VERMESSUNG DER STRÖMUNGEN AUS HYPERSCHALLDÜSEN MIT PIV

FLOW-FIELD MEASUREMENTS BY PIV IN HYPERSONIC FLOWS

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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.

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

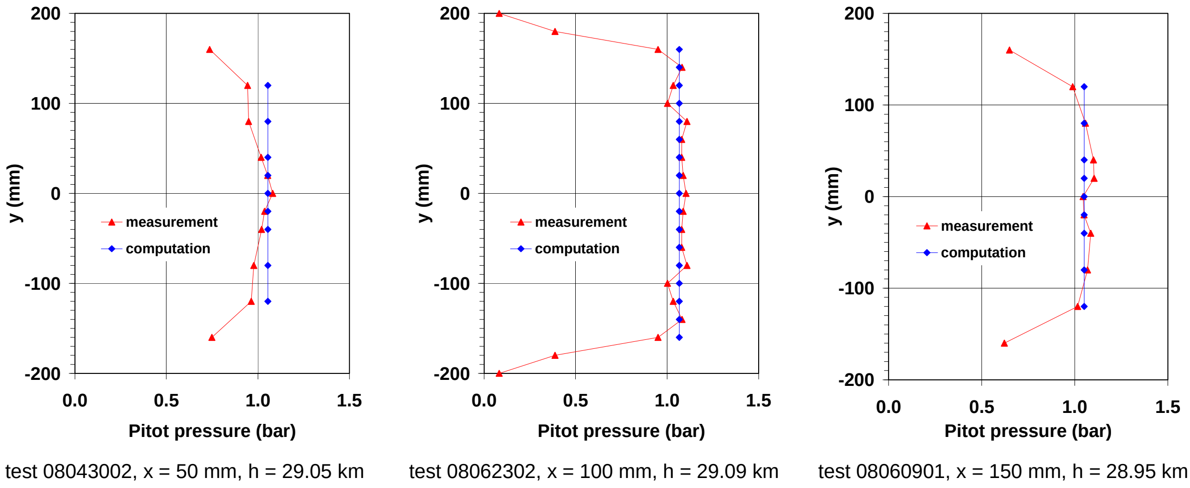

Fig. 4: Pitot-pressure measurement profiles at different distances from the Mach-8.0 nozzle exit

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.

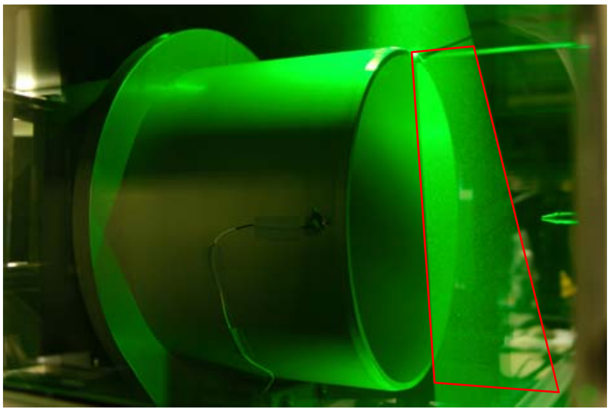

Fig. 5: Vertical laser-light sheet for the PIV measurement in front of the Mach-8.0 nozzle

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