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TO THE NON-UNIQUENESS PROBLEM OF HYPERSONIC STEADY-STATE FLOW ON THE BLUNTED BODIES LEADING AGE.

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Keywords: *hypersonic flow, shock wave, cylinder, vortex structure, non-uniqueness.*

Abstract

The problem of non-uniqueness of steady-state modes of hypersonic flow past long bodies with a blunted frontal edge is investigated using the direct numerical simulation by means of the "FLUENT" software and experimentally.

The following investigations are performed in the experiments at TsAGI wind tunnel UT-1M: schlieren flow visualization and investigations of surface heat flux distribution by TSP-method (temperature sensitive paint - luminophor). One of the most important result is experimental reproduction of 3D single vortex pair flow-mode in the nominally uniform oncoming flow at Mach number M_∞=8 and Reynolds number range Re_∞=[3160 ÷ 13000]

1 Introduction

Hypersonic vehicles contain elements having a cylindric frontal surface. The features of hypersonic flow and heat transfer on such elements were investigated during more than 50 years. One of the topical problems is non-uniqueness of steady-state modes of hypersonic flow past the frontal surface of blunt bodies. In particular, along with the plane flow mode (Fig.1), a three-dimensional steady-state vortex structures were revealed in some calculations and experiments related to transverse hypersonic flows past bodies with a cylindric frontal bluntness [1–4]. As the physical reason of the development of such structures, we can distinguish three basic mechanisms:

1) external excitation of vortices induced by spatial inhomogeneity of the free stream or boundary conditions on the body; 2) internal excitation caused by the development of the transverse flow instability in the neighborhood of the leading stagnation point (for example, the Taylor–G¨ortler instability) [2]; 3) self-generation of span-periodic structures under homogeneous external conditions initiated by strong interaction between the bow shock and the vortex flow in the shock layer.

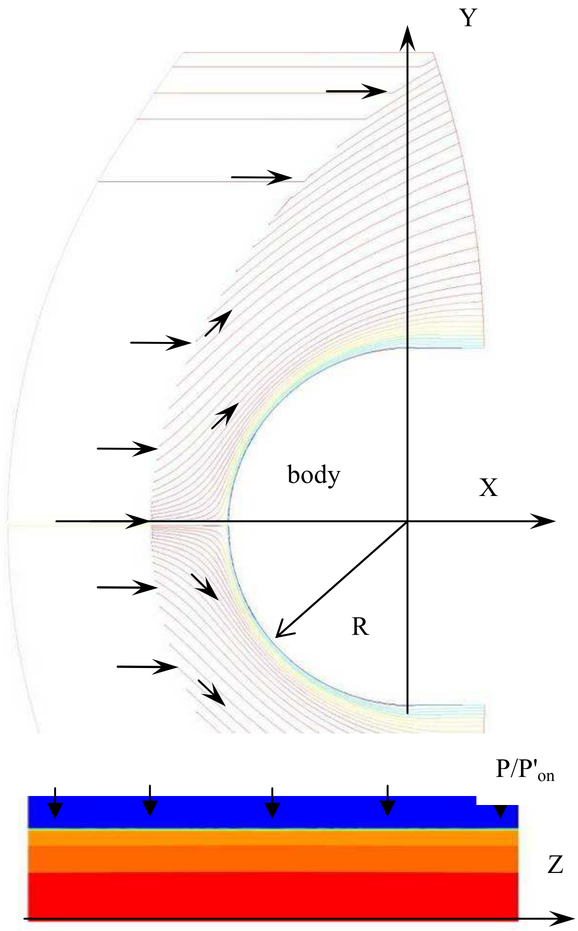


Fig. 1. Streamlines of 2D plane mode of steady-state flow past a body with a cylindrical bluntness and pressure distribution in the plane Y=0. Calculation at M = 8, Re = 6628, Re_0 = 676.

