ESTIMATION OF ENERGY CONSUMPTION FOR BODY DRAG REDUCTION IN A SUPERSONIC FLOW

V. Yu. Borzov, I. V. Rybka, and A. S. Yur'ev

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Comparative estimation of the drag reduction effect attained versus the required energy consumptions is made from numerical results of axisymmetric supersonic nonviscous gas flow past a blunt body with heat energy supplied to the gas in the vicinity of the symmetry axis.

Complying with two opposite requirements for an aerodynamic vehicle shape is one of the most complex problems of designing a high-speed vehicle. On the one hand, high force and heat loads on the design increase thicknesses of its elements and rounding radii of their frontal surfaces and, on the other hand, improving the aerodynamic characteristics requires the mentioned parameters to be decreased. Because of this, the possibility of substantially increasing the hypersonic aerodynamic quality due to the choice of an aerodynamic shape is practically exhausted at present. At the same time the flow control, namely, the goal-directed effect on the gas flow to reconstruct its structure according to the required changes in aerodynamic coefficients or other flow parameters, is a promising means of further improvement of such vehicle aerodynamics. Among the flow control modes that differently affect the flow and are most suitable for super- and hypersonic flights there are mainly those that enable one to realize the long-range principle, i.e., to prepare beforehand incoming flow past a body. Therefore, in studies most attention has been paid mainly to mechanical (aerodynamic needles, needles with disk or any other nozzle in the frontal body part) and gas dynamic (axial or radial gas blowing-out of the vehicle elements) flow control modes and their combinations [1-3]. Along with a favorable effect, these modes also possess some drawbacks such as substantial restrictions on the distance of the incoming flow effect region from a body, difficulties in changing this regions position and shape, and reduction of the positive effects with a growing attack angle. The flow control mode based on developing a low-density layer in the incoming flow due to heat energy supply to the gas is, in essence, close to the above stated ones but having none of the mentioned drawbacks. This is supported by the analysis of the flow structure and the nature of flow past different obstacles with energy supply to the gas [4-6]. However, use of heat energy supply to the flow as a flow control mode requires the preliminary estimation of the energy supply efficiency of the flow control process, i.e., comparison of the attained level of improving the aerodynamic characteristics and the necessary energy consumptions. Such an analysis has been made in [7]; however, it points to a very low energy supply efficiency of this process when the long-range principle is not satisfied, i.e., heat energy supply in a hypersonic shock layer flow past a cone. A considerable change of aerodynamic coefficients is reached with energy supply to the incoming flow outside the shock layer as in [5, 6], but these works do not analyze energy consumptions and consider flow around bodies whose shape differs greatly from that of the elements of high-speed vehicles. Based on this, the results below are concerned with an axisymmetric hypersonic ideal gas flow past a body having an elliptic component when the energy supply region is present in the incoming flow (Fig. 1). In what follows, attention is paid not only to the analysis of the flow structure and the body load distribution, but also to the comparison of the drag change with the energy consumption necessary for this.

Numerical study has been made by using the algorithm that implements S. K. Godunov's method at the incoming flow Mach number $M_\infty = 17$. The energy supply is assigned as an extra term in the energy conservation equation within a cylindrical region Ω, whose axis coincides with that of the body, and the radius $r_\Omega = 0.1D$. As for the length of the region Ω two limiting cases are considered: 1) concentrated energy supply when the region Ω length is $\Delta l = 0.025D$, which corresponds to the shock layer thickness on the symmetry axis with no energy supply; 2) distributed energy supply $\Delta l = l$, i.e., energy is supplied along the entire region Ω from its leading edge to the frontal body surface. The parameter l, distance of the leading edge of the energy supply region, can be varied. The energy supply power density is proportional to the med-

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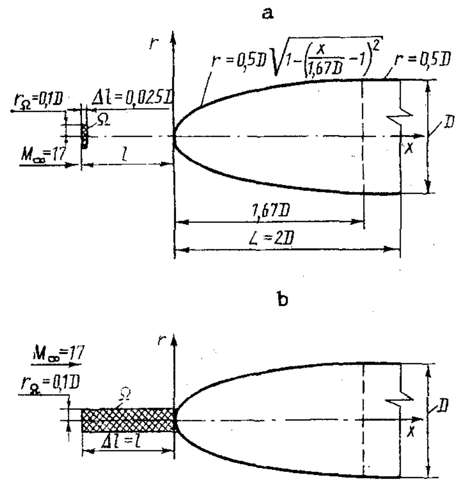

Fig. 1. Design diagrams of flow past a body with heat energy supply to the flow: a) concentrated energy supply; b) distributed energy supply.

