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HYPERSONIC AEROTHERMODYNAMICS INVESTIGATION FOR AEROSPACE SYSTEM

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Abstract

Hypersonic aerospace technology is key indicators of international power of any country concern with the guarantor of security, standard of scientific and technical development. The difficulty in the development of hypersonic vehicle is caused by quite number of problems of modeling full-scale flight conditions in wind tunnels. So, the analysis of the aerodynamic and aerothermodynamic characteristics of hypersonic vehicle at high-altitude requires numerous numerical calculations. In this paper present the methods to calculate aerodynamic and aerothermodynamic characteristics of hypersonic vehicles at all range of regimes.

1 Introduction

Aerospace system is key indicators of international power of any country concern with the guarantor of security, standard of scientific and technical development. Return of the spacecraft vehicle to the Earth, it is necessary know the behavior of its aerodynamic and aerothermodynamic characteristics for all flow regimes (free-molecular, transitional and continuum regimes). During de-orbiting, the spacecraft passes through the free molecular, then through the transitional regime and the finalized flight is in the continuum flow. The difficulty in the development of hypersonic vehicle is caused by quite number of problems of modeling full-scale flight conditions in wind tunnels. The analysis of the aerodynamic and aerothermodynamic characteristics of hypersonic vehicle at high-altitude requires numerous numerical calculations

It is well known that for flight in the upper atmosphere, where it is necessary to take into account the molecular structure of a gas, kinematics models are applied, in particular, the Boltzmann equation and corresponding numerical methods of simulation. In the extreme case of free-molecular flow, the integral of collisions in the Boltzmann equation becomes zero, and its general solution is a boundary function of distribution, which remains constant along the paths of particles. While aircraft are moving in a low atmosphere, the problems are reduced to the problems that can be solved in the frame of continuum theory or, to be more precise, by application of the Navier-Stokes equations and Euler equations. It is natural to create engineering methods, justified by cumulative data of experimental, theoretical and numerical results, enabling the prediction of aerodynamic and aerothermodynamic characteristics of complex bodies in the transitional regime.

To correctly simulate hypersonic flows, the flows must be understood and modeled correctly and this more true than in the numerical simulation of hypersonic flows. Hypersonic must be dominated by an increased understanding of fluid mechanics reality and an appreciation between reality and the modeling of that reality. The benefits of numerical simulation for flight vehicle design are enormous: much improved aerodynamic shape definition and optimization, provision of accurate and reliable aerodynamic data and highly accurate determination of thermal and mechanical load. Multi-parametric calculations can be performed only by using an approximation engineering approach. Computer modeling allows to quickly analysis the aerodynamic characteristics of hypersonic vehicles by using theoretical and experimental research in aerodynamic of hypersonic flows. Direct simulation Monte Carlo method (DSMC) is the basic quantitative tool for study of hypersonic rarefied flows. DSMC method is required large amount of computer memory and expensive at the initial stage of spacecraft design and trajectory analysis. The solution for this problem is the approximate engineering methods. The Monte Carlo method remains the most reliable approach, together with the local engineering methods, that provides good results for the global aerodynamic coefficients.

The purpose of this work is to calculate aerodynamic and aerothermodynamic characteristics of perspective hypersonic vehicles. This local engineering method are suitable to calculate for taking into account the influence of Reynolds number, and provide good results for various hypersonic vehicle shapes. In this paper present calculation results of the coefficients of drag force C_D, lift force C_L, pitching moments m_z and heat flux coefficient C_h with value of angle of attack α from 0 to 90 deg for perspective space vehicle “Clipper, TsAGI model” (Fig. 1a) and hypersonic vehicle “Falcon HTV-2, US project” (Fig. 1b). Results and methods can be use to calculate aerodynamic and aerothermodynamic characteristics of new generation hypersonic aerospace vehicle designs.