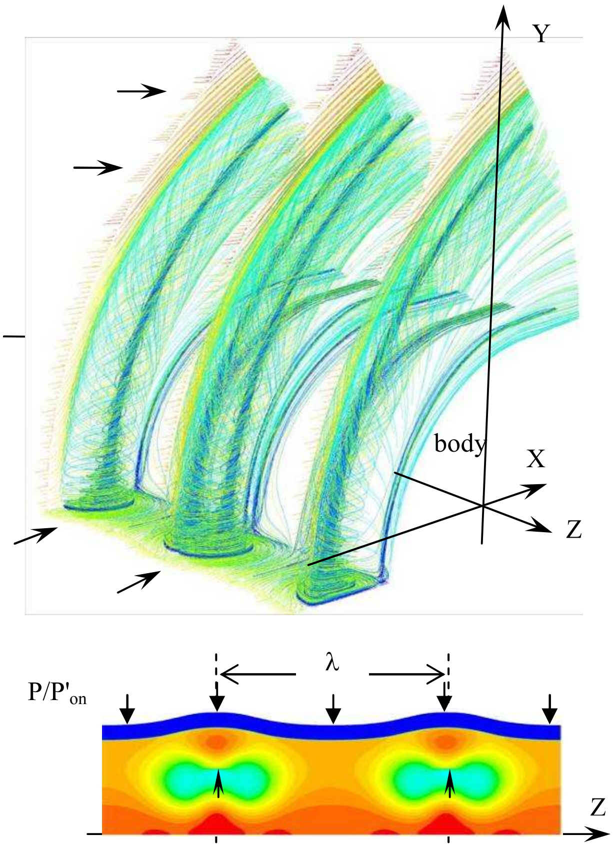


Fig. 2. Streamlines of 3D periodic vortex mode of steady-state flow past a body with a cylindrical bluntness and pressure distribution in the plane Y=0. Calculation at M = 8, Re = 6628, Re_0 = 676.

The fact that vortex structures can appear as a result of the external impact is theoretically understood; therefore, in the present study the first mechanism is considered only as one of the ways of the initial perturbation of the primary (plane) flow mode. The second mechanism was proposed in [3, 4], where it was shown that in the case of transverse hypersonic (M ≥ 5) flow past bodies with the cylindrical bluntness of the frontal surface a steady-state spatial flow mode consisting of paired vortices which are periodic along the *Z* axis of the cylinder (Fig. 1) can exist simultaneously with a plane (two-dimensional) mode.

The physical essence of the third mechanism consists in the following. Let due to some reason the shock wave ahead of the blunt body have the shape curved along the *Z* axis (Fig. 2). Then, in accordance with the Rankine–Hugoniot relations, when $M_\infty \gg 1$ the gas downstream of the curved section of the shock acquires a considerable vorticity and paired oppositely rotating vortices can develop ahead of the body over a certain Reynolds number range. Flow between the vortices is directed opposite to the free stream and push the shock wave back from the body. Thus, the curved shock wave generates vortex structures, while the vortices maintain its curved shape.

The first aim of this study is to confirm the fact that three-dimensional vortex structures developed on the frontal surface of bodies in a homogeneous hypersonic stream represent one of the steady-state modes of the solutions of the Navier–Stokes equations and do not result from the calculation grid roughness or the exciting action of the boundary conditions.

And the main aim of the study is experimental verification of three-dimensional vortex structures existence in the nominally uniform hypersonic flow.

2 Calculation results

Consider the three-dimensional flow of a perfect gas (air) with *cp* = 1006 J/kg/K and $\gamma = c_p/c_v$ =1.4 past a blunt wedge by solving numerically the Navier–Stokes equations (using ANSYS FLUENT software). The two variants of blunted body geometry are considered. The wedge-1 has a bluntness radius is *R* and the wedge half-angle ϕ =7.4° (Fig. 3). The wedge-2 has a plane end face with rounded corners and the wedge half-angle ϕ =12.4° (Figs.4, 9). The shape of blunt wedge is taken instead of the cylinder since, firstly, it is precisely this shape is characteristic of the leading edge of the air-intake of one of the vehicles designed and, secondly, because, when $M_\infty \gg 1$ and ϕ is small, flow on the wedge has no upstream effect on flow in the neighborhood of the cylindrical bluntness. Moreover, the calculation of flow past a wedge is simpler than the calculation of flow past the rear semicircle of the cylinder, where, as a rule, a time-dependent flow separation develops.

The Cartesian coordinate system (*X, Y, Z*) (Figs. 1, 2) is used and the main parameters of the calculation regimes correspond to typical parameters of experiments in the TsAGI UT-1M shock tube at Mach number M=8.

The Reynolds numbers is determined using the cylinder radius R and the free-stream parameters. The temperature dependence of the viscosity was determined from the Satherland formula.

$$Re_\infty = \frac{\rho_\infty U_\infty R}{\mu_\infty}; \quad Re_o = Re_\infty \frac{\mu_\infty}{\mu_o}$$

The temperature dependence of the thermal conductivity coefficient χ was determined from the tabular data for air in the interval 50–800 K which were approximated by the 2nd power polynomial.

