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IMPLEMENTATION OF PARTICLE IMAGE VELOCIMETRY SYSTEM AT ITU TRISONIC WIND TUNNEL

Hasan Tabanli[1], Orcun Bekem[2] and Kemal Bulent Yuceil[3]

Istanbul Technical University
Istanbul, Turkey

ABSTRACT

In this study, it is aimed to gain a capability for and to perform particle image velocimetry (PIV) measurements in the ITU Trisonic Wind Tunnel for complex flow problems in supersonic inlet models. The goal required to develop means to make modifications on the tunnel test section and stagnation chamber, which had not been attempted since the procurement of the wind tunnel at the University. In the first step following the establishment of the PIV system, particle image velocimetry was conducted to investigate the mean velocity field in the empty test section at Mach 2. Afterwards, the mean velocity field and Mach contour of the single ramp internal compression inlet model at supersonic condition were obtained

INTRODUCTION

Particle image velocimetry (PIV) is a nonintrusive measurement technique used for obtaining velocity field information for low speed and high speed applications. One of the most favored research areas for PIV measurement is the study of the turbulent flows since measurement of turbulent structures requires compatibility with the wide dynamic range of scales in length and velocity [Humble, Scarano & van Oudgeusden, 2007]. This technique utilizes a stroboscopic illumination source, a short interframe transfer CCD camera and particles which are few microns in size (tracers). Pulsed-lasers are generally used for stroboscopic illumination due to the fact that their short time exposure reduces the blur significantly. The laser is then made planar; a cylindrical lens is commonly used for this application. Upon illumination; seeding process, which is the ejection of the seeding particles from an upstream location, is performed. The camera captures multi-exposure images of particles in specified interrogation areas and measures the particle displacement distance between image pairs which are then divided by the time interval resulting in a velocity output. Hence, instantaneous velocity field of the illuminated cross section is obtained. For this technique to give reliable and accurate velocity measurements, the particles must be near neutrally buoyant and they should be able to scatter light properly [Grant, 1997]. Even though PIV measurements are used extensively in low speed experiments, the high speed applications

[1] Graduate Research Assistant, Department of Astronautical Engineering, Email: hasantabanli@itu.edu.tr
[2] Undergraduate Student, Department of Astronautical Engineering, Email: orcunbekem96@gmail.com
[3] Assistant Professor, Department of Astronautical Engineering, Email: yuceil@itu.edu.tr

which include high compressibility effects or shock waves are still problematic. Compressibility may cause extreme velocity gradients which will make particles unable to follow the flow faithfully. As a result, large slip errors are introduced to the measurement. If a supersonic flow containing shocks is being studied in the experiment, the velocity discontinuity arising from shocks amplifies these slip errors making the results unreliable and inaccurate. In order to cope with this kind of error, a proper selection of the seeding particles must be considered [Ross, Lourenco & Krothapalli, 1994]. Another error as a result of high speed PIV experiments is the inhomogeneous refractive index in the flow field. Different refractive indexes in the flow field results in the particle-image blur which in turn causes faulty measurements. Non-uniform particle seeding density due to high speed application also has a negative effect on the accuracy and reliability of the end results [Scarano, 2007]. Using a proper PIV setup and correct data processing techniques, those errors can be minimized. Popularity of the PIV experiments in high speed applications is increasing with the developing technology allowing more accurate and reliable results to be obtained. Therefore, understanding how the different parameters can be determined and how to create a proper setup for a high speed experiment is crucial. In this study implementation of high speed PIV technique for determination of the velocity field inside a supersonic internal compression inlet at M = 2 will be discussed and PIV results from a sample case of this flow field study will be presented.

EXPERIMENTAL SETUP

The main objective of this study is to observe mean velocity field at the center plane section of the supersonic inlet models. For this reason, a PIV system was established and is shown schematically in Fig. 1.

