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Aerodynamic Investigation for Prospective Aerospace Vehicle in the Transitional Regime

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Abstract

The basic quantitative tool for the study of hypersonic rarefied flows is the direct simulation Monte Carlo method (DSMC). The DSMC method requires a large amount of computer memory and performance and is unreasonably expensive at the first stage of spacecraft design and trajectory analysis. A possible solution to this problem is approximate engineering methods. However, the Monte Carlo method remains the most reliable approach to compare to the engineering methods that provide good results for the global aerodynamic coefficients of various geometry designs. This paper presents the calculation results of aerodynamic characteristics for spacecraft vehicles in the free molecular, the transitional and the continuum regimes using the local engineering method. Results and methods would be useful to calculate aerodynamics for new-generation hypersonic vehicle designs.

Key words: hypersonic vehicles, aerodynamic, space technology, engineering methods, DSMC.

1. Introduction

The aerospace system is the main indicator of the international power of any country concerned with guaranteeing security, the standard of scientific research and technical development. When designing the launch system of cargo and people into orbit, we used high-altitude aviation and rocket technology. In the future, almost all the projects are to design new space systems for multiple use - to launch loads into orbit and return from it. First, this is related to the use of winged spacecraft for descent and landing on usual aerodromes. To estimate the aerodynamic loads and to predict the landing area, one should know at the stage of initial design, the coefficients of aerodynamic forces and moments of spacecraft for varying temperatures, densities and flight velocities for numerous possible descent trajectories.

The development of spacecraft and rocket technologies requires reliable data on the aerodynamic and aerothermodynamic characteristics for hypersonic speed in an entire range of flow regimes, i.e., from the continuum flow regime to the free-molecular regime. During de-orbiting, the spacecraft passes through the free molecular, then through the transitional regime and the final flight is in the continuum flow.

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 [1]. 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 aerodynamics characteristics of complex bodies in the transitional regime [2].

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The difficulty in the development of a hypersonic vehicle is caused by quite a number of problems of modeling full-scale flight conditions in wind tunnels. The analysis of the aerodynamics and aerothermodynamic characteristics of a hypersonic vehicle at high-altitude requires numerous numerical calculations [3-5].

To correctly simulate hypersonic flows, the flows must be understood and modeled correctly and this truer than in the numerical simulation of hypersonic flows. Hypersonics must be dominated by an increased understanding of fluid mechanics reality and an appreciation between reality and the modeling of that reality [6]. 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 [7]. Multi-parametric calculations can be performed only by using an approximation engineering approach. Computer modeling allows rapid analysis of the aerodynamic characteristics of hypersonic vehicles using theoretical and experimental research in aerodynamics of hypersonic flows.

The basic quantitative tool for the study of hypersonic rarefied flows is the direct simulation Monte Carlo method (DSMC) [8, 2]. The DSMC method requires a large amount of computer memory and performance and is unreasonably expensive at the initial stage of spacecraft design and trajectory analysis. Approximate engineering methods pose a possible solution to this problem. These methods allow us to calculate aerodynamic characteristics of vehicles for multiple variants of free-stream parameters within a reasonable time and to refine the results at the most important segments of the flight trajectory by the DSMC method. The early work of [2] indicated that the local engineering method could have a significant effect on aerodynamic characteristics of various hypersonic vehicles.

The purpose of this work is to create an engineering program for aerodynamic characteristics calculation of the perspective hypersonic vehicles. This method is suited to calculate for hypersonic vehicles, taking into account the influence of Reynolds number, and provide good results for various vehicle shapes.

2. Calculation Methods for Hypersonic Aerodynamics

Difficulties of solving aerodynamic problems of overflow on bodies of rarefied gas stimulated the development of engineering semi-empirical methods based on the accumulated experimental data. The most suitable method to compute aerodynamic forces of a spacecraft relies on bridging formulae. When modeling the natural conditions, it is necessary to consider the basic similarity criteria. The hypersonic aerodynamic coefficients most commonly used parameters are:

Mach number M

$$\mathrm{M}_{\infty} = \frac{V_{\infty}}{a_{\infty}}$$

Knudsen number Kn

$$\mathrm{Kn} = \frac{\lambda_{\infty}}{L_{ref}}$$

Reynolds number Re

$$\mathrm{Re}_{\infty} = \frac{\rho_{\infty} V_{\infty} L_{ref}}{\mu_{\infty}}$$

where, λ_{∞} - the mean free path, L_{ref} - reference length of vehicle, μ_{∞} - the viscosity coefficient. In hypersonic flow calculation more efficiently accepted to use Reynolds number than Knudsen number.

