PIV measurements of shock wave interaction in continuous operated supersonic wind tunnel

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Abstract A common prerequisite for successful development of aerospace systems is implementation of advanced numerical methods and experimental techniques for their validation and application for the cases which are beyond the capabilities of numerical methods. Particle-tracking based velocimetry techniques, such as PIV and PTV are promising in this sense as they are capable of providing high density quantative information about the flow. At the same time limited spatial resolution, particular experimental or image interrogation features can affect results. For the industrial-scale setups and supersonic flows experimental technique becomes even more sophisticated and interpretation of the retrieved data becomes even more challenging task.

An aim of the present work was to study performance of particle-tracking based planar velocity measurement techniques for the complex rarefied supersonic flow that includes relatively smooth velocity gradients, strong and weak shockwaves, and contact discontinuities. Such flow is of much interest as it incorporates different kind of spatial features and can clearly reveal advantages and weak spots of the measurement technique and interrogation approaches. Moreover, classical problem of Mach reflection of the conical shockwave from the axis of symmetry, that was chosen as the case for investigation, is still of scientific interest and lacks experimental, especially quantitative data. To provide more neat experiment preparations and subsequent data interpretation PIV experiments were supplemented by schlieren visualization and numerical simulation data. Particular features of the experimental technique, including hardware requirements, flow seeding and image quality for that case, image and data processing methods are considered and velocity measurement results are presented and analyzed in the paper

Keywords: PIV, supersonic flow, Mach reflection.

1 Introduction

To the present moment PIV is still not commonly used technique for investigations of supersonic flows, although quite large number of applied works and investigations related to the performance of PIV for supersonic flows are published.
A series of measurements in shock tunnels and shock tubes at Mach number 3.5-6 were performed in French-German Research Institute of Saint-Louis (ISL) [1, 2]. Large number of experiments was performed in wind tunnels of DLR and ONERA [3] wind tunnels. An overview on feasibility of PIV in supersonic flows is given in [4]. Thorough investigation of particle relaxation is performed by Scarano et al. In [5]. Many other aspects of PIV application for investigation of supersonic flows are also discussed in literature, see e.g. [6,7]
This and other works have demonstrated quite ambiguous results concerning applicability of PIV for supersonic flow studies. It was clearly proved, that in principle PIV can be applied for investigation of supersonic flows to retrieve unique information about the flow. However, depending on experimental conditions measurement results may contain bias errors, be more or less precise, and thus should be carefully interpreted.
In the present work an application of planar particle-tracking based technique for the investigation of rarified supersonic flow with an oblique shock wave reflection from the axis of symmetry is presented and analyzed.
Such flow configuration includes different kind of spatial features, such as shock wave fans, weak and strong discontinuities.
A problem of oblique shock wave reflection is one of the classical complex problems of gas dynamics, that has been studied theoretically and experimentally through the last century. Transition from Mach reflection to regular reflection, according to [8] should be interpreted as Mach reflection with exponentially

diminishing Mach stem. Regular reflection observed in experiments, from this point of view, is simply due to limited resolution of experimental techniques. This interpretation, well-founded from theoretical positions, is still becomes subject of scientific interest and the problem is adressed in publications [9], [10]. Series of experiments on shock wave reflection were earlier performed in TSNIImash [11] (see fig.1), and current work can be considered as a succsessor of the one mentioned above.

