Flow structure of supersonic underexpanded jet with artificial streamwise vortices at the boundary

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Abstract
The effect of a crosswise microjet blown into the main stream, and a chevron located on the nozzle exit, on the generation of streamwise vortices in the mixing layer of an initial section of the supersonic underexpanded jet has been investigated experimentally. It is shown that such an interaction results in the formation of large-scale streamwise vortices, and two types of disturbances are registered. The first type of disturbances is caused by the basic interaction between the microjet (chevron) and main flow. The second type is caused by the Mach waves distributing in the supersonic region of the jet mixing layer. The effect of a tab on the vortices formation in the supersonic jet mixing layer has been studied numerically.

1. Introduction

The search of possibilities of mixing intensification in high velocity flows is the important research task of aerogasdynamic. It's founded from the experiments, that the initial region in the supersonic nonisobaric jet shear layer has three dimensional structure. Jet issues from the axisymmetric nozzle. Streamwise vortices structures [1, 2] appear it the initial region of the jet in the shear layer. Streamwise vortices intensify the mixing process and decrease jet noise level [3, 4]. The curvature of streamlines [5], affecting developing of the Taylor-Goertler instability, influences considerably on streamwise vortices generated by artificial microroughness. The microjets injected in the main flow form intensive streamwise vortices in the mixing layer of the supersonic underexpanded jet [6]. The target of this work is studying of the structure of supersonic jet while generating streamwise vortices with stationary artificial disturbances specifically cross microjets and chevrons effecting on main stream of the jet.

2. Experiment with a microjet

Supersonic underexpanded jet issues out from the nozzle with polished inner surface (Ma = 1.0, n_p= 2.64, Re_d=$2.21\cdot10^6$) into the environment: Eiffel chamber has sizes 1300X550 millimetres. Reynolds number Re_d is calculated according to the flow parameters and the diameter on the nozzle exit. The nozzle radius on the exit was R_a=15 mm. The experiments were done without heating using of the jet insert for hypersonic wind tunnel of blow down type operation T-326 ITAM SB RAS. The experimental data were obtained in the nozzle with constant pressure ratio $Npr = P_0/P_c$ = 5.0 (here P_0 and P_c are the stagnation pressure and the ambient pressure in the Eiffel chamber, respectively). Experiment acquisition system for this work was designed only for stationary measurements. A microjet was exhausted through a convergent nozzle (micronozzle) with exiterior diameter d= 5 mm and the diameter of exit section d_j= 1.5 mm. The micronozzle had inner contour in the form of cone. The injection was done by the normal to the edge of the underexpanded jet near the nozzle exit. At the Figure 1,a there is a photo of the main nozzle and the device with the micronozzle. A layout view of the spatial position of the microjet device and the main profiled nozzle are shown in Figure 1,b.

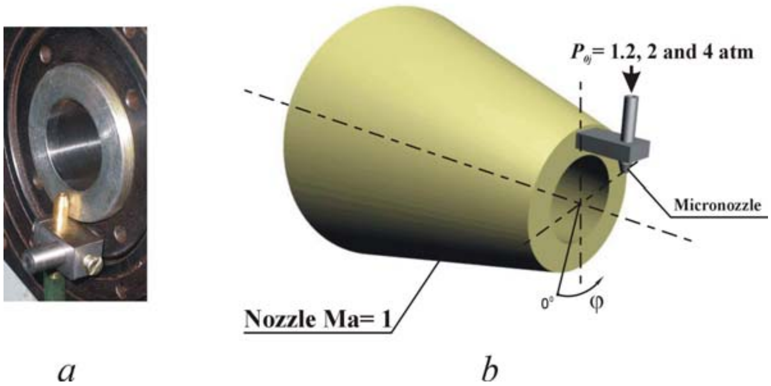

Figure 1.

While conducting the experiments the pressure in the receiver of the microjet device P_{0j} varied and took the values P_{0j}= 1.2, 2.0 and 4.0 bar. Micronozzle has possibilities of moving in the longitudinal and radial directions. At given value P_{0j} the total Pitot pressure was measured at the longitudinal section of the jet x according as radial r and angular φ coordinate $P_t(x,r,\varphi)$. During experiments the microjets were injected to the main flow with parameters – Npr_j= 1.33, 2.22 and 4.44, where $Npr_j = P_{0j}/P_c$. The pressure ratio Npr_j= 1.33 corresponds to the exhaustion of the microjet with subsonic velocity at the nozzle exit. In case of Npr_j= 2.22 and 4.44 was realised exhaustion of supersonic underexpanded microjet.