The famous Newtonian sine squared law indicated that the force varies as the square of the sine of the deflection angle. More than half century later it was indicated that Newton's sine-squared law was not very accurate and, indeed, the preponderance of fluid dynamic experience up to the present day confirms this finding, the exception to this is the modern world of hypersonic aerodynamics [9]. The pressure coefficient at all forward facing points of the body is

$$C_p = 2\sin^2\theta$$

where, θ is the local inclination of the surface to the free stream.

An alternative representation of the pressure coefficient for hypersonic flow, replacing the factor 2 by the appropriate value of the stagnation-point pressure coefficient at the flow condition of interest, which is known as modified Newtonian flow theory [10]

$$C_p = C_{p,\mathrm{mod}} \sin^2\theta$$

where $C_{p,\mathrm{mod}}$ could be found experimentally or by using the Rayleigh's pitot formula [11, 12].

$$p_{\mathrm{stag}} = p_{\infty}\left[\frac{(\gamma+1)\mathrm{M}_{\infty}^2}{2}\right]^{\gamma/(\gamma-1)}\left[\frac{\gamma+1}{2\gamma\mathrm{M}_{\infty}^2-(\gamma-1)}\right]^{1/(\gamma-1)}$$

Where, p_{stag} – the stagnation pressure, γ - specific heat ratio.

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For the last 50 years, the introduction of modified Newtonian theory continues to be used often to generate approximation for the pressure acting on configurations in hypersonic flows [13-15].

In this work, the expressions for the elementary pressure forces and friction forces are applied in the form described in [2, 16, 17]. The local formulae take directly into account the geometry of the vehicle and calculate pressure and skin friction distribution on the body surface.

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

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

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

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 the values corresponding to the Newton theory, methods of thin tangent wedges and cones at $\mathrm{Re}_0 \to \infty$. By the analysis of computational and experimental data, the empirical formulas are proposed, as follow

$$p_0 = p_\infty + [p_\infty(2-\alpha_n) - p_\infty]p_1 / z\,,$$

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

$$\tau_0 = 3.7\sqrt{2}[R + 6.88\exp(0.0072R - 0.000016R^2)]^{-1/2}$$

Here,

$$z = \left(\frac{\pi(\chi-1)}{\chi} t_w\right)^{1/2}$$

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

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

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

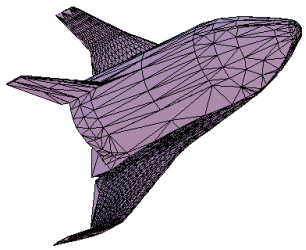

Fig. 1. Calculation diagram of prospective spacecraft vehicle "Clipper"

The technique was proved to be good for the calculation of hypersonic flow for convex and not very thin 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 the experiment and calculation through the Boltzmann equation with an accuracy of 5%. Considering the accuracy of the relation of the locality method, it 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 $\mathrm{M}_\infty \sin\theta >> 1$ [2].

Thus, the locality method in 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 sufficient result for lift force coefficient C_L. A comparison of the experimental and calculated results (dashed curve) of drag coefficient C_D for the sphere using the local engineering method ($\mathrm{M}_\infty = 5.15\text{-}10$, $T_w/T_0 = 1$) is performed in fig. 2 [16]. It can be seen that the influence is small. Figure 3 presents the results of drag coefficients C_D (α) for the space shuttle with the use of this method.

