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Simulation of the reentry vehicle supersonic brake jets interaction with landing surface

Anatoliy A. Dyad'kin[1], Valeriy P. Sukhorukov[1], Sergey P. Rybak[1], Valeriy I. Zapryagaev[2], Nikolay P. Kiselev[2], Sergey G. Kundasev[2], Alexander V. Sobolev[2], Dmitriy A. Gubanov[2]

1 KorolevEnergiya Rocket and Space Corporation,
141070 Korolev, Moskovskaya Oblast, Russia,

2 Khristianovich Institute of Theoretical and Applied Mechanics SB RAS,
630090 Novosibirsk, Russia

zapr@itam.nsc.ru

Abstract

Design of promising reentry vehicles admits a possibility of using multi-jet systems for vehicle deceleration near the landing surface. The paper describes the results of studying the flow structure of a model cold supersonic jet and a jet interacting with a flat obstacle. The free supersonic jet exhaustes from an axisymmetric nozzle with the exit Mach number M_a=3.5 or from an beveled nozzle with a rectangular throat. Schlieren pictures of the flow structure, radial distributions of the Pitot pressure, and fluctuations of the measured total pressure in characteristic cross sections of the jet are presented. The effects of the nozzle bevel and the nozzle throat shape (rectangular or cylindrical) on the gas-dynamic structure of the flow are analyzed. For the cases of jet interaction with normal and inclined obstacle, the distributions of the mean and dynamic pressures on the obstacle surface for different values of obstacle inclination and different distances between the nozzle exit and the obstacle are obtained. The flow structure of a supersonic radial jet arising due to jet - obstacle interaction is presented.

1. Introduction

Numerous investigations are performed for the purpose of development of new reentry vehicles with the use of multi-jet systems for effective deceleration near the landing surface. It is of interest to consider the flow structure and the results of experimental investigations of supersonic jets modeling decelerating gunpowder jets of a reentry vehicle. The flow structure and the results of experimental investigations of aerodynamic characteristics of reentry vehicles during their deceleration with the use of supersonic jets were presented in [1]. An important problem is the study of jet flow characteristics of the vehicle approaching the landing surface. It is necessary to determine the gas-dynamic and acoustic loads on the reentry vehicle body. In the case of interaction of supersonic nonisobaric jets of the braking system with the landing surface, secondary flows are formed between the reentry vehicle body and the landing surface; gas flows induced by jet-surface interaction may also arise. The study of the vortex flow structure and characteristics of fluctuations in the separation region formed due to interaction of supersonic jet flows with the obstacle is an important problem.

It is planned to dispose the nozzles of the braking system of the vehicle (eight nozzles aligned at an angle of 51.5 degrees to the vehicle axis) on the side surface of the vehicle; therefore, the problem is to study the flow structure in the supersonic jet exhausting from the obliquely cut (beveled) nozzle (Fig. 1.1). The braking system operation mode (momentum) is determined by the nozzle throat, which is assumed to have a rectangular shape. Therefore, a special study was performed to compare the structure of a supersonic jet exhausting from a nozzle with a rectangular throat to the jet exhausting from a usual nozzle with an axisymmetric throat.

The paper describes the vertical jet setup (VJS) based at ITAM SB RAS, the model, and the experimental equipment, as well as the results of studying the characteristics of a single supersonic free jet and its interaction with an inclined flat obstacle. The distributions of the measured total pressure, pressure fluctuations in the transverse direction, visualization of the free jet flow, and pressure distribution on the obstacle are reported.

a b

Fig. 1.1. Overall structure of the developed promising manned reentry vehicle (a) and experimental model (b)