Schlieren-photo of the main underexpanded jet (n_p= 2.64, Ma =1, Re_d=2.21·10^6) with supersonic microjet (Npr_j= 4.44, Ma =1, Re_d= 0.4·10^5) is shown in Figure. 2. The direction of the flow is from the left to the right. The visualization of the flow was done with by using of the shadow device IAB-451. The exposures were done by a digital camera with resolution of 640X480 pixel.

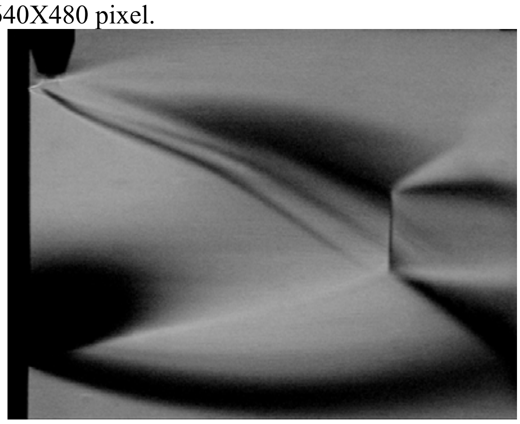

Figure 2.

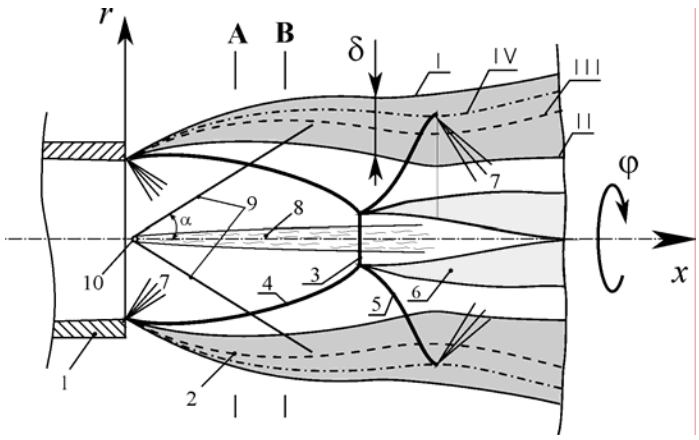

Figure 3.

Layout view of the main elements of supersonic underexpanded jet with microjet is represented in Figure3 It is shown in the figure: 1 – nozzle; 2 – shear layer (I – external boundary of the mixing layer, II – internal boundary of the mixing layer, III – middle of the mixing layer, IV – line, corresponding to the flow velocity in the shear layer with the number Mach M= 1); 3 – Mach disk; 4, 5 – barrel and reflected shock waves; 6 – shear layer formed behind the triple point of intersection of shock waves 3, 4, and 5; 7 – expansion fan, 8 – basic microjet wake, 9 – Mach waves, 10 – micronozzle.

In cross sections A, B, measuring of the total pressure was done by the Pitot probe *Pt(r,φ)*, A – *x/Ra*= 1.5, B – *x/Ra*= 2.0 with artificial disturbance given as transverse microjet near the nozzle exit (Figure 3).

Radial pressure distribution when *x/Ra*= 2.0 for microjets Npr_j= 1.33 (squares), 2.22 (circles) и 4.44 (triangles) are shown in Figure 4. Full line in the figure shows the data for the main jet flow without microjet.

The Figure 4 represents the data when the micronozzle is spacial position x_j/Ra= 0.67 and r_j/Ra= 1.67, where x_j and, r_j the value of the longitudinal and radial coordinate of the micronozzle (towards the exit of the main nozzle). We can see in the picture, that increasing Npr_j the disposition of the internal boundary of the mixing layer (the point of maximum pressure in the figure) shifts to the axe, external boundary of the mixing jet layer ($P_t/P_0 \approx 0.2$) moves away. The microjets Npr_j= 2.22 and 4.44 affects the shear layer the most intensively.

The form of the barrel shock (r/R_a= 0.55 for "clear" jet) while changing the micronozzle position x_j and r_j, shifts to the jet axe when Npr_j= 1.33 and 2.22 (Figure 4). So, increasing the microjets intensity barrel shock deforms. The degree of the distortion of the main underexpanded jet increases proportionally to the microjet growth of Npr_j.

