Investigation of supersonic jets shock-wave structure

Cite as: AIP Conference Proceedings **1893**, 030058 (2017); https://doi.org/10.1063/1.5007516
Published Online: 26 October 2017

V. I. Zapryagaev, D. A. Gubanov, I. N. Kavun, et al.

Investigation of Supersonic Jets Shock-Wave Structure

V.I. Zapryagaev[1, a)], D.A. Gubanov[1], I.N. Kavun[1], N.P. Kiselev[1], S.G. Kundasev[1] and A.A. Pivovarov[1]

[1]*Khristianovich Institute of Theoretical and Applied Physics SB RAS, 630090 Novosibirsk, Russia*

[a)]Corresponding author: zapr@itam.nsc.ru

Abstract. The paper presents an experimental studies overview of the free supersonic jet flow structure $M_a = 1.0$, $N_{pr} = 5$, exhausting from a convergent profiled nozzle into a ambient space. Also was observed the jets in the presence of artificial streamwise vortices created by chevrons and microjets located on the nozzle exit. The technique of experimental investigation, schlieren-photographs and schemes of supersonic jets, and Pitot pressure distributions, are presented. A significant effect of vortex generators on the shock-wave structure of the flow is shown.

INTRODUCTION

The practical need to study high-speed gas jets, including supersonic jet streams, is caused by the use of such flows in aerospace engineering and in various technological devices. Exhaust of supersonic jets is accompanied by a high level of force, heat and pulsation loads that arise when supersonic flow interacts with an obstacle, as well as a high level of acoustic noise emission into the ambient space. In the case of interaction of a jet with an obstacle, self-oscillatory regimes accompanied by high-intensity noise generation.

The use of computational modeling to solve aerodynamics and gas dynamics problems concerning advanced aerospace vehicles requires the verification of computational schemes and the validation of the results of numerical calculations obtained using software packages. The latter results in requirement in experimental data with the most detailed description of the flow structure, visualization results and experimental conditions. In this paper methods of complex diagnostics of supersonic jet streams, including flow visualization, probe and nonintrusive measurements of mean and pulsating values of flow parameters, automated data acquisition system are presented. New data on the investigation of high-speed jet flows are presented. The question of the features of simulation of supersonic jets is discussed.

SUPERSONIC NONISOBARIC FREE JET

A supersonic non-isobaric jet is formed when pressure P_a on the nozzle exit differs from the ambient pressure P_h. Different cases of the exhausting into the gas environment can be realized. Depending on the ratio of the nozzle exit pressure Pa to the ambient pressure P_h, called flow off-design ratio of the supersonic jet $n_p = P_a/P_h$ It is customary to call the jet outflow regime with overexpansion, under the condition $n_p <1$, the jet is called underexpanded if $n_p> 1$, and for $n_p = 1$ designed regime of the jet exhausting [1].

Hypersonic Wind Tunnel T-326 ITAM SB RAS

Investigation of the structure of supersonic non-isobaric jets were carried out using a jet module of a hypersonic aerodynamicblow down wind tunnel T-326 ITAM SB RAS. The settling chamber of the jet module is a pipe with an internal diameter of 113 mm and has a seat for the installation of replaceable nozzles. The jet exhausts into the test

Proceedings of the XXV Conference on High-Energy Processes in Condensed Matter (HEPCM 2017)
AIP Conf. Proc. 1893, 030058-1–030058-6; https://doi.org/10.1063/1.5007516
Published by AIP Publishing. 978-0-7354-1578-2/$30.00

chamber with dimensions of 1.3×0.87×0.93 m^3. The supersonic jet exhausts into the test chamber and then flows to the exhaust diffusor to an ambient space.

The traversing gear, fixed in the test chamber above the nozzle, was used to move the pylon with the Pitot tube (Figure 1.1) in three coordinates - X, Y, Z in automatic mode. The range of movement is 200×200×200 mm^3. The position accuracy is not worse than 20 µm. In the experiment, when probing the flow, a Pitot tube with an outer diameter of 0.6 mm was used. To measure the pressure, high-precision pressure transducers were used with a measuring range from 0 to 0.6 MPa and a measurement accuracy of 0.1%. The accuracy of maintaining the pressure in the settling chamber was 0.4%.

FIGURE 1.1 Photo of the test chamber of the jet module of the wind tunnel T-326 ITAM SB RAS

Nozzle with a designed Mach number at the exit Ma = 1.0 was used. The contour of the subsonic part of the nozzle is calculated by using of the Vitoshinsky formula for realized of smooth accleratetion of flow. To minimize the natural disturbances generated by the roughness of the inner surface of the nozzle, a profiled nozzle with a high class of roughness of the inner surface was specially manufactured. The diameter of the outlet section of the nozzle is Da = 30 mm.