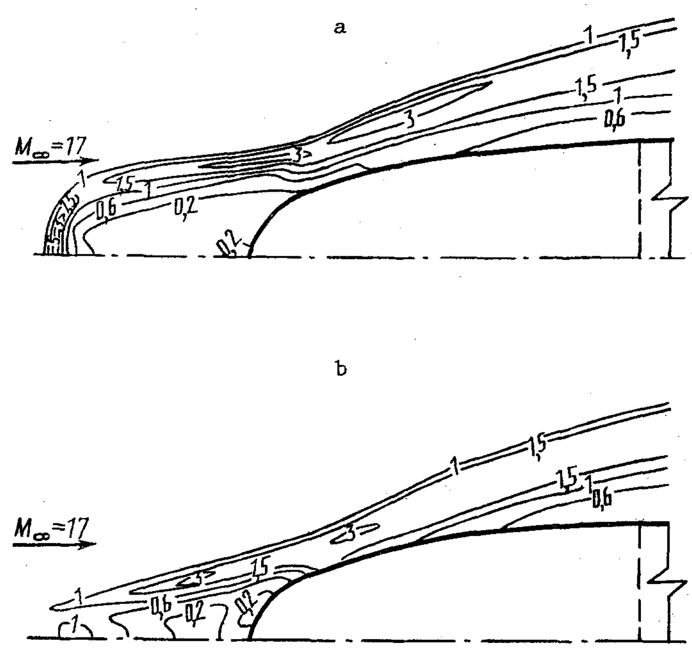

Fig. 2. Isolines of the relative flow density ρ/ρ_∞ at l = 0.8D: a) concentrated energy supply; b) distributed energy supply.

ium density at a given point, which is consistent with some cases of real energy supply. The energy supply power in the entire region Ω is determined as

$$I = \int_\Omega \rho q d\Omega,$$

where ρ is the gas density; q is the specific power of the energy supply, i.e. energy supplied to unit gas mass per unit time.

In varying l, the specific power is calculated as

$$q = \frac{u_\infty^3}{\Delta l},$$

where u_∞ is the incoming flow velocity.

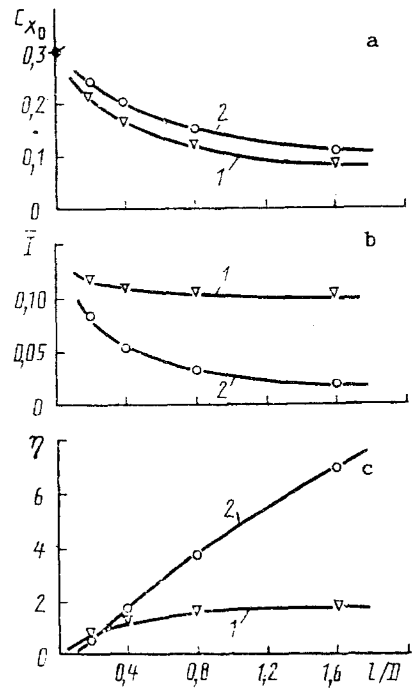

Fig. 3. Process parameters vs. the distance of the leading edge of the region Ω from a body [1) concentrated energy supply; 2) distributed energy supply]: a) drag coefficient; b) dimensionless energy supply power; c) energy supply efficiency index.

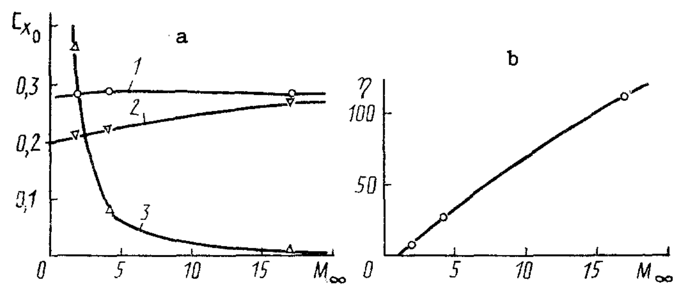

Fig. 4. Process parameters vs. the incoming flow Mach number: a) drag coefficient [1) wave component with no energy supply, 2) with energy supply, 3) limiting bottom component]; b) energy supply efficiency index.

To estimate the energy supply efficiency of the flow control process the index adopted in [7] is used:

$$\eta = \frac{-\Delta X_0 u_\infty}{I}.$$

Thus, the denominator stands for the power of energy supply to the flow and the numerator, the decrease (due to drag reduction) of the useful power of a propulsion system that provides the thrust in a steady level flight. If the integral power of energy supply reduces to a dimensionless form

$$\bar{I} = \frac{2I}{\rho_\infty u_\infty^3 S},$$

where ρ_∞ is the incoming flow density and S is the characteristic body area, then the index of energy supply efficiency is determined as

$$\eta = \frac{-\Delta Cx_0}{\bar{I}},$$

where ΔCx_0 is the drag coefficient at the control of flow past a body.