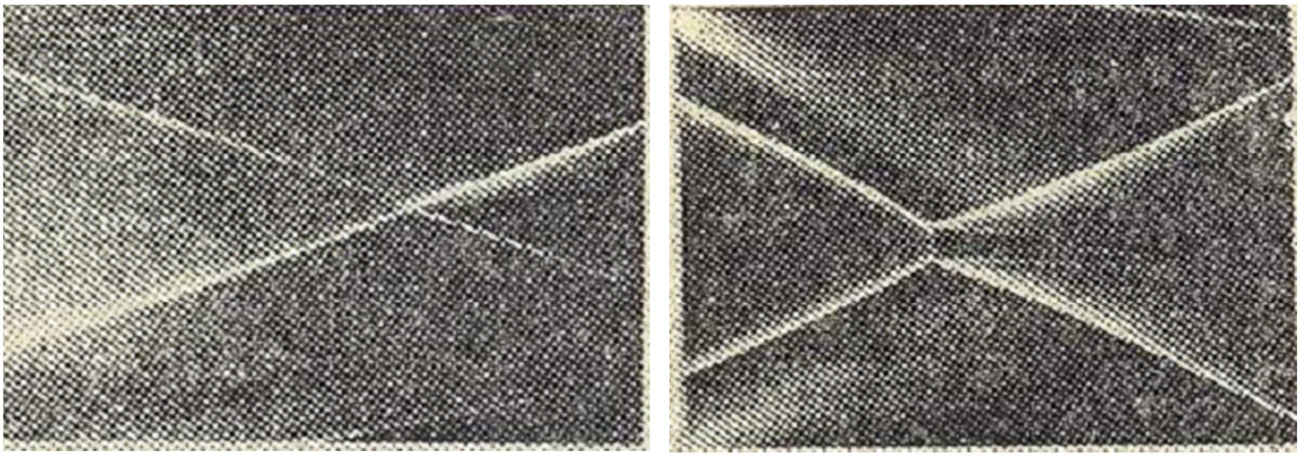

Fig. 1 Schlieren visualization for 5° (left) and 10° degree nozzles (right). After Krasilnikov A.V. [11].

2 Setup and equipment

Experiments were carried out in the TsNIIMash «U-4M» continuous operated supersonic wind tunnel at Mach number 4 [12]. «U-4M» is a continuous operated blowdown wind tunnel with variable density and test section dimensions of 0.6x0.6x2.8 m. The flow in the test section was highly rarified (≈0.01 bar), stagnation temperature of the flow was -5° C. Wind tunnels mass-flow rate was ≈ 7 kg/s, and volumetric flow rate was about 250 m3\s.
A converging oblique shock wave configuration was generated by axisymmetric conical «mock nozzles» of 5° and 10° cone angle (see fig. 2), introduced into the flow. In the flow under consideration a regular shock wave interaction was expected for the 5° angle and irregular (Mach) interaction for the 10° angle.
In order to assess the horizontal plane of symmetry a series of Schlieren visualizations for 5 – and 10 degree mock nozzles were carried out in vertical plane of view. Time-averaged Schlieren images of the shock-wave interaction area are shown in fig. 3. Schlieren visualization has shown a slight asymmetry of the flow and presence of the disturbance propagating from the mock nozzle holder. In both cases Mach shock wave reflection with generation of contact discontinuity was observed, though for 5° nozzle one was hardly detectable.

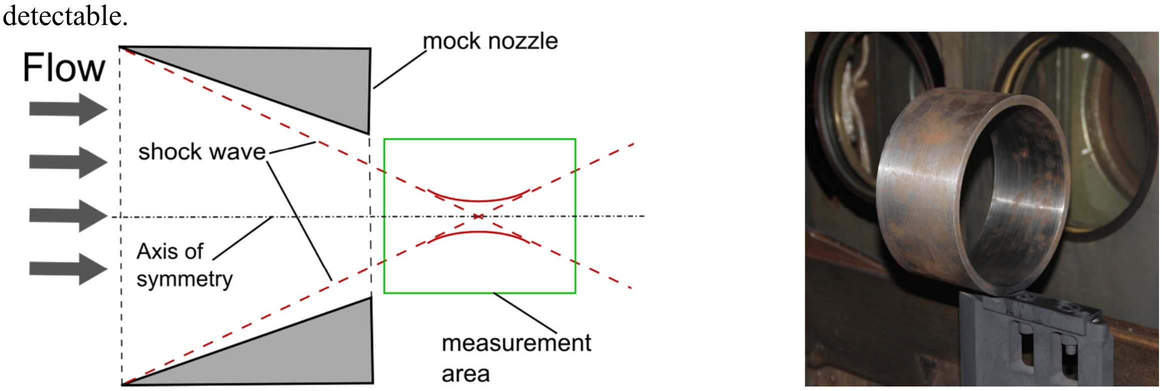

Fig. 2 – Scheme of the experiment (not to scale), mock nozzles with 10 degree angle.

In accordance to the results of Schlieren visualization laser light sheet was aligned to the horizontal plane of symmetry. Alignement precision was about 2 mm, and was mainly restricted by the precision of alignment stage together with long distance between laser and measurement area (≈ 1.5 m).