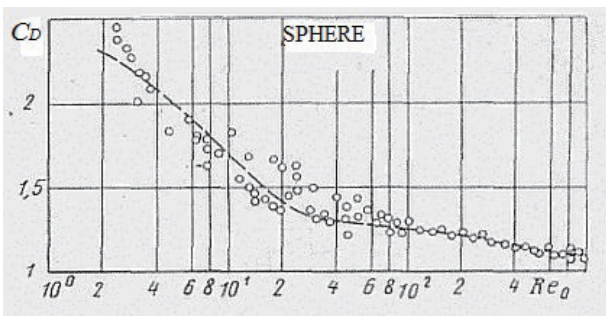

Fig. 2. Drag coefficient C_D for a sphere at various Reynolds number [16]

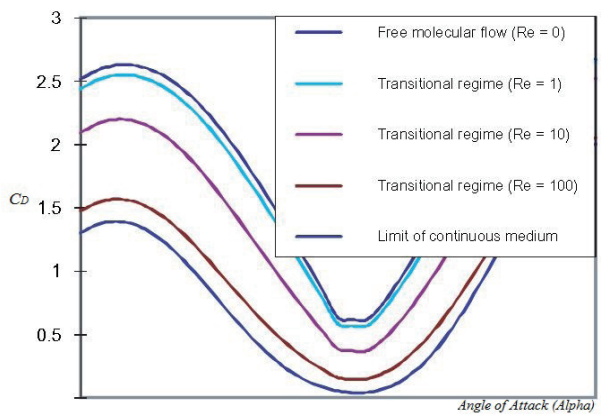

Fig. 3. Drag coefficient of Space Shuttle at the various stages of flight trajectories [2]

3. Computational Results and Discussion

The coefficients of drag force C_D, lift force C_L and pitching moment M_Z ware calculated according to equations, as below

$$C_i = \frac{F_i}{\frac{1}{2}\rho_\infty V_\infty^2 S_{ref}} \quad i = D, L,$$

$$M_Z = \frac{M}{\frac{1}{2}\rho_\infty V_\infty^2 L_{ref} S_{ref}}$$

L_{ref}, S_{ref} – references length and surface; F_i M – resultant force acting on the vehicle and moment, respectively.

The calculation has been performed 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 γ = 1.4; temperature factor $t_w = T_w/T_0$ = 0.01; velocity ratio M_∞ = 15, Reynolds number Re_0 = 0, 10, 10^2, 10^4.

The dependencies of the drag force coefficient C_D, lift force coefficient C_L and pitching moment coefficient M_Z on angle of attack α from 0 to 90 deg for the prospective spacecraft vehicle "Clipper, TsAGI model" (fig. 1) [17, 18] are presented in figs 4-9. Comparisons of the numerical values of C_D, C_L, M_Z for the spacecraft vehicle using the DSMC method, Newton's method and local engineering method

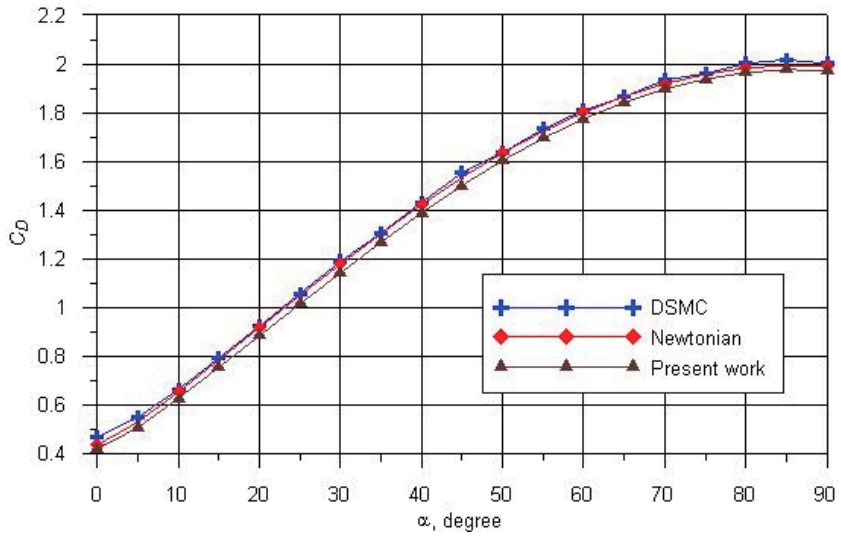

Fig. 4. Drag coefficients C_D for "Clipper" (t_w = 0.01)

