The computer produced a design (20 St 41C 19 St) (the breakdown step was the same as in Example 1). Plate thickness h = 0.905 m.

The stiffness characteristics for the design obtained were as follows:

$$S^{11}_{1111} = 1.0028\cdot 10^9,\quad S^{12}_{1111} = 0.0001\cdot 10^7,\quad S^{22}_{1111} = 0.118\cdot 10^5$$

(relative error of the solution 0.02).

LITERATURE CITED

1. D. Caillerie, "Thin elastic and periodic plates," Math. Meth. Appl. Sci., No. 6 (1984).
2. A. G. Kolpakov and S. I. Rakin, "Problem of synthesizing a composite material of unidimensional construction with prescribed characteristics," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1986).
3. A. G. Kolpakov and S. I. Rakin, "Problem of synthesizing a composite of unidimensional structure in a prescribed class of materials," in: Solid Mechanics, No. 78 [in Russian], IG Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1986).
4. A. G. Kolpakov, "Effective stiffness of composite plates," Prikl. Mat. Mekh., 46, No. 2 (1982).
5. A. N. Tikhonov and V. Ya. Arsenin, Methods of Solving Incorrect Problems [in Russian], Nauka, Moscow (1986).
6. V. M. Alekseev, V. M. Tikhomirov, and S. V. Fomin, Optimum Control [in Russian], Nauka, Moscow (1979).
7. A. G. Kolpakov, "Average characteristics of laminated composites (numerical algorithm)," in: Numerical Methods for Solving Elasticity and Plasticity Theory Problems: Proc. 9th All-Union Conf, Inst. Teor. Prikl. Mekh., Sib. Otd., Akad. Nauk SSSR, Novosibirsk (1986).
8. B. D. Annin and A. G. Kolpakov, "Planning of laminated composites with prescribed stress-strength characteristics," Mekh. Komposit. Mater., No. 1 (1987).
9. K. A. Lur'e and A. V. Cherkaev, "Regularization of optimum design problems for inhomogeneous elastic bodies by means of composite materials," in: 5th All-Union Conf. on Theoretical and Applied Mechanics [in Russian], Nauka, Alma-Ata (1981).

HYPERSONIC FLOW OVER BLUNT EDGES AT LOW REYNOLDS NUMBERS

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UDC 533.6.011.8:533.694.71/72

In a planned descent from orbit a space vehicle is subjected to intense heating due to air flow. At the same time, even for relatively low flight heights and low blunting radii of individual vehicle elements, and thus low local Reynolds number values, the shock wave in those regions can no longer be considered as a discontinuity upon which the Rankin–Hugoniot relationships are satisfied, and the effect of viscosity is no longer limited to a thin boundary layer. At hypersonic velocities, because of the high flow energy, such physicochemical processes as heterogeneous chemical reactions, dissociation, and excitation of oscillatory, rotational, and translational degrees of molecular freedom may become significant in the disturbed region. The initial source of information on this transitional region was experiment. Subsequently, numerical methods were used successfully for solution of the Boltzmann equation for a homogeneous gas, the most widespread being the direct statistical modeling or Monte Carlo method. However, upon consideration of physicochemical processes in air such studies have as a rule been performed only with the Navier–Stokes equations or models thereof, with slippage boundary conditions and a temperature discontinuity. There is no strict justification for the applicability of such equations, although many comparisons with experimental results and numerical calculations of the Boltzmann kinetic equation for a homogeneous gas show that the Navier–Stokes equations can be used successfully for study of hypersonic flows

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 161-168, July-August, 1989. Original article submitted June 26, 1986.

at low Reynolds numbers. The present state of this question is described in [1]. Below, within the framework of the theory of a thin viscous shock layer, we will perform a numerical study of flow over blunt and knife-edge details of a hypersonic vehicle and compare the results obtained to experimental data.