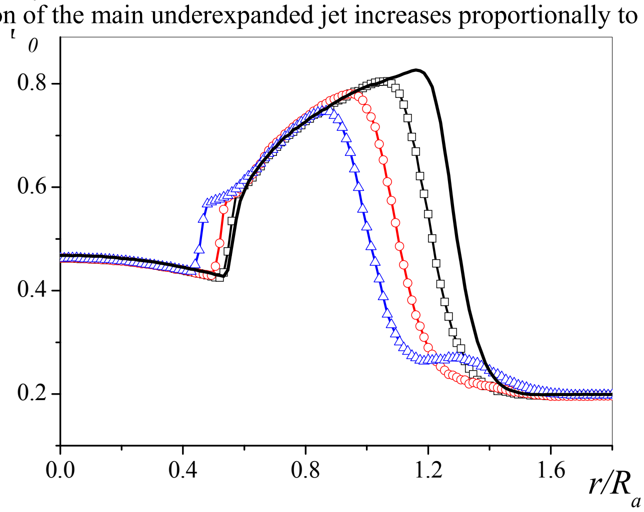

Figure 4.

The thickness of the mixing layer δ is defined as r_2-r_1 (r_1, r_2 are the internal and external boundaries of the jet mixing layer) is shown in Figure 5. The mixing layer thickness presented for three streamwise cross sections of the jet x/R_a = 1.5, 2.0, and 3.0, increases as the microjets intensity Npr_j rises. Thus, the mixing process is more intensive in the point of microstructure action.

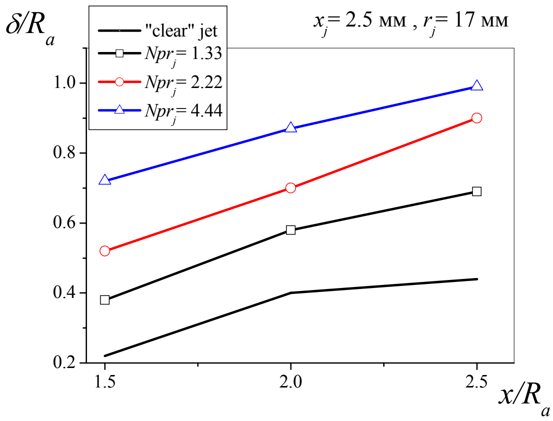

Figure 5.

The azimuthal dependencies of the pressure in two radial sections r/R_a= 0.93 and 1.2 with microjet Npr_j= 4.44 are shown in the Figure 6. The data when x/R_a= 1.5 and 2.0 are represented on the graphics. When φ= 0^0 we can observe minimal pressure, due to the microjet affection, which corresponds to the angular position of the micronozzle. Furthermore, two additional minimum-maximum of the less value are realized (Figure 5,*a*), corresponding to the Mach waves, spreading в in supersonic area of the jet shear layer.

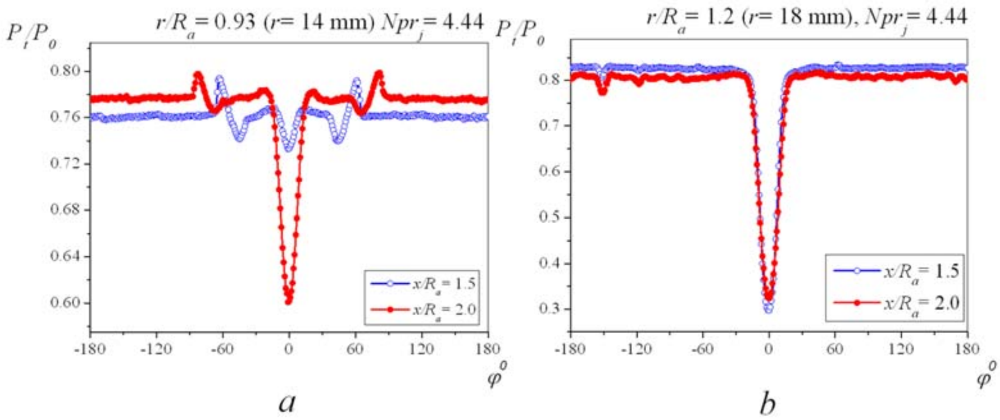

Figure 6.

