calculated values are determined by using the shock-tunnel measurements and a one-dimensional shock-tube / nozzle code. The Pitot-pressure is measured with an accuracy of about ± 5% compared to the calculated value. The measurements demonstrate that the flow core has a diameter of about 260 mm.



test 08043002, x = 50 mm, h = 29.05 km   test 08062302, x = 100 mm, h = 29.09 km   test 08060901, x = 150 mm, h = 28.95 km

Fig. 4: Pitot-pressure measurement profiles at different distances from the Mach-8.0 nozzle exit

The shock tunnel conditions were also such as the atmospheric altitude is near 30 km. The Mach-8-nozzle flow field was recorded for a field of view of 380 x 140 mm, a camera focal length of 105 mm, and an aperture of f-5.6. Taking into account the pulse delay of 0.3 µs, the optical calibration factor of 115 µm/pixel allowed a maximum particle displacement of about 6 pixels for a velocity of 2500 m/s. The pair of images was analyzed using ISL's PIV software with a correlation window of 64 pixels x 64 pixels and a grid step of 16 pixels, which lead to a spatial resolution of 1.84 mm x 1.84 mm. That large correlation window is selected because the particle displacement is pretty long.

Figure 5 shows the Mach-8.0 nozzle illuminated by the vertical laser-light sheet. The velocity measurement region is marked in red.

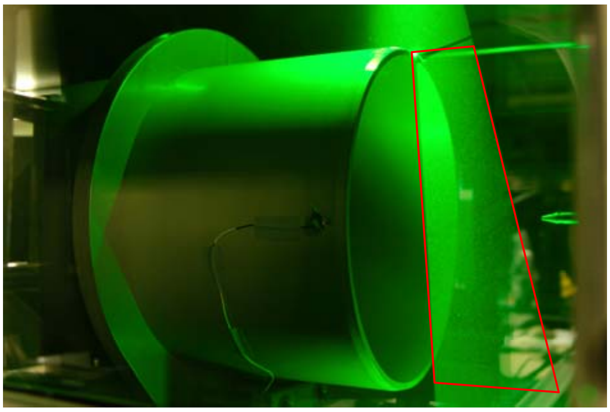


Fig. 5: Vertical laser-light sheet for the PIV measurement in front of the Mach-8.0 nozzle

The qualifying of the flow field behind the nozzle was performed by doing 2 different tests: the first one consists in the PIV measurement of the half upper part of the nozzle flow-field and the second one deals with the PIV measurement of the half lower part of the nozzle flow-field. The measurements were carried out in such a way that an overlapping of the maps took place.

On the left part of figure 6, the PIV picture of the half upper part of the nozzle flow field shows a rather homogeneous seeding density except in the upper region of the nozzle. On the right part of the figure, the PIV picture of the half lower part of the nozzle flow field shows a much more homogeneous seeding density particularly in the flow-field core.

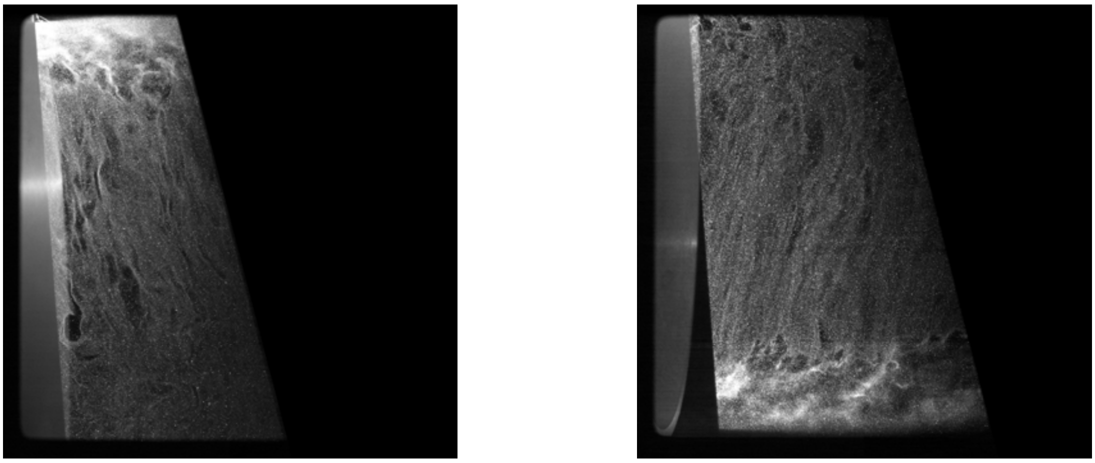


Fig. 6: Mach-8.0 nozzle flow field with Al_2O_3 particles, PIV pictures of upper (left) and lower parts (right)

