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VORTEX STRUCTURE GENERATION ON THE FRONTAL SURFACE OF THE CYLINDER IN THE TRANSVERSAL HYPERSONIC FLOW

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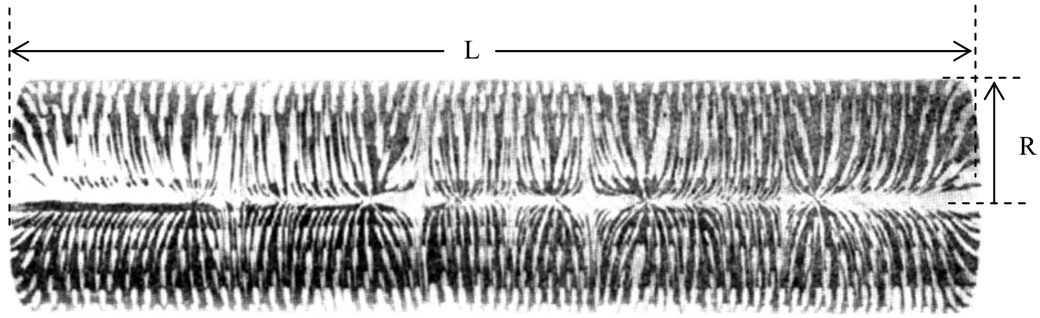
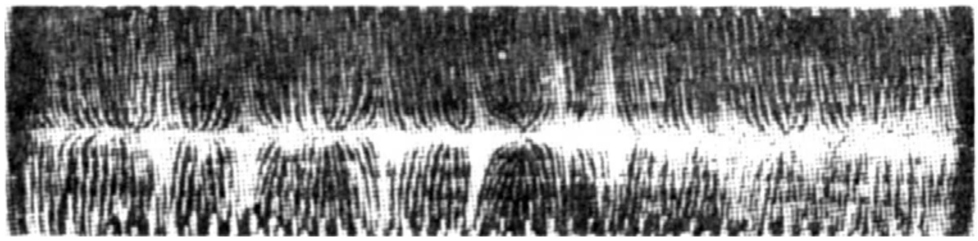
Abstract. The problem of formation of spatially periodic structures on the frontal surface of a cylindrically blunted body set transversely in a hypersonic flow is studied. Within the framework of the model adopted, a possible mechanism of vortex structure generation on the frontal surface of the blunt body is proposed and confirmed by calculations. In this mechanism, the curved bow shock produces a vortex flow, while in its turn the vortex, which persists under weak dissipation, acts on the shock thus maintaining its curved shape. It is shown that the spatially periodic mode of hypersonic flow past a cylinder can exist in the case of a uniform incident flow and under homogeneous boundary conditions on the body surface. For the independent verification of vortex self generation effect the 3D calculations have been performed using "Fluent" software. The results obtained completely acknowledge the existence of such flow regime.

INTRODUCTION

Spatial periodic structures near the frontal surface of the cylinder set perpendicular to the free stream are found at moderate and large Reynolds number (Re) both in an incompressible liquid *(Gortler H., 1955*) and in the case of compressible gas flow[1,2]. At hypersonic speeds these structures detect themselves as a system of crests and minimums of the heat flux in the vicinity of the cylinder leading edge. In the experiments which have been carried out at moderate and large Re, an essential excess of the heat flux in comparison with heat flux in the homogeneous (2D) flow is revealed. Thus, in[2] the results of an experimental investigation of the flow structure and the heat flux distribution over the frontal surface of a cylinder set transversely in a supersonic or hypersonic flow (M = 3, 5, and 6) are presented. The heat flux distribution was measured using the heat-indicating coating technique, while the limiting streamline pattern on the cylindrical surface was visualized using the smeared point method. A typical feature of the surface streamline patterns thus obtained is their spatial periodicity along the cylinder leading line (Fig.1)[2]. The same periodicity was observed when analyzing the heat flux distribution, whose amplitude could be as high as ±25% and even higher.



a) M=3 , L/R=8 , Re=3×10^6



b) M=6 , L/R=8 , Re=2.5×10^6

Fig.1 Flow lines on the cylinder frontal surface[2].

Similar investigations have been repeatedly carried out over the last thirty-forty years[3-6]. Their topicality stems from the fact that the leading edges of the wings and air-intakes of all hypersonic vehicles are blunt bodies of the type of a cylinder embedded in a flow at a zero or nonzero yaw angle. A considerable number of studies were performed in the Central Aerohydrodynamics Institute (TsAGI), though only isolated results were published (see, for example[2,5]). Despite of a plenty of researches, the nature of vortex flow in front of the cylinder is not clear. Now this problem remains actual both with fundamental and applied points of view.

