SUPERSONIC FLOW OF VISCOUS GAS PAST BLUNT BODIES

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A hypersonic viscous shock layer was investigated in [1, 2]. The present paper gives the results of calculation of a flow of viscous gas at moderate and low supersonic free-stream velocities ($M_\infty \leq 10$), when the specific heat of the gas can be regarded as constant. The formulation of the problem is similar to that used in [1, 2]. The solution of the "shortened" Navier–Stokes equations is obtained by the method of finite differences in accordance with an implicit nine-point scheme. The number of points on the calculation net (up to 30) was chosen to secure the required accuracy of the calculations. The nonlinear system of difference equations was solved by an iterative method. For cases of a thermally insulated and cooled surface the shape and position of the shock wave were determined, the stream lines and sonic lines were constructed, the profiles of the gasdynamic parameters in the shock layer were obtained, and the distribution of heat flux and friction over the surface of the sphere in different flow regimes was investigated. A wide range of Reynolds numbers (R_∞) was considered.

A numerical solution of the Navier–Stokes equations for viscous flow at low Reynolds numbers was given in [3-6]. Magomedov [7] used asymptotic expansions and estimates to investigate a viscous hypersonic layer.

1. The calculations were made for a diatomic gas ($\gamma = 1.4$) with Prandtl number 0.72, in the range of Mach numbers $1.4 \leq M \leq 10$ and Reynolds numbers $10^2 \leq R_\infty \leq 10^5$ ($R_\infty = \gamma^{1/2} M_\infty R$). It was assumed that the coefficient of dynamic viscosity was related to the temperature by a power law with an index of 0.5. In the investigation of flow past a cooled sphere the dimensionless temperature of the surface was taken as 0.05. In the following account the symbols of [2] will be used. Some of the obtained results are given below.

2. Figure 1 shows the profiles of the gasdynamic parameters across the shock layer for the case of flow past a thermally insulated sphere at $M_\infty = 10$, $R = 26.7265$. The circles are Tolstykh's results [3]. The calculations showed that the standoff distance and shape of the shock wave differed by not more than 5%. The comparison indicates that the employed model of the viscous layer, formally valid for $R_\infty \gg 10^3$, can be used for lower Reynolds numbers. It should be noted that the profiles of T and v are almost linear in a wide range of Reynolds numbers.

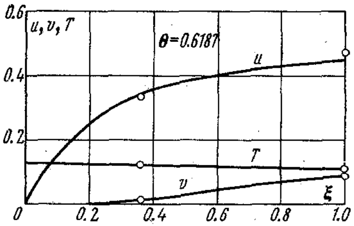

Fig. 1

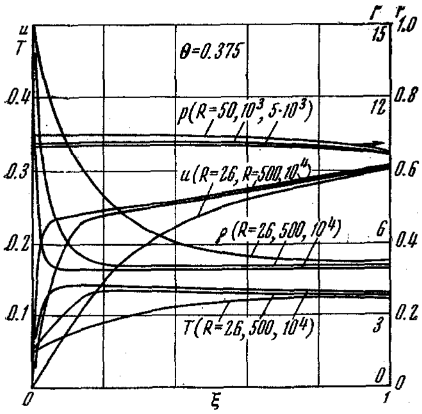

Fig. 2

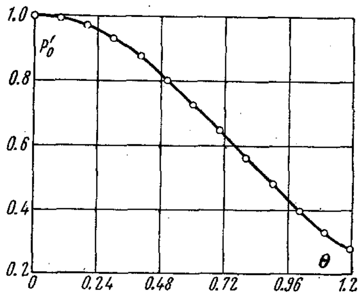

Fig. 3

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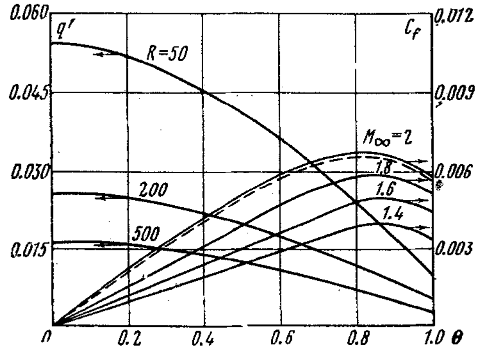

Fig. 4

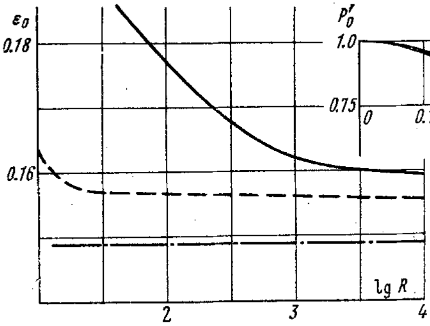

Fig. 5

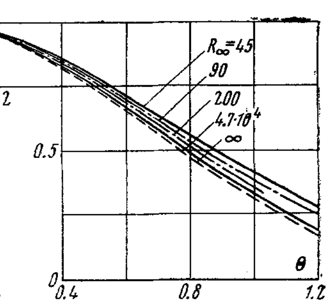

Fig. 6

Figure 2 shows the variation of the gasdynamic parameters in the shock layer for $M_\infty = 6$ and different Reynolds numbers in the case of a cooled sphere. The figure shows that at large R the main change in the tangential velocity component u and in the temperature and density occurs in a narrow region near the body surface. The size of this region decreases with increase in R. The values of the gasdynamic functions outside this region depend weakly on the Reynolds number.

The calculations showed that at different R the pressure across the shock layer varies insignificantly for both cooled and thermally insulated spheres.

Figure 3 shows the calculated pressure distribution over the sphere for $M_\infty = 2$, $R = 10^4$ (continuous curve), and the results of Ryabinkov's measurements [3] (points). A comparison shows that the theoretical data are in good agreement with the experimental results.

As an example of the variation of the heat transfer and friction parameters, Fig. 4 shows the heat flux distribution over the surface of a cooled sphere for $M_\infty = 6$ and various values of Reynolds number and the friction coefficient on the surface of a thermally insulated sphere for $R = 10^4$ and various Mach numbers. The broken curve denotes the results of boundary layer calculations from the data of [9].

Figure 5 shows the shock standoff distance ε_0 on the axis of symmetry as a function of the Reynolds number for $M_\infty = 6$ in the case of a thermally insulated surface (continuous curve), a cooled surface (broken curve), and nonviscous flow (dot–dash curve plotted from the data of [8]). In the first case an increase in R has little effect on ε_0. The standoff distance in the case of a cooled surface is smaller than for a thermally insulated surface, which can be attributed to removal of the heat energy from the shock layer due to cooling of the body surface, and, beginning at $R \approx 20$, varies insignificantly. In both cases the standoff distance is greater than its value in an ideal gas.

Figure 6 shows the distribution of pressure, relative to the pressure at the stagnation point, over the surface of a thermally insulated sphere for $M_\infty = 4$ and various Reynolds numbers. The broken curve shows the data for an ideal gas [8], the dot–dash curves show the results of [4], and the continuous curve the results of the present work. It should be noted that with increase in R_∞ the distribution of reduced pressure differs less and less from the pressure distribution for an ideal gas.

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