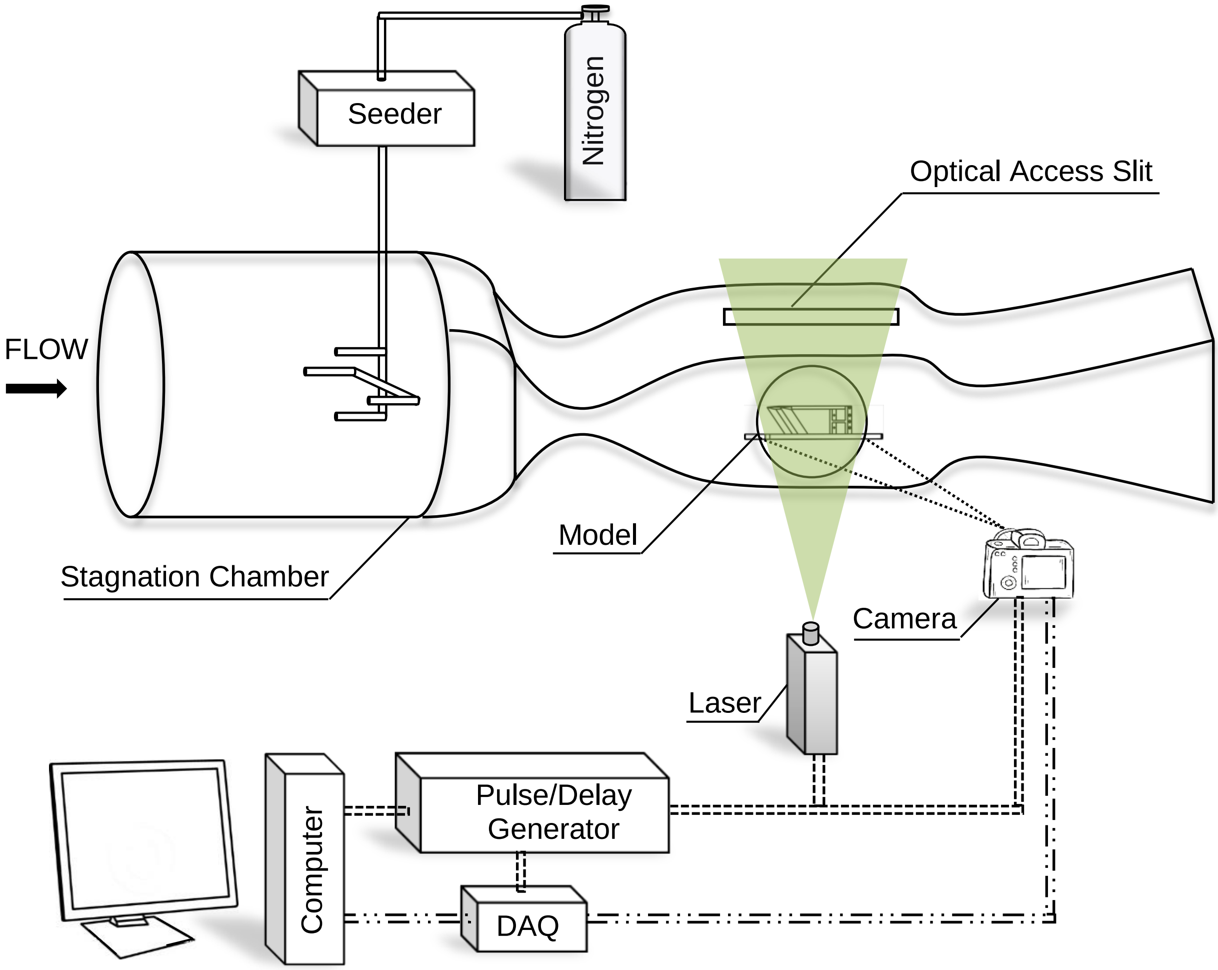


Figure 1: Schematic of particle image velocimetry setup.

As part of any PIV measurements, seeding particles need to be introduced into the flow. In order to ensure that the test section of the wind tunnel is uniformly seeded, the PIV seed particles were delivered into the stagnation chamber of the wind tunnel. A home-made spray nozzle rake was built using stainless steel tubing and tube fittings. In order to adapt it to wind tunnel necessary modifications were made on the safety membrane port holes of the stagnation chamber. This rake consisted of four nozzles and positioned facing the flow direction so that particles spread over an area and the seeding can disperse uniformly within the measurement region of the tunnel. The image of the rake and stagnation chamber in the mounting position is shown in Fig. 2. A particle seeder (SCITEK PS-10) which is able to operate in pressurized facilities was connected to the rake and driven by compressed nitrogen. The seeder employs sonic jets which create high shear flow fields which break up the powder while it is being dispensed in the outlet chamber. The powder dispensing method avoids clogging and also ensures uniform seeding density during operation.