1. The analysis performed in [2] shows that in the transitional region at velocities less than or of the order of escape velocity nonequilibrium physicochemical processes in air exert a relatively weak effect on the processes of momentum and energy transport to surface elements of the body flowed over. In the first approximation in such regimes the air composition can be considered frozen and the flow in the thin viscous shock layer in the vicinity of the blunt edge can be described by the following system of equations:

$$\frac{\partial}{\partial s'}(h_2'\rho'u') + \frac{\partial}{\partial n'}(h_1'h_2'\rho'v') = 0,$$

$$\rho'\left(\frac{u'}{h_1'}\frac{\partial u'}{\partial s'} + v'\frac{\partial u'}{\partial n'}\right) = -\frac{\varepsilon}{2h_1'}\frac{\partial p_w'}{\partial s'} + m\frac{\partial}{\partial n'}\left(\mu'\frac{\partial u'}{\partial n'}\right),$$

$$\frac{\partial p'}{\partial n'} = 2k'\rho'u'^2, \quad \rho'\left(\frac{u'}{h_1'}\frac{\partial w'}{\partial s'} + v'\frac{\partial w'}{\partial n'}\right) = m\frac{\partial}{\partial n'}\left(\mu'\frac{\partial w'}{\partial n'}\right), \tag{1.1}$$

$$\rho'\left(\frac{u'}{h_1'}\frac{\partial H'}{\partial s'} + v'\frac{\partial H'}{\partial n'}\right) = m\left[\frac{\partial}{\partial n'}\left(\frac{\mu'}{\Pr}\frac{\partial H'}{\partial n'}\right) + \left(1 - \frac{1}{\Pr}\right)\frac{\partial}{\partial n'}(u'^2 + w'^2)\right],$$

$$p' = 2\rho'h', \ \mu' = \mu'(h').$$

Here and below, $s'R$ and $\varepsilon n'R$ are coordinates related to the external normal to the body surface; R, radius of curvature at the critical point; h_1 and h_2, Lamé coordinates; k'/R, curvature of the surface; $u'U_\infty$, $\varepsilon v'U_\infty$, and $w'U_\infty$, velocity components along the tangent, normal, and binormal directions to the body; U_∞, velocity of the undisturbed flow; $\rho'\rho_\infty/\varepsilon$, density; $p'\rho_\infty U_\infty^2/2$, pressure; $h = c_pT = h'U_\infty^2/2$, enthalpy; $H' = h' + u'^2 + w'^2$; $\mu'\mu_0$, viscosity; γ, specific heat ratio; Pr, Prandtl number; $\mathrm{Re}_0 = \rho_\infty U_\infty R/\mu_0$, Reynolds number calculated for the viscosity coefficient μ_0 at the braking temperature $T_0 = U_\infty^2/2c_p$; $\varepsilon = (\gamma - 1)/2\gamma$; $m = (\varepsilon \mathrm{Re}_0)^{-1}$; the prime denotes dimensionless quantities; the superscripts ∞ and w refer to parameters at infinity and on the body surface.

We will assume that on the body surface system (1.1) satisfies slippage and temperature discontinuity boundary conditions

$$u' = \frac{2 - a_1\beta_1}{\beta_1}(2\pi\varepsilon h')^{1/2}\frac{m\mu'}{p'}\frac{\partial u'}{\partial n'}, \quad \rho'v' = (\rho_w'v_w') = g_w,$$

$$w' = \frac{2 - a_1\beta_1}{\beta_1}(2\pi\varepsilon h')^{1/2}\frac{m\mu'}{p'}\frac{\partial w'}{\partial n'}, \tag{1.2}$$

$$h' = h_w' + \frac{2 - a_2\beta_2}{\beta_2}(2\pi\varepsilon h')^{1/2}\frac{2\gamma}{\gamma + 1}\frac{m\mu'}{p'\Pr}\frac{\partial h'}{\partial n'}.$$

The accomodation coefficients β_i for all calculations except those variants where their effect was studied were taken equal to unity, $a_1 = 0.988$, $a_2 = 0.827$.

