Experimental investigation of a high-speed jet velocity field by using optical methods

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Abstract

The necessity of experimental investigation of jet flows is caused by the practical applying of the jets in fuel-supply systems, ejection systems, oil and gas extraction plants and other facilities where mixing processes are important. The main questions which should be solved via further researches are the methods of mixing intensification at supersonic flow velocities and reduction of the noise generated by a high-speed flow. This paper presents the results of the experimental investigation of the flow structure in high-speed jet flows with the Schlieren-method, laser knife method and PIV-method.

1 Wind tunnel and methods of experimental investigation

Experiments were performed in a jet module of the periodical hypersonic wind tunnel T-326 in ITAM SB RAS. The design of the wind tunnel T-326 follows the direct-flow type [1].

In the work we used a convergent nozzle with the outlet radius Ra = 15 mm, M = 1.0. The pressure in the settling chamber of the jet module was maintained at such a level to satisfy the condition Npr = p0/pc = 5.0 (n = 2.64). Here p0 is the pressure in the settling chamber, pc is the pressure in the Eufel chamber. The PIV-system “Oxford Lasers PIV system DP3D” was used in the experiments.

Application of such common optical methods as the Schlieren-method and laser knife method is quite often in an aero-physical experiment. In modern investigations, however, the quantitative non-contact panoramic laser method PIV is one of the most attractive ways of the optical diagnostics. This method enables to obtain instantaneous and averaged velocity fields with high resolution in the studied cross section. Because of high velocity gradients, it is complicated to apply this method in high-speed supersonic flows.

In order to obtain the instantaneous velocity field, it is necessary to measure the displacement of particles in the laser knife plane within the specific time gap between two shots. Initial couples of photos produced by a digital photo camera are divided into segments. The particle shift is determined by dint of the cross-correlation analysis of two consecutive images. The physical principles of the method are presented in [2].

2 Discussion of experimental results and comparison with the numerical calculation

The calibration measurement was done in the velocity field for a subsonic axisymmetric jet flowing out from the profiled nozzle at Npr = 1.7, M = 0.9. Design flow velocity at the nozzle exit is Va = 286 m/s. On fig. 1 the isolines of the mean flow velocity distribution are presented.

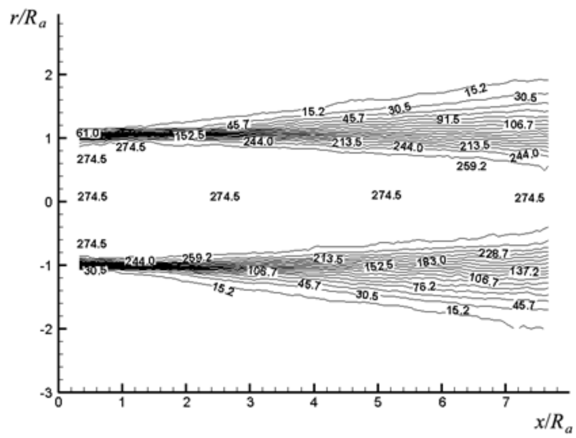

Figure 1: Mean velocity isolines for the transonic jet Ma = 0.9, Npr = 1.7 obtained by using PIV method.

Numbers indicate of the velocity values, m/s. On fig. 1 the potential jet core is shown (flow velocity is ≈ 278 m/s). The velocity of tracer particles agrees within 1

The distribution of the relative mean velocity in the initial part on the axis of the transonic jet Ma = 0.9, obtained by dint of the PIV-method, can be found in [1]. fig. 2 presents the radial velocity profiles in transversal cross sections of the jet x/Ra = 0.3, 2.0, 4.0, 6.0, 7.0. The radial profiles of the mean velocity look similar to the velocity distributions submerged jet [3].

Opposite to the subsonic jet, the supersonic jet [1] features a complex flow structure; the cell flow structure is visible: the first cell of the jet beginning, Mach disk, jet shear layer.