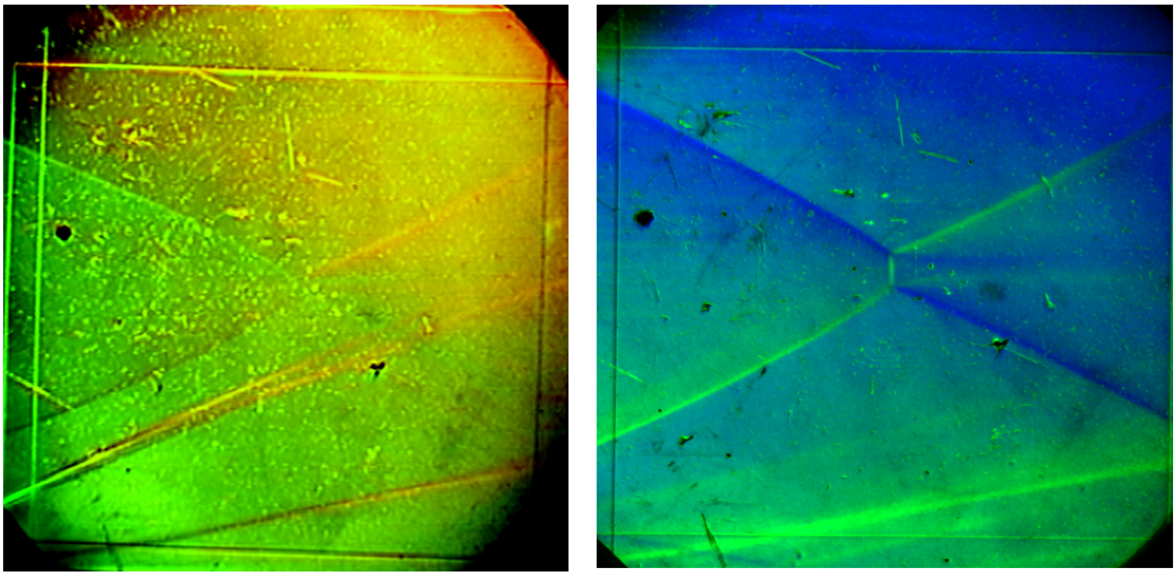

Fig. 3 Schlieren visualization for 5° (left) and 10° degree nozzles (right). Different color scheme due to changes in optical filter settigs.

PIV system included 380 mJ-per-pulse dual head Nd:YAG laser, CCD-camera, two seeding devices and synchronization unit (fig. 4.). Long-distance laser sheet optics was developed and used in experiments to form a light sheet at a large distance (up to 5 m.) from the laser head.

Two modified Laskin nozzle-based atomizers, each with 120 nozzles were employed to seed the flow with water-glycerol mixture tracers. Tracer particles were introduced into the flow thorough a single hollow tube with orifices, installed in a settling chamber. Such seeding scheme was employed, although it lacks effectivity, as the wind tunnel design didn't provide any special intakes for seeding and one of the probe inlets was used. No additional tracer distribution systems were allowed in this case, since they could lead to excessive flow cluttering and affect the flow. Moreover, bends and long tubes in this tracer transport system caused increase of hydraulic resistance, which, in turn, resulted in formation of liquid film that brakes into large droplets at the orifices and contaminates wind tunnel. To minimize this effect a special care was taken for keeping hydraulic resistance of the tracer transport system as low as possible. Eventually, it resulted in relatively poor seeding density, but seeding quality was still sufficient for further interrogation of images.