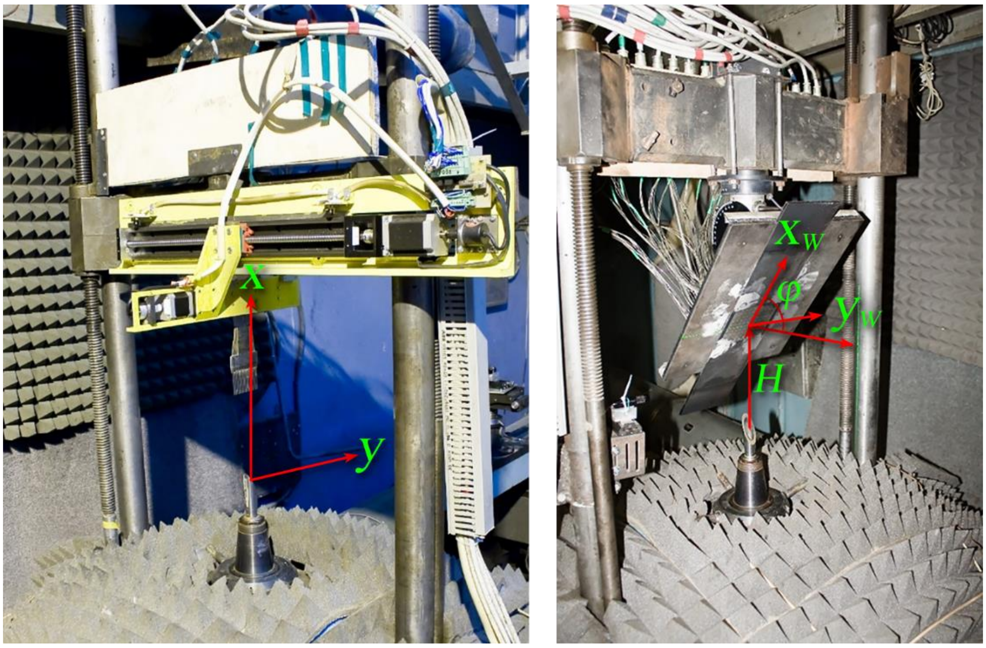
2. Experimental equipment

The experiments aimed at studying free and impact jets were performed in the vertical jet setup (VJS) based at ITAM SB RAS.

2.1. Experimental setup, models, methods

The VJS has a vertically aligned settling chamber with a system of mounting replaceable nozzles and a system for compressed air injection (up to 18 MPa). The cylindrical settling chamber with an inner diameter of 330 mm contains a honeycomb at the entrance and a grid for air flow damping.

Fig. 2.1,a shows the vertical jet setup with a beveled nozzle. A traversing gear with a Pitot pressure rake is used. The motion of this gear can be controlled by an external panel both directly near the nozzle and remotely from the VJS control panel.



a b

Fig. 2.1. Photograph and scheme of the VJS for measuring the Pitot pressure distribution in the free jet (a) and the pressure on the obstacle (b)

The automated data acquisition system allows one to control, and record the gas-dynamic parameters of the experiment, to perform probing tests of the flow by using a two-component traversing gear, and to change the distance between the nozzle and the obstacle [1]. The gas-dynamic parameters were measured by absolute pressure sensors with the measurements

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range of 0.1 MPa (pressure in the ambient space, P_e) and 16 MPa (pressure in the settling chamber, P_0). The temperature was measured by sensors located in the settling chamber and in the room where the setup was located. The pressure P_e was measured directly in the room at a distance of approximately four meters from the nozzle exit. The time interval between the measurements was 0.4 s. The signals from the sensors were recalculated to the corresponding quantities (pressure or temperature).

The pressure in the free jet was measured by a total pressure rake consisting of 21 probes. The distance between the neighboring probes was 3 mm. A data acquisition system and a two-component gear were used for measurements. The experiment arrangement is illustrated in Fig. 2.1,a.

The pressure fluctuations in the free jet flow were measured by a Pitot rake consisting four probes located with a step of 20 mm. The data were digitized by a TiePie differential analog-to-digital converter with a sampling frequency of 390.625 kHz/channel. Data processing included the fast Fourier transform (FTT) combined with the Bartlett smoothing (64 windows with 8192 samples each) and the calculation of the total levels.

The automated data acquisition system of the vertical jet setup was used for studying jet interaction with the obstacle. The experiment arrangement is illustrated in Fig. 2.1,b. The origin of the coordinate system corresponds to the point of intersection of the nozzle axis with the obstacle. A moving insert with pressure taps was moved along the obstacle the pressure taps were connected with the pressure probes through pneumatic pipelines. The flat obstacle model (see Fig. 2.1,b) has an insert that could be moved in the x direction; the insert had 90 pressure taps (field consisting of nine (along the x axis) rows with ten (along the y axis) holes with a step of 10 mm in both directions). The number of measurement points could be increased and the distance between then could be reduced by shifting the insert. The obstacle was mounted on the moving traversing gear, which made it possible to change the distance between the nozzle and the obstacle (height H/D). It was also possible to change the angle between the axis of the nozzle exit and the local vertical line of the obstacle φ.