2 Methods to Compute Aerodynamic Characteristics of Hypersonic Vehicles

As applied to hypersonic flows, the Newton model for calculating pressure on the exposed leading part of the body surface is widely used.

$$p = 2\sin^2\theta\,,\ \tau = 0$$

In hypersonic flow, to define pressure and friction forces which are dependent on the coating materials and other global parameters are as follows [2, 3]

$$p = 2(2-\sigma_n)\cos^2\theta + \sigma_n\left[\frac{\pi(\gamma-1)}{\gamma}t_w\right]^{1/2}\cos\theta$$

$$\tau = 2\sigma_\tau\sin\theta\cos\theta$$

where $t_w = T_w/T_0$, T_w, T_0 are surface temperature and adiabatic stagnation temperature respectively, σ_n – normal accommodation coefficient and σ_τ - tangent momentum accommodation coefficient.

$$T_0 = T_\infty\left[1+\frac{\gamma-1}{\gamma}\mathrm{M}_\infty^2\right]$$

where γ - specific heat ratio and M_∞ – Mach number. It can assumed that a fraction of particles $(1-\sigma_\tau)$ is reflected mirror-like from the surface and σ_τ is ejected with Maxwell distribution which is characterized by reflected temperature T_r, then so called mirror-diffusion reflection.

In this work we use the expressions for the elementary pressure forces and friction forces are applied in the form described in [11, 3].

$$p = p_0\sin^2\theta + p_1\sin\theta$$

$$\tau = \tau_0\sin\theta\cos\theta$$

where, coefficients p_0, p_1, τ_0 (coefficients of the flow regime) are dependent on the Reynolds number $\mathrm{Re}_0 = \rho_\infty V_\infty L/\mu_0$, in which the viscosity coefficient μ_0 is calculated at stagnation temperature T_0. Except Reynolds number the most important parameter is the temperature factor T_w/T_0.

The dependency of the coefficients of the regime in the hypersonic case must ensure the transition to the free-molecular values at $\mathrm{Re}_0 \to 0$, and to the values corresponding to the Newton theory, methods of thin tangent wedges and cones, at $\mathrm{Re}_0 \to \infty$. On the basis of the analysis of computational and experimental data, the empirical formulas are proposed

$$p_0 = p_\infty + \left[p_\infty(2-\sigma_n) - p_\infty\right]p_1/z$$

$$p_1 = z\exp[-(0.125+0.078t_w)\mathrm{Re}_{0eff}]$$

$$\tau_0 = 3.7\sqrt{2}\,[R + 6.88\exp(0.0072R$$
$$-0.000016R^2)^{-1/2}$$
$$z = \frac{\pi(\gamma-1)}{\gamma} t_w^{\;1/2}$$

$$R = \mathrm{Re}_0\left(\frac{3}{4}t_w + \frac{1}{4}\right)^{-0.67}$$

$$\mathrm{Re}_{0эфф} = 10^{-m}\,\mathrm{Re}_0\,,\ m = 1.8(1-h)^3$$

where h is a relative lateral dimension of the apparatus, which is equal to the ratio of its height to its length.

The technique proposed proved to be good for the calculation of hypersonic flow of convex, not very thin, and spatial bodies. The calculation fully reflects a qualitative behavior of drag force coefficient C_D as a function of the medium rarefaction within the whole range of the angles of attack, and provides a quantitative agreement with experiment and calculation through the Boltzmann equation with an accuracy of 5%. On the accuracy of the relation of the locality method can be said that they are applied with the smallest error in the case of the bodies that are close to being spherical, and are not applied in the case of very thin bodies, when the condition is $\mathrm{M}_\infty \sin\theta >> 1$ [3].

Thus, the locality method of the calculation of aerodynamic characteristics of the bodies in the hypersonic flow of rarefied gas in the transitional regime gives a good result for C_D for a wide range of bodies, and a qualitatively right result for lift force coefficient C_L. In this case, it is necessary to involve more complete models that take into account the presence of the boundary layer [3]. In early papers [13-18] described the results of aerodynamic characteristics of various hypersonic vehicles by using engineering method.

3 Method to Compute Aerothermodynamic Characteristics of Hypersonic Vehicles

In the free molecular regime, to determine the heat transfer coefficient equation can write analytically [2]

$$C_h = \alpha_e \frac{1}{2\sqrt{\pi}}\frac{1}{S_\infty^3}\quad S_\infty^2 + \frac{\gamma}{\gamma-1} - \frac{1}{2}\frac{\gamma+1}{\gamma-1}\frac{T_w}{T_\infty}$$
$$\chi\left(S_{\infty,\theta}\right) - \frac{1}{2}e^{-S_{\infty,\theta}^2}$$
$$\chi(x) = e^{-x^2} + \sqrt{\pi}x\left(1 + \mathrm{erf}(x)\right),$$
$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-x^2}dt$$