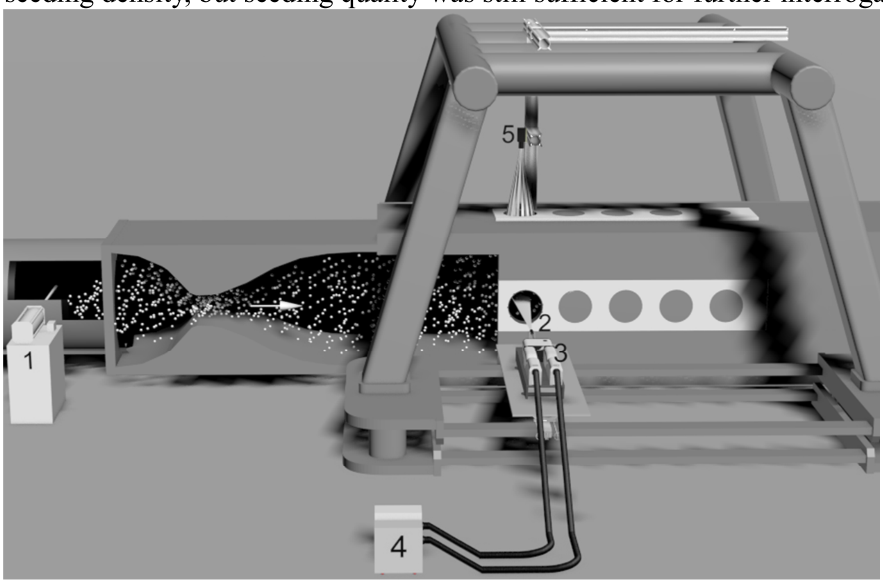

Fig. 4 Wind tunnel and PIV equipment. Tracer particle generator; 2- laser sheet; 3- laser head; 4- laser PSU; 5- CCD-camera.

3 Investigation methods

To assess an effect of optical magnification variation for each of the nozzles two subsequent experiments with different camera lenses but same flow parameters and laser sheet alignment were carried out. For both lenses aperture number was set to 2.8 (fully open aperture) as particle image intensity was quite low.
Images, acquired in experiments were interrogated using PIV crosscorrelation algorithms and relaxation PTV algorithm. Iterative cross correlation algorithm tended to yield a lot of spurious data (up to 50% in some of the images) due to nonuniform seeding. At the same time, due to the discontinuous nature of the flow, common algorithms for data validation, such as moving average or median validation, were hardly applicable for the case, as they suggest continiouty and 'smoothness' of velocity field. To exclude non-seeded areas form interrogation an adaptive sampling procedure was implemented. Sampling was based on particle detection algorithm, employed in PTV: vectors yielded from interrogation windows, that included less than threshold number of detected particles, were marked as false. Contrary to [13], no adaptive window size was applied.
Such interrogation scheme, that took advantage of PIV crosscorrelation, which usually provides more precise data, and PTV particle detection, which is more appropriate for nonuniform seeding, yielded most acceptable results.
To assess the obtained results quantitatively, numerical simulation of the shock-wave reflection for experimental flow conditions was performed. Flow was simulated without consideration for nonideality of the flow and effects introduced by the nozzle holder. k-ε turbulence model and high-order Godunov's numerical scheme were employed for simulation. Spatial distributions of physical values is presented in fig. 5 and 6.