The pressure in the free jet P_t and the static pressure on the obstacle P_w were measured by TDM-A high-accuracy absolute pressure transducers (produced in Zelenograd) with a range of 2.5 MPa. The pressure on the obstacle P_w was calculated as the difference between the pressure on the obstacle measured in the experiment and the mean pressure on the obstacle before and after the experiment. The dynamic pressure in the free jet and on the obstacle was measured by A-SENS piezo-resistive transducers of pressure fluctuations with a range of 0.63 MPa.

Model nozzles with the geometric Mach number at the nozzle exit M_a=3.5 were used in this work: axisymmetric nozzle and beveled nozzle with a rectangular throat modeling the ducts of vertical nozzles of landing engines of the braking system. The nozzle exit diameter was D=20 mm (Fig. 2.2). The cross-sectional areas of the nozzle throats were identical.

Fig. 2.2. Pairs of photographs of the axisymmetric nozzle (left) and beveled nozzle with a rectangular throat (right) in two projections

3. Supersonic free jet

Section 3 describes the experimental data on the gas-dynamic structure of supersonic free jets exhausting from the axisymmetric nozzle and from the beveled nozzle with a rectangular throat for the nozzle exit Mach number M_a= 3.5. These investigations were performed by a contactless method (schlieren visualization) and probing methods (with the use of the total pressure and Pitot pressure probes).

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3.1. Visualization

The flow in the region of the initial part of the supersonic jet exhausting from the axisymmetric and beveled nozzles was visualized in the plane of symmetry and in the plane perpendicular to it by an IAB-451 shadowgraph device and a digital CCD camera with a resolution of 1400×1000. Time-averaged (within the exposure time of 4 ms) schlieren pictures of supersonic jets were obtained. Typical schlieren pictures are presented in Fig.3.1,a, b, d.

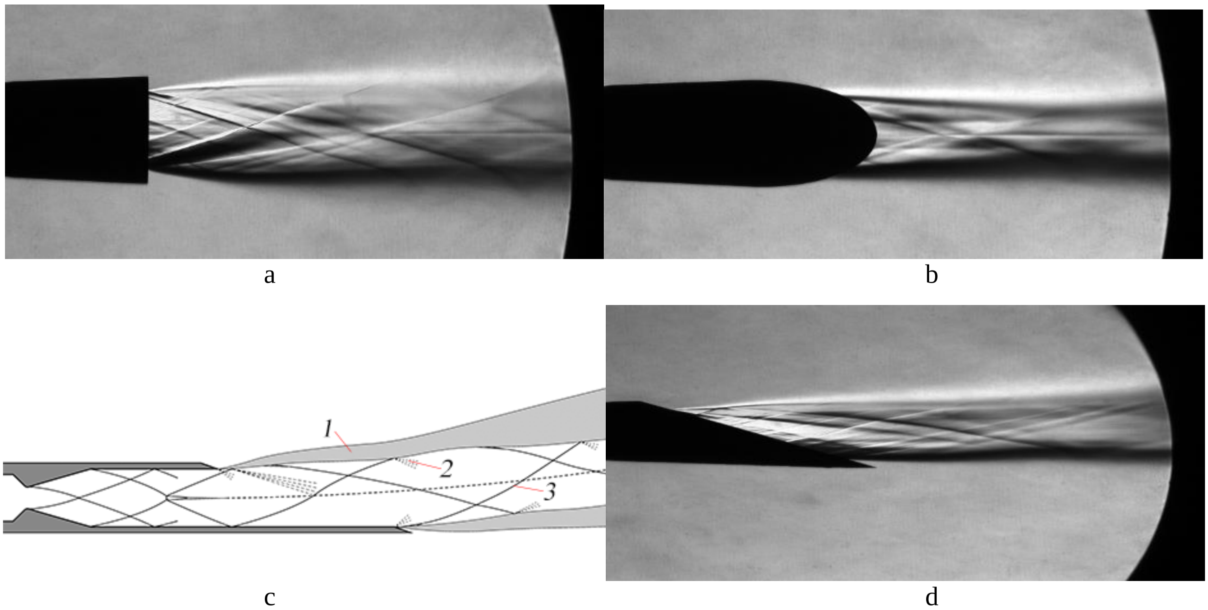

Fig. 3.1. Schlieren visualization of the jet exhausting from the axisymmetric nozzle (a) and beveled nozzle in two projections (b and d) and scheme of the jet in the beveled axisymmetric nozzle (c)
(*1* – mixing layers, *2* – expansion wave, *3* – shock waves)