In 2003 a group including V. Ya. Borovoy, S. M. Drozdov, and I. V. Struminskaya conducted an experimental study of the heat flux distribution over the frontal surface of a cylinder in a hypersonic flow. The experiments were carried out in the TsAGI UT-1M shock tunnel at a Mach number M = 6.1 over the Reynolds number range Re_∞ =[0.5 - 3.3]·10^5 on a model of cylinder R=15mm in radius equipped with 85 heat flux transducers mounted along the cylinder leading line with a high spatial resolution (1 mm). The study showed[7] that on the frontal surface of the cylinder there is formed a steady pattern of spatial heat-flux fluctuations with an amplitude that amounts to ±20% of the mean value and a typical period approximately equal to the cylinder radius $\lambda \approx R$. Certain results of these experiments are presented in Fig. 2 as a dependence of the heat flux q normalized by the character heat flux value q_o at the forward stagnation point on the cylinder calculated from the Fay-Riddell formula[4]. The horizontal coordinate is z/R, where z is directed along the cylinder leading line. The most intense and clearly defined wave pattern of the heat flux distribution is obtained at medium Reynolds numbers $Re_\infty \approx 1.7 \cdot 10^5$. Generalizing briefly the experimental results, one can argue that over a wide range of supersonic and hypersonic regimes of transverse flow past a cylinder at moderate and high Re the streamline pattern and the heat flux distribution are appreciably nonuniform along the cylinder leading line. This means that the plane (two-dimensional) mode is either not realized or distorted by spatial disturbances which can be considerably enhanced in the flow near the cylinder.

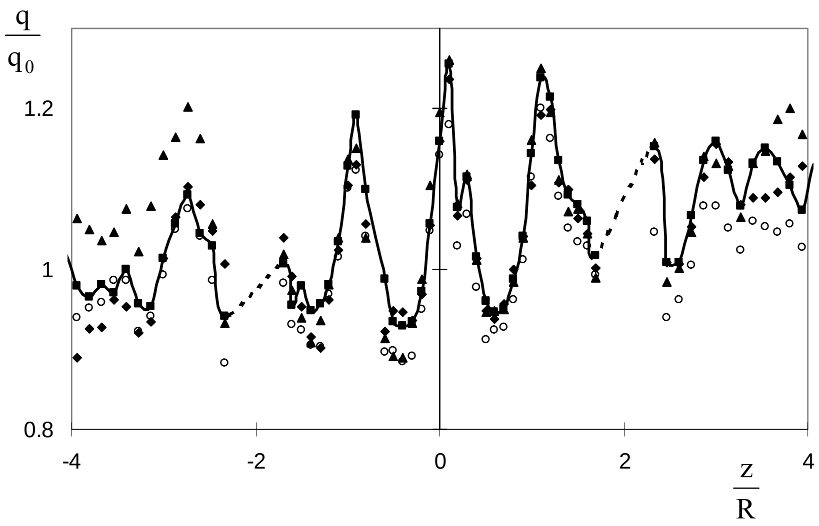


Fig.2 Heat flux distribution along the cylinder leading line[7]. Wind tunnel tests at $M_\infty=6.1$, $Re_\infty \approx 1.7\cdot 10^5$.

In most available studies, for example[1,2], the mechanism of formation of such spatial vortex structures is associated with one or another type of instability of the plane mode of the flow. For example, in the boundary layer downstream of the cylinder leading line the Gortler instability can develop. However, in the case of supersonic and hypersonic flows, this theoretical explanation faces obvious difficulties:

- Gortler vortexes are located in the boundary layer whereas the structures detected at supersonic and hypersonic velocities have a characteristic size (period λ) in transversal direction (z) about radius of frontal bluntness R or, more precisely, about twice thickness δ of the compressed layer. This conclusion directly follows from results of experimental researches[2] where was established, that the period of the structures is about 100 times grater then the characteristic wavelength of Gortler instability.
- The radial scale of vortex structures should be about thickness of compressed layer too, because it is very doubtful that vortex structures have essentially various transversal and radial scales. Such strained structures cannot exist without an external excitation.
- For the evolution of Gortler instability to final vortex structure some downstream distance is necessary. Hence, the developed Gortler vortexes can not appear directly on the symmetry plane behind the cylinder leading edge. However experiments show, that periodic crests of the heat flux disturbances occur just on the leading edge (Fig.1,2).

Thus, the secondary vortex flow has a scale much grater then boundary layer thickness, should interact with the shock wave and disturb it. On the reasons submitted above the new hypothesis of the vortex structures self-generation mechanism is proposed, in which the Gortler instability does not play an essential role.

The main purpose of this study is to present this new mechanism of vortex structure generation on the frontal surface of a blunt body in hypersonic flow and to validate it by two independent approaches: 1. Simplified numerico-analytical model and 2. Direct numerical simulation using commercial software "Fluent".