On the outer boundary of the shock layer generalized Rankin–Hugoniot conditions are used:

$$\rho'v' = -\cos\chi\sin\sigma, \ p' = 2\cos^2\chi\sin\sigma,$$

$$\cos\chi\sin\sigma(\cos\chi\cos\sigma - u') = m\mu'\partial u'/\partial n',$$

$$\cos\chi\sin\sigma(\sin\chi - w') = m\mu'\partial w'/\partial n', \tag{1.3}$$

$$\cos\chi\sin\sigma(H_\infty' - H') = m\mu'\left[\frac{1}{\Pr}\frac{\partial H'}{\partial n'} + \left(1 - \frac{1}{\Pr}\right)\frac{\partial}{\partial n'}(u'^2 + w'^2)\right],$$

where χ is the angle between the velocity vector of the undisturbed flow and the plane perpendicular to the leading edge of the surface (sagittal angle); σ is the angle of inclination of the discontinuity surface to the plane of symmetry of the body.

For the dependence of the viscosity coefficient of air on temperature the numerical calculations used the approximation $\mu_*(T)$ proposed in [3], which is linear for low temperatures, corresponds to the Southerland law at moderate temperatures, and for high temperature is close to exponential with exponent $n = 0.67$ and 0.85.

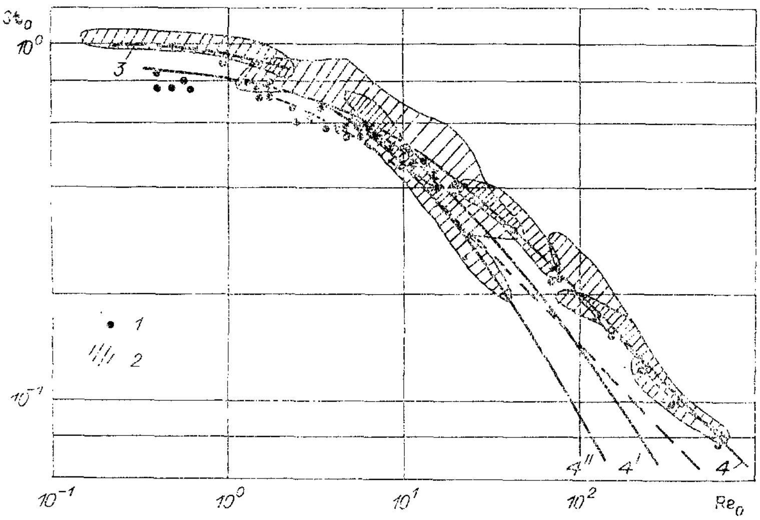

Fig. 1

For numerical integration system (1.1) with boundary conditions (1.2) and (1.3) was transformed to new Dorodnitsyn–Lees-type variables and solved by a finite difference method [4]. The calculations encompassed a wide range of similarity parameters and were performed for flows with axial and planar symmetry over bodies with directrices specified by second-order curves.

2. For hypersonic flows with frozen air composition the similarity laws formulated for a thermodynamically ideal gas remain in force. According to these, conditions for modelling such flows can be satisfied upon equality of the similarity criteria: the Mach number M_∞, Re_0, the temperature factor $t_w = T_w/T_0$, γ, the set of parameters κ_i defining the air transport properties, and β_i.

Choice of a similarity criterion system including Re_0 is based on the following reasons. First, this parameter does not change in the limiting case of overflow as $M_\infty \to \infty$. Second, in the hypersonic stabilization regime use of the criterion Re_0 permits correlating results not only for change in M_∞, but also in a number of cases for change in the other similarity parameters [5]. Third, at U_∞ = const there follows from the condition Re_0 = const satisfaction of the binary similarity law $\rho_\infty R$ = const for modeling of nonequilibrium flows near the body flowed over [2].

The effect of the similarity criteria indicated above on the aerodynamic and thermal characteristics of blunt edges at low Re_0 can be evaluated using the example of flow in the vicinity of an axisymmetric critical point ($j = 1$), which has been investigated in a large number of studies. Analysis of these data indicates that in the transitional region the transport properties of the medium and the degree of cooling of the body surface have a significant effect on flow over a blunt body [3]. At $t_w = O(1)$ the effects of slippage on the body surface are quite large, while for small Re_0 they are also significant in the shock wave. Consideration of such effects causes the calculation data obtained with the Navier–Stokes equation to approach much more closely to the available experimental data. Only at sufficiently low values of t_w (≤ 0.1) and exact modeling of the medium transport properties does the role of the effects mentioned above become negligibly small. For example, this follows from the dependence of the Stanton number $St_0 = q_{w0}/c_p\rho_\infty U_\infty T_0(1 - t_w)$ on Re_0 shown in Fig. 1 (the experimental 1, 2 and calculated 3 data taken from [6-8], respectively; calculations 4 obtained in the thin viscous shock-layer approximation). The agreement between all calculated and experimental results is completely satisfactory.