It is seen that the jets exhausting from the beveled nozzle and from the axisymmetric nozzle form a complex three-dimensional shock wave pattern of the flow with a large number of shock waves. A simplified scheme of the flow in a supersonic jet issuing from the beveled axisymmetric nozzle and cylindrical part near nozzle exit (Fig. 3.1,c) is borrowed from [2]. The shock wave structure inside the nozzle is reconstructed from the results of numerical simulations performed in [2]. When the jet exhausts from the beveled axisymmetric nozzle, a nozzle shock is formed in the supersonic part of the nozzle (Fig. 3.1,c). In the jet considered in the present study, this shock is weak and does note exert any significant influence on flow evolution. In passing from the expanding to cylindrical part of the nozzle, a compression corner is formed, where the flow turns in the shock wave, which interacts with the opposite shock wave on the jet axis; as a result a normal shock (Mach disk) is formed. An internal mixing layer is developed from the contact discontinuity line formed by intersection of the shock waves. The shock wave emanating from the triple point is reflected from the external mixing layer in the form of an expansion fan and from the inner wall by a compression shock wave. It is seen from the figures that the jet is deflected by a small angle toward the external normal.

3.2. Pitot pressure distributions

For the axisymmetric and beveled nozzles, the pressure distributions (profiles) along the diameter of the supersonic free jet were measured by the Pitot tube in cross sections x/D=2–22.5 in a constant gas-dynamic regime $Npr=P_0/P_e$=91.5 (see Fig. 3.2). The Pitot pressure profiles were obtained in the symmetric plane of the beveled nozzle exit (see Fig. 3.1,d). The positive coordinate y/D is directed toward the deflection of the jet in the beveled nozzle from the axis of symmetry.
In the case of the axisymmetric nozzle, the radial profiles are symmetric with respect to the axis y/D=0.

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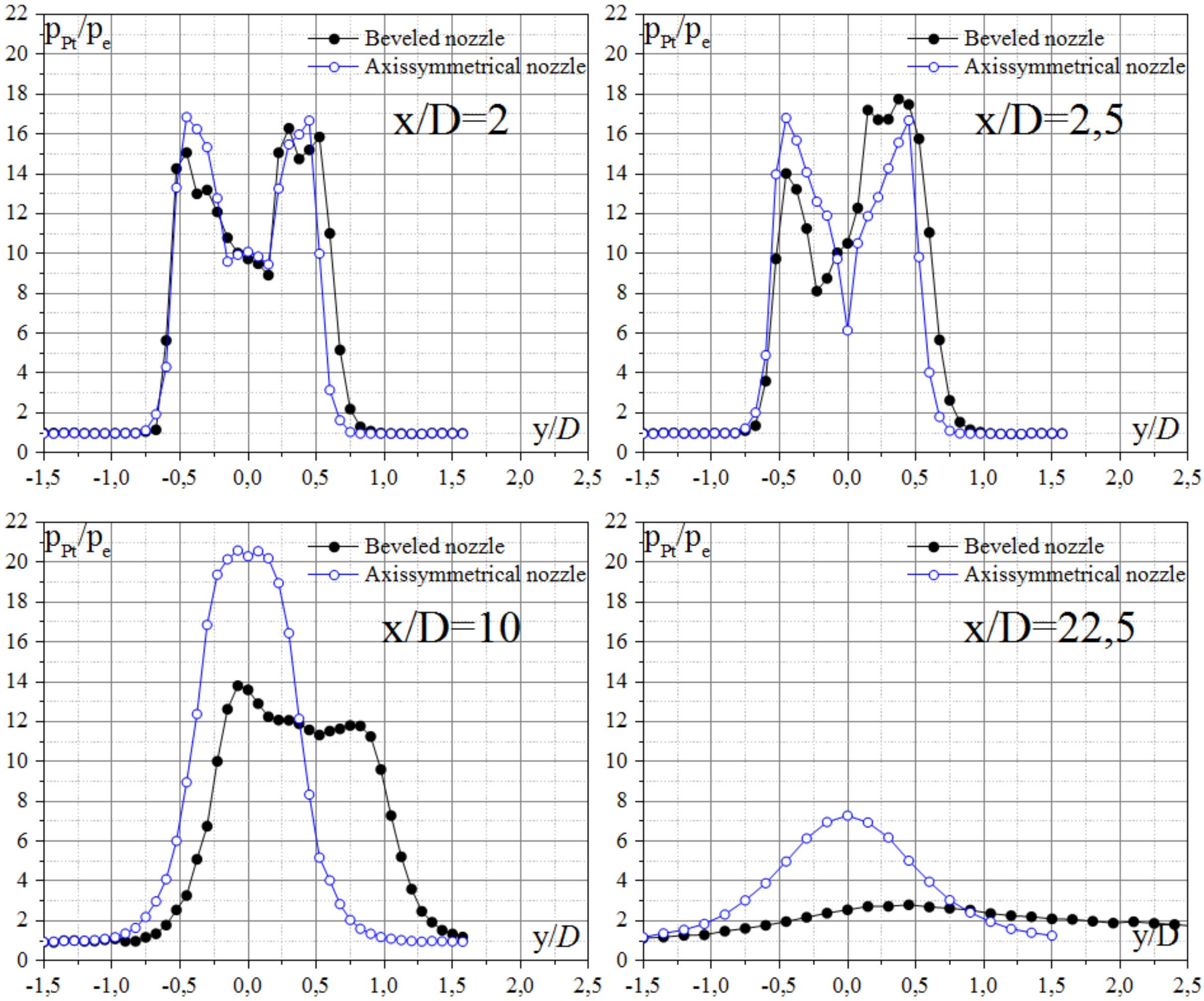