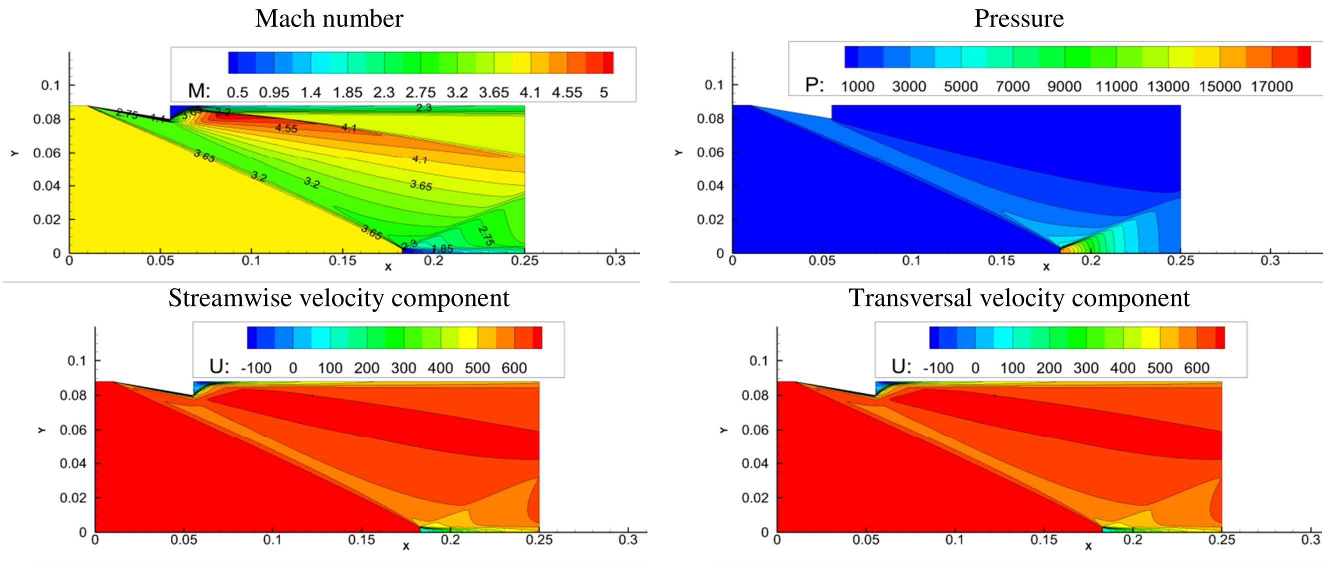

Fig 5. Numerical simulation of shock wave reflection area for 10° nozzle

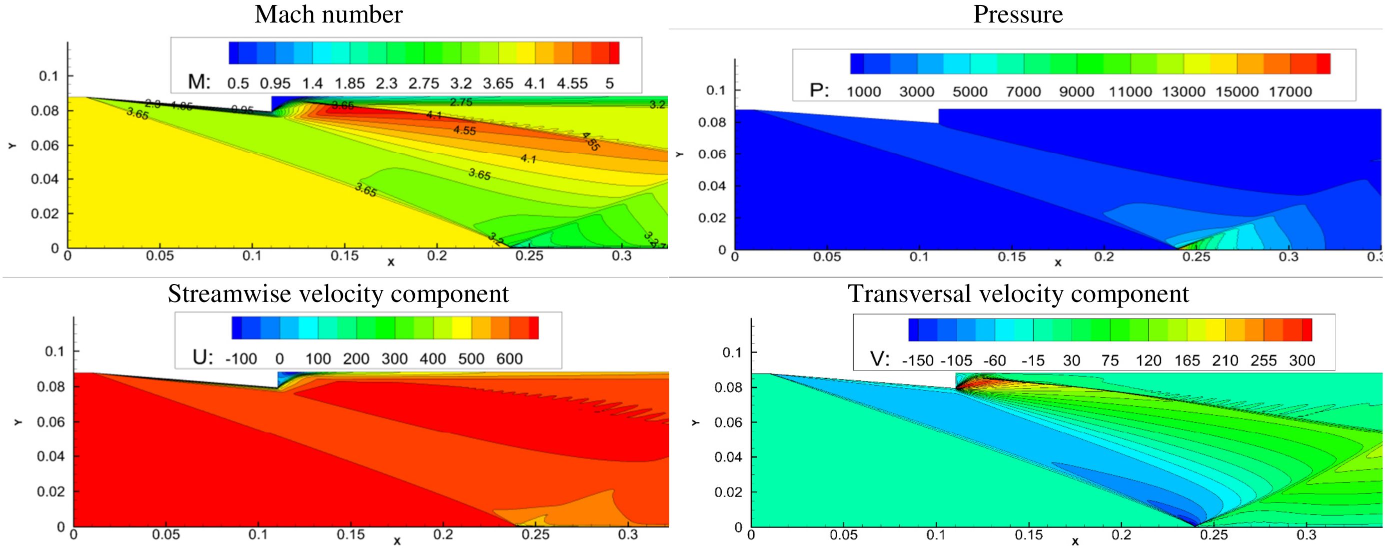

Fig 6. Numerical simulation of shock wave reflection area for 5° nozzle

4 Results and discussion

Velocity distributions for both mock nozzles were retrieved from particle images (fig. 7, 8). In case of 10° mock nozzle a distinct Mach reflection was, with clearly visible Mach stem and contact discontinuity downstream of it was observed. For the case of 5° a downstream contact discontinuity and mach stem were also detected, but, the size of mach stem was almost about the size of interrogation window (≈2 mm), and contact discontinuity showed smaller change of streamwise velocity than it was expected. According to the results of numerical simulation, transversal size of the contact discontinuity indeed amounts to ≈2 mm. Hence, spatial averaging over interrogation window and, what is more important, over the laser sheet thickness, might result in underestimation of the flow deceleration .