Figure 7 shows the measurement result of the half upper part of the horizontal (left) and vertical (right) components of the velocity behind the nozzle. Figure 8 depicts the same kind of measurement result of the half lower part of the velocity components behind the nozzle.

The detailed measurement results shows a homogeneous flow in the nozzle core, which has a diameter of near 260 mm, corresponding to the same size as the one found by Pitot-pressure measurement. The flow is parallel in that core and the average values of the velocity components and their mean standard deviations are calculated; the quality index “flag” is lower than 5 in the core region. The average horizontal and vertical components are respectively 2481 m/s $\pm$ 35 m/s and 28 m/s $\pm$ 15 m/s in the upper part. They are respectively equal to 2510 m/s $\pm$ 31 m/s and 13 m/s $\pm$ 13 m/s in the lower part.

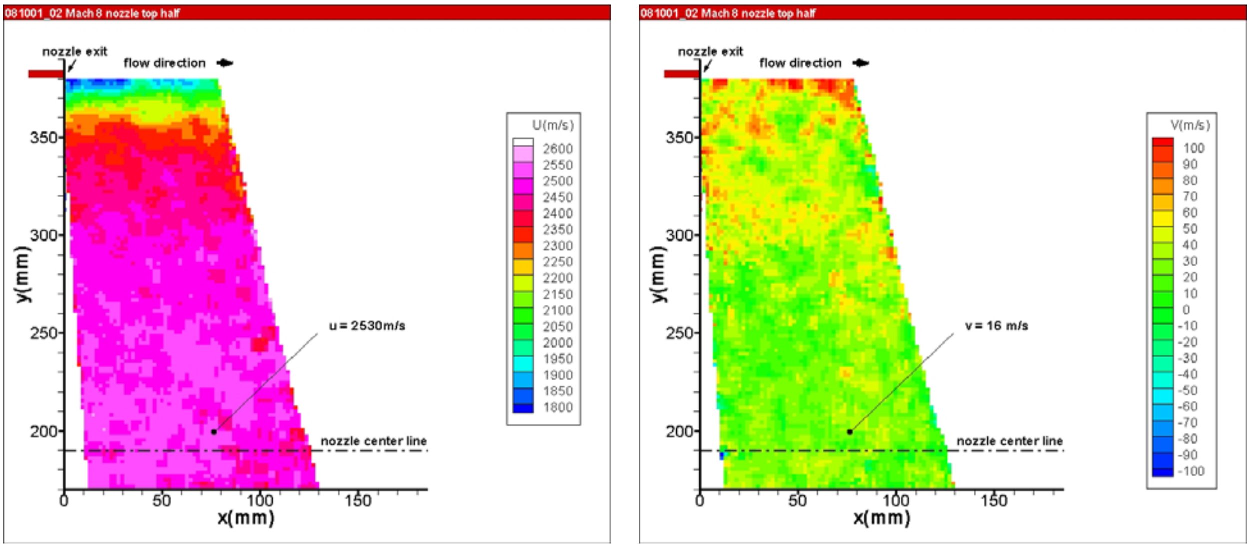


Fig. 7: Test 08100101, horizontal (left) and vertical (right) components of the velocity