1. NUMERICO-ANALYTICAL APROACH

Numerico-analytical approach to the flow investigation in the vicinity of the frontal surface of cylindrically blunted bodies is based on the three-dimensional Navier-Stokes equations where the simplifying assumptions characteristic for hypersonic flows are accepted[3-6]: the shock layer thickness δ is small as compared with the body bluntness radius *R* , the detached bow shock is similar in shape to the frontal surface of the body, the specific heat ratio of gas γ is close to 1, the density ρ can be considered to be constant in a small sector near the symmetry plane (the plane parallel to the cylinder axis and the free stream velocity vector).

$$\frac{\rho_\infty}{\rho} = \frac{(\gamma-1)}{(\gamma+1)} = \frac{1}{\rho_s} << 1 \qquad (1.1)$$

In this case, the flow in the vicinity of the symmetry plane ahead of a smooth blunt body can be calculated without taking account of all the details of the downstream flow[3,5,6]. The full version of used numerico-analytical approach is presented in[7]. Here only basic theses are given.

Consider the cylindrical coordinate system (r, φ , z) with center on the cylinder axis (Fig. 3). We will assume that on a certain parameter range (M_∞>>1 , Re_∞>>1) a steady vortex flow, periodic along the cylinder axis z, is formed on the frontal surface of the cylinder of radius R.

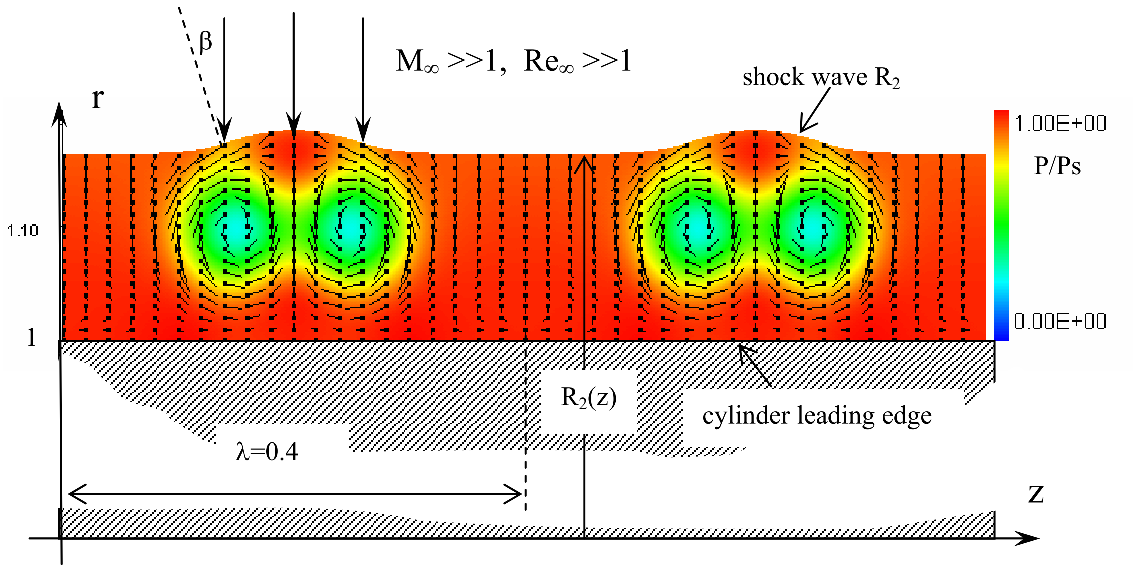


Fig.3 Calculation of the periodic vortex flow in the (r, z) plane in front of the cylinder: Pressure field and velocity vectors at Re=5000 , γ=1.2

Designate the profile of the intersection of the bow shock by the symmetry plane by a function $R_2(z)$ where R_2 is the detached shock radius (Fig. 3). Then the local angle β between the free stream direction and the normal of the shock surface is determined by the expression

$$\mathrm{tg}(\beta) = \frac{dR_2}{dz} \qquad (1.2)$$

A kernel of the new hypothesis of vortex structures generation is follows: From the Rankine-Hugoniot boundary conditions[3,5,6] one can obtain that for $M_\infty >> 1$ and $\gamma \le 1.4$ in the frontal region of the cylinder the free stream velocity component normal to the shock decreases almost by an order across the shock, while the tangential component remains the same. As a result, the flow that has crossed the shock acquires a strong vorticity even at a small shock inclination $\beta << 1$ (Fig.3). Moreover, the magnitude of the velocity on a streamline that has crossed the curved region of the shock is considerably greater than the velocity on a streamline that has crossed the shock perpendicularly. If the viscous dissipation is low ($Re_\infty >> 1$), then the flow interacting with the wall can turn counter to the oncoming flow and push the bow shock away from the body. Then a second stagnation (saddle) point appear between the body and the shock. As a result, an equilibrium state may be attained in which the curved shock produces a vortex flow, while the vortex acts on the shock, maintaining its curved shape. Energy is fed into this vortex system due to the difference in the momentum (total pressure) losses for gas particles that have crossed the shock perpendicularly and with a some inclination β.