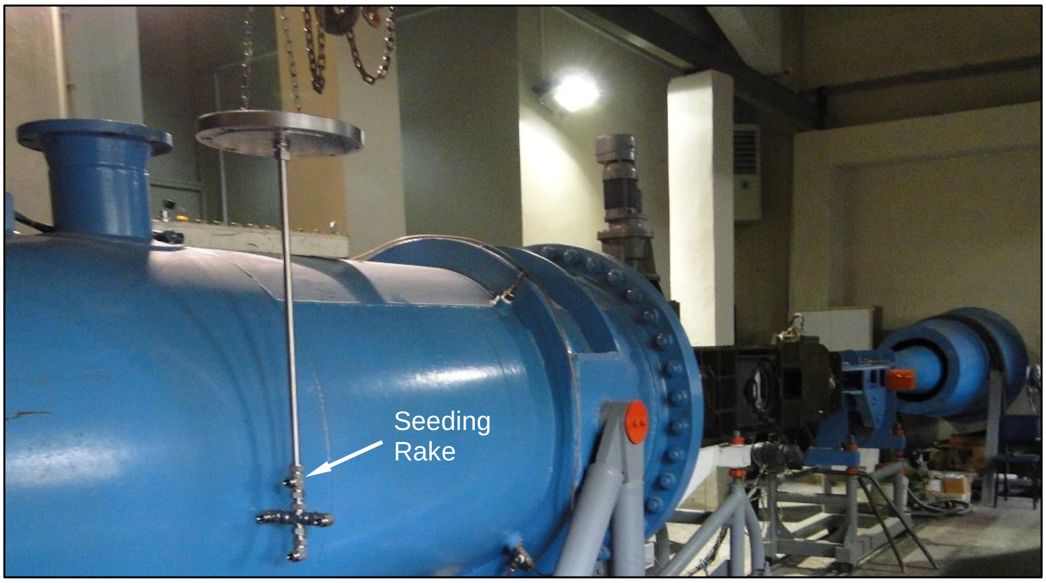


Figure 2: Image of the seeding rake at the mounting position

In ITU Trisonic Wind Tunnel, the Liners test section / nozzle module which provides Mach numbers 0.4 – 2.2 has boundary layer suction devices at each upper and lower walls in its original design. The boundary layer suction device at the lower wall had been removed in previous studies and this part of the test section floor was modified to be able to mount the inlet models and the pressure transducers, flush with the surface, on the floor. In this study, it is necessary to provide optical access to the test section and within the model at *y*-direction so that the area of interest within the inlet model can be illuminated. For this purpose, the boundary layer suction device at the upper wall of the test section was also removed, and modifications were made both at the lower and upper walls of the test section and at the lower and upper outer walls of the Liners module. In order to pass the laser sheet through these four walls, new parts with transparent slots made of acrylic were designed and manufactured.

In order to accurately obtain the velocity field from the raw particle images acquired by PIV measurements, the actual physical distance between the pixels in the particle images must be determined by means of a calibration image. To this end, a home-made calibration target suitable for the test section was manufactured. Calibration target was designed to be located correctly in exactly the same plane as the light sheet. The target contains calibration markers in known positions and the camera was primarily focused on these markers. Also, prior to experiments, the test section was injected with smoke (as seen in Fig. 3) to ensure that the camera was correctly focused on the laser sheet.