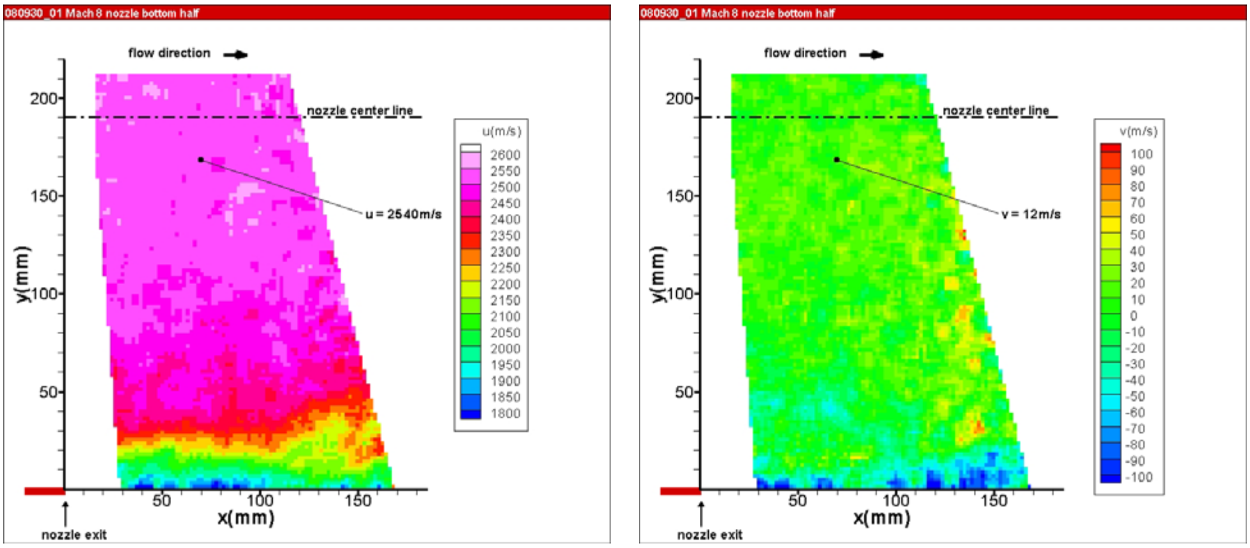


Fig. 8: Test 08093002, horizontal (left) and vertical (right) components of the velocity

Figure 9 presents the horizontal velocity profiles measured and computed at different distances from the nozzle exit. The calculated value is also determined by using the shock-tunnel measurements and a one-dimensional shock-tube / nozzle code. The velocity is measured according to an accuracy lower than ± 2% compared to the calculated value.

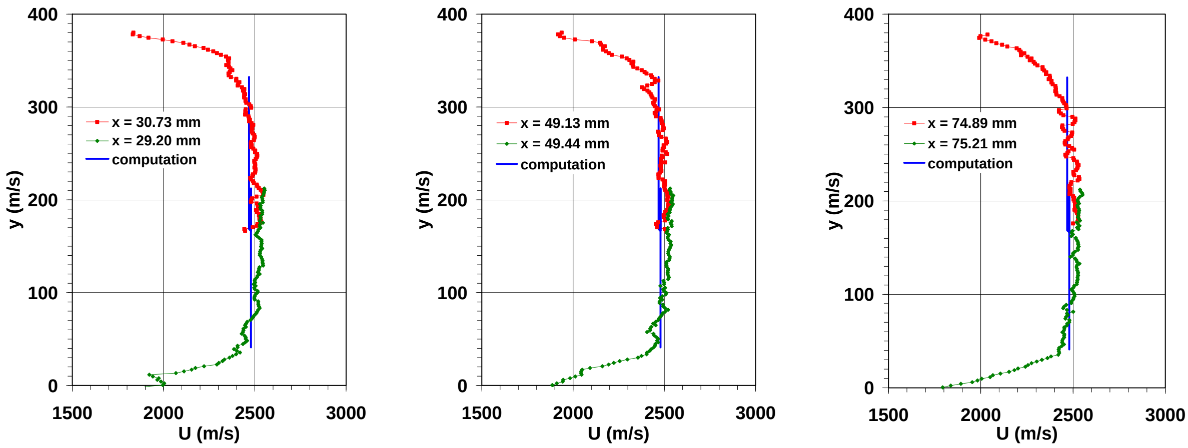


Fig. 9: Horizontal velocity profiles at different distances from the Mach-8.0 nozzle exit

The one-dimensional shock-tube / nozzle code provides also the flow velocity and the Mach number in the core flow for the corresponding altitude. The computed values obtained for Pitot-pressure and PIV experiments are compared with the average values got from PIV measurements (Tab. 1).