At the moment, the information about the shear layer is insufficient to reveal the flow pattern in supersonic flows, flow visualization with the ultra-short exposure permits registering nonuniformities (vortex forms) in the shear layers of the supersonic flows, which enables to explain qualitatively the structure and peculiarities of the flow in free axisymmetric jets.

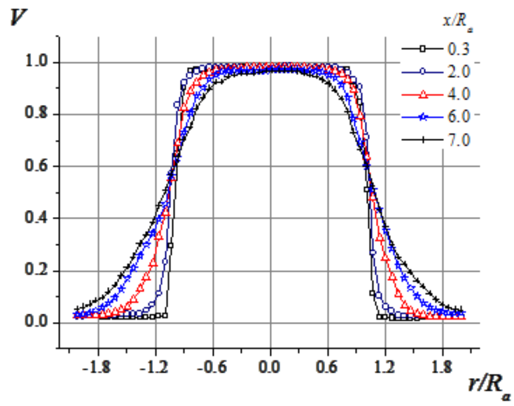

Figure 2: Distribution of the relative mean velocity in transversal cross sections of the subsonic jet Ma = 0.9.

Analysis of the instantaneous photos (exposure of 5 ns) shows that vortex forms occur and develop downstream in the shear layer formed behind the triple point (fig. 3). The Figure depicts the vortex forms which feature a dark central area; it is caused by the particles removal onto the external boundary of the vortex under the action of the centrifugal force. The transverse size of the shear layer formed behind the triple point, increases along with the distance from the nozzle cut. Then the shear layers merge downstream, and the flow turbulizes on the jet axis.

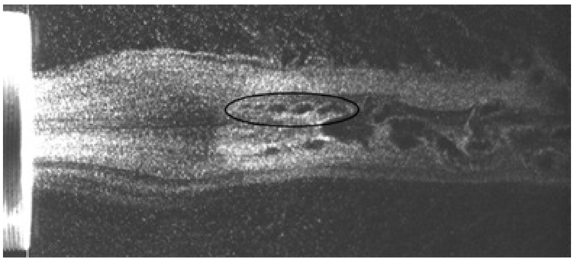

Figure 3: Visualization (laser knife) of the supersonic underexpanded jet Ma = 1.0, Npr = 5.0.

On fig. 4 the distribution for the relative mean flow velocity obtained in the beginning part of the flow by the PIV method for the supersonic underexpanded jet is shown. The cell structure of the supersonic jet is visible on the jet axis, as well as minimums and maximums of the velocity distribution. Alternating minimums and maximums in the figure designate the location of the first and second jet cells. The minimums correspond to cell boundaries. It is evident that the measured flow values may be either above or below the design values. This difference may result from the fact that the velocity of light-diffusing particles is lower at the section of flow acceleration ahead of the Mach disk, and after the Mach disk it is higher than the gas velocity (particles velocity relaxation), which predominantly appears in the areas of high velocity gradients. In the second jet cell, the maximum PIV-measured velocity turns out to be above the calculation (fig. 4).

The radial velocity profiles obtained by the PIV method and presented in fig. 5 correspond to the radial pressure profiles [1]. It is possible to distinguish the jet shear layer, its external and internal boundaries in the velocity profiles. It is important as namely at in the shear layer a mass transfer between jet gas and ambient air occurs.

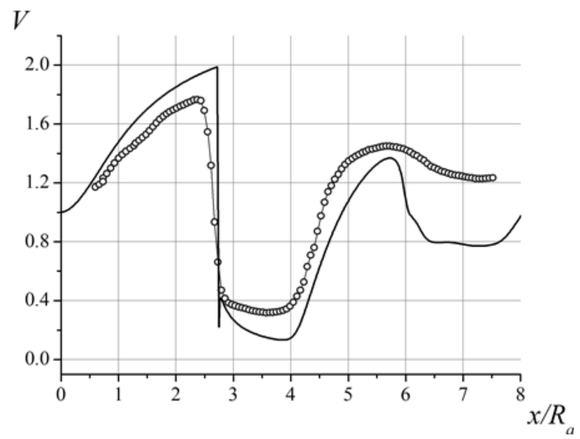

Figure 4: Distribution of the relative mean velocity along the jet axis Ma = 1.0, Npr= 5.0, symbols indicate the PIV data, solid line is the numerical calculation data.