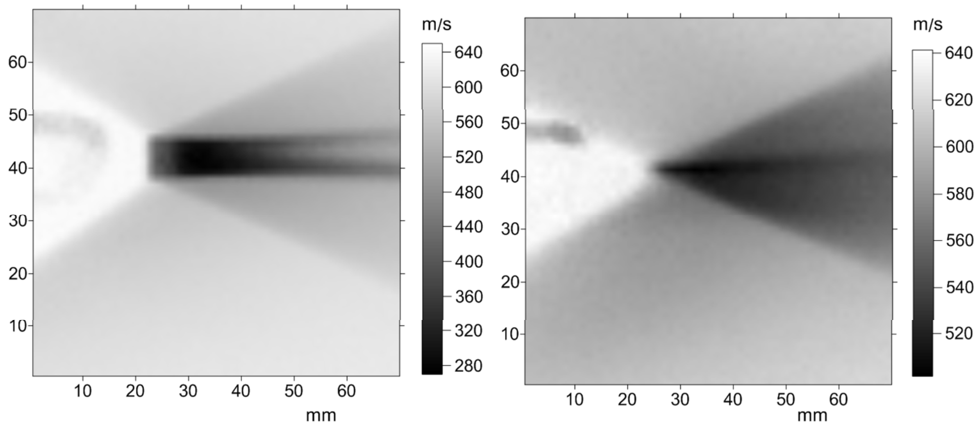

Fig. 7 Visulisation of streamwise velocity component distribution for 10° (left) and 5° degree (right) nozzles. R= 0.034 mm/pix.

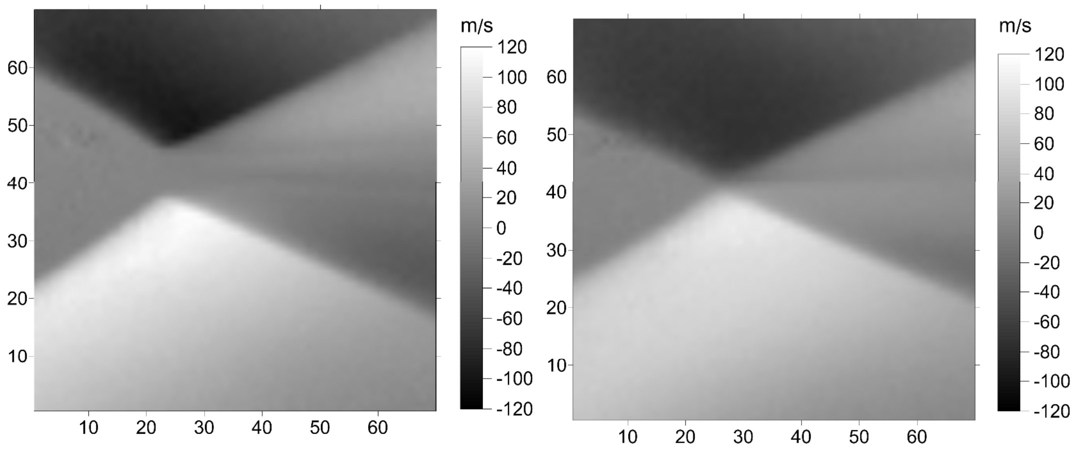

Fig. 8 Visulisation of transversal velocity component distribution for for 10° (left) and 5° degree nozzles (right). R= 0.034 mm/pix.

As for the different magnification factors (see fig 9), decrease of magnification from R=0.0695 mm/pix to R=0.034 mm/pix allows to achieve more clear visualisation of the reflection region and to get better resolution for the steep velocity gradient area, but, qualitatively, reveals no additional features in the flow.