A good agreement between the computation and the measurements is obtained and the PIV measurements are coherent with the Pitot-pressure ones. The difference between the computation and the measurement could be due to the fact that the effective area of the nozzle is a little bit higher than the expected one leading to a higher measured value than the computed one.

Tab. 1: Horizontal freestream velocity: comparison of PIV measurement with calculated value

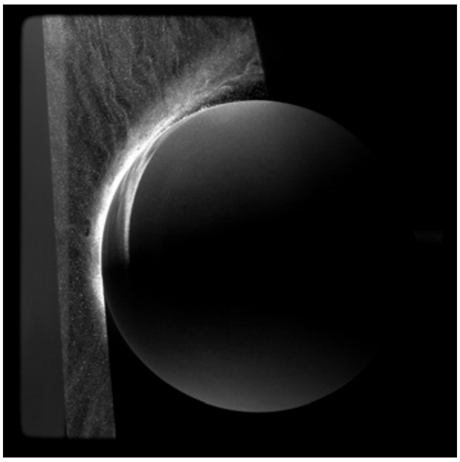
Test	Computed Mach number	Computed altitude (km)	Calculated velocity (m/s)	PIV, U component (m/s)	Difference measurement / calculation, %
08043002	7.68	29.05	2506	Pitot-pressure	
08062303	7.69	29.09	2504	Pitot-pressure	
08060901	7.67	28.95	2544	Pitot-pressure	
08093001	7.72	29.40	2479	2510 ± 31	1.3
08100102	7.73	29.50	2467	2481 ± 35	0.1

Mach-8.0 Sphere Flow

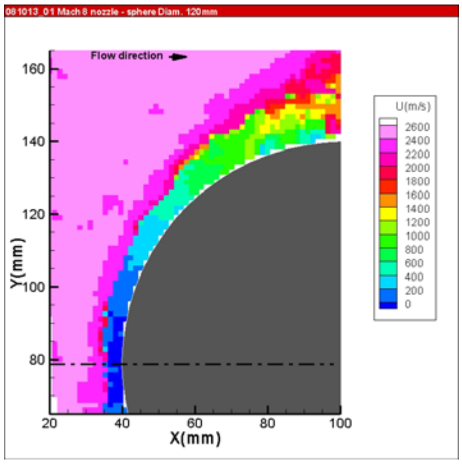
A detached bow shock wave is formed in front of a sphere in a supersonic-hypersonic flow. Between the shock and the sphere a three-dimensional flow with subsonic, transonic and supersonic zones is established, which make this kind of flow important and interesting for the validation of computational fluid dynamics codes, for example.

A first feasibility experiment was carried out and a sphere of 120-mm of diameter was installed in the shock tunnel. The experiment at Mach-8.0 flow conditions was conducted for an altitude of 30 km. The flow was studied using the same PIV system and the same particles as in the previous experiments.

In anyway, the bow shock is very well visible in figure 10a at the edge of the increased particle density. The PIV analysis was also performed by ISL's software with a 64 pixels x 64 pixels correlation window size. The corresponding result of the PIV correlation process is shown in figure 10b where the subsonic and transonic zone (blue) can be well distinguished from the supersonic zone (green and red) behind the bow shock.



a) PIV picture



b) horizontal velocity component

Fig. 10: Test 081013_01, PIV measurement around a sphere

Theoretically, the bow shock has a negligible thickness, but the measured shock is spread out on 6 mm wide (x/D = 0.05); this thickness can be reduced by improving the seeding of the flow field and decreasing the correlation window size.

Conclusion

Particle Image Velocimetry was applied to hypersonic flows in the high-energy shock-tunnel of ISL. The freestream nozzle flow with a Mach number of 8.0 was measured similarly to previous experiments for various Mach numbers. The PIV measurement is coherent with Pitot-pressure measurement in terms of flow structure and the core flow has a diameter of about 260 mm. The PIV measurement of about 2500 m/s agreed very well with the calculated nozzle velocities and showed less than 2% difference.

The PIV measurement of the supersonic flow around a sphere clearly showed the detached bow shock and the complex flow field between the shock and the sphere surface. However, more investigations should be done in order to improve the velocity drop through the bow shock in front of the sphere. In spite of some difficulties, the PIV correlation algorithm is able to treat the strong density gradients at shock waves.

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