Let us verify the validity of this hypothesis in calculations. To obtain a dimensionless form of equations the coordinates (r, z) are scaled by R and the radial v, azimuthal *w*, and axial *u* velocity components by the free stream velocity V_∞. The pressure is represented in the form:

$$P = P_\infty \rho_s \gamma M_\infty^2 P(r,\varphi,z) = P_\infty \frac{(\gamma+1)}{(\gamma-1)} \gamma M_\infty^2 P(r,\varphi,z)$$

Assuming, in addition, that in a small vicinity of the symmetry plane the viscosity is constant and equal to a certain mean viscosity μ_s (for example, the viscosity at the temperature T_s behind the shock or the stagnation temperature T_o*)*, we can bring the system of equations for the gas flow between the shock and cylinder into the form:

$$\begin{aligned}
& v\frac{\partial v}{\partial r} + \frac{w}{r}\frac{\partial v}{\partial \varphi} + u\frac{\partial v}{\partial z} - \frac{w^2}{r} = -\frac{\partial P}{\partial r} + \frac{1}{Re}[\nabla^2 v - \frac{v}{r^2} - \frac{2}{r^2}\frac{\partial w}{\partial \varphi}] \\
& v\frac{\partial w}{\partial r} + \frac{w}{r}\frac{\partial w}{\partial \varphi} + u\frac{\partial w}{\partial z} + \frac{vw}{r} = -\frac{1}{r}\frac{\partial P}{\partial \varphi} + \frac{1}{Re}[\nabla^2 w - \frac{w}{r^2} + \frac{2}{r^2}\frac{\partial v}{\partial \varphi}] \\
& v\frac{\partial u}{\partial r} + \frac{w}{r}\frac{\partial u}{\partial \varphi} + u\frac{\partial u}{\partial z} = -\frac{\partial P}{\partial z} + \frac{1}{Re}\nabla^2 u \\
& \frac{\partial (rv)}{\partial r} + \frac{\partial (ru)}{\partial z} + \frac{\partial w}{\partial \varphi} = 0
\end{aligned} \qquad (1.3)$$

Here $\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \varphi^2} + \frac{\partial^2}{\partial z^2}$, and Re is the Reynolds number based on the free stream velocity V_∞ and the flow parameters behind the shock (as distinct from Re_∞ based on the free stream parameters).

$$Re = \frac{\rho_s \rho_\infty V_\infty R}{\mu_s} = Re_\infty \, \rho_s \frac{\mu_\infty}{\mu_s} \qquad (1.4)$$

The no-slip boundary conditions are imposed on the body surface:

$$r = 1 \; : \; u = v = w = 0. \qquad (1.5)$$

For Re>>1 behind the shock, which generally may have a wavy shape $R_2(z)$, the Rankine-Hugoniot relations hold

$$(V_\infty)_N = \rho_s (V)_N \;\; ; \;\; (V_\infty)_\tau = (V)_\tau \;\; ; \;\; \frac{P_\infty}{\rho_\infty} + (V_\infty)_N^2 = \frac{P}{\rho_\infty} + \rho_s (V)_N^2 \qquad (1.6)$$

Under the assumption made above that the shock shape coincides with that of the frontal surface of the body, the conditions (1.6) take the following dimensionless form:

$$\rho_s(v - u\frac{dR_2}{dz}) = -\cos\varphi \ ; \quad \sin\varphi = w$$

$$u + v\frac{dR_2}{dz} = -\cos\varphi\frac{dR_2}{dz} \ ; \ \rho_s P(1+\left(\frac{dR_2}{dz}\right)^2) + \frac{\cos^2\varphi}{\rho_s} = \cos^2\varphi \qquad (1.7)$$

System (1.3) with boundary conditions (1.5), (1.7) can be considered only in the vicinity of the symmetry plane φ<<1. From the condition of symmetry there follows the functional dependence of the solutions on φ:

$$v(r,\varphi,z)=V(r,z)+\ldots+o(\varphi^{2k}) \ ; \ w(r,\varphi,z)=\varphi W(r,z)+\ldots+o(\varphi^{2k+1}) \ ; \ k=1, 2, 3\ldots \qquad (1.8)$$
$$u(r,\varphi,z)=U(r,z)+\ldots+o(\varphi^{2k}) \ ; \ P(r,\varphi,z)=P(r,z)+ \varphi^2 Q(r,z)+\ldots+o(\varphi^{2k+2})$$

Retaining in Eq. (1.3) the terms of the leading order in φ we obtain:

$$V\frac{\partial V}{\partial r} + U\frac{\partial V}{\partial z} = -\frac{\partial P}{\partial r} + \frac{1}{Re}[\Delta V - \frac{V+2W}{r^2}]$$

$$\frac{W^2}{r} = \frac{\partial Q}{\partial r}$$

$$V\frac{\partial W}{\partial r} + U\frac{\partial W}{\partial z} + \frac{W^2+WV}{r} = -\frac{2Q}{r} + \frac{1}{Re}[\Delta W - \frac{W}{r^2}] \qquad (1.9)$$

$$V\frac{\partial U}{\partial r} + U\frac{\partial U}{\partial z} = -\frac{\partial P}{\partial z} + \frac{1}{Re}\Delta U$$

$$\frac{\partial(rV)}{\partial r} + \frac{\partial(rU)}{\partial z} + W = 0 \quad ; \quad \Delta = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2}$$