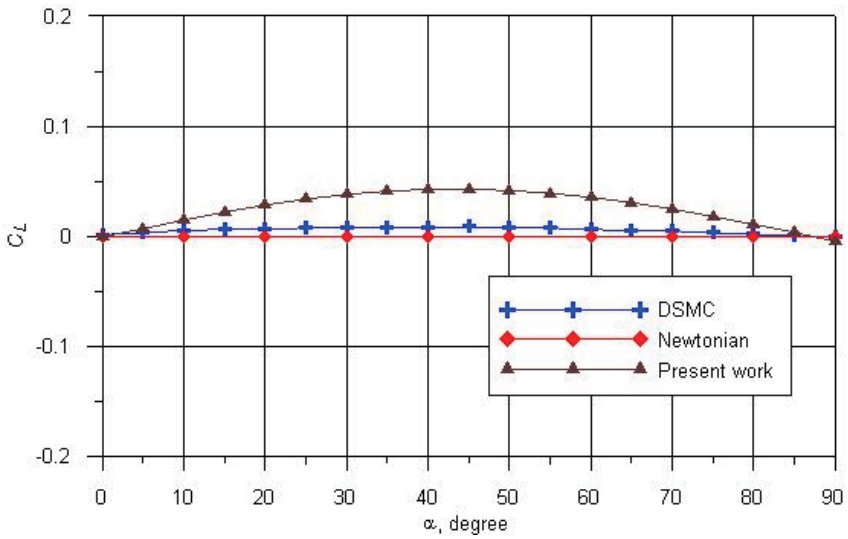

Fig. 5. Lift coefficients C_L for "Clipper" (t_w = 0.01)

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are also presented in figs 4-6. Thus, the dependencies of the C_D, C_L, M_Z on the Reynolds number are significant in all ranges of angle of attack. This comparison led to the corrections of the computation of the aerodynamic characteristics coefficients.

From these results, it can be seen that the influence of results by DSMC, Newton's method and local engineering method at $Re_0 \to 0$ (in the free molecular regime) is not significant. The growth of a temperature ratio for the free molecular regime, leads to a considerable growth of the absolute value of C_L and to the loss of symmetry of $C_L(\alpha)$ in respect to the coordinate origin, and these tendencies were noted to by analysis of the results obtained by the Monte Carlo method. Thus, it can see that the local engineering method gives good results in the calculation of aerodynamic characteristics of hypersonic vehicles in rarefied gas flow. The methods considered do not take into account the influence of the interaction of a boundary layer with the inviscid hypersonic flow at the large numbers of Re_0.

It has to be pointed out that when the Reynolds number increased, the drag coefficients C_D of vehicle diminished,

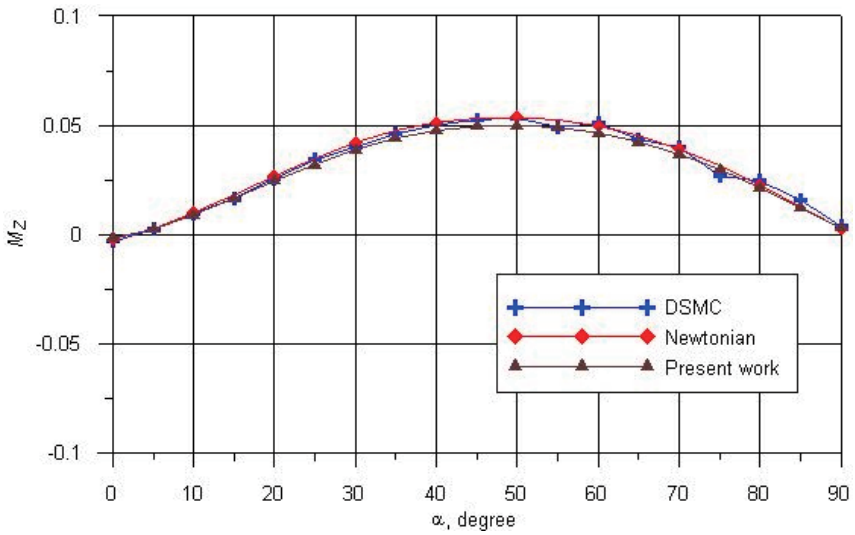

Fig. 6. Pitching moment coefficients M_Z for "Clipper" ($t_w = 0.01$)

