CALCULATION OF THE BASIC CHARACTERISTICS OF THE HYPERSONIC NEAR WAKE

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The problem of determining the parameters of the near wake is important, in particular, for calculation of the characteristics of nonequilibrium hypersonic wakes and determining the total drag of slender bodies [1]. In recent years there have been numerical investigations of the characteristics of the hypersonic near wake for quite large Reynolds number, based on the complete system of hydromechanical equations [2]. The computational technique used in [2] is very laborious, requires initial data for its application, obtained using complex methods of calculating flow over a body [3], and is limited to the case of a perfect gas. In [4] a relatively simple technique was proposed for approximate calculation of the characteristics of the viscous subregion of the near wake behind bodies, allowing for the real properties of gases, and free of the limitations imposed by the velocity of the supersonic gas stream near the body trailing edge, as occurred in [5], and by the temperature of the lateral body surface. A first stage in this technique is the calculation of the pressure, velocity, and enthalpy in the near-axial region of the near wake in the perfect gas model. The computational scheme for these quantities is based on a whole series of simplifying assumptions, when the associated errors cannot be estimated beforehand. The objective of the present paper is to demonstrate the possibilities of the method of [4] for computing the characteristics of the laminar near wake, and to justify it by a broad comparison of the computational data with known test data and with computational data obtained from a rigorous formulation of the problem.

Calculations have been made for the near wakes behind cones washed by a perfect gas, for the cases shown in Table 1, where α is the cone semiopening angle, r is the nose radius, referenced to the base section radius, H_w is the enthalpy of the lateral surface, referenced to the total enthalpy of the oncoming stream, M is the Mach number, Re is the Reynolds number, referenced to the oncoming stream parameters and the base diameter, and $\varkappa$ is the specific heat ratio. The right-hand column gives the reference in which the corresponding case has been investigated, either experimentally or numerically.

The information, required for the calculation, on the distribution of the gas parameters ahead of the base section was taken from the reference, whose results were used for the comparison (if these data were given in the reference); alternatively the values were calculated using the method of [4].

We turn first to the question of calculating the upstream influence of the base pressure. The pressure drop ahead of the base section was computed in [4], using a formula for the critical pressure drop. The use of this formula, which is not strictly valid for the case considered, is based on numerous computations with the technique of [14]. Examples of the results of such calculations are shown by points 1-3 in Fig. 1, where the pressure drop is given (referenced to the pressure at infinity) ahead of the base section for cases 8-10. The coordinate x is referenced to the base diameter, and is reckoned from the base along the symmetry axis. The solid lines show the data of [2, 3], obtained by numerical integration of the system of Navier–Stokes equations. The numbers on the curves correspond to the Table 1 cases. When using the method of [14] we took the unperturbed pressure value to be the value corresponding to the point $x = -0.25$ (which is 2 or 3 boundary-layer thicknesses from the base). In accordance with asymptotic theory [14] this value goes off to minus infinity, which means that at this point our computational data do not lie on the solid curve. It is clear that the ratio of the unperturbed pressure to the base value is about 1.89, which agrees well with the formula for the critical pressure drop. It can be seen from Fig. 1 also that the technique of [14], which is strictly valid for asymptotically large Reynolds number, agrees with the results of the numerical analysis of [2], which refer to comparatively low values of Reynolds number.

Figure 2 shows the pressure distribution along the wakes (the curve number corresponds to the Table 1 case). The solid lines show the calculation using the technique of [4], and the broken lines show the corresponding data given in Table 1 reference (the broken curve 7 is given for average points in the region of test data scatter, and the coordinate axes for curves 9 and 10 are shown on the left and right).

Figure 3 shows the relative enthalpy H_0 of the viscous sublayer at the section corresponding to the computational position of the rear stagnation point for cases 1, 2, 6-12. The case numbers from Table 1 are shown on the abscissa axis.

It was assumed in [4], from results of experimental [13] and theoretical [15] investigations, that the total enthalpy is constant in the viscous sublayer (the value is determined by calculation and depends, in particular, on the profiles of the flow parameters ahead of the base, or, in other words, depends on the condition for forming the flow field along the lateral body surface). Since the calculated total enthalpy is essentially the average value of the viscous sublayer enthalpy, and mainly axial values were measured in the tests, it is difficult to compare directly with the test data. Judging from the data of [11, 13], where radial total enthalpy distributions were given, its average value over the viscous sublayer exceeds its axial value by about 20%. Therefore, in the comparison with calculated data, the axial enthalpy values given in [2, 7, 11-13] have been multiplied by the factor 1.2. These values are shown in Fig. 3 by the points 1, while points 2 are the