The angle insuring propagation of Mach wave is found. The angle is equal to α= 32° corresponding to the Mach number M= 1.9. The specialty of azimuthal dependence of the pressure into the middle of the jet shear layer (Figure 6,*b*) is insignificant difference of pressure minimums due to main affecting of microjets for two sections – P_t/P_0= 0.32 when x/R_a= 1.5 and 0.3 for x/R_a= 2.0. The intensity of artificial large-scale axial streamwise vortices changes insignifically on the initial jet region.

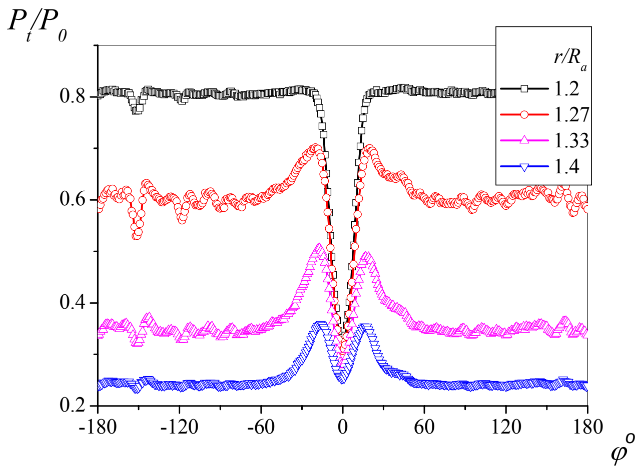

Figure 7.

Experimental data (azimuthal pressure dependences) in the section x/R_a= 2.0 crosswise the jet in radical sections r/R_a= 1.2, 1.27, 1.33 и 1.4 if there is microjet Npr_j= 4.44 are shown in the Figure 7. Value φ= 0° corresponds to the microjet axe.

We can obviously see at the graphs well-ordered character of the dependencies $P_t(\varphi)$, due to the microjet's presence. In the jet shear layer with radius increasing of the streamwise vortices transforms causing pressure maximums, disposed symmetrically to main minimum, due to trace influence of microjet. The value of pressure minimums and maximums at the external boundary of shear layer (r/R_a= 1.4 in the Figure 7.) becomes identity. At the azimuthal dependence the amplitudes of pressure irregularity caused by radial secondary flow becomes comparable.

As a consequence of forming of the pair large oppositely rotating streamwise vortices a flow in radial direction is formed (pressure minimum when φ= 0^0), causing injection of the low-pressured gas into the jet. The appearing pressure maximum corresponds to the flow of high-pressured gas to the exterior edge forming secondary streamwises.

Therefore, in the shear layer supersonic jet large-scale artificially made streamwise structures are formed artificially and secondary small-scale streamwises vortices are formed. At the jet periphery large streamwises vortices transforms to smaller ones. The intensity of main and secondary vortices at the extended boundary of the jet becomes comparable.

The interpretation of this pattern of distribution of main and secondary vortices is represented in the Figure 8.

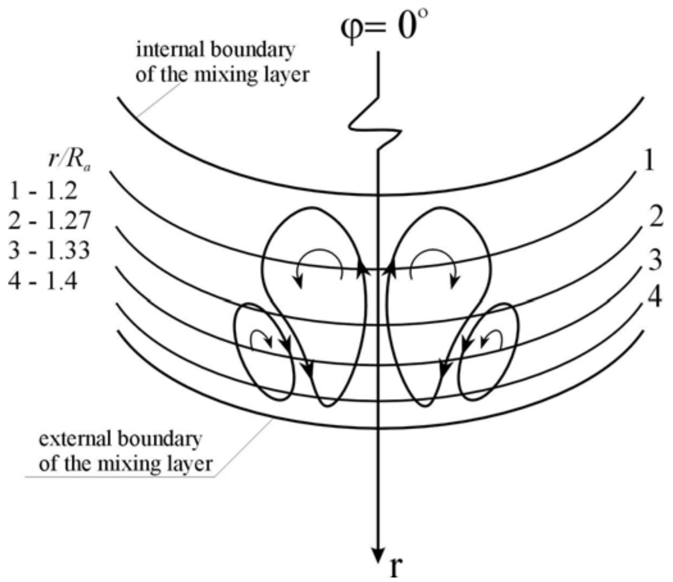

Figure 8.