Fig. 3.2. Total pressure distributions measured in the cross section of the jet exhausting from the axisymmetric and beveled nozzles for different values of *x/D*

Near the nozzle exit section (*x/D*=2), the radial pressure profiles measured in the beveled and axisymmetric nozzle are only slightly different. The main differences are observed in the peak regions (*y/D*=±0.5) and in the mixing layer for positive values of *y/D*. The difference increases in the downstream direction (*x/D*=2.5), and an almost twofold difference is observed at *x/D*=10; the displacements of the jet toward positive values of *y/D* can be also noted. For the beveled nozzle, the central minimum is shifted toward the long edge of the nozzle at *x/D*=2.5. The local minimums in the cross sections *x/D*=2 and 2.5 inside the jet are caused by numerous oblique shock waves interacting with each other.
At a large distance from the nozzle exit (*x/D*=22.5), the jet exhausting from the beveled nozzle is more smoothed than the jet exhausting from the axisymmetric nozzle: the maximum pressure does not exceed 3, whereas the pressure in the axisymmetric jet reaches 7. Thus, the shape of the rectangular throat and oblique cutting of the nozzle significantly affect the gas-dynamic structure of the supersonic jet flow: additional shock waves are formed owing to the rectangular throat shape and the jet axis is deflected toward positive values of *y* owing to oblique cutting of the nozzle. As a result, the pressure distribution is asymmetric, and the total pressure loss reaches more than 100% as compared to the normally cut axisymmetric nozzle.

3.3. Pitot pressure fluctuations

Fig. 3.3,a shows the distributions of the total level of the pressure fluctuations on the geometric axis of the nozzles (coordinate y=0 mm) as functions of the distance *x/D*. It is found that the level of the pressure fluctuations in supersonic regions of the jet exhausting from the beveled nozzle monotonically decrease with increasing distance. For the axisymmetric nozzle, the behavior of the total level of the pressure fluctuations in the considered cross sections is nonmonotonic.