The above relation for determination of the specific power of energy supply provides the invariable integral power of energy supply when Δl changes if the gas density in the region Ω remains invariable. However, the calculations show that the density distribution in the design region and also in the energy supply zone depends both on the dimension of the region Ω, Δl, and on its position relative to the body, characterized by the parameter l. Hence, the integral supply power I varies. The density variation is the cause of the radial gas blowing-out of the region Ω and its deceleration at its inlet due to thermal expansion. These processes are detailed in [6]. Typical density distributions for concentrated (a) and distributed (b) energy supplies are shown in Fig. 2. At small values of l/D, i.e., with energy supply in a shock layer the flow pattern changes slightly, the change in the drag coefficient Cx_0 is practically absent, which correlates with the results cited in [7], and the index η is close to zero (Fig. 3). With an increase the distance of the leading edge of the region Ω from the frontal body surface, the flow is essentially reconstructed, and the gas density and the local Mach numbers decrease in the axial part of the flow incoming onto the body; moreover, the gas acquires a radial velocity component before it interacts with the body. This results in reducing the pressure coefficient on the body surface, especially in the vicinity of the forward stagnation point, where a toroidal vortex originates under the majority of the considered regimes. As the ratio l/D increases, Cx_0 decreases greatly (Fig. 3).

It should be noted that in falling outside the restrictions on the geometrical parameters characteristic of mechanical and gas dynamic means for flow control ($l/D < 1$) the aerodynamic characteristics are substantially improved, which is accompanied by further energy consumption reduction in the case of a distributed energy supply. As the results below will show, the purposeful variation of the geometrical and energy parameters of the flow control modes enables one to obtain substantially great values of the index η.

Along with the variation of the geometrical parameters of the energy supply region, the hysteresis that takes place at periodic energy supply is an important factor in improving the flow control efficiency. Drag reduction occurs with some delay after the initial energy supply, and this delay grows with increasing l/D. The delay is also observed in the opposite process; i.e., after the energy supply ceases, during some time the drag coefficient remains practically invariable and only then returns smoothly to its initial value. To estimate the energy supply efficiency of such a process the integral index

$$\eta_\Sigma = \frac{-\int_0^T \Delta X_0 u_\infty dt}{\int_0^T I dt}$$

is suitable, i.e., the time-integral saved-to-spent energy ratio. Calculation results on the flow past the frontal body part at l = 1.6D for single energy supply pulses of $\tau \approx 2.5D/u_\infty$ show that if the maximum value η_{max} is approximately equal to the integral energy supply efficiency index η_Σ at a distributed energy supply, then for a concentrated energy supply $\eta_\Sigma \approx 1.5\eta_{max}$.

Of practical interest is also the energy supply efficiency index as a function of incoming flow Mach number, provided that the integral power is chosen so that the ratio between the energy supplied to the flow and the internal energy of the gas flowing through the region Ω cross section per unit time remains constant

$$\overline{\Delta\varepsilon} = \frac{I}{\varepsilon_\infty \rho_\infty u_\infty S_\Omega} = \text{const},$$

where S_Ω is the area normal to the flow in the region Ω cross section; ε_∞ is the internal energy of unit gas mass in the undisturbed flow.

In this case, the dimensionless integral power is

$$\bar{I} = \frac{2\overline{\Delta\varepsilon}\bar{S}_\Omega}{M_\infty^2 \varkappa (\varkappa - 1)},$$

where $\bar{S}_\Omega = S_\Omega/S$ is the relative area of the energy supply region; $\varkappa = 1.4$ is the air adiabat index.

The calculation results obtained with $\bar{I}$ chosen assuming $\overline{\Delta\varepsilon} = 5$, $\Delta l = D$, $l = 3.5D$, $r_\Omega = 0.025D$ are shown in Fig. 4. They point to a substantial increase of the energy supply efficiency index due to the Mach number growth when the energy supply effect on the drag coefficient somewhat decreases. Such a plot of η against M_∞ is caused by the fact that the drag coefficient decreases linearly with the growth of the Mach number while the dimensionless integral power of energy supply is inversely proportional to the squared Mach number.

Thus, the numerical results allow one to conclude that the heat energy supply to the incoming gas flow is an effective (from the energy point of view) flow control mode. The regimes corresponding to considerable (several times the size of the body) distances of the leading edge of the energy supply region at its longer length and higher incoming flow Mach numbers are most favorable from the viewpoint of the drag reduction and energy consumptions to realize the process.

NOTATION

M, Mach number; Ω, region to which heat energy is supplied; r_Ω, radius of the region Ω; D, maximum body diameter; Δl, length of region Ω along the x-axis; I, integral (with respect to the region Ω volume) power of energy supply; u, flow velocity; η, energy supply efficiency index of the flow control process; ΔX_0, drag force change at energy supply; S, body midsection area; $\bar{I}$, dimensionless power of energy supply; Cx_0, body drag coefficient at a zero attack angle; t, process time; η_Σ, integral energy supply efficiency index of the flow control process; τ, energy supply pulse time; $\Delta\bar{\varepsilon}$, ratio of the integral energy supply power to internal energy of the gas flowing through the cross section of the region Ω per unit time; ε, internal gas energy. Indices: ∞, undisturbed flow.

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