Where, α_e – energy accommodation coefficient on surface, $S_{\infty,\theta} = S_\infty \cos\theta$ - speed ratio, T_w, T_∞ - surface temperature and flow temperature respectively. To calculate heat transfer coefficient in continuum regime, equation can described as follow [19, 20]

$$C_h(s,\theta) = C_{h0}\cdot\frac{1}{\sqrt{s/r + \frac{1}{s/r+1}}}$$
$$\sqrt{1 + \frac{\gamma+3}{\gamma+1}\frac{\gamma}{2}\mathrm{M}_\infty^2\cos^2\theta \,/\, 1 + \frac{\gamma+3}{\gamma+1}\frac{\gamma}{2}\mathrm{M}_\infty^2}$$

$$C_{h0} = \frac{2^{k/2}}{2}\mathrm{Pr}^{-2/3}\sqrt{\frac{\gamma+1}{\gamma-1}\sqrt{\frac{\gamma-1}{\gamma}}}\,\frac{1}{\sqrt{\mathrm{Re}_{\infty,r}}}\left(\frac{\gamma-1}{2}\mathrm{M}^2\right)^{\omega/2}$$

Here, C_{h0} – heat transfer coefficient on stagnation point, s – distance along the stream line, r – radius of nose of vehicle, Pr – Prandtl number, Re – Reynolds number, ω - exponent in power of viscosity dependence on temperature. k = 1 for spherical stagnation point, k = 0 for cylindrical stagnation point. In the present work suggested the bridging function to calculate heat transfer coefficient in transitional regime

$$C_{h,ds} = C_{h,fm,ds} \cdot F_b\left(\mathrm{Re}, \mathrm{M}, \theta, \ldots\right) + C_{h,cont,ds} \cdot \left(1 - F_b\left(\mathrm{Re}, \mathrm{M}, \theta, \ldots\right)\right)$$

$$F_{b,1} = \frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{\sqrt{\pi}}{\Delta \mathrm{Kn}_1} \cdot \lg\left(\frac{\mathrm{Kn}_0}{\mathrm{Kn}_m}\right)\right)\right),$$

$$F_{b,2} = \frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{\sqrt{\pi}}{\Delta \mathrm{Kn}_2} \cdot \lg\left(\frac{\mathrm{Kn}_0}{\mathrm{Kn}_m}\right)\right)\right).$$

where, $C_{h,fm,ds}$ – heat transfer coefficient in free molecular regime and $C_{h,\ cont,ds}$ - heat transfer coefficient in continuum regime. If $\mathrm{Kn}_0 < \mathrm{Kn}_m$, we should use the function $F_{b,1}$ and in opposite reason $F_{b,2}$. The values $\mathrm{Kn}_m = 0.3$, $\Delta\mathrm{Kn}_1 = 1.3$ and $\Delta\mathrm{Kn}_2 = 1.4$ were determined by calculating with the use of DSMC method.

4 Results and Discussions

The calculation results of the coefficients of drag force C_D, lift force C_L, pitching moments m_z and heat transfer C_h with value of angle of attack α from 0 to 90 deg for Russian perspective aerospace vehicle "Clipper, *TsAGI model*" and USA perspective hypersonic technology vehicle "Falcon HTV-2" are presented.

The calculation has been carried out through the method described in the previous section within the range of angles of attack α from 0 deg up to 90 deg with a step of 5 deg. The parameters of the problem are the following: ratio of heat capacities $\gamma = 1.4$; temperature factor $T_w/T_0 = 0.01$; velocity ratio $s = 15$, Reynolds number $\mathrm{Re}_0 = 0,\ 10,\ 10^2,\ 10^4$.

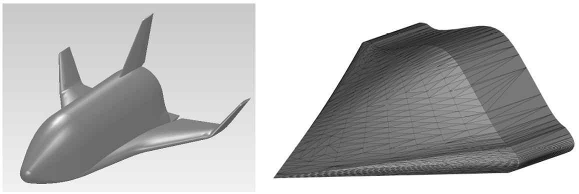

Fig. 1. Geometry view of space vehicle "Clipper" (*a*) and hypersonic technological vehicle "Falcon HTV-2" (*b*)

The dependencies of $C_D(\alpha)$, $C_L(\alpha)$ and $m_z(\alpha)$for aerospace vehicle "Clipper" are presented in Figs. 2-4. It can be seen from these results that when the Reynolds number increased, the drag coefficients C_D of vehicle diminished which can be explained by the decrease of normal and tangent stresses. At high Reynolds number $\mathrm{Re}_0 \geq 10^6$, characteristics almost not changed.