Note that in the pressure representation (1.8) the term with φ^2 should be retained. Otherwise, the pressure derivative with respect to φ vanishes and, together with it, the factor responsible for the spreading of the gas along the frontal surface of the body[6]. The boundary conditions on the body surface are as follows:

$$r = 1 \ : \ U=V=W=0 \qquad (1.10)$$

The hypersonic nature of the original compressible flow is conserved only in the boundary conditions behind the shock $r = R_2(z)$:

$$\rho_s(V - U\frac{dR_2}{dz}) = -1 \ ; \quad W = 1 \ ; \quad U + V\frac{dR_2}{dz} = -\frac{dR_2}{dz} \qquad (1.11)$$

$$\rho_s P(1+\left(\frac{dR_2}{dz}\right)^2) - \frac{\rho_s - 1}{\rho_s} = 0; \quad \rho_s Q(1+\left(\frac{dR_2}{dz}\right)^2) + \frac{\rho_s - 1}{\rho_s} = 0$$

The above flow model (1.8)—(1.11) is quasi-three-dimensional. As in the theory of viscous hypersonic shock layers (see, for example[3-6]), in the model proposed the variation of the flow downstream of the attachment line is described by a power series in the angle φ with the least possible number of terms. But in our case, both the pressure gradient normal to the body surface and all the terms of the Navier-Stokes equations responsible for the flow variation in the transverse (z) and radial (r) directions are retained. This makes it possible to describe the strong interaction between the shock layer flow and the bow shock, which is a necessary condition for vortex structure generation. On the other hand, this model is considerably simpler than the three-dimensional system of Navier-Stokes equations, whose solution presents serious problems at high Reynolds numbers $Re > 10^4$ from the standpoint of both the mathematical correctness of numerical algorithms used and the sufficient spatial resolution of the grid.

In order to fix the domain of integration of system (1.9) between the shock and the body we introduce a new variables:

$$\xi = z; \quad \eta = \frac{r-1}{[R_2(z)-1]}; \quad -\infty < \xi < \infty \quad 0 \le \eta \le 1 \tag{1.12}$$

Let the flow in the vicinity of the attachment plane on the frontal surface of the cylinder be periodic along x with a certain period λ=2π/s. Then the shock radius and stand-off distance δ are also periodic functions of x which can be represented by convergent Fourier series:

$$R_2(\xi) = \sum_{n=-\infty}^{\infty} B_n \exp(ins\xi); \quad \delta(\xi) = R_2(\xi) - 1 \tag{1.13}$$

The periodic solution of (1.9)-(1.11) can also be represented in the Fourier series:

$$\begin{pmatrix} U \\ V \\ W \\ P \\ Q \end{pmatrix} = \sum_{n=-\infty}^{\infty} \begin{pmatrix} iU_n(\eta) \\ V_n(\eta) \\ W_n(\eta) \\ P_n(\eta) \\ Q_n(\eta) \end{pmatrix} \exp(ins\xi) \tag{1.14}$$

$$U_0(\eta) \equiv 0, \quad U_{-n}(\eta) = -U_n(\eta), \quad V_{-n}(\eta) = V_n(\eta)$$
$$W_{-n}(\eta) = W_n(\eta), \quad P_{-n}(y) = P_n(\eta), \quad Q_{-n}(\eta) = Q_n(\eta)$$

Substituting (1.14) in Eq. (1.9) with regard (1.12) gives a system of ordinary differential equations for the amplitudes of the harmonics. The Fourier coefficients of the nonlinear terms are represented in explicit analytical form, for example:

$$< V \cdot W >_n = \sum_{k=-\infty}^{\infty} V_k W_{n-k} \tag{1.15}$$

For further analysis, it is necessary to consider only the basic structure of the amplitude equations, their complete algebraic form being used only in writing programs. Formally, the amplitude system consists of an infinite number of blocks, each of which represents a balance of the terms of the equations (1.9) corresponding to the harmonic with number *n*. The nonlinear terms (1.15) relate blocks with different values of *n*. Assuming the fast convergence of Fourier coefficients the series (1.13), (1.14) have been limited by final number N>>1 of harmonics.

The boundary value problem for the system of ordinary differential equations in the Fourier coefficients was solved by a finite difference method in which the derivatives were approximated using a second-order central difference scheme. The nonlinear algebraic system of difference equations was solved by the modified Newton method. All calculations were performed with double accuracy. The correctness of the calculations was checked against the rapid convergence of the iteration procedure in the Newton method and the results of increasing the number of harmonics N in the Fourier series (1.14), as well from a negligibly small error in the integral balance of forces and moments acting on a single flow period. The main calculations were performed at the following spatial resolution: number of harmonics per period N=30 and number of gridpoints in the η coordinate 201.