The calculation domain (Figs. 3, 4) is bounded by the following surfaces on which we imposed the boundary conditions given in brackets below: *1,2* denotes the body surface (no-slip condition for the velocities and a given wall temperature $Tw = 0.386T_0$); the inflow surface (free-stream conditions: M_∞, P_∞, T_∞, and the direction of the velocity); the plane of symmetry $Y = 0$ (symmetry means vanishing the normal velocity component, the friction, and the heat influx); and the outlet surface (nonreflecting boundary conditions). In the transverse variable Z, the domain is bounded by two planes $Z = 0$ and $Z = L=0.5\lambda$ on which we imposed conditions of symmetry. This is equivalent to periodic continuation with a period λ .

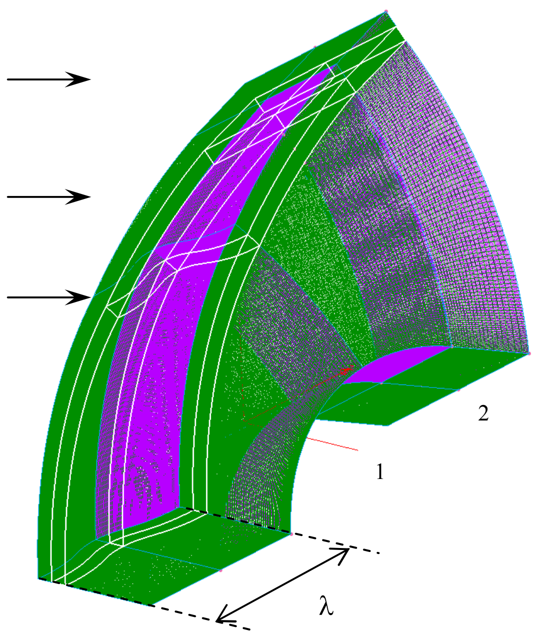


Fig. 3. The calculation domain and greed for the wedge-1.

The inflow surface shape of flow domain repeats the shape of head shock wave.

For wedge-2, along with the flat forward face, the small separating plate installed normally on the forward face is considered in the calculations and experiment (Fig. 4). This plate is used for stabilization of coordinate Z of vortex pair position only (Figs. 5 ,6).

Flow past the blunt wedge was simulated numerically using a numeric code of the second or third order of approximation in space and of the second order in time which was designed for calculating high-speed compressible flows. Initially, fairly long-term calculations were carried out and, after approaching a steady-state solution, the stationary version of the code on the base of an implicit scheme of the third-order space approximation (MUSCL scheme) was switched on.

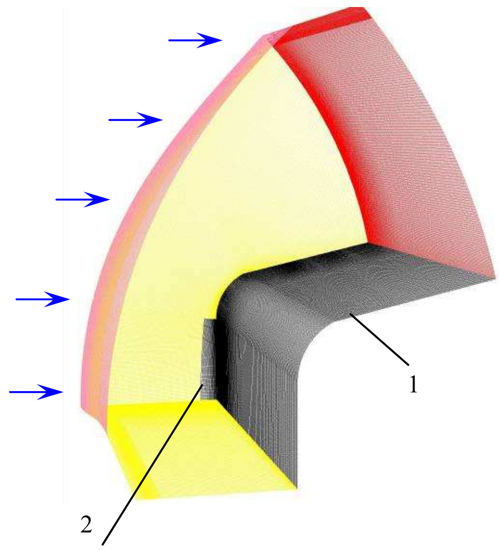


Fig. 4. The calculation domain and greed for the wedge-2. 1-wedge surface, 2-separating plate.

In the present study the main attention is focused on the analysis of steady-state vortex flow modes obtained according to the following scenario. First of all, a plane 2D flow mode (independent of *Z*) was obtained for homogeneous flow (Fig. 1). Then, a forced three-dimensional flow was excited by creating spaceperiodic perturbations in the free stream of the form $M(z) = [1 - \Delta\cos(2\pi z/\lambda)]M_\infty$, where $\lambda/R = 0.9333$. Calculations showed that the steady-state flow with small three-dimensional perturbations of the plane mode is realized in the case of a low perturbation level ($\Delta < 0.02$). When creating the higher perturbation level ($\Delta > 0.03$) over a certain Reynolds number range, the flow is qualitatively restructured and a vortex mode is implemented in the form of paired *Z*-periodic vortices. Once the forced vortex mode has obtained a sufficient development (the shock wave became appreciably curved and the Mach number of the reverse jet between the vortices $Mr > 1.2$), the perturbations of the boundary conditions are eliminated and a long-term transition process is kept in the homogeneous free stream. Three-dimensional vortex flow is conserved and stabilized after completing the transition process in the interval $4000 < Re < 7000$. For example in Fig. 2 we have plotted streamlines and pressure distribution of the vortex mode of flow past a blunt wedge-1. An analysis of the grid independence and other tests demonstrating the consistence of the steady-state three-dimensional solutions obtained.