Thus, two types of disturbances as a result of microjet interaction and the main jet were found: the microjet causes deformation of barrel shock wave and generates of weak disturbances. Those disturbances are like of Mach waves. It is needs to note using of the microjets for generation of streamwise vortices is enough convenient owing to the good controllability of microjet's gasdynamics parameters.

3. Experiment with a chevron

The experiments on streamwise vortices generation have been as well carried out with a chevronon the internal surface of the nozzle, on the jet insert module of the hypersonic blowdown wind tunnel T-326, ITAM SB RAS. The gas-dynamic regimes of the main jet outflow were the same as in the experiment with the microjet, namely n_p= 2.64, Ma =1, Re_d=2.21·10^6. The chevron was situated on the exit section of the nozzle in such a way that its surface continued the internal surface of the nozzle. The chevron is a triangle form with base 4 mm and height is 8 mm. In the experiments, two angles of chevron plane inclination θ = 0° and 10° toward the nozzle axis were used. Figure 8 shows the supersonic underexpanded jet with the chevrons on the nozzle exit. It is clearly seen in the Figure that as the chevron and main stream interact, similarly to the case of the microjet, the rather broad main action is registered. The action is caused by the chevron and is weak. The weak action correlates with the disturbances of a Mach wave type, propagating in the supersonic region of the jet mixing layer.

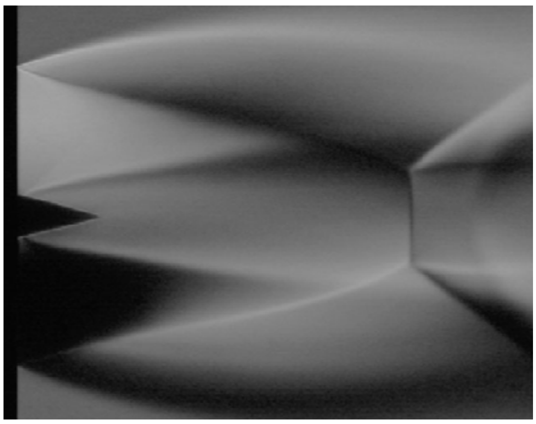

Figure 8

In the crosswise sections of the supersonic jet, the measurements were carried out with a full-pressure tube, in radial and azimuth directions. In the azimuth direction, the data have been obtained across the mixing layer. Figure 9 shows the radial profiles of the Pitot pressure in the jet shear layer at x/R_a= 2.0. The solid line on the pressure profile correspond on the azimuthal angle where is weakly influence of the chevron (clear jet), circles correspond on the chevron axis azimuthal angle.

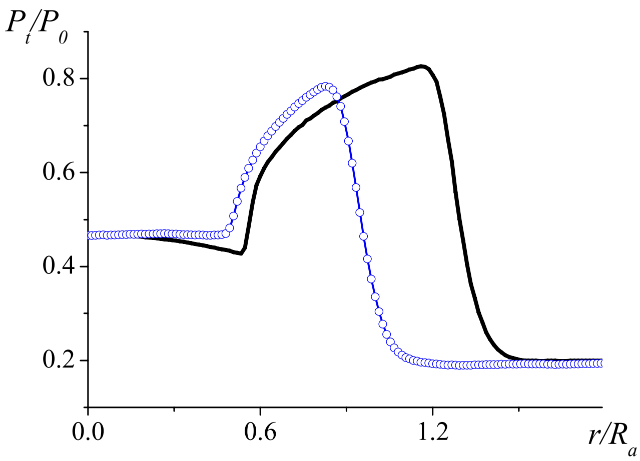

Figure 9

One can see the following peculiarities in the Figure: the internal boundary of the jet (location of maximum pressure in the Figure), the position of the barrel shock wave (P_t/P_0= 0.6), and location of external boundary of the jet (P_t/P_0 = 0.2) for the nozzle with the chevron move toward the jet axis. Hence, the chevron presence results in the jet deformation, but the thickness of the mixing layer is constant for the "pure" and chevron-stagnated δ/R_a = 0.33.