The results of the numerical study showed that for a uniform free stream, in the vicinity of the symmetry plane ahead of a cylinder of constant radius r=1 only a uniform-in-z flow is formed if the initial approximation is uniform in *z*. In this flow, all the harmonics (1.14), except for the zeroth one (n=0), are equal to zero. The zeroth harmonics and the shock stand-off distance δ are identical to the solution of the system (1.9) at two-dimensional case. This is quite natural, since the two-dimensional solution is the first branch of the three-dimensional problem. The essence of the problem is in determining a three-dimensional branch or demonstrating its nonexistence.

A new branch can be reached by solving an evolution problem starting from a nonuniform field of the initial approximation. In the first set of calculations a flow with ε=1% three-dimensional saw-tooth fluctuations of the velocity V_∞ was imposed. The calculations showed that in the shock layer on the frontal surface of the cylinder the velocity disturbances essentially increased, however en elimination of external disturbances again led the flow onto the two-dimensional branch. Only at $\varepsilon \geq 2\%$ the initial disturbance transformed into a system of steady z-periodic vortices which do not vanish after the disturbances in the oncoming flow have been eliminated.

Figure 3 shows the pressure distribution and flow pattern in the symmetry plane (r, z). The calculations were carried out for γ= 1.2, Re = 5000, and λ=0.4. One flow period consists of two vortices rotating in opposite directions with an intense circulation. As might be expected, the shock becomes curved in *z,* the flow behind the shock becomes vortical and the velocity vector between the vortex centers is directed counter to the oncoming flow. The calculations showed that the vortex flow is fairly intense. The pressure in the vortex cores decreases by a factor of about two. In a compressible flow this could lead to a certain decrease in the gas density but hardly have a considerable effect on the basic mechanism of vortex generation. The vortex flow intensifies the heat transfer from the flow to the cylinder surface, therefore the periodic streamline pattern is associated with a periodic variation of the heat flux to the wall. However, within the framework of this model the energy equation is not used and the value of the heat flux to the wall cannot be calculated.

Calculations made in the range Re=[500 - 8×10^4] , γ= [1.1 - 1.4], λ=[0.2 - 1] show that a spatially-periodic mode of the hypersonic flow past a cylinder can in fact exist for a uniform free stream and under homogeneous boundary conditions. Hence confirmed the physical mechanism of vortex structure generation on the frontal surface of a blunt body in which the curved bow shock produces a vortex flow, while in its turn the vortex, which persists under weak dissipation, acts on the shock, thus maintaining its curved shape. But the quantitative imperfection of the model used is evident and an independent verification of investigated phenomena is necessary.

2. DIRECT NUMERICAL SIMULATION

Direct numerical simulation of hypersonic vortex flow near cylinder is made by one of well known software FLUENT. FLUENT is a state-of-the-art computer program for modelling incompressible and compressible fluid flow and heat transfer in complex geometries. In this work FLUENT is used for 3D simulation of perfect viscous and heat conducting gas flow near the frontal surface of cylinder. Calculation domain consists of: I-main region with fine grid, II-region with rarefied grid and III-buffer region with rough grid (Fig.4, 5). Total grid has a 588406 hexahedral cells. On the frontal surface of the domain the free stream conditions M_∞ , P_∞, T_∞ are imposed and on the exit surface the no-reflection conditions are put. On the cylinder the no-slip boundary condition and wall temperature Tw are put and the grid has 10 additional rows for boundary layer resolution. In the transversal direction z the flow domain is limited by two plates z=0 and z=λ/2 where the symmetry conditions are put.

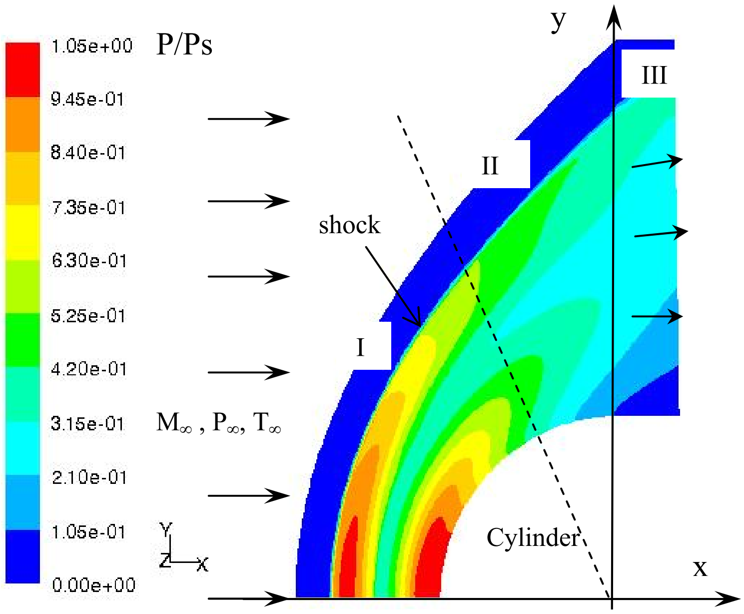


Fig.4. Scheme of calculation domain and pressure field P/Ps (section z=0) at M_∞=6.1 , Re_∞=3240 , Re=2700, γ=1.4