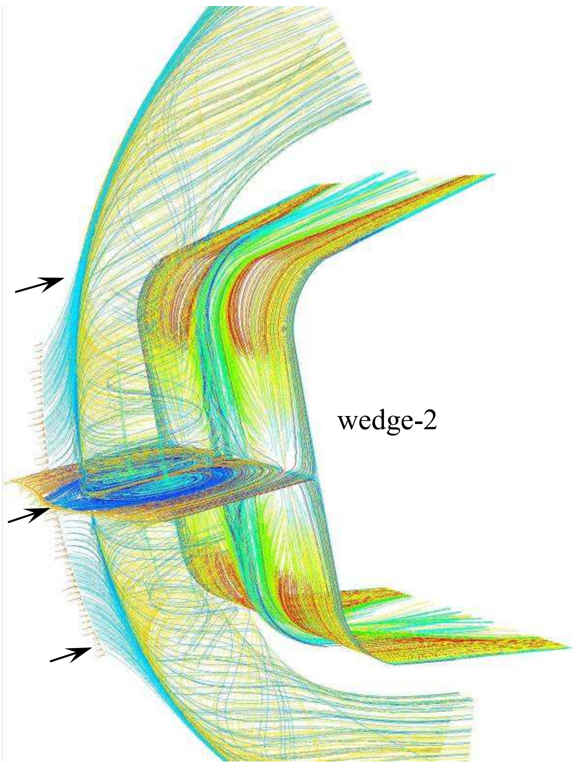


Fig. 5. Streamlines of 3D periodic vortex mode of steady-state flow past a wedge-2 . Calculation at M = 8, Re = 4113, $Re_0 = 420$.

Typical calculation results for steady-state flow mode in the form of a single vortex pair past wedge-2 are presented in Figs.5, 6. In Fig. 6 we have reproduced the M number distribution behind the shock wave in the plane $Y = 0$. We can see that the plane flow is disturbed by a pair of three-dimensional vortices with supersonic ($Mr=1.59$) opposite jet between them. Such strong vortices produce two peaks of the doubled-value heat flux on the wedge forward surface.

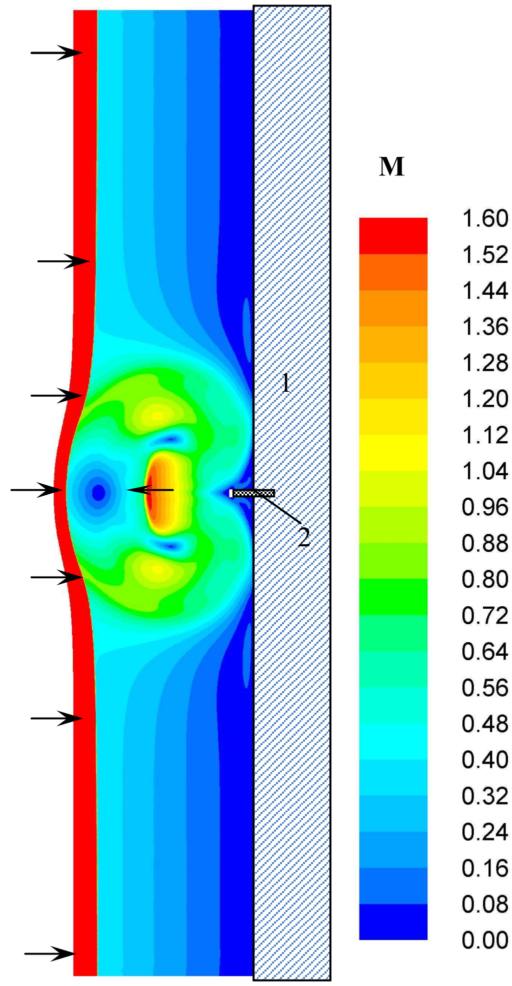


Fig. 6. 3D steady-state flow mode in the form of a single vortex pair past a wedge-2 . Mach number distribution in the plane Y=0. Calculation at M = 8, $Re_\infty = 4113$, $Re_0 = 420$. 1 – wedge, 2 - separating plate.