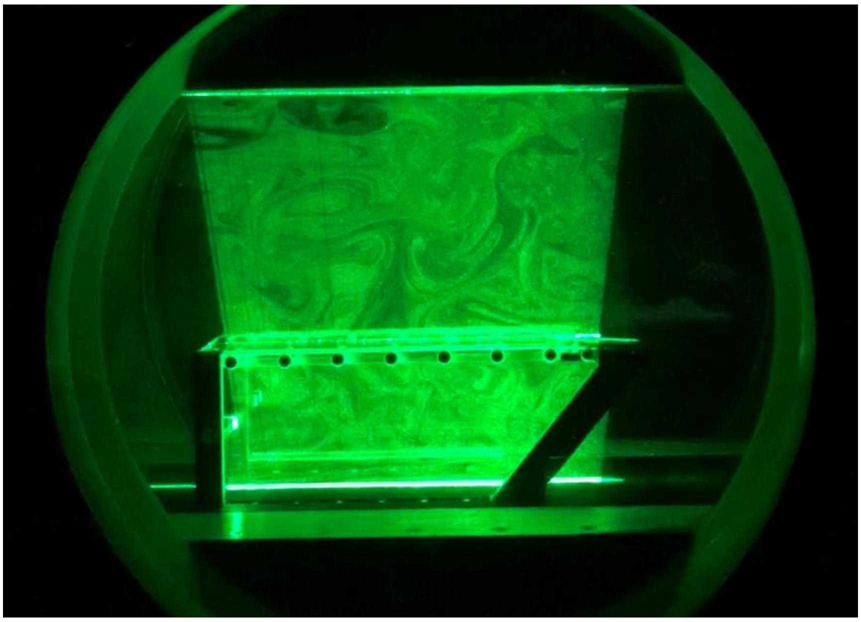


Figure 3: PIV Laser sheet made visible by smoke in the test section with the inlet model.

RESULTS

Flow seeded by Expancel 091 DE microspheres. The microspheres are white spherically formed particles with a thermoplastic shell encapsulating a gas. The seed-particles diameter and density are specified by manufacturer as 5 μm and 20 kg/m^3, respectively. The seed-particles used in this study are approximately 200 times lighter than the TiO_2 which is the most commonly used PIV particles. This property makes such particles superior in terms of flow-tracking performance and uniformity of seed concentration. A measure of the particles' ability to track velocity changes in the flow is the particle response time τ_p [Melling, 1997]. By definition, a particle experiencing a step change in velocity will take a time τ_p to reach 63% of the velocity step change. Particle response time is given by:

$$\tau_p = \frac{d_p^2 \rho_p}{18\mu}(1 + Kn) \tag{1}$$

where d_p is the particle diameter, ρ_p is the particle density, μ is dynamic viscosity of the gas which is calculated herein with Sutherland's formula, and Kn is the Knudsen number which is equal to the mean free path (λ) divided by the particle diameter. For the Mach 2 freestream flow, the particle Kn number is 0.0173 and τ_p computes to be 2.5 μs. Stokes number quantifies the degree of the seeding-particles ability to tracking velocity fluctuations. Stokes number is defined as $St = \tau_p/\tau_f$, where $\tau_f = \delta/\Delta U$ is the characteristic flow time scale, ΔU is the characteristic velocity difference and δ is the characteristic width of the flow. The τ_f here is the estimation of the characteristic time-scale of the outer-scale (equivalently, large-scale) structures only. Samimy and Lele (1991) suggested that for particles to faithfully track the velocity fluctuations in a turbulent shear layer, the Stokes number must be less than about 0.5. In the current work, The Mach 2 freestream velocity is about 515 m/s and the boundary layer thickness, determined from pitot-probe measurements, is about δ_{99} = 16 mm. Taking the characteristic flow time to be the outer scale time, δ_{99} / U_∞ = 31 μs, then the Stokes number is about 0.08, which shows that the particles easily track the large-scale velocity fluctuations in the boundary layer.

The seeded flow was illuminated by a New Wave Solo120 double-pulsed Nd:Yag laser with 200 mJ pulsed energy and 3-5 ns pulse duration at wavelength 532 nm. The laser was triggered at 15 Hz with a pulse separation of 2 μs, which produced a particle displacement of approximately 1.1 mm in the freestream flow. This corresponds to approximately 9 pixels maximum displacement. Particle images were recorded by a Dantec Flowsense 10-bit camera with 1600×1200 pixel-sized sensor. The Dynamic Studio v3.14 software was used for the acquisition of the measurement and processing of the data. Prior to correlation computations, each image was background-subtracted using the mean background image subtraction function built into the software. This served to remove some of the background noise due to undesired reflections and particles sticking to the tunnel and inlet walls. As an example, the raw image and background-subtracted image are shown in Fig. 4a and Fig. 4b, respectively. In comparison, the processed image is seen to have far less background reflections and less of a background haze. Background subtraction technique provides higher quality data, consequently it is observed that the number of valid vectors was increased by using this technique. After background subtraction, the images were processed using the average-correlation method with an interrogation window of 32×32 pixels and 50% overlapping in each direction. In addition, to enhance the results of measurement, velocity data were filtered by a coherence filter with 30 pixels filtering radius. The coherence filter only modifies the vectors that are likely to be erroneous and inconsistent with the dominant surrounding vectors.