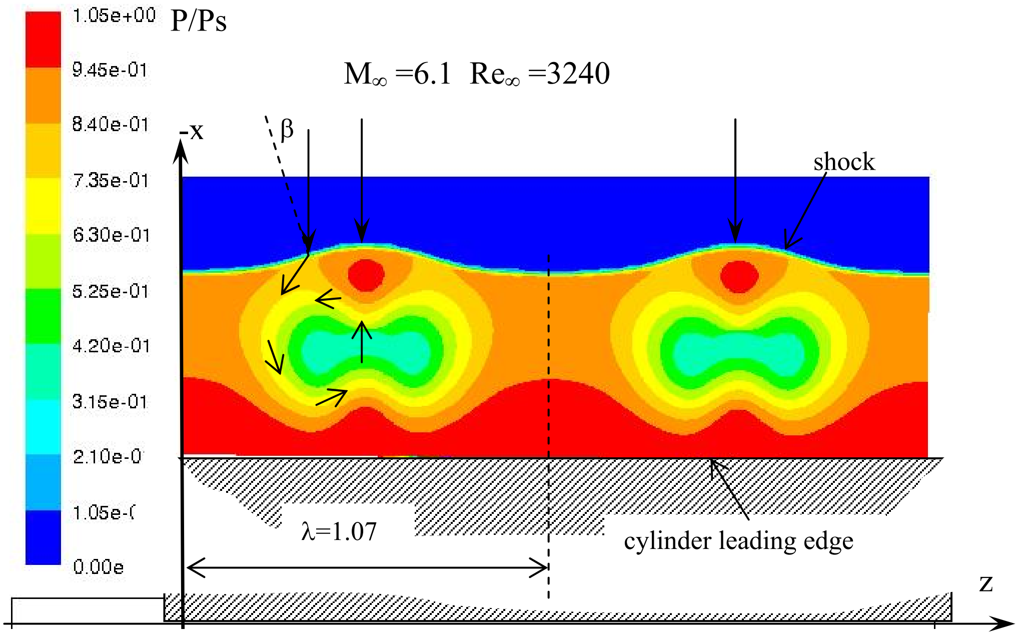


Fig.5. Scheme of calculation domain and pressure field P/Ps on the symmetry plane y=0 at M_∞=6.1 , Re_∞=3240 , Re=2700 , γ=1.4

In the calculations the vortex flow mode has been provoked using the same procedure like in the numerico-analytical approach. Some calculation results obtained at M_∞=6.1 , Re_∞=3240 , Re=2700 , γ=1.4 , T_w/T_0=0.49 are presented in the Fig.4-7. The strong vortices are generated in front of the cylinder. The pressure in the vortex core drops more then two times and back flow achieves supersonic velocity M≈1.3 (in Fig.3,4,5 Ps - stagnation pressure past the normal shock).