For the critical line ($j = 0$) with sagittal angle χ results of an analogous study in the viscous shock layer approximation are presented below. In contrast to [9, 10] to study the questions involved in modeling, as in [3], the following flow regimes were studied: 1) U_∞ = 7.8 km/sec, $M_\infty \gg 1$, $0.02 \le t_w \le 0.05$; 2) $M_\infty = 15$, T_0 = 2000 K, $t_w = 0.15$; 3) $M_\infty = 6.5$, T_0 = 1000 K, $t_w = 0.3$. Remaining similarity criteria were identical in all cases: $\gamma = 1.4$, Pr = 0.71, $\beta_i = 1$; the temperature dependence of the viscosity coefficient corresponded to the $\mu_*(T)$ approximation. The first variant considered corresponds to conditions for full-scale overflow for frozen air composition, while the second and third can be realized in vacuum aerodynamic tubes.

Calculations performed for $2 \le Re_0 \le 10^3$ and $0 \le \chi \le 75°$ revealed that relative heat transfer on the critical line $St'_0(\chi) = St_0(\chi)/St_0$ (where St_0 is the Stanton number at $\chi = 0$) is given by

$$St'_0(\chi) = (\cos\chi)^{a_0+a_1t_w+a_2t_w^2}, \tag{2.1}$$

where $a_0 = 1.36 - 0.26\ Re_0^{-1/2} + 0.03\ Re_0^{-1}$, $a_1 = -1.01 + 1.29\ Re_0^{-1/2} - 0.52\ Re_0^{-1}$, $a_2 = 1.07 + 7.6\ Re_0^{-1/2} - 9.06\ Re_0^{-1}$.

Just as for axial symmetry, heat exchange on the critical line at $t_w \lesssim 0.1$ is practically independent of the degree of body surface cooling. Values of St_0 corresponding to this case are presented in Fig. 1 (dashed line).

For other quantities, such as the longitudinal friction coefficient C_f and the shock-layer thickness n_s, the analogous relationships are independent of t_w over the entire range of similarity parameters:

$$\begin{gathered} c'_{f0}(\chi) = c_{f0}(\chi)/c_{f0} = (\cos\chi)^{b_0},\ b_0 = 1.34 - 1.03\,Re_0^{-1/2} - 0.73\,Re_0^{-1}, \\ n'_{s0}(\chi) = n_{s0}(\chi)/n_{s0} = (\cos\chi)^{c_0},\quad c_0 = -0.26 - 2.24\,Re_0^{-1/2} + 1.92\,Re_0^{-1}. \end{gathered} \tag{2.2}$$

For $\chi \le 60°$ the error of these approximations in the indicated regimes does not exceed 5%, reaching 10% at $\chi = 75°$.

For incomplete accommodation of momentum and energy on the body surface, additional numerical studies show that at $0.5 \le \beta_i \le 1$ changes in St_0 proved to be maximal at $t_w = O(1)$ and reached 30% at $Re_0 = 2$. With increase in Re_0 and decrease in t_w the effect of these processes on heat transport decreases.

3. In the continual flow region an effective means of reducing thermal flux to the body is draft of a cooling gas. It is known that, with decrease in Re_0, the effect of this process on heat exchange decreases, disappearing in the limiting case of free molecular overflow. For a quantitative estimate of this effect we will make use of results of a numerical study of the equations of a thin viscous shock layer, Eq. (1.1).

For the critical point and the line at $\chi = 0$ the results of such systematic studies were presented in [11], where a universal dependence of relative heat transport for draft of a homogeneous gas $St_{0j}' = St_{0j}/St_0$ on the generalized parameter $F_0 = g_w\sqrt{Re_0}/[(1 + j)^{1/4}\cdot(1 + 2.2t_w^{1/3}Re_0^{1/2})]$ was obtained, the latter parameter combining the similarity criteria Re_0, t_w, g_w.