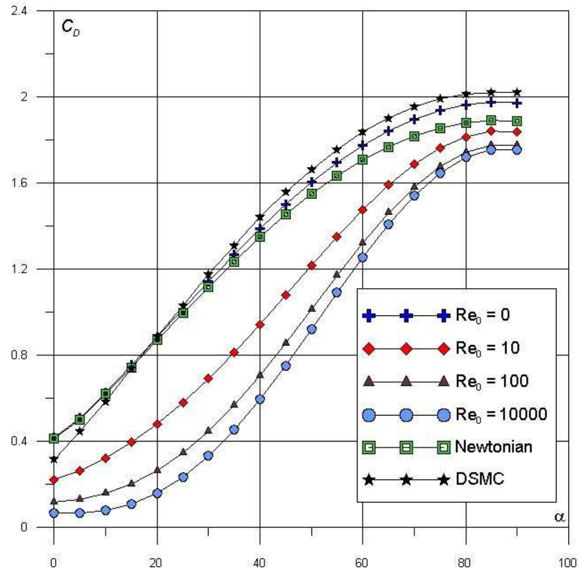

Fig. 2. Dependencies of drag coefficients $C_D(\alpha)$ for aerospace vehicle "Clipper"

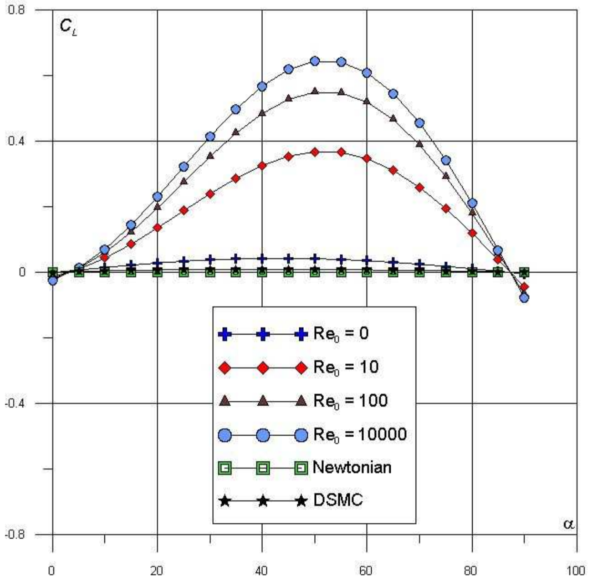

Fig. 3. Dependencies of lift coefficients $C_L(\alpha)$ for aerospace vehicle "Clipper"

The dependency $C_L(\alpha)$ is increased at high Reynolds number which can be explained by the decrease of normal and tangent stresses. The values of m_z are quite sensitive to the variation of Re_0. m_z changes its sign less than zero at $Re_0 \sim 10^2$. At $Re_0 \sim 10^4$, the value of m_z = - 0.03 at the angle of attack is reached at $\alpha \approx 40$ deg. Results by using local engineering method are compared with the results obtained by DSMC method and Newtonian method.

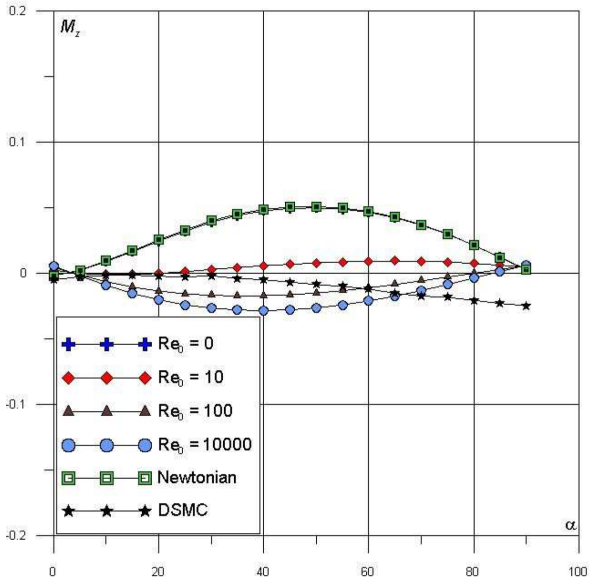

Fig. 4. Dependencies of pitching moment coefficients $m_z(\alpha)$ for space vehicle “Clipper”