Supersonic Underexpanded Jet M_a= 1 N_{pr}= 5

The supersonic underexpanded jet has a characteristic shock-wave structure with gasdynamic cells (see Figure 1.2, left). The gasdynamic structure of the initial section of the jet is characterized by the presence of shock waves, expansion waves and inner and outer mixing layers. The flow pattern in the initial section of a supersonic underexpanded jet at Ma = 1 is shown in Figure 1.3. Lines I and II conditionally designate the inner and outer surface of the mixing layer at the boundary of the jet, III and IV - the middle of the mixing layer and the conventional boundary of the jet.

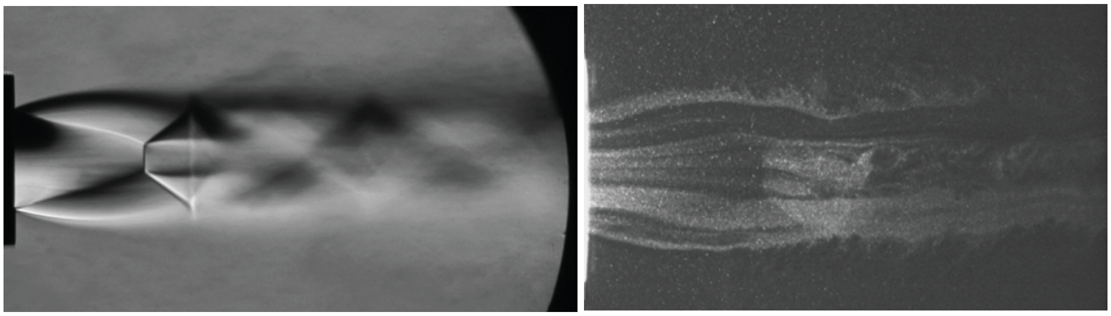


FIGURE 1.2 Visualization of the initial section of the supersonic jet exhaust from the convergent nozzle at Ma = 1.0, N_{pr} = 5.0, obtained with the help of the shadow method (left) and with the laser knife method (right)

The line IV of constant Mach number M = 1 is into of the supersonic jet shear layer. The barrel shock 4 appears due to the fan compression waves intersection of the supersonic jet and it is located at some distance from the nozzle exit as shown in the figure. However, there is an assumption that the region of formation of nonuniformities in the jet stream locates in the immediate near of the nozzle exit for an underexpanded jet, which is subject need to further detailed investigation.

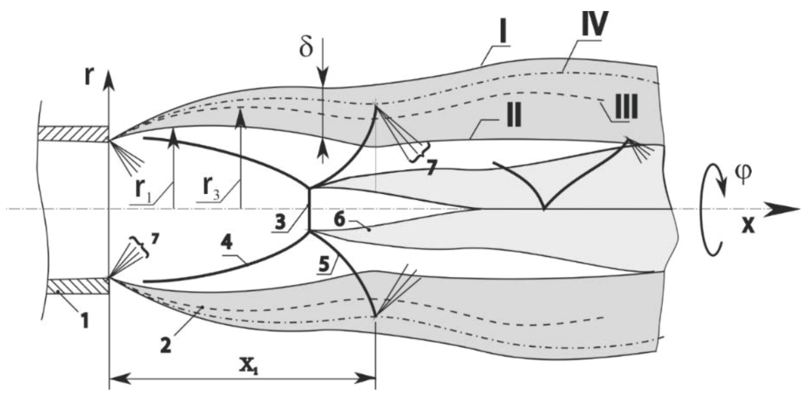


FIGURE. 1.3 The flow scheme in the initial section of a supersonic underexpanded jet with Mach number M_a = 1. 1 - nozzle; 2 - the mixing layer (I, II - the outer and inner boundaries, III - the middle of the mixing layer); 3 - the Mach disc; 4, 5 - barrel and reflected compression shocks; 6 - the shear layer formed behind the point of intersection of shock waves 3, 4, 5; 7 - fan of rarefaction waves, r_1, r_3 - radial distances corresponding to the position of the inner boundary and the middle of the mixing layer