Values of St_{0j} taken from that study for the critical point, corresponding to full-scale overflow conditions at $g_w = 0.1$ and 0.2, are shown in Fig. 1 (curves 4' and 4", respectively). With decrease in Re_0 the effectiveness of the homogeneous draft decreases, although at $Re_0 = 10^2$ it is still significant. For lower Re_0 a large effect can be achieved by draft of a different gas. Calculations performed for helium show that the effectiveness of a draft of a different type of gas is maintained even at $Re_0 = 10$.

For $\chi \ne 0$ similar calculations performed over a wide range of similarity criteria show that the values obtained at $g_w = 0$ for the relative parameters $St_0'(\chi)$, $c_{f0}'(\chi)$, $n_{s0}'(\chi)$ of Eqs. (2.1) and (2.2) are maintained for weak draft with an error not exceeding 6% at $\chi \le 60°$. Some results of a comparison of heat transport $St_0'(\chi)$ for $Re_0 = 10$, $M_\infty \gg 1$, $t_w = 0.02$ are shown in Table 1.

We will now turn to evaluating the efficiency of a weak concentrated draft. In the vicinity of the body critical point through an orifice of radius r_* let there pass a draft of gas with mass flow rate Q_w. In this case, the second boundary condition of Eq. (1.2) on

TABLE 1

g_w	$St'_0(\chi)$, χ, deg: 15	30	45	60	75	g_w	$St'_0(\chi)$, χ, deg: 15	30	45	60	75
0	0,950	0,811	0,610	0,386	0,176	0,19	0,951	0,813	0,619	0,400	0,190
0,10	0,950	0,812	0,615	0,393	0,183	0,32	0,943	0,805	0,627	0,408	0,200