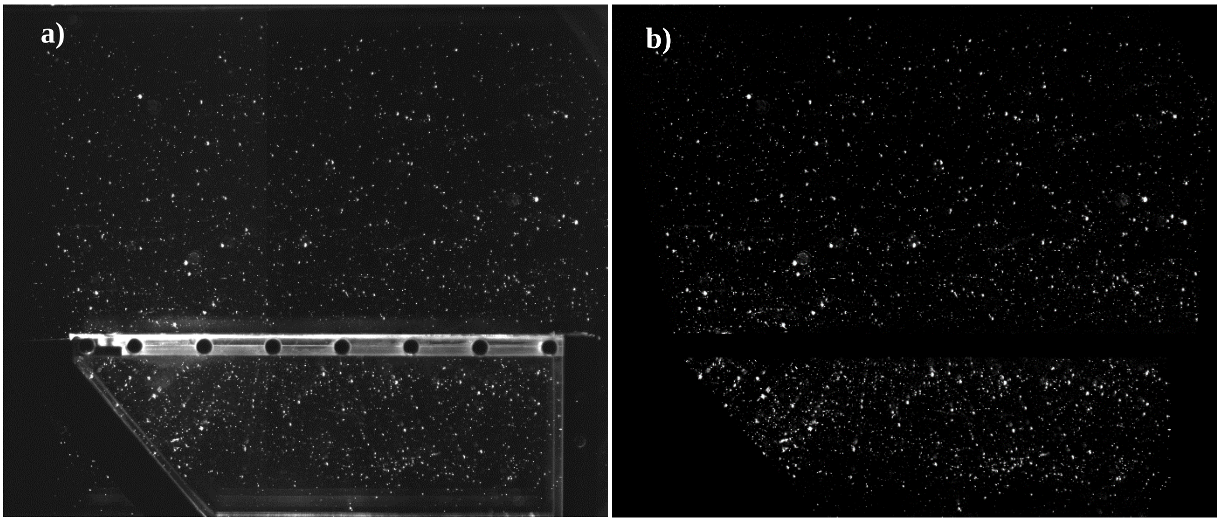
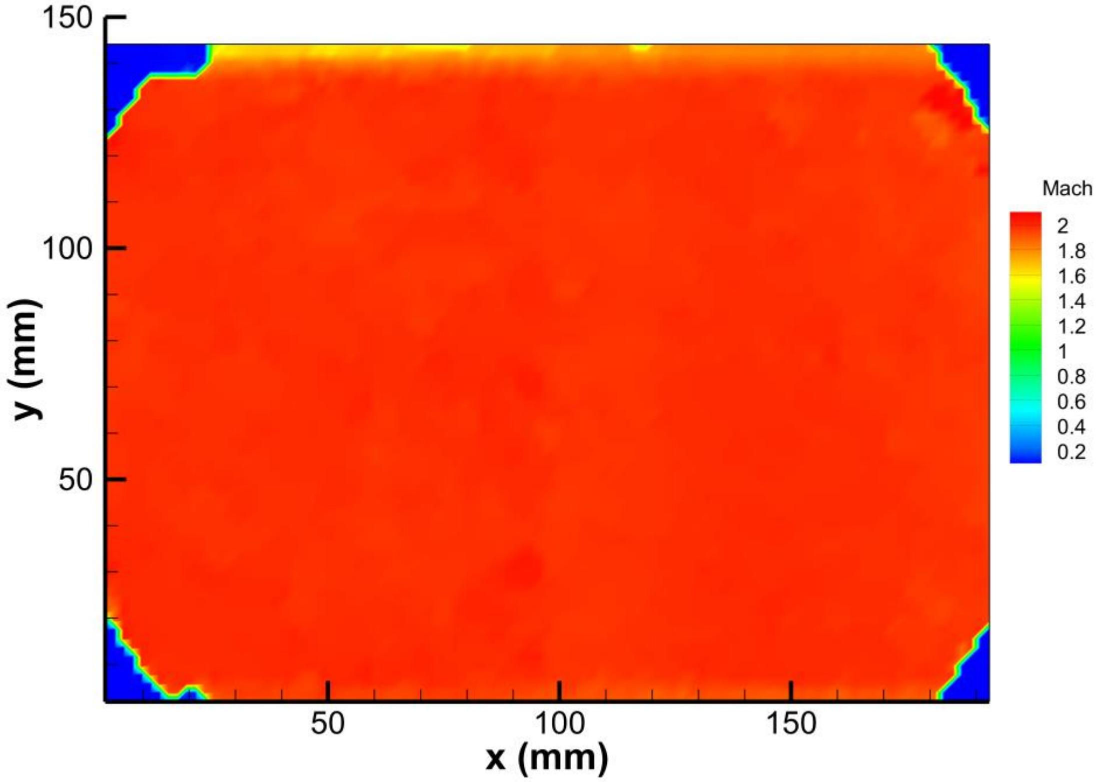