STRUCTURE OF SUPERSONIC JET FLOW IN THE PRESENCE OF ARTIFICIAL VORTICES

Intensification of mixing processes is one of the fundamental problems of aerogasdynamics in high-speed jets, which is also coupled with the search ways to control the processes of sound radiation. The Institute conducts research on the study of physical mechanisms of intensification of mixing in a shear layer supersonic jet by streamwise vortex structures generation by vortex generators. There are various vortex generators - corrugations, chevrons, tabs, lobed mixers, microjets interacting with the mixing layer of main jet. The initial disturbance in the flow generate by local effects results the longitudinal vortex creation. The presence of such vortex structures leads to a significant intensification of mass exchange in the jet mixing layer. The influence of a single disturbance as single chevron or microjet at the nozzle exit on the flow structure in a supersonic underexpanded jet was experimentally investigated in [2, 3]. Has been observed that a shock-wave pattern consist of not only typical structure characterized by a gas-dynamic regime, but also an intense trace from the chevron and Mach-type perturbations.

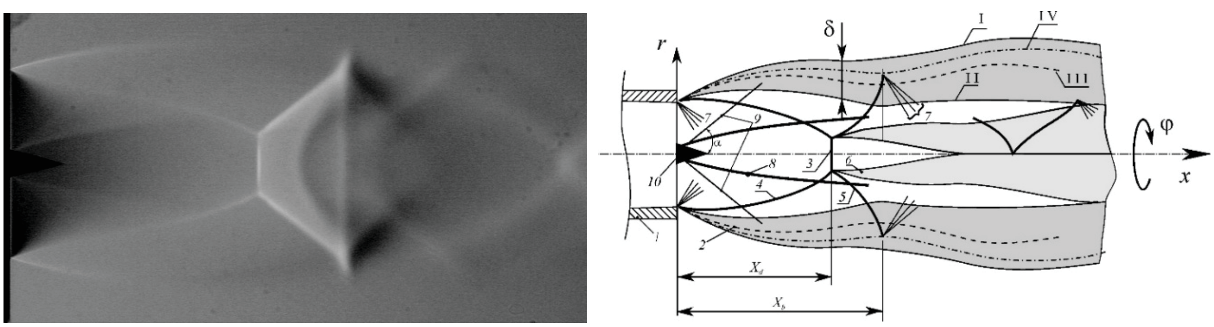
For the intensification of mixing, are used special devices - vortex generators forming large-scale longitudinal vortex structures. Experimental studies on the influence of chevrons on the structure of flow in a supersonic jet were carried out on the jet module of the T-326 wind tunnel of ITAM SB RAS and vertical jet facility of ITAM SB RAS.

Single Vortex Generator

The influence of a single disturbance on the example of a jet with a single chevron and microjets located on the nozzle exit was studied experimentally.

The gasdynamic parameters of the main jet were determined by the designed Mach number on the nozzle exit equal to $M_a = 1.0$ and the degree of nozzle pressure ration $n_p = P_a / P_c = 2.64$ (P_a is the nozzle exit pressure, $P_c = 0.1$ MPa is the pressure in the facility test chamber). The Reynolds number, calculated from the flow parameters and the diameter at the nozzle exit, was $Re_d = 2.3 \times 10^6$.

The visualization of the supersonic jet and the flow pattern of the underexpanded jet in the presence of a chevron on the nozzle exit are shown in Figure 2.1.



(a) (b)

FIGURE 2.1 The shadowgraph photo (a) and the flow structure (b) in the initial section of the supersonic underexpanded jet Ma = 1, n_p = 2.64 in the presence of a chevron: 1 - nozzle (R_a = 15 mm); 2 - the mixing layer (I, II - inner and outer boundaries, III - the middle of the mixing layer, IV - the line along which the Mach number M = 1 is constant,); 3 - the Mach disc; 4, 5 - barrel and reflected shock; 6 - the shear layer formed behind the triple point of intersection of shock waves 3,4,5; 7 - fan of expansion waves, 8 - chevron trace, 9 - Mach waves, 10 - chevron, x_b - length of the first jet cell, x_d - distance from nozzle cut to Mach disk

It is seen that the supersonic jet exhausts with presence of intense trace from the chevron 8 and weak disturbances of the Mach- waves 9 (see Fig. 2.1, b) in addition to the typical shock-wave structure characterized by the gasdynamic regime [2].

The structure of the flow in the initial section of a supersonic underexpanded jet with a single controlled disturbance in the form of a supersonic microjet (Figure 2.2), whose axis is perpendicular to the axis of the main jet, is experimentally studied. [3].