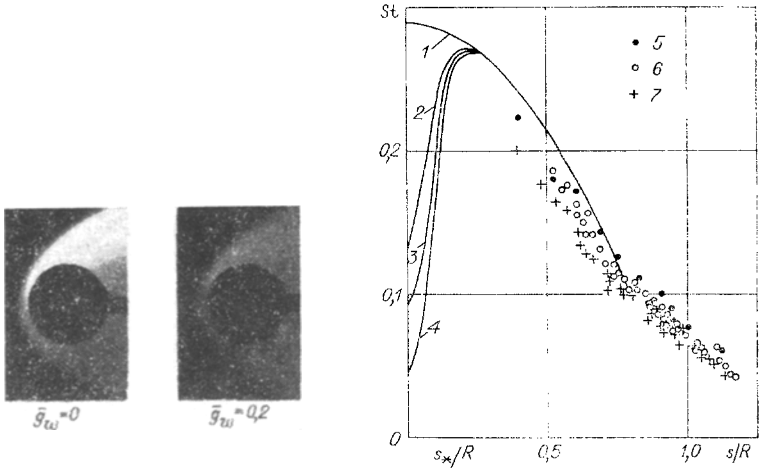

Fig. 2

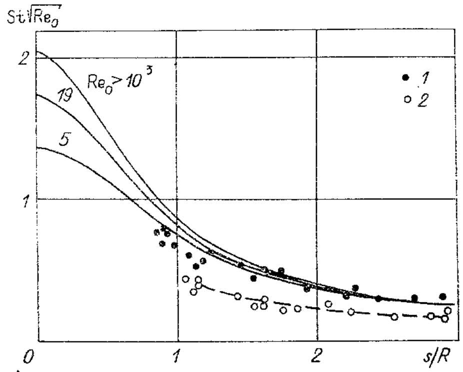

Fig. 3

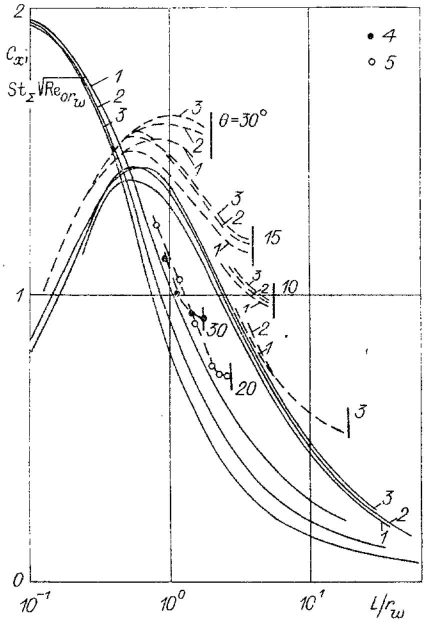

Fig. 4

the body surface can be written in the form

$$\rho'v' = \bar{g}_w = Q_w/\pi\rho_\infty U_\infty r_*^2 \quad \text{for} \quad 0 \leqslant r \leqslant r_*, \quad \rho'v' = 0 \quad \text{for} \quad r > r_* \tag{3.1}$$

(where r is the distance from the axis of symmetry to the body directrix). In correspondence to this concentrated draft with discontinuous boundary conditions, Eq. (3.1), we set up a continuous peak-shaped draft

$$g_w = g_{w0} e^{-\alpha(r'/r'_*)^2} \tag{3.2}$$

with the same total mass flow rate Q_w, now passing through the whole surface of the body

$$\bar{g}_w = 2g_{w0} \int_0^{s_*} e^{-\alpha(r'/r'_*)^2} r' ds',$$

where s_* is the length value at the Newtonian detachment point.

Numerical integration of Eq. (1.1) with boundary condition (3.2) was performed for a spherical surface at several values of $g_{w0}/\bar{g}_w$. For tube conditions ($Re_0 = 48$, $M_\infty = 6.5$, $T_w = 0.3$, $\gamma = 1.4$) results of these heat-transport calculations are shown in Fig. 2 (curve 1, $\bar{g}_w = 0$; curve 2, $g_{w0}/\bar{g}_w = 1$; curve 3, $g_{w0}/\bar{g}_w = 1.5$; curve 4, $g_{w0}/\bar{g}_w = 2.5$). These show

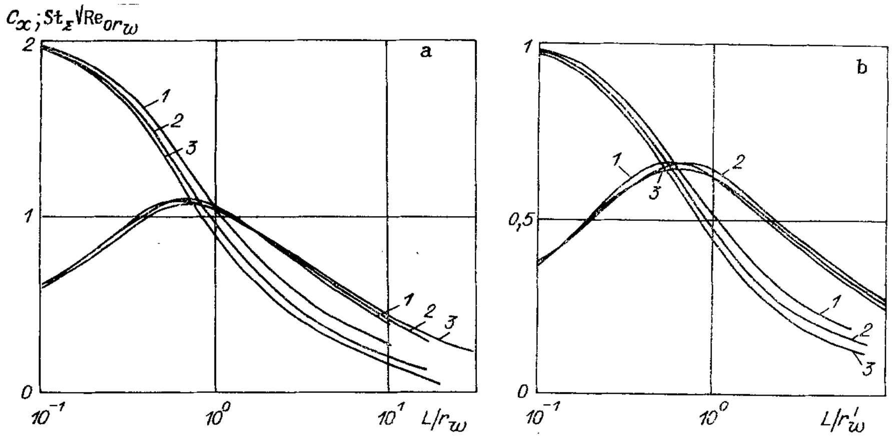

Fig. 5

that the effect of concentrated draft is localized near the draft zone and does not propagate along the body directrix.

A similar result was obtained in experiments performed in a vacuum aerodynamic tube under the conditions described above. The tests were performed on a spherical ebonite model. The cooling gas (air or helium) draft was applied through an orifice of radius $r_* = R/30$ at the critical point of the sphere. Gas flow rate was determined by the pressure drop in a supply vessel of fixed volume upon escape of gas through measurement washers of various diameters.

The thermo-indicator coating method was used to measure thermal fluxes. One- and two-layer thermo-indicator coatings with critical temperatures $T_* = 50\text{-}66°C$ were used in the experiments. The methodology of using this technique in vacuum aerodynamic tubes was discussed in [12].