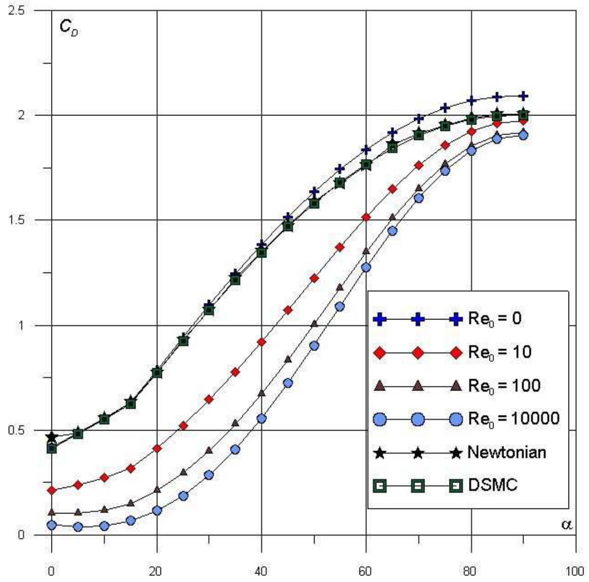

Fig. 5. Dependencies of drag coefficients $C_D(\alpha)$ for hypersonic vehicle “Falcon HTV-2”

The dependencies of $C_D(\alpha)$, $C_L(\alpha)$ and $m_z(\alpha)$ for “Falcon HTV-2” are presented in Figs. 5-7.

In Fig. 5, it can be seen with the increasing of Reynolds number, the drag coefficients C_D of vehicle decreased. It can be explained that by the decrease of normal and tangent stresses. Drag coefficients C_D of Falcon more than Clipper. The dependency $C_L(\alpha)$ is increased, and the value is reached to 0.54 at $Re_0 \sim 10^4$. The values of m_z are quite sensitive to the variation of Re_0, changes its sign at $\alpha \sim 5$ deg.

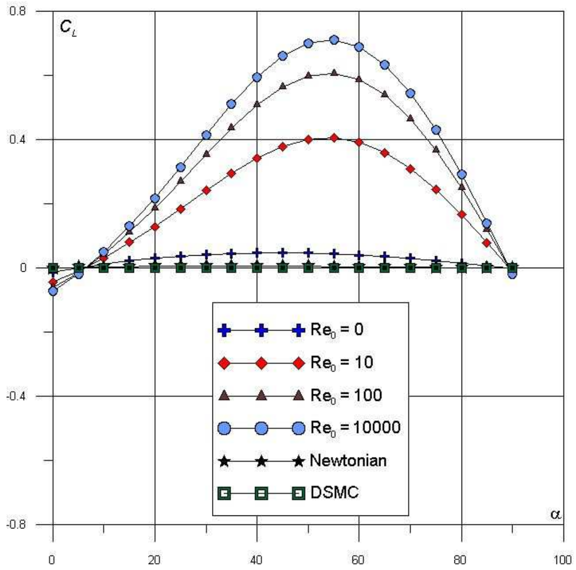

Fig. 6. Dependencies of lift coefficients $C_L(\alpha)$ for hypersonic vehicle “Falcon HTV-2”

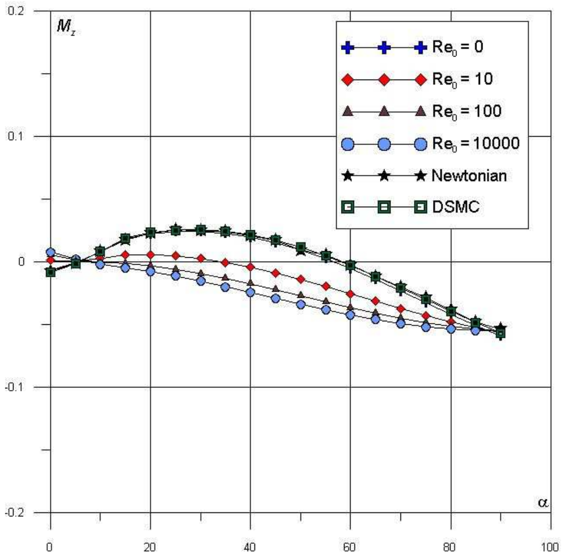

Fig. 7. Dependencies of pitching moment coefficients $m_z(\alpha)$ for hypersonic vehicle “Falcon HTV-2”