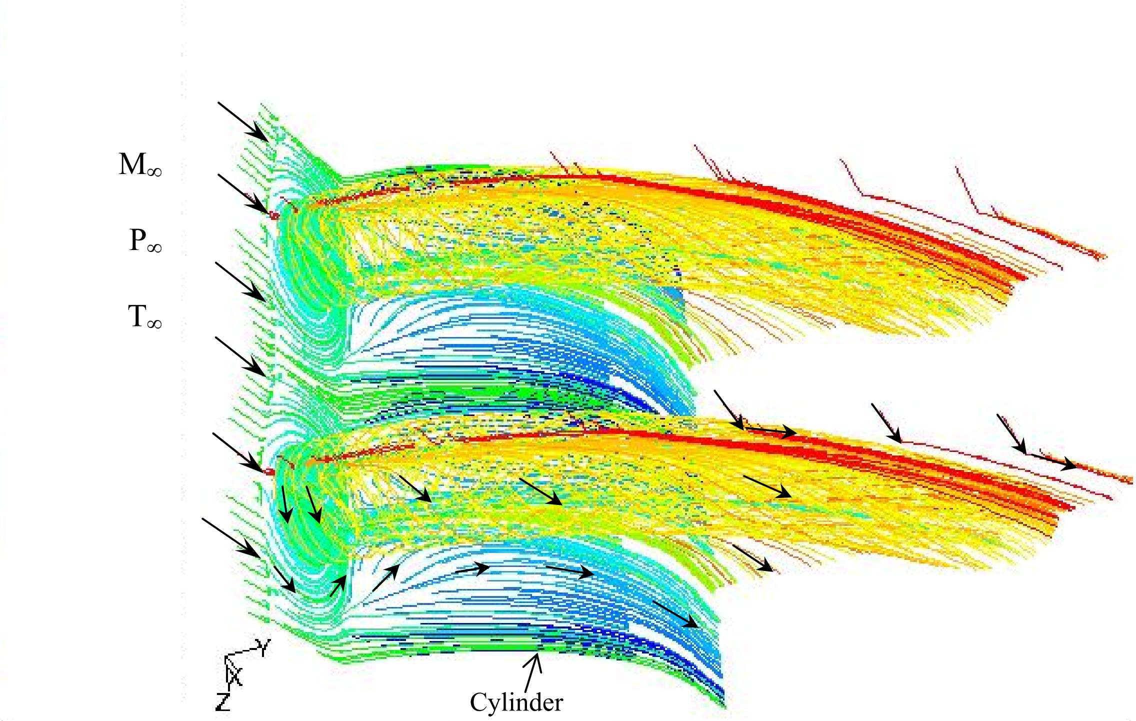


Fig.6. Vortex flow lines in front of the cylinder
at M_∞=6.1 , Re_∞=3240 , Re=2700 , γ=1.4

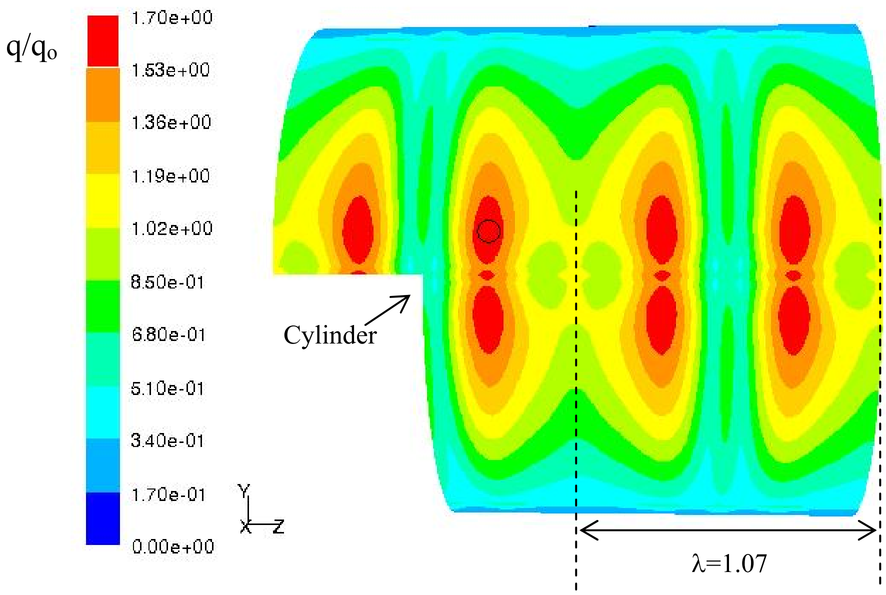


Fig.7. Heat flux on the cylinder q/q_o at M_∞=6.1 , Re_∞=3240 , Re=2700 , γ=1.4 (front view).

The picture of vortex flow lines in front of the cylinder is presented in Fig.6. The vortex flow intensifies the heat transfer from the flow to the cylinder surface. As shown in Fig.7 the peaks of heat flux become 1.7 times greater than heat flux q_o in forward stagnation point at two-dimensional flow mode.

Calculations performed for air (γ= 1.4) at M_∞=6.1 in the range Re_∞=[1000 - 4000] , show that a spatially-periodic mode of the hypersonic flow past a cylinder is exist in the range Re_∞>2000 for a uniform free stream and under homogeneous boundary conditions. The vortex flow mode is received also in calculations at the big hypersonic speed M_∞=12 for gas with γ= 1.2 . In this case the peaks of heat flux become 3 times greater than heat flux q_o in forward stagnation point at two-dimensional flow mode.

CONCLUSION

A new hypothesis for the mechanism of formation of spatially-periodic structures on the frontal surface of a cylindrically-blunted body in a transverse hypersonic flow is suggested. Calculations within the framework of numerico-analytical model and direct numerical simulation using the FLUENT software show that a spatially-periodic mode of the hypersonic flow past a cylinder can in fact exist for a uniform freestream and under homogeneous boundary conditions. Calculations also confirm the physical mechanism of vortex structure generation on the frontal surface of a blunt body in which the curved bow shock produces a vortex flow, while in its turn the vortex, which persists under weak dissipation, acts on the shock, thus maintaining its curved shape. Energy is fed into this vortex system due to the difference in the momentum (stagnation pressure) losses for gas particles that have crossed the shock normally and with a some inclination. The vortex flow characterized by strong circulation that produces the peaks of heat flux on the cylinder that 1.7 - 3 times exceed the heat flux q_o in forward stagnation point at two-dimensional flow mode. Such flow regime, if appear, will be dangerous for the wing leading edge and air-intake of hypersonic vehicles.

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