The experimental results are presented in Fig. 2. The distribution of St over the sphere surface for $s' > 0.4$ proved to be one and the same within the limits of experimental accuracy for all values of relative draft gas flow rate (curve 5, $\bar{g}_w = 0$; curve 6, air, $\bar{g}_w \leq 0.32$; curve 7, helium, $\bar{g}_w \leq 0.02$). Localization of the disturbance near the concentrated draft zone is shown by the flow photographs of Fig. 2, obtained by the glow discharge method.

4. We will consider the effect of the blunt body form on resistance C_x and net thermal flux St_Σ on the edge surface s with characteristic midsection dimension r_w:

$$C_x = \frac{1}{\pi^j r_w^{j+1}} \int_s (p' \sin\theta + c_f' \cos\theta)\, ds, \quad \mathrm{St}_\Sigma = \frac{1}{\pi^j r_w^{j+1}} \int_s \mathrm{St}\, ds. \tag{4.1}$$

As the previous analysis has shown, at low Reynolds numbers ($Re_0 < 10^2$) effects of medium rarefaction become significant in the vicinity of the critical point (line). To consider these when determining the local characteristics p', c_f', St appearing in Eq. (4.1) requires precise satisfaction of the modeling conditions over the entire similarity criterion range indicated above. For example, for noncorrespondence between temperature factors of full-scale and tube experiments the difference between St values at $Re_0 = O(1)$ can exceed 40%.

With removal from the body's critical point the role of rarefaction effects on the flow will decrease, and for the local characteristics the well-known functional relationships stemming from boundary-layer theory become established. This follows, for example, from the calculated (solid lines) and experimental (points 1 [13]) data of Fig. 3 on local heat transport along the surface of a paraboloid of revolution ($5 \leq Re_0 \leq 19$, $M_\infty = 6.5$, $t_w = 0.3$, $\gamma = 1.4$). For $s/R \gtrsim 2$, the experimental and calculated values of $St\sqrt{Re_0}$ cease to be dependent on Re_0 and approach the limiting dependence corresponding to $Re_0 > 10^3$. Such a conclusion is also confirmed by the experimental results of [13] on heat transport, obtained for a blunted cone with apex angle $2\theta = 20°$ for $2.6 \leq Re_0 \leq 8.6$ (points 2 of Fig. 3).

Results of numerical calculations of aerodynamic and thermal characteristics of axisymmetric bodies ($j = 1$) with directrices in the form of parabolas (solid lines) and hyperbolas with asymptotic half-aperture angles $\theta = 3$, 10, 15, and 30° (dashes) are shown in Fig. 4, where changes in C_x and $St_\Sigma\sqrt{Re_0 r_w}$ as a function of relative body length L/r_w are shown for full-scale overflow conditions ($M_\infty \gg 1$, $0.02 \le t_w \le 0.05$) for several fixed values of $Re_0 r_w = \rho_\infty U_\infty r_w/\mu_0$ ($Re_0 r_w$ = 16, 32, and 64; curves 1-3). The vertical lines indicate limiting values of L_*/r_w for the hyperboloids for which $R/r_w = 0$.

The data presented show that for a fixed value of midsection the resistance of a paraboloid C_x decreases monotonically with increase in L/r_w, while the net thermal flux on the surface St_Σ changes nonmonotonically, reaching a maximum for a finite body elongation. With decrease in L/r_w this effect is an obvious one, since it is related to decrease in thermal flux at the body critical point with increase in radius of curvature R. The result obtained for increase in relative body length is more interesting: despite the significant growth in local thermal flux at the body critical point as $R \to 0$, the net thermal flux toward the body decreases for the L/r_w range studied.

For bodies with θ = const (hyperboloids, blunted cones) decrease in net aerodynamic and thermal characteristics with increase in L/r_w up to limiting values of L_*/r_w corresponding to flow over a sharp-edged body. Minimum values of these characteristics are achieved at finite radii of curvature at the critical point. For the net heat transfer this follows from the calculated functions shown in Fig. 4, $St_\Sigma\sqrt{Re_0 r_w}$ for hyperboloids, while for C_x it follows from the experimental data for blunted cones also shown there, obtained in a vacuum aerodynamic tube at $20 \le Re_0 \le 40$, $M_\infty = 6.5$, $t_w = 0.3$, $\gamma = 1.4$ (curves 4 and 5 for θ = 20 and 30°).