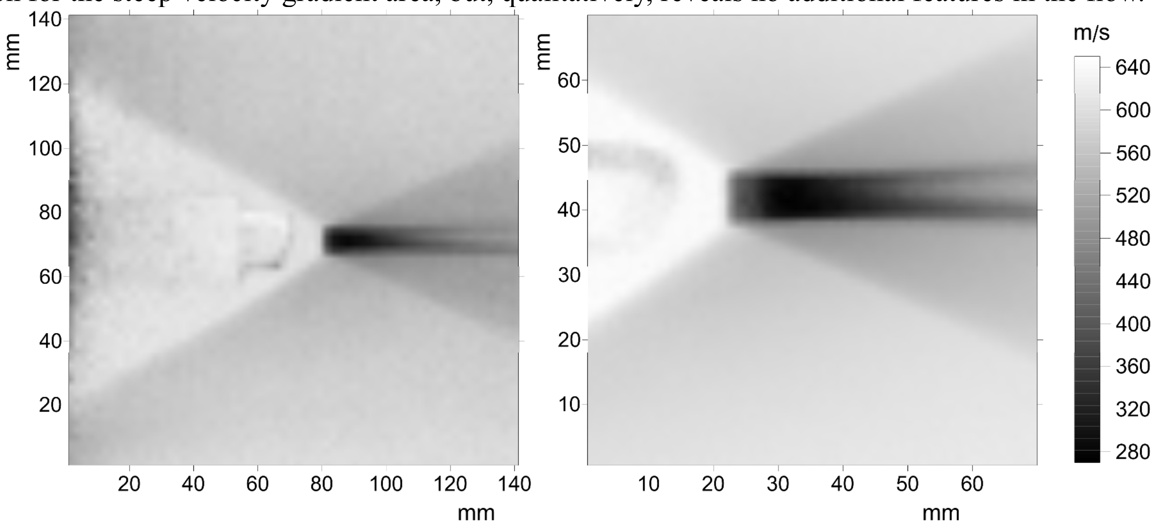

Fig. 9 Visulisation of streamwise velocity component distribution for different optical magnifications. R=0.0695 mm/pix (left), R= 0.034 mm/pix (right).

For the region distant from the shock wave reflection area, experimental data qualitatively conforms to the numerical simulation data. Some discrepancies (see profiles in fig. 10) are most likely, due to non-ideal flow conditions and mock-nozzle alignment. For the streamwise velocity profiles in the region of Mach stem strong disparities between numerical and experimental data can be observed . Minimum of the experimental data is shifted downstream from the Mach steam and minimum experimental velocity value is almost 100 m\s larger. Obviously, this is due to the particle velocity relaxation, which in this case introduces considerable error. Velocity profile bend can be interpreted here as the point, where gas and tracer particles velocity becomes equal. It can be seen, that particles don't follow the flow not only at the step deceleration, but also lag behind the gas at the acceleration area.

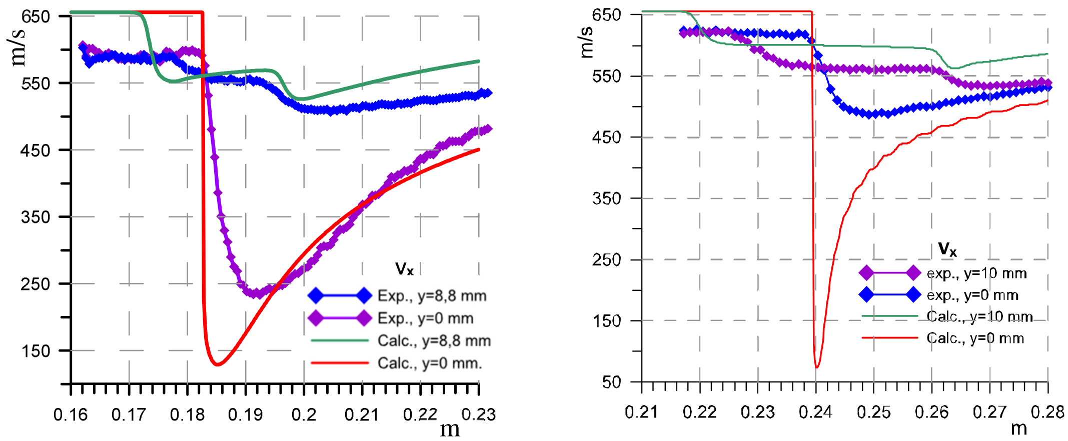

Fig. 10 Velocity profiles across mach stem and weak oblique shock for 10° (left) and 5° (right) nozzle

Currently a large number of approaches for particle velocity lag correction is presented. Advanced approaches of particle drag calculation usually take into account temperature, pressure and gas density variations [14, 15], while most simple suggest Stokes drag law for the spherical particle in gas flow and uniform temperature and density distribution over the measurement area. Nevertheless, all approaches rely on numerical calculation of velocity derivatives and demand precise knowledge of tracer size. As velocity data usually contains noise and tracers have nonuniform polydesperse distribution, this two components should inevitably contribute to the error in correction.