Figure 4: Example of background subtraction technique of Dynamic Studio;
a) raw image, b) same image after the subtraction process

Prior to model testing, a set of measurements is done on the empty test section. Mach contours, velocity contours, vector map and velocity profiles across the test section can be seen in Figs. 5 and 6, respectively.

a)



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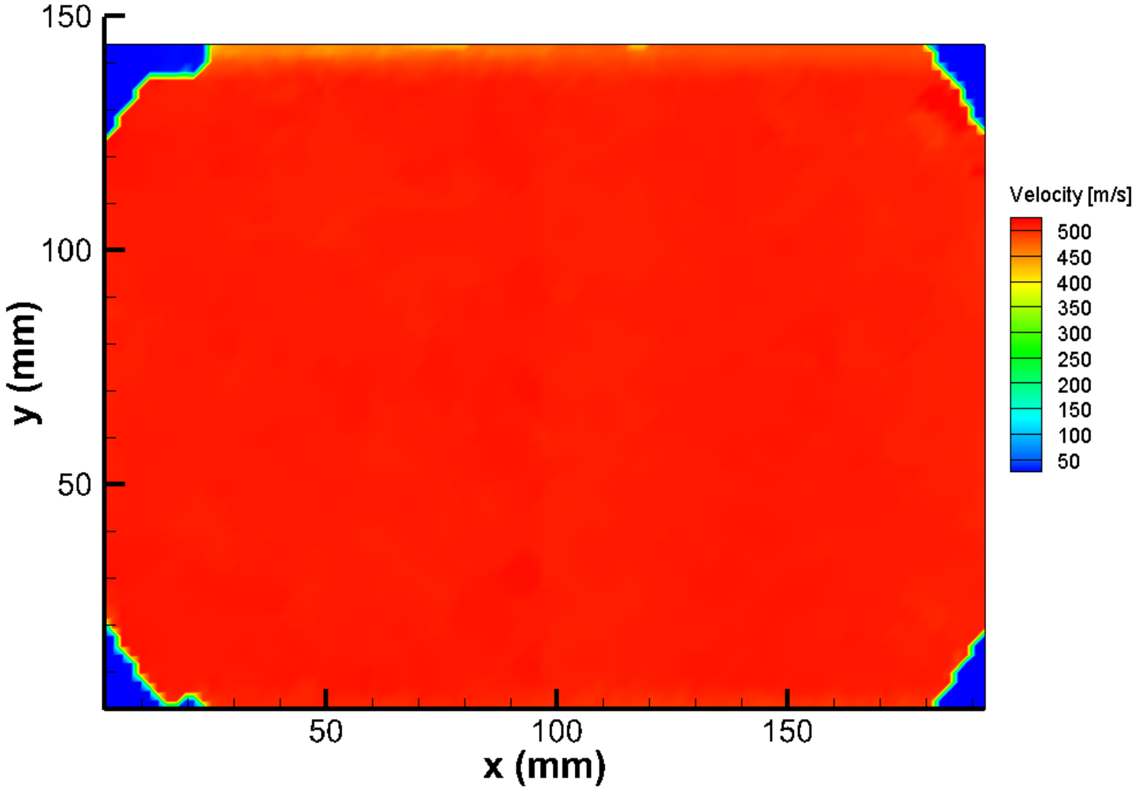

Figure 5: Results of PIV measurement of empty test section;
a) Mach contours, b) velocity contours.