For the flow mode in the form of a single vortex pair the mechanism of steady-state maintaining of the vortices is also based on the curved shape of the shock wave in the plane of symmetry ahead of the cylinder ($Y = 0$) (Fig. 6). As compared with the normal shock section, flow has the higher M number and total pressure downstream of the shock wave inclined to the free-stream velocity vector. This excess in the mechanical energy is absorbed by the viscous vortex flow and reverse internal shock. It is important to note that the boundary condition on the sides $Z=\pm 1.47R$ does not affect the appearance and maintenance of the vortex pair since the characteristic dimension of the vortex flow domain $l \approx 0.9\Delta \approx 0.4R$ is independent from the chosen lateral size L.

The results of the direct numerical simulation of flow past a wedge with a cylindrical and flat frontal surface show that for uniform incidence flow at $M_\infty = 8$, $Re_\infty = 4000$–7000 there exist three steady-state flow modes, namely, the plane (2D) mode, the 3D mode in the form of paired vortices periodic along the span of the wedge, and 3D single vortex pair. The three-dimensional vortex modes have the property of convergence on grids, are in agreement with physics of perfect viscous gas flow, and consequently, there are no reasons to consider such solutions as a result of numerical errors.

3. Experimental results

Experimental part of the work contains of several sets of tests performed in the TsAGI shock tunnel UT-1M at M_∞=8 and Reynolds number range Re_∞=[3000 ÷ 60000]. The flow structure and heat flux distribution are investigated with the cylinder and blunted wedge-2. General aim of experiments is to obtain and investigate of 3D flow modes on the blunted bodies leading age in the artificially perturbed and nominally uniform hypersonic flow. The artificial controlled perturbations are made in the shock tunnel test section by means of thin (0.05 ÷ 0.2 mm.) wire and fishing line strained on the shock tunnel nozzle exit. During these experiments Schlieren flow visualization method was used for flowfield visualization (fig.7) and heat flux measurements on the model surface (fig.8) was performed using TSP-method (temperature sensitive paint - luminophor). According to the generally accepted method the results of the heat flux measurements on the model surface are presented in a dimensionless form $Q=q/q_o$, where q_o is the heat flux value in the forward stagnation point of the body bluntness with radius R, calculated by the Fay-Riddel formula.

Experimental results show that the flow pattern and heat flux distribution on the leading age of blunted body are strongly sensitive to the vortex perturbations in the oncoming hypersonic flow. The strong vortices appeared on the leading surface produce peaks of the doubled-value heat flux (Fig.8).

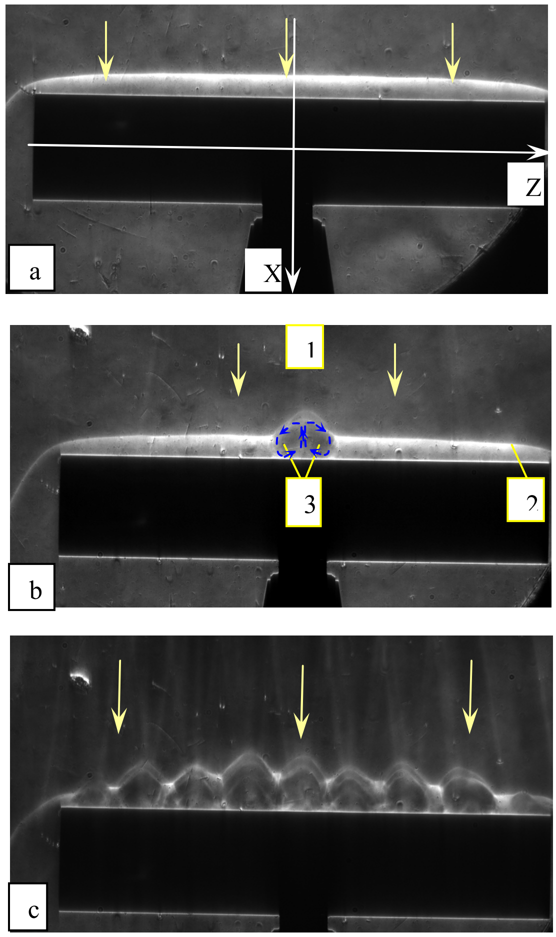


Fig.7. Schlieren flow visualization past the cylinder at M=8 , Re_o≈3000. a – uniform flow; b – flow perturbed by single wire d=0.1 mm.; c– flow perturbed by s13 wire d=0.1 mm. 1 - wire wake, 2 –head shock, 3 – vortex pair.