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TABLE 1

Case number	$\alpha°$	r	H_w	M	$Re/10^5$	$\varkappa$	Reference
1	7	0	0,88	4,3	0,9	1,4	[6]
2	9	0	0,49	7	5	1,4	[7]
3	10	0,2	1	16	1,2	1,67	[8]
4	7	0	0,86	6,3	0,9	1,4	[9]
5	10	0	1	16	1,2	1,67	[10]
6	5	0	0,32	11,8	0,5	1,4	[11]
7	9	0,3	0,25	12,8	2	1,4	[12]
8	10	0,78	0,6	15	0,25	1,4	[2]
9	10	0,78	0,6	20	1,3	1,4	[2]
10	10	0,78	0,6	20	0,25	1,4	[2]
11	10	0	0,125	16	1,3	1,4	[13]
12	5	0	0,1	11,8	0,5	1,4	[11]

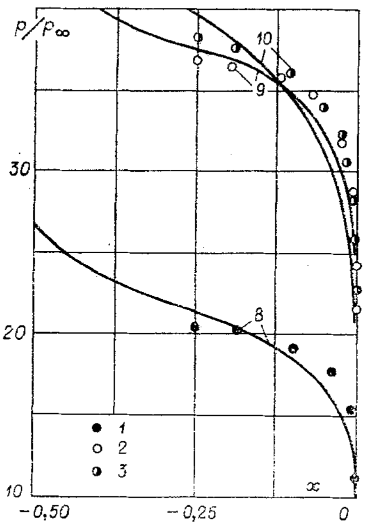

Fig. 1

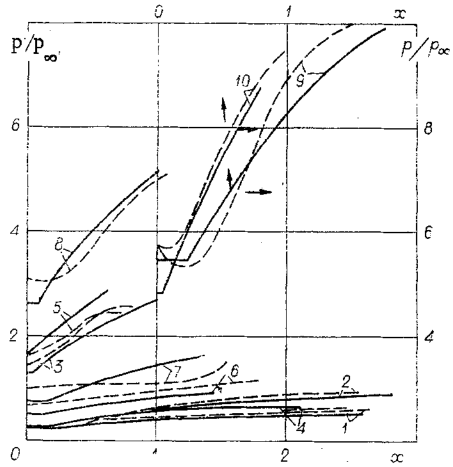

Fig. 2

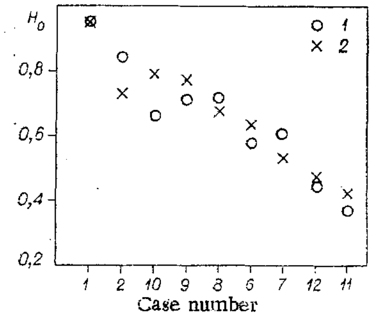

Fig. 3

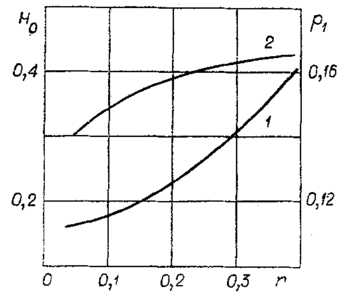

Fig. 4

calculated values. Figure 4 demonstrates the influence of cone blunting radius on the base pressure and the viscous sublayer enthalpy. The data shown here refer to cones with $\alpha = 10°$, of length L = 1.5 m, moving at altitude H = 50 km with velocity 7.4 km/sec. The conditions ahead of the base section were obtained by computing the boundary layer along the body, allowing for nonequilibrium in the physical and chemical processes and nonuniformity in the external flow [16]. The lateral surface of the cone was considered to be perfectly catalytic, and its temperature was taken to be 1000°K, so that $H_w = 0.04$. In calculating the near wake, in accordance with [4], the properties of the mixture of gases were calculated from mixture-average values of the specific heat ratio and the molecular weight.

The abscissa in Fig. 4 shows the relative blunting radius, curve 1 is the base pressure, referenced to the unperturbed pressure ahead of the base p_1, and curve 2 shows the relative total enthalpy of the viscous sublayer. As the degree of blunting increases the base pressure and the enthalpy increase. These features agree qualitatively with the data of [5, 17]. For the cone with low-radius blunting r = 0.04 the ratio of base pressure to the pressure at infinity is 2.5. This value is close to the known test values, referring to sharp cones and presented in [10] (in the case considered $M^3/\sqrt{Re_L} = 13$).

Thus, the present calculated values agree, on the whole, both qualitatively and quantitatively with the data of calculations based on a rigorously posed problem, and with the known experimental data. While not claiming to give a detailed description of the parameters in the near-axial zone of the near wake, the method of [4] can be used for a relatively simple calculation of the main characteristics of this zone: the enthalpy and the pressure distribution (and also the composition of a mixture of gases and the temperature), over a wide range of external conditions. We note that there is no difficulty, in principle, in generalizing the method of [4] to the case of turbulent conditions in the wake.

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