The shear layer is an important characteristic of the gas-dynamic structure of the

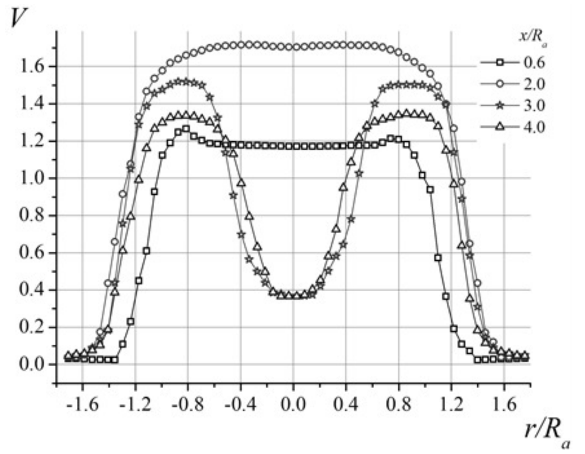

Figure 5: Transverse profiles of the relative mean velocity of the supersonic underexpanded jet.

supersonic jet. fig. 6 shows the dependence of the shear layer thickness on the relative longitudinal coordinate. The internal boundary of the jet (Ma = 0.9) was found from the velocity distribution fields as per 0.9*Va, the external boundary correlated with 0.1*Va [3]. It follows from Fig. 6 that the character of the dependence of the shear layer thickness is similar for the subsonic and supersonic jets and linearly depends on the longitudinal coordinate.

Fig. 7 presents the distributions of the relative mean velocity versus the dimensionless coordinate. For comparison, the graph also depicts well-known experimental results of other researchers [5], as well as the curve plotted by the Prandtl-Schlichting theory. Evident that the PIV-measured velocity profiles in the shear layer of the subsonic jet correlate with the velocity profiles obtained by the probe methods.

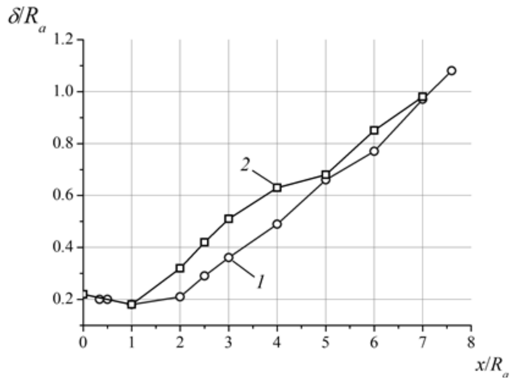

Figure 6: Relative thickness of the shear layer versus the longitudinal coordinate: 1 is the subsonic jet, 2 is the supersonic underexpanded jet [4].

It is known that the vortex-generating devices are applied to reduce the level of aerodynamic noise [6, 7, 8]. Chevrons present such a device; with them, the flow structure reconstructs, and the mixing intensifies. It is the topical task to study the gas-dynamic structure of the supersonic non-isobaric jet flowing out from the nozzle with chevrons of various geometries.

In the experiment we used a component with chevrons installed on the nozzle exit (see the photos and schematic in fig. 8). Six chevrons were installed at equal distances over

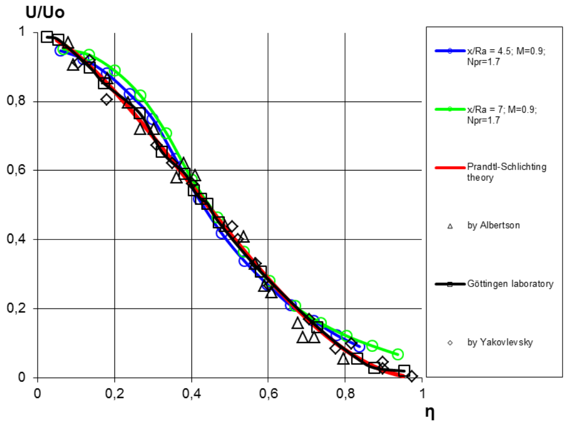

Figure 7: Distributions of the relative mean velocity in the transverse section of the shear layer in the subsonic jet.