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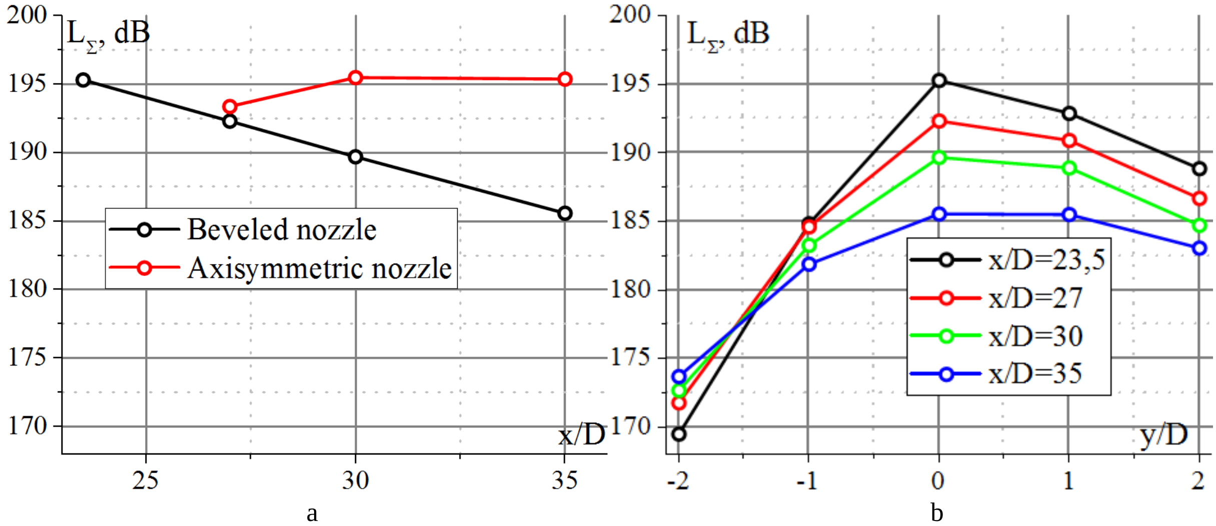

Fig. 3.3. Overall levels of pressure fluctuations on the height of mounting of the dynamic pressure transducer at the point y=0 mm (a); distribution of integral levels over the beveled nozzle cross sections (b)

The analysis of the distributions of the pressure fluctuations as functions of the distance *x/D* of dynamic pressure transducer mounting (Fig. 3.3,b) shows that the jet exhausting from the beveled nozzle is deflected toward the external normal to the exit cross section. For the axisymmetric nozzle, the profiles are almost symmetric. The maximum levels of these spectra are observed on the jet axis.

The amplitude spectra of the pressure fluctuations are uniform and monotonically decrease with increasing frequency for both nozzles. The high-frequency components in the spectra depends on the distance *x/D*. The decrease in the level of the pressure fluctuations in the jet core is approximately 25 dB at the height *x/D*=23 and 30 dB at *x/D*=30.

4. Jet interaction with the obstacle

Section 4 describes the experimental investigations of interaction of a supersonic jet exhausting from the beveled nozzle M_a= 3.5 at the regime with N_{pr}=91.5 with an inclined flat obstacle. Detailed measurements of the pressure and pressure fluctuations on the obstacle model surface for different heights and obstacle inclination angles were performed in order to determine the flow structure, degree of action, and size of the contact spot.

4.1. Visualization

Fig. 4.1 shows a typical instantaneous schlieren picture of interaction of a supersonic axisymmetric jet with M_a=3 and N_{pr}=21.4 with an inclined obstacle [3].

The supersonic jet exhausts from the nozzle, interacts with the obstacle, and spreads over the obstacle surface in the form of a radial supersonic expanding jet. The flow in the supersonic overexpanded jet exhausting from the nozzle has a complex shock wave structure; the formation of the shock wave near the nozzle edge is caused by the regime of jet overexpansion: a shock wave is formed to increase the pressure in the jet. In addition to the shock waves and mixing layers, one can see streamwise lines associated with streamwise Taylor-Goertler vortices formed in the mixing layer of the supersonic jet.

The supersonic flow passing through the oblique shock wave turns along the contact surface of the impinging jet and becomes accelerated, forming a supersonic expanding jet with the main elements, i.e., the hanging and reflected shock waves. As is seen in the schlieren picture, the expanding jet flow is directed along the inclined surface toward the obtuse angle between the obstacle surface and the jet axis, i.e., away from the nozzle exit. The figure shows the density fluctuations associated with self-sustained oscillations in the jet and also acoustic emission into the ambient space from the region of supersonic jet-obstacle interaction.