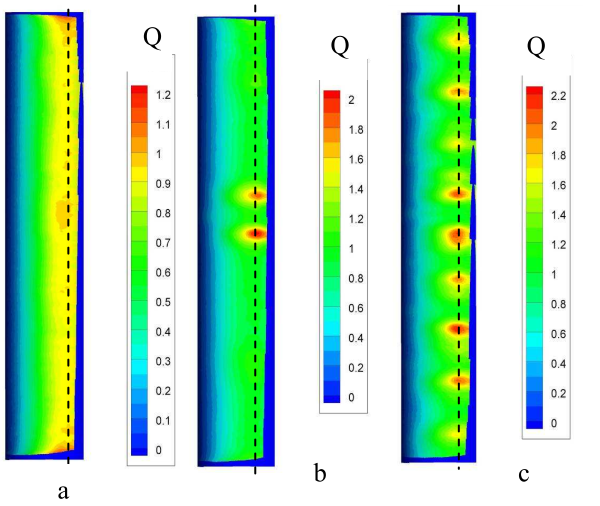
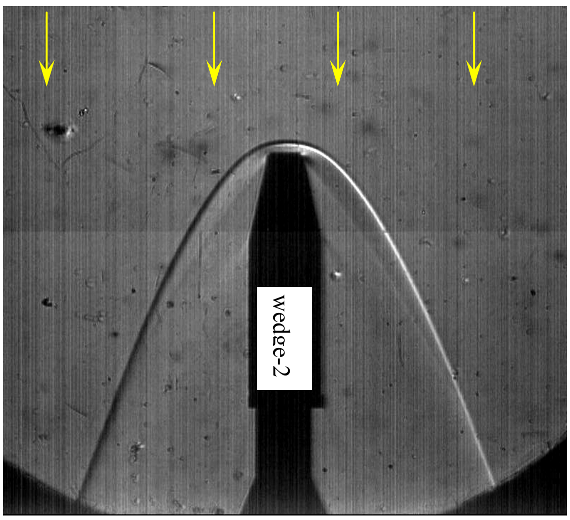
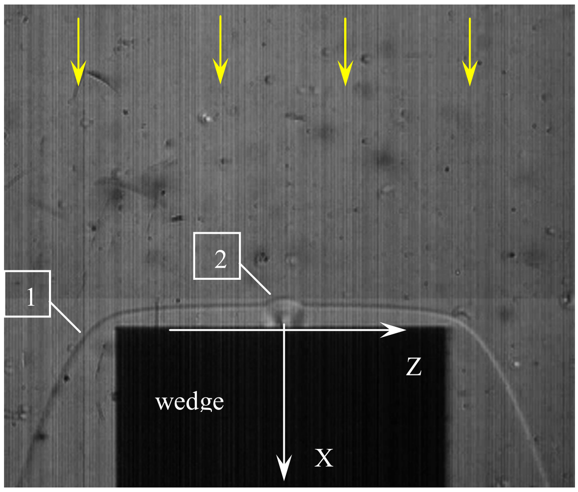


Fig.8. Dimensionless heat flux distribution on the cylinder at M=8 , Re_o≈3000. a – uniform flow; b – flow perturbed by single wire d=0.1 mm.; c– flow perturbed by 13 wire d=0.1 mm.

One of the most important result of work is experimental reproduction of 3D single vortex pair flow-mode at the wedge-2 frontal surface in the nominally uniform oncoming flow at Mach number M_∞=8 and Reynolds number range Re_∞=[3160 ÷ 13000] (Re_0=[322 ÷ 1190]). On the fig.9b one can see the vortex pair on the wedge-2 frontal surface behind the curved shock wave. This vortex pair has been produced by thing fishing line which has been destroyed at the middle of run (t≈25 ms.). After fishing line destruction vortex pair remains, becomes steady and stable up to end of run at t≈130 ms.



a) the view on (X,Y)



b) the view on (X,Z)

Fig.9. Schlieren flow visualization past the wedge-2 at uniform flow M=8 , Re_o≈1100. 1 –head shock, 2 – vortex pair.

Conclusion

The non-uniqueness of hypersonic steady-state flow-modes on the blunted bodies leading age is received and verified in calculations and confirmed experimentally.

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