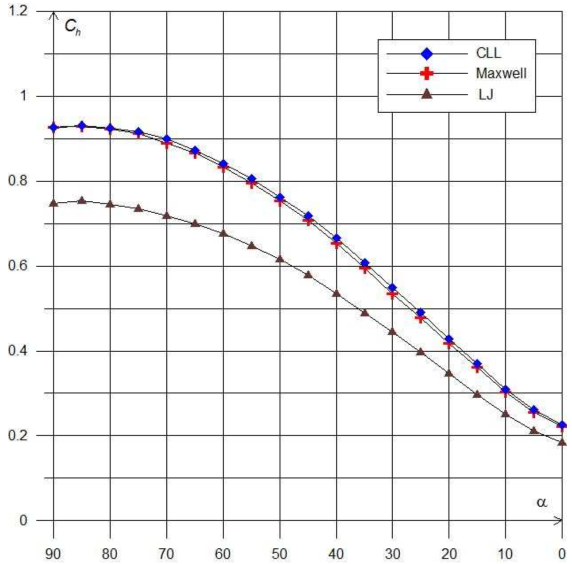

Fig. 8. Dependencies of heat transfer coefficient $C_h(\alpha)$ for "Clipper" with various gas surface interaction models (Maxwell, CLL, Lennard-Jones)

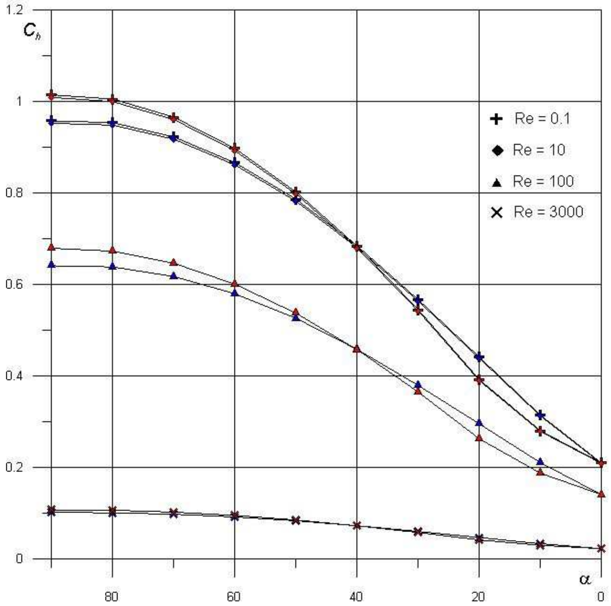

Fig. 9. Dependencies of heat transfer coefficients $C_h(\alpha)$ for "Clipper" (in blue) and "Falcon HTV-2" (in red)

Heat transfer coefficient C_h for "Clipper" with various gas surface interaction models (Maxwell, Cercignani-Lampic-Lord (CLL), Lennard-Jones (LJ)) by DSMC method are presented in Fig 8. The dependences of $C_h(\alpha)$ for "Clipper" and "Falcon HTV-2" are presented in fig. 9 with the use of bridging functions. It can see that the values of "Falcon HTV-2" are more than "Clipper" and reached to 1.02 at Re 0.1 ($40 \leq \alpha \leq 90$). The values at Re = 0.1 and 10 are not very significant, but when the Re more than 10 the values are significant.

5 Conclusions

The different methods to calculate aerodynamic and aerothermodynamic characteristics of perspective hypersonic vehicles in rarefied gas flow are carried out. The approximate engineering method to calculate hypersonic aerodynamic in transitional regime are described. The results of calculation of aerodynamic and aerothermodynamic characteristics for hypersonic vehicles by various engineering methods in rarefied gas flow with various Reynolds numbers were presented. Thus, the methods of the calculation of aerodynamic and aerothermodynamic characteristics of the bodies in the hypersonic flow of rarefied gas in the transitional regime give good and qualitatively right results for a wide range of bodies not very thin bodies. The obtained results by engineering methods are compared with the DSMC and Newtonian method. The obtained data can be applied in the future hypersonic vehicle designs.

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