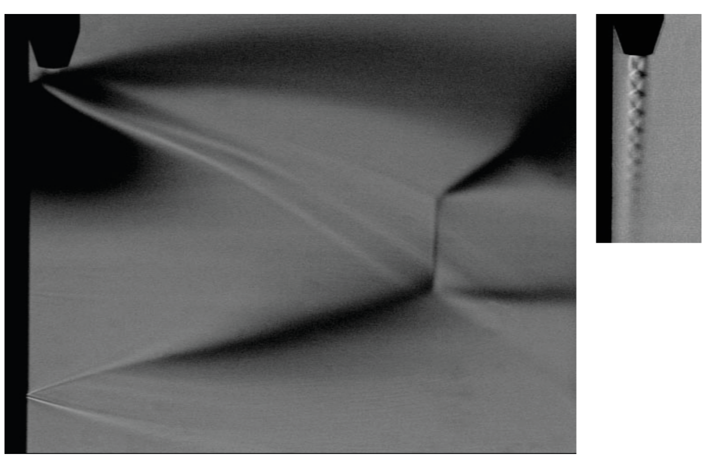


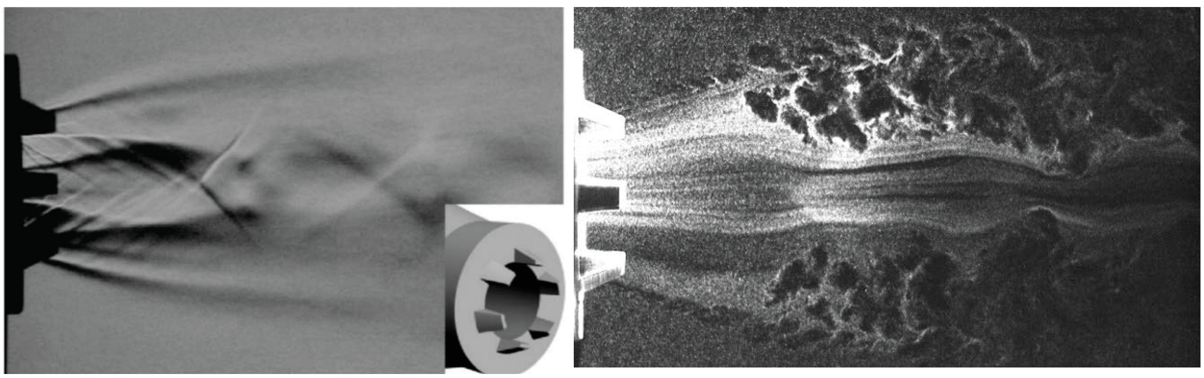
FIGURE 2.2 Schlieren photographs of the main underexpanded jet (M_a = 1.0, n_p = 2.64) in the presence of a supersonic microjet M_a = 1.0, n_p = 2.35 (left) and supersonic underexpanded microjet (right)

When the microjet interacts with the main supersonic jet that two longitudinal vortex structures form in the mixing layer. The shock wave formed in front of the microjet in the main jet penetrates deep inside this jet, causes disturbance of the flow in the shear layer and deformation of the barrel compression shock. As the pressure in the microjet increases, a local displacement of the mixing layer of the main underexpanded jet occurs. The most significant effect is exerted by the microjet with the maximum total pressure (Figure 2.2, right).

As a result of interaction with the chevron and microjet, two types of disturbances are formed: a disturbance caused after the vortex generator, and a weaker disturbance in the form of an insignificant shock wave (such as Mach waves).

Supersonic Jet Exhausting From Nozzle with Chevrons at the Exit

The flow structure of a supersonic axisymmetric underexpanded jet M_a= 1.0, n_p= 2.64, exhausting from a convergent nozzle with six chevrons on a exit [4] is investigated. In Fig. 2.3 presents photographs of the initial section of a supersonic underexpanded jet exhausting from a nozzle with chevrons on the exit.



(a) (b)

FIGURE 2.3 Photos of the supersonic underexpanded jet M_a = 1.0, N_{pr} = 5.0 exhausting from the nozzle with chevrons located on the exit, obtained by the shadowgraph (a) and using a laser knife in the cross section between the chevrons at φ = 30 ° (b)

A more complicated picture of the gas flow in the jet exhausting from the nozzle with chevrons is registered. The boundary of the jet becomes smoother. The chevrons interact with the flow of the supersonic jet, which leads to the appearance of a series of shock waves interacting with each other and intersecting on the axis. The Mach disk at this time is not registered.

In Fig. 2.4 presents the experimentally obtained fields of the azimuthal Pitot pressure distributions in different cross sections of the jet exhausting from the nozzle with chevrons.