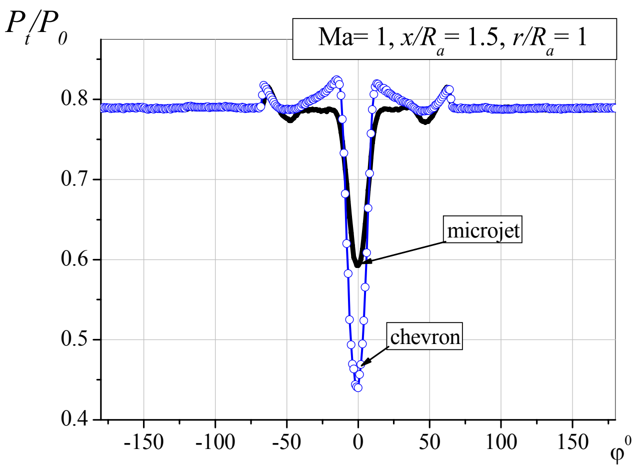

Figure 10

The azimuth profiles of the Pitot pressure for the jet with the microjet interaction and chevron in the jet shear layer r/R_a = 1 are shown in Figure 10. The minimum pressure in the profile at $\varphi = 0^o$ corresponds on the microjet axis position ($Np\ r = P_{0j}/P_c$ = 4.44) and chevron (θ = 0°). It is shown from the Figure that the chevron acts more intensively on the pressure distribution than the microjet. This is caused by the fact that at such an inclination angle the chevron interacts directly with the main stream of the jet, and this results in on the flow distortion.

At $\varphi = \pm 60^o$, one observes two additive maximums corresponding on weak disturbances – Mach waves in the supersonic region of the jet shear layer. It follows from the coincidence of the maximums positions for both types of the artificial disturbances correlating with the Mach waves that for the chevron, these disturbances also propagate under the angle of $\alpha = 32^o$ (Figure 3).

3. Numerical results

The regime of the supersonic underexpanded jet issuing from the nozzle, with the artificial disturbances like tabs or chevrons, has a complicated shock-wave flow structure. Thus, to analyze it more accurately, the numerical calculation results should be involved. Such an approach has been used, for instance, in [7, 8] for the study of jet flowing out from the chevron nozzles.

The calculation was performed for a convergent nozzle with the exit cross section radius R_a= 15 mm. The pressure at the nozzle exit was set of P= 2.64 atm, Mach number at the exit was Ma = 1. The calculation simulated the outflow of the supersonic underexpanded jet with the off-design ratio is n_p= 2.64.

Two cases were under consideration: the outflow of the supersonic underexpanded jet from the axisymmetric nozzle (Figure 11, a, on the left), and the outflow from the nozzle with three tabs located on the nozzle exit, with the pitch of 120 degrees (Figure, 11, a, on the right). The height of each tab was 7 mm, width 5 mm, thickness 3 mm. The internal surface of the tab naturally continued the internal surface of the nozzle.

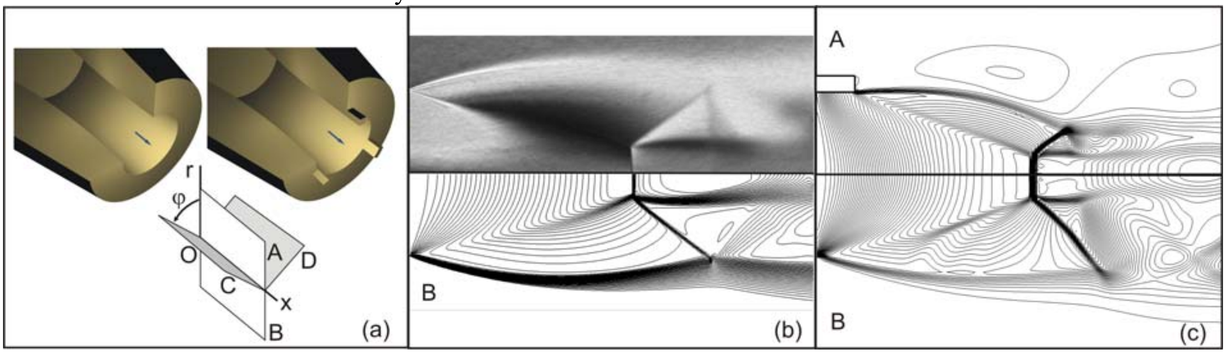

Figure 11

For the sake of convenient further explanations (Figure 11,a, on the bottom) presents the sketch of cross sections planes, where the numerical calculation of the shock-wave flow structure will be carried out by the density isolines. The plane A presents the top half-plane of the streamwise vertical section xOr, plane B – the bottom half-plane, correspondingly, and the plane A asses through the tab's center, whereas the plane B – between the tabs. The plane C is turned around the axis to the angle of φ = 60°, the plane D – to the angle of φ = -60°, correspondingly.