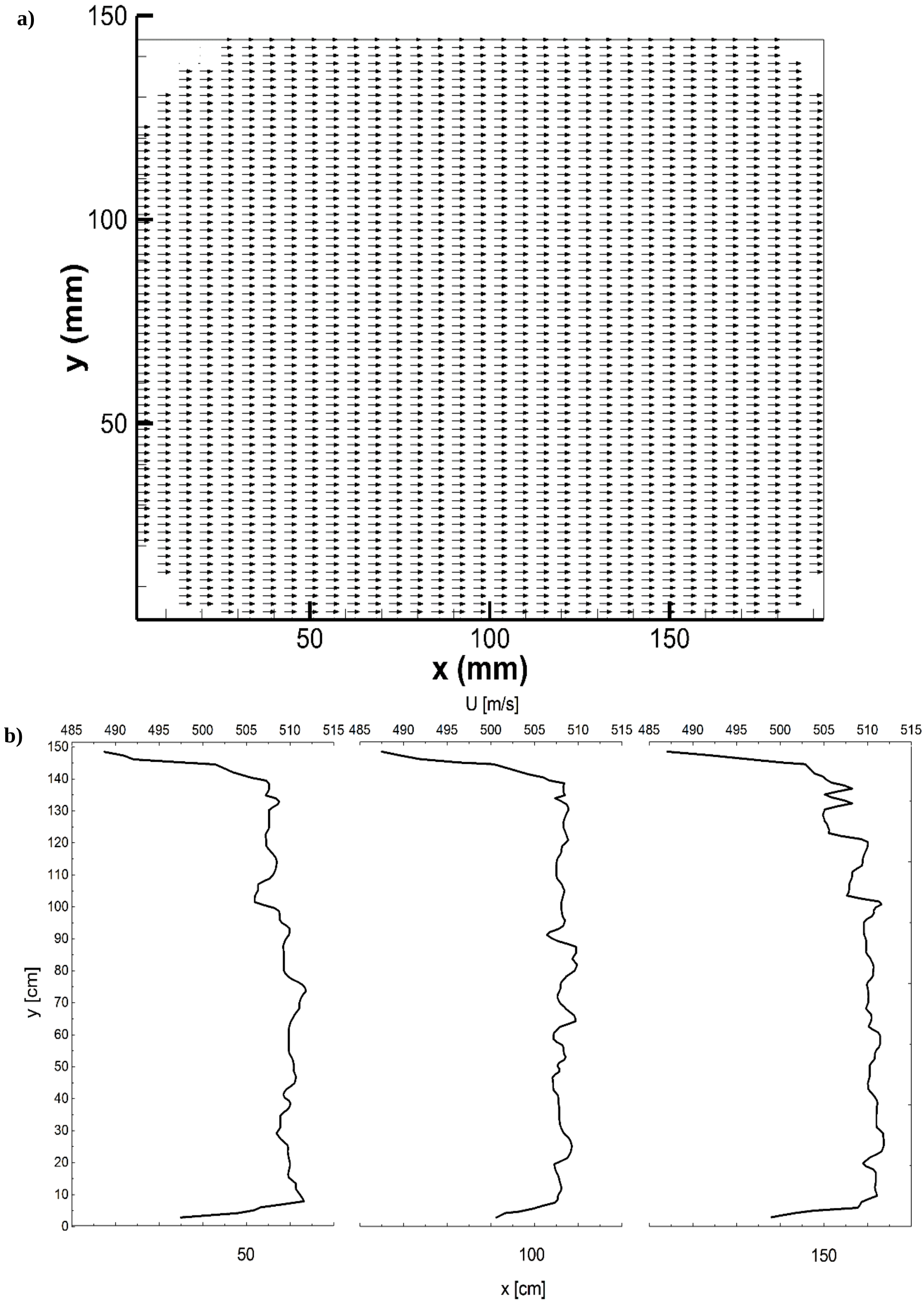

Figure 6: Results of PIV measurement of empty test section;
a) vector map, b) velocity profiles

A supersonic internal compression inlet model with a 12-degree ceiling ramp is tested at Mach 2 using the PIV system. The flow structure in the inlet model is also visualized by using schlieren visualization technique. The schlieren image is used for verifying the results of the PIV measurement. Results of the experiments are given in Fig. 7.