For $L/r_w = O(1)$, when the flow near the blunted body is essentially determined by flow singularities near the critical points, the net aerodynamic and thermal characteristics at small Re_0 will depend on the entire set of similarity parameters which defines hypersonic flow over a body by a rarefied gas. With increase in L/r_w the effect of noncorrespondence between individual similarity criteria on the net characteristics decreases, some of these, for example $St_\Sigma\sqrt{Re_0 r_w}$, become universal for similar bodies, independent of $Re_0 r_w$.

For blunt edges ($j = 0$) with parabolas as directrices results of similar numerical calculations for full-scale flow conditions ($M_\infty = 25$, $t_w = 0.02$) are shown in Fig. 5a, b (χ = 0 and 45°, respectively), where the change in characteristics C_x and $St_\Sigma\sqrt{Re_0 r_w}$ are presented as functions of the relative body length at L/r_w when $Re_0 r_w$ = 16, 32, and 64 (lines 1-3). Aside from reduction in resistance and net thermal flux to the blunt edges with increase in sagittal angle χ, the transition from the axisymmetric ($j = 1$) to the planar ($j = 0$) case introduces no other qualitative changes to the behavior of those characteristics.

LITERATURE CITED

1. É. A. Gershbein, S. V. Peigin, and G. A. Tirskii, "Supersonic flow over bodies at low and moderate Reynolds numbers," in: Achievements in Science and Technology, Ser. Liquid and Gas Mechanics, No. 19 [in Russian], VINITI, Moscow (1985).
2. V. N. Gusev, V. P. Provotorov, and V. V. Ryabov, "The role of physicochemical processes in problems of modeling hypersonic flows of rarefied gas," Uch. Zap. Tsentr. Aerogidrod. Inst., 12, No. 4 (1981).
3. V. N. Gusev and V. P. Provotorov, "Modeling natural high-altitude flight conditions in aerodynamic tubes," Uch. Zap. Tsentr. Aerogidrod. Inst., 13, No. 3 (1982).
4. O. V. Denisenko and V. P. Provotorov, "Study of viscous gas flows at moderate Reynolds numbers," Tr. TsAGI, No. 2269 (1985).
5. V. N. Gusev, A. I. Erofeev, et al., "Theoretical and experimental studies of flow over objects of simple form by a hypersonic rarefied gas," Tr. TsAGI, No. 1855 (1977).
6. V. N. Gusev and Yu. V. Nikol'skii, "Experimental study of heat transfer at the critical point of a sphere within a hypersonic rarefied gas flow," Uch. Zap. Tsentr. Aerogidrod. Inst., 2, No. 1 (1971).
7. S. Nomura, "Correlation of hypersonic stagnation point heat transfer at low Reynolds number," AIAA J., 21, No. 11 (1983).
8. I. N. Larina and V. A. Rykov, "Effect of rotational degrees of molecular freedom on energy fluxes in a rarefied gas," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 5 (1977).
9. I. G. Brykina and É. A. Gershbein, "Hypersonic viscous shock layer on sagittal wings of infinite span, with overflow at an angle of attack," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2 (1979).
10. É. A. Gershbein, V. S. Shchelin, and S. A. Yunitskii, "Numerical study of hypersonic viscous shock layer on infinite span wings with overflow at attack and slip angles, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2 (1984).

11. V. P. Provotorov and É. A. Stepanov, "Numerical study of a viscous shock layer in the vicinity of the critical point in the presence of gas draft," Uch. Zap. Tsentr. Aerogidrod. Inst., 16, No. 4 (1985).
12. V. N. Gusev, T. V. Klimova, and L. G. Chernikova, "Experimental monitoring of thermal flux measurements using two-layer thermo-indicator coatings," Uch. Zap Tsentr. Aerogidrod. Inst., 14, No. 5 (1983).
13. T. V. Klimova and L. G. Chernikova, "Study of heat transfer in hypersonic flow of a rarefied gas. Rarefied gasdynamics," in: Proceedings of the 6th All-Union Conference, Part 2, Novosibirsk (1980).