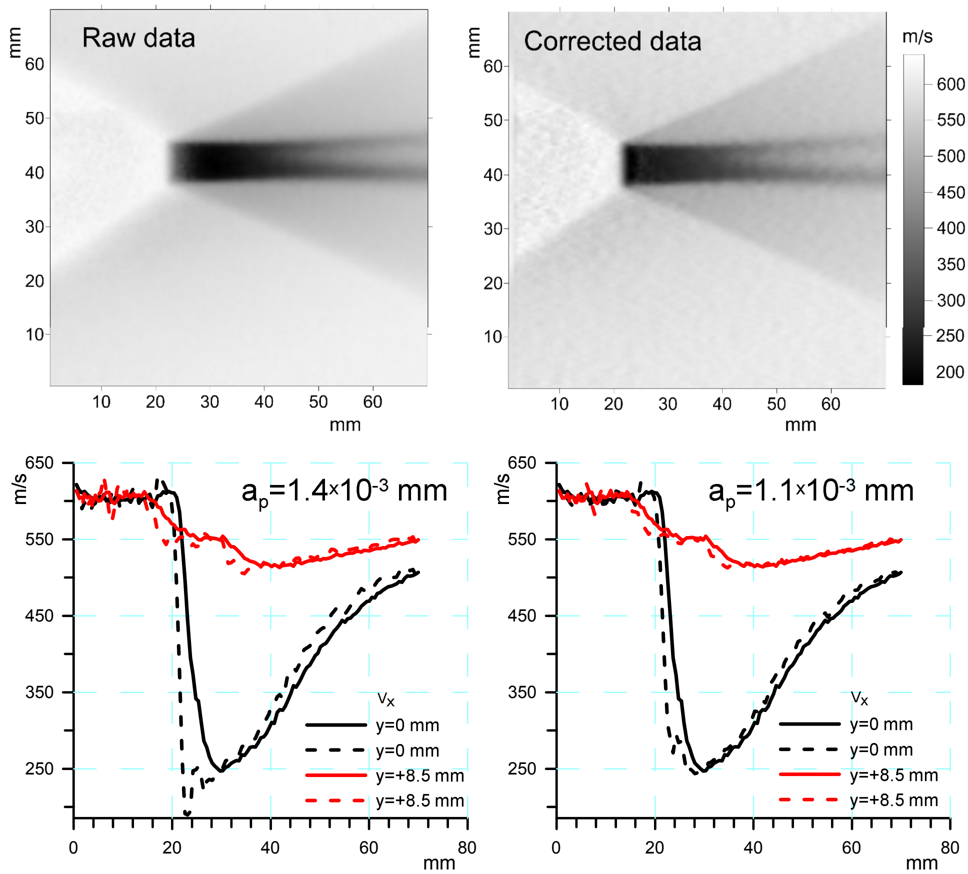

Fig. 11 Visulisation of streamwise velocity component distribution and profiles across different croosections for raw (solid line) and corrected (dashed line) data for 10° nozzle. R= 0.034 mm/pix, solid

To make at least a coarse estimation of bias error due to particle lag and to assess the performance of correction technique a simple correction method without consideration for pressure or temperature variations was applyied to the data. Results of te correction are presented in fig. 11. Correction, as expected, introduces substantial amount of noise to the data. Besides, a large disparity for particle size a_p=1.1 μm and a_p=1.4 μm can be observed. According to [16], size distribution of tracers generated by Laskin nozzle depends on many factors, including tempertaure, pressure drop, design features, level of liquid in atomizer etc. Generally speaking, it is almost impossible to derive one coefficient, so called "effective aerodynamic size" without particle sizing directly in experiment. Nevertheless, correction technique, as it can be seen from fig. 11, can provide substantial data improvment in terms of particle lag compensation if reasonable particle size is chosen for the correction.

Conclusion

Results obtained in the experiments have confirmed that particle-based velocity measurements are capable of delivering quantitative velocity distribution for supersonic flows with discontinuities and can faithfully represent the large-scale structure of the flow. Complex experimental data on the flow field in test section of the wind tunnel, including velocity distribution, flow nonuniformity and skewness was retrieved.
At the same time, as shock wave reflection experiments have revealed, small-scale features of the flow can be strongly distorted or even missed due to the lack of spatial resolution of the method, poor alignment, or, especially for rarified flows – to the dynamic characteristics of seeding particles. Also it worth mentioning that that due to the locality of measurements, particle-based techniques can be applied as a tool for advanced visualization of small-scale weak discontinuities.
Quantitative correction of the results in accordance to Basset equation might yield more proper gas velocity data at the shock wave front, but as it is extremely sensitive to particle velocity measurement uncertainty and tracer size variations, large uncertainty of the corrected data should be expected.

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