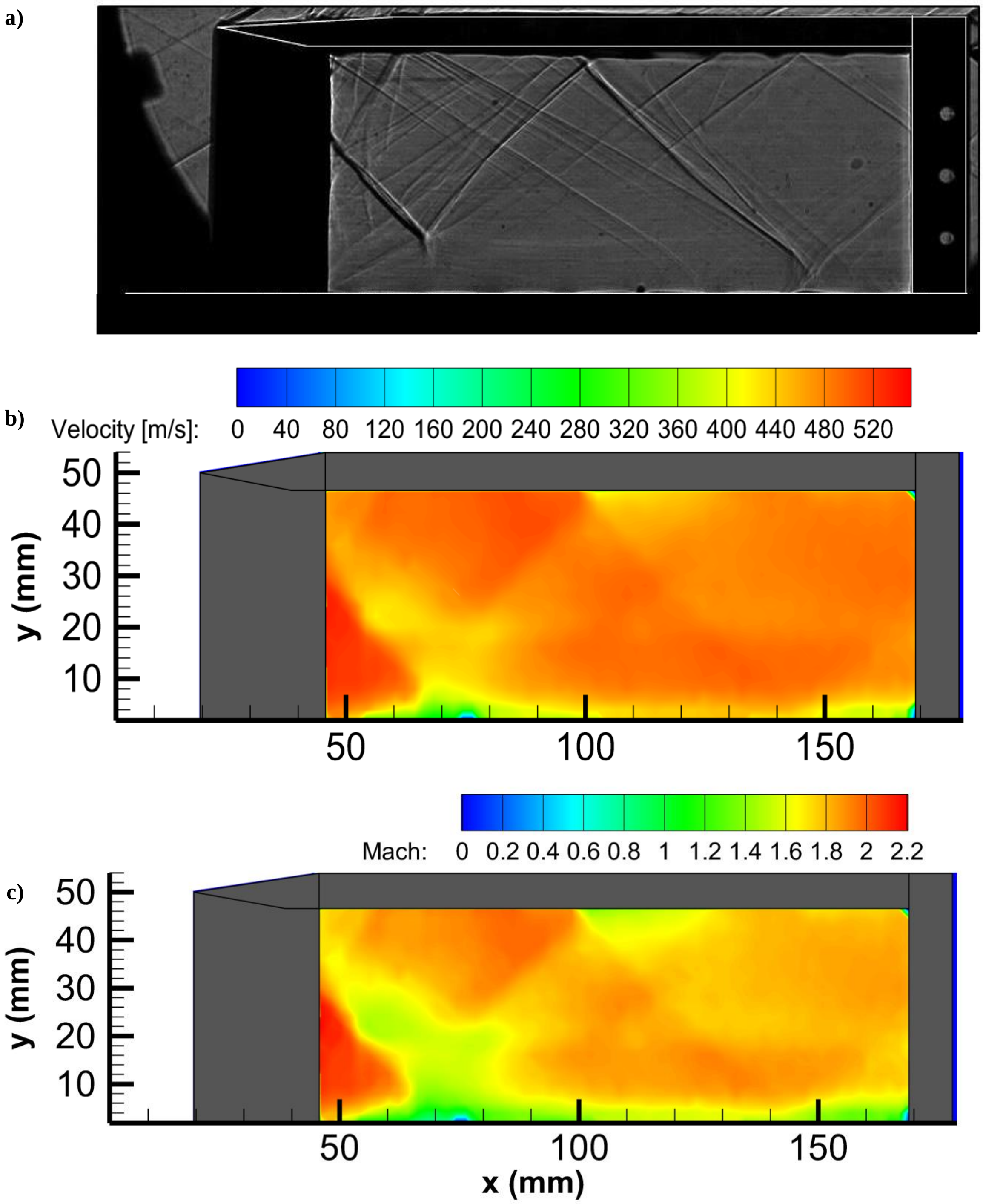

Figure 7: Comparison of PIV measurements with schlieren image:
a) Schlieren image, b) Velocity contour, c) Mach contour

The PIV measurement shows the boundary layer separation region induced by the oblique shock wave which is generated by the ceiling ramp. When the images are compared, there is a visible similarity in the shock structures as well as the locations of the interactions between oblique shocks and the boundary layer. In both images the locations of the points where oblique shock waves interact with the floor boundary layer are about at x = 65 mm and x = 145 mm. The location of the point where the reflected oblique wave interacts with the ceiling boundary layer is about at x = 100 mm. The agreement between the schlieren visualization and the PIV measurements shows that the results obtained in the PIV measurements are to be trusted.

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