Figure 11, b shows the schlieren-photo (experiment) of the underexpanded jet (on the top), and designed stationary flow structure constructed in the plane B (on the bottom). Coinciding positions of the Mach disc, barrel shock wave, and also jet size show that the design data coincide satisfactory with the experimental data. Hence, the calculations can be performed in the supersonic flow stagnated by the tabs or chevrons. Figure 11, c shows the jet structure in the vertical cross section (planes A and B) for the nozzle with three tabs. It is seen that the jet is deformed as the mainstream interacts with the tab.

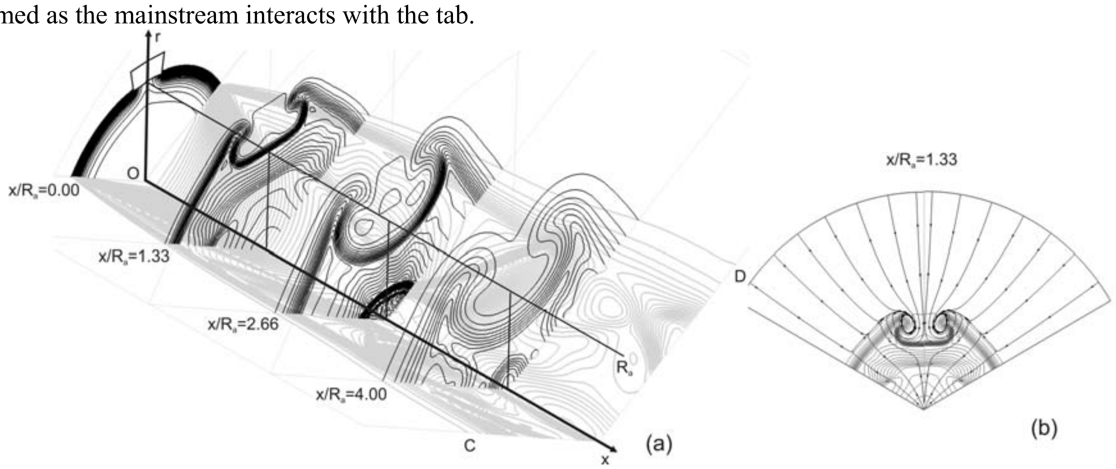

Figure 12

Figure 12, a presents the streamwise sections of the isolines of the densities distribution for the jet with the tabs. The Figure gives the flow structure in the segment bounded by the planes C and D (Figure 12, a). One can see the essential effect of the tab upon the structure of the jet initial section, which results in the formation of a couple of large-scale vortices, the cross-flow dimensions of the vortices grow downstream. The velocity vectors of the streamlines constructed by the radial and tangential components in the cross section x/R_a = 1.33 are shown in Figure 12, b.

The present calculation describes the development of the artificially-generated streamwise vortices in the mixing layer of the supersonic underexpanded jet.

Conclusion

The structure of flow in supersonic jet with artificial disturbances as microjets and chevrons was studied. An interaction of microjet with high total pressure (or presence of chevron near nozzle exit) and the main supersonic jet flow results in the formation of large-scale streamwise vortices on jet boundary. Two types of flow disturbances are registered. The first type of disturbances (wake disturbance) is caused by the basic interaction between the microjet (chevron) and main flow. The second type is caused by the Mach waves distributing in the supersonic region of the jet mixing layer.

It was found out that we can observe at the periphery the transformation of large artificially made vortices into smaller ones. This hypothesis was based on detailed measurements of the distribution of Pitot pressure in cross sections of underexpanded supersonic jet at the presence of a singular artificial disturbance as microjet (chevron). As a result the intensity of main and secondary vortices at the extended boundary of the jet becomes comparable.

The numerical investigation performed for the axisymmetrical supersonic underexpanded jet has revealed the satisfactory agreement between the numerical and experimental results. It has been shown that the tabs introduced in the jet result in essential flow transformation and in the formation of a couple of vortices developing in the mixing layer downstream from the tabs. Authors thanks of Palchikov V.V. for help in performing of experiments.

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