Intense waves induced by acoustic emission from the jet-obstacle interaction region and from the supersonic jet have different character, depending on their direction: away from the nozzle exit and toward the nozzle exit.

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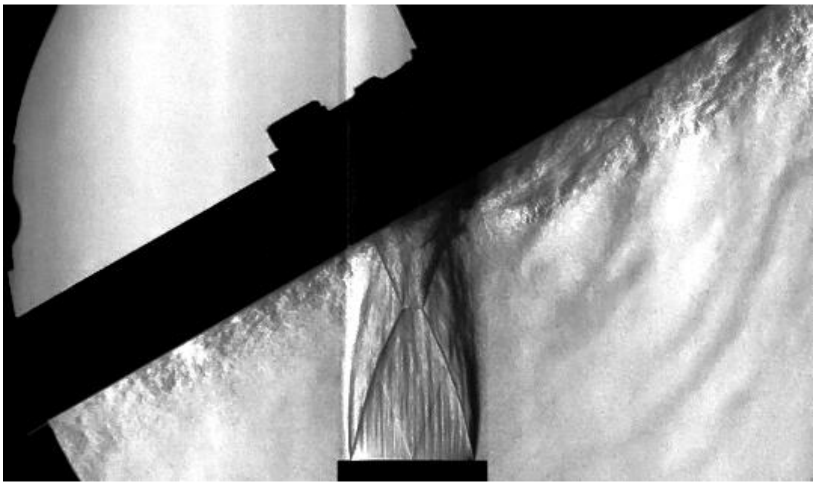

Fig. 4.1. Instantaneous schlieren picture of impingement of a supersonic axisymmetric jet with M_a=3 onto an inclined obstacle (φ=30° and H/D=2)

4.2. Pressure distribution

Fig. 4.2 shows the measured pressure distributions on the obstacle for the case of impingement of the jet from the beveled nozzle with the rectangular throat (see Fig. 2.2,b) for N_{pr}=91.5, heights H/D= 11,8. 15.7, and 23.5, and two angles of inclination of the obstacle φ= 0° and 50.5°. The contact spot has an elliptical shape caused by the nozzle exit geometry. A pressure peak is formed at the spot center (line y_w/D=-0.25). With distance from the obstacle surface, the measured pressure $\Delta P_w/P_e$, ($\Delta P_w = P_w - P_e$) with $\Delta P_w/P_e$= 12.0 at the height H/D= 11.8 significantly decreases to 1.9 at the height of 23.5 calibers, and the contact spot diameter increases.
When the jet interacts with an inclined obstacle (Fig. 4.2,d), pressure redistribution occurs because the obstacle moves away from the short exit part of the nozzle and approaches the long part of the nozzle in the case of a negative value of y_w/D. The amplitude of the action decreases at the center because the nozzle moves farther as the angle of inclination is changed.
The total levels of the pressure fluctuations in the free jet flow at a distance of 23.5 calibers are greater approximately by 2 dB on the geometric axis of the jet than on the normal obstacle, but approximately 1 dB smaller for y_w/D=±1. For 30 calibers, the total levels are identical for y_w/D=0 and ±1; at the point y_w/D=2, the fluctuations in the free jet are smaller approximately by 2 dB.