The stationary structure of the jet was transformed as a result of the interaction of the chevron with the main jet Each chevron generates a pair of longitudinally opposite swirling vortices. It is seen that the vortex structures have a mushroom shape. The process of formation, development and dissipation of artificially created disturbances of the mushroom form is distinctly traced.

The process of formation is observed at x/R_a = 1, the development process at x/R_a = 2 ÷ 3, the dissipation process at x/R_a = 6.5. Behind the chevron (φ= 0°) the vortex flow is directed in such a way that the low pressure gas exhausts into the jet in the radial direction. Between two adjacent chevrons (φ= 30°) high-pressure gas is exhausted to the periphery of the jet. As the nozzle exit is removed (x/R_a = 5.0, 6.5), the ordered structure of the flow blurs, the intensity of the eddy flow weakens, the "legs" of the mushroom structures thin out, the pressure decreases, the vortex separates from the jet core. It should be noted that the mushroom structures exist at a sufficiently large distance from the nozzle exit.

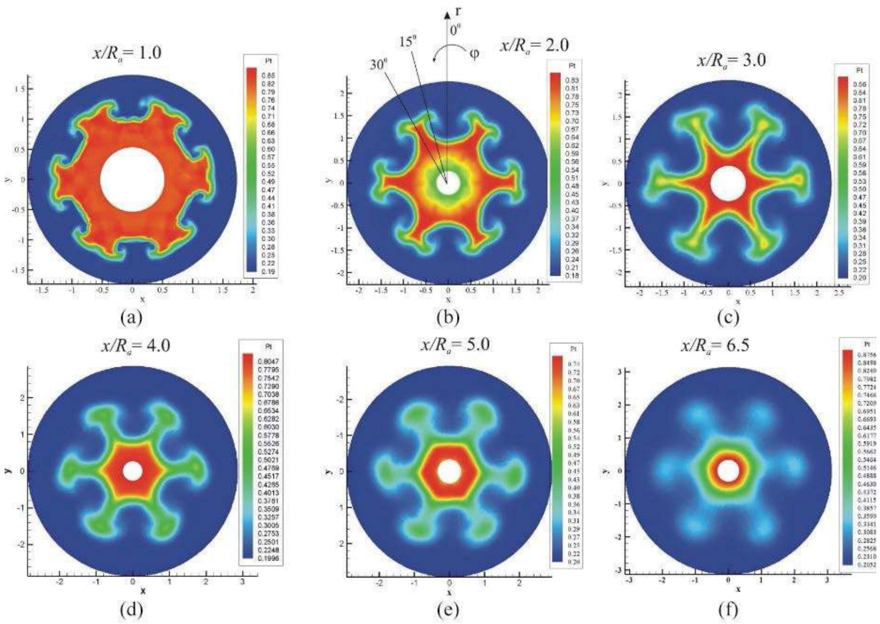


FIGURE 2.4 The azimuthal Pitot pressure distributions in the cross sections of the jet are a - x/R_a = 1.0, b - x/R_a = 2.0, c - x/R_a = 3.0, d - x/R_a = 4.0, e -x/R_a = 5.0, f -x/R_a = 6.5

CONCLUSIONS

The technique has been developed that makes it possible to carry out complex experimental studies of supersonic jet unsteady flows on the jet module of the T-326 wind tunnel, ITAM SB RAS and the Vertical jet facility of ITAM SB RAS basis.

Reliable experimental data on the gas-dynamic structure of the supersonic non-isobaric jet flow exhausting into the submerged outflow have been obtained for test cases creation for computational results validation.

The significant influence of artificial longitudinal vortex structures created by vortex generators on the shock-wave structure, mixing intensification processes and acoustic characteristics of the flow of a supersonic non-isobaric jet is revealed.

REFERENCES

1. V. G. Dulov and G. A. Luk'yanov, *Gas Dynamics of Exhaustion Processes*, edited by N. A. Zheltukhin (Nauka, Novosibirsk, 1984).
2. V. I. Zapryagaev, I. N. Kavun, and N. P. Kiselev, Int. J. of Aerospace Innovations **2**(4), 277–294 (2010).
3. V. I. Zapryagaev and N. P. Kiselev, J. Appl. Mech. Tech. Phys. **50**(3), 447–453 (2009).
4. V. I. Zapryagaev, I. N. Kavun, and N. P. Kiselev, J. Appl. Mech. Tech. Phys. **51**(2), 202–210 (2010).