the azimuth angle; they are trapezoidal, with the height of 10 mm and base of 7 and 4.5 mm. The internal surface of the chevron continues the internal nozzle surface.

Figure 8: Photos and schematic of the nozzle with six chevrons.

The velocity fields were measured in the supersonic jet flowing out from the nozzle with the chevrons. The profiles of the mean velocity in various flow sections for chevron orientation about the laser knife plane of $\phi = 30°$ are obtained (fig. 9). When comparing respective profiles, one can observe variations in the flow structure: the transverse size of the jet rises, and the subsonic area behind the Mach disk is absent.

3 Conclusion

The complex study was performed on the structure of supersonic non-isobaric jets by the Schlieren-method, laser-knife method, and non-contact panoramic method (PIV). This approach enables to clarify the detailed structure in complicated supersonic flows. Visualization of the jet flow by the laser-knife method with the small exposure permitted to find coherent vortex structures in compressible mixing layers which are associated with the Kelvin-Helmhotz hydrodynamic instability in the supersonic underexpanded jet.

Experimental velocity distributions obtained by the PIV method in the shear layer of the subsonic jet are in satisfactory agreement with the results of other researchers and with the known Prandtl-Schlichting theory.

Above experimental techniques are applied for the nozzle with chevrons. The performed experiments show that in the supersonic underexpanded jet flowing out from the nozzle with six chevrons, the level of velocity fluctuations in the Mach disk area decreases as compared to the experiments in the nozzle without vortex-generating devices. The

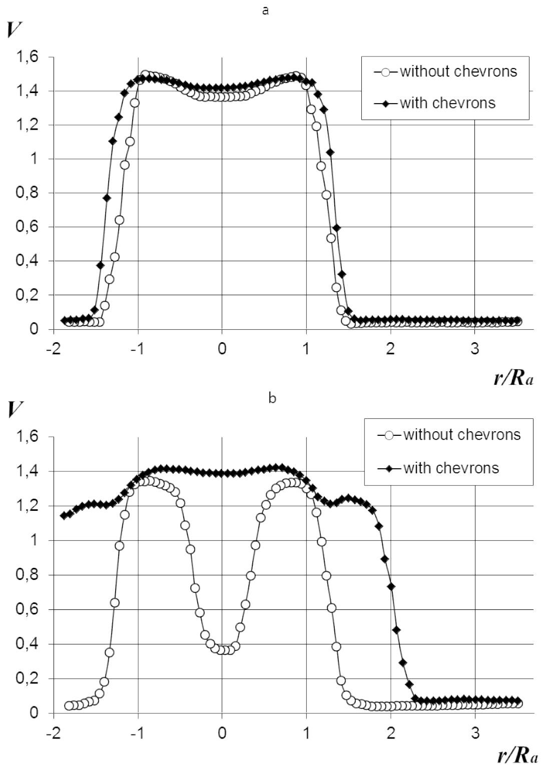

Figure 9: Comparison of the radial distributions of the mean velocity in two sections x/Ra = 1 (a), x/Ra = 4 (b), $\phi = 30°$.

considerable change in the flow structure and increase of the jet transverse sizes which is associated with the intensified mixing by the nozzle exit chevrons is founded.

Thus, the combination of the PIV-method and numerical calculation enables to gather information on the shock-wave structure of the flow: the spatial location of the Mach disk, to determine the supersonic jet boundaries, as well as to obtain the data for the distribution of the longitudinal and transverse flow velocity in the studied flow area. Presented experimental data can be used for verification of CFD calculation results.

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