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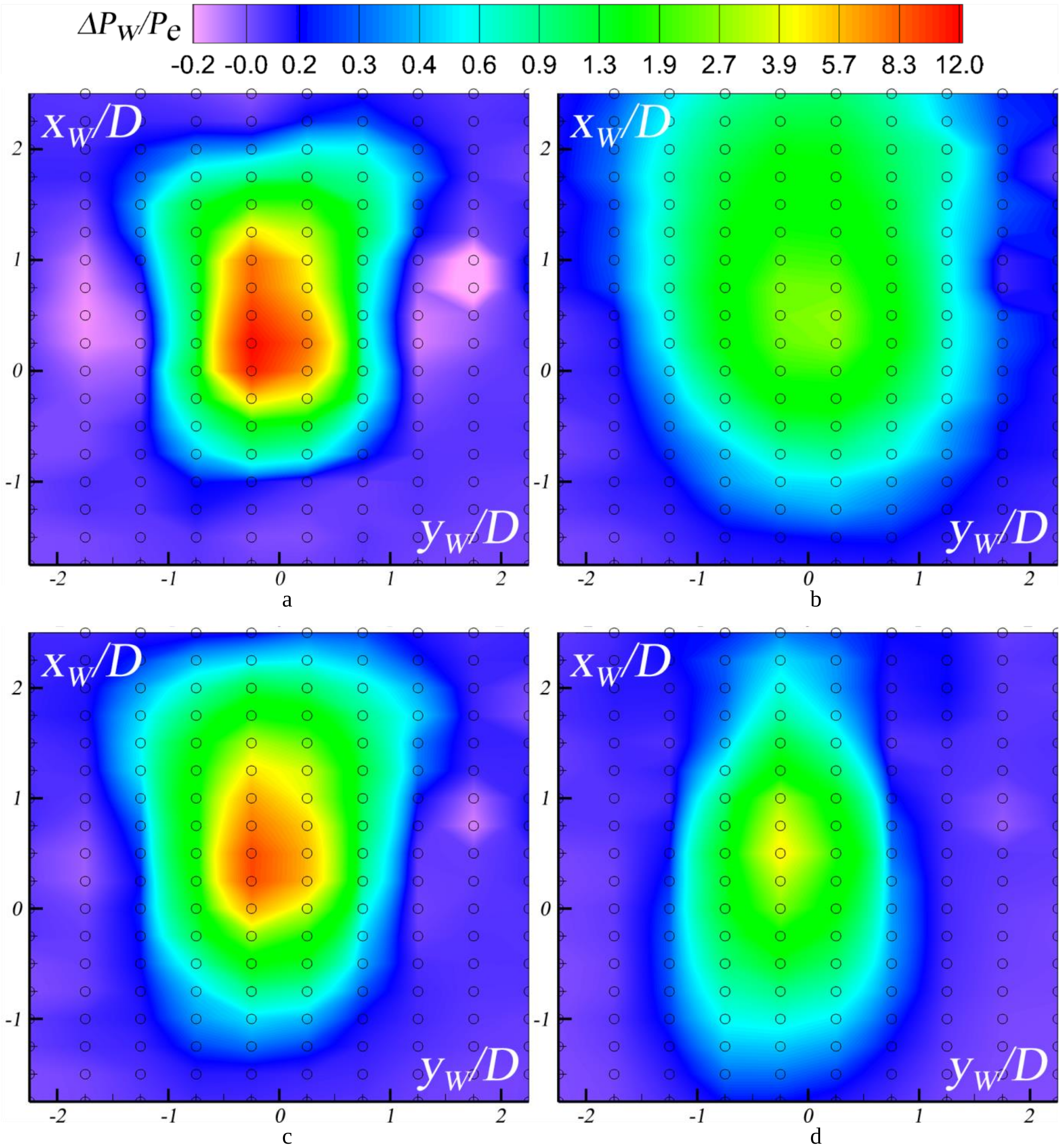

Fig. 4.2. Pressure distribution on the obstacle for φ=0°, a) *H/D*=11.8, b) *H/D*=23.5
and for *H/D*=15.7, c) φ=0°, d) φ=50.5°

5. Conclusions

The characteristics of a single free jets flow with M_a=3.5 are exhausted from a beveled nozzle with a rectangular throat and its interaction with an inclined flat obstacle are studied. Distributions of the measured total pressure and pressure fluctuations, visualization of the free jet flow, and also pressure distributions on the obstacle for different angles of inclination and distances between the nozzle and the obstacle are presented. The influence of the beveled shape of the nozzle and of the rectangular shape of the nozzle throat as compared to the jet issuing from an axisymmetric nozzle is observed.

It is found that there are only minor differences in the jet profiles near the nozzle exit cross sections. However, further downstream, the jet from the beveled nozzle is deflected toward the external normal of the nozzle exit plane. The total pressure in the jet exhausted from the beveled nozzle decreases appreciably faster.

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At distances greater than 20*D*, the total level of the pressure fluctuations in the jet exhausting from the beveled nozzle monotonically decreases with distance, whereas the corresponding behavior in the axisymmetric jet has a nonmonotonic character. The radial distribution of the total level of the pressure fluctuations on the side of the external normal has a peak in the case of the beveled nozzle, whereas the profiles for the axisymmetric nozzle are symmetric. The maximum levels of the measured total pressure fluctuations are observed near the geometric axis of the nozzle.

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