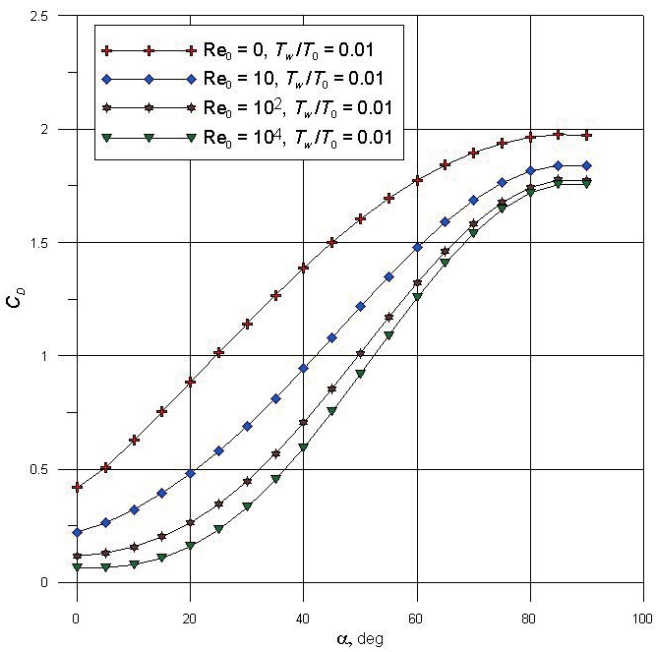

Fig. 7. Dependencies of drag coefficients $C_D(\alpha)$ for "Clipper" on various Reynolds number

which can be explained by the decrease of normal and tangent stresses (fig. 7). At high Reynolds number $Re_0 \geq 10^6$, characteristics are almost unchanged. The dependency $C_L(\alpha)$ is increased at a high Reynolds number, which can be explained by the decrease of normal and tangent stresses (fig. 8). The values of M_Z (in respect to the center of mass of a uniform body) are quite sensitive to the variation of Re_0. M_Z changes its sign to 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 (fig. 9). As it follows from these results, the coefficient of moment of tangent M_Z is less sensitive to the variations of the temperature ratio, but its value means that this factor should be necessarily taken into account by the analysis of the variations of the body's orientation, when this body is subject to the action of a flow of strongly rarefied gas.

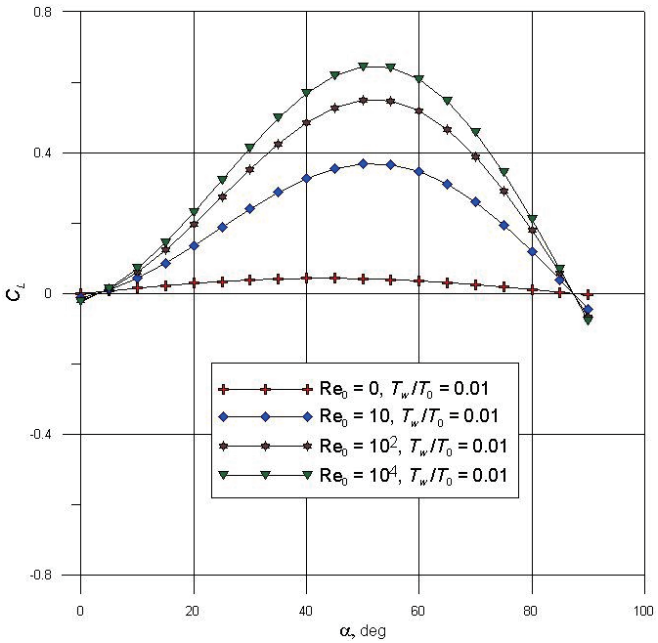

Fig. 8. Dependencies of lift coefficients C_L (α) for "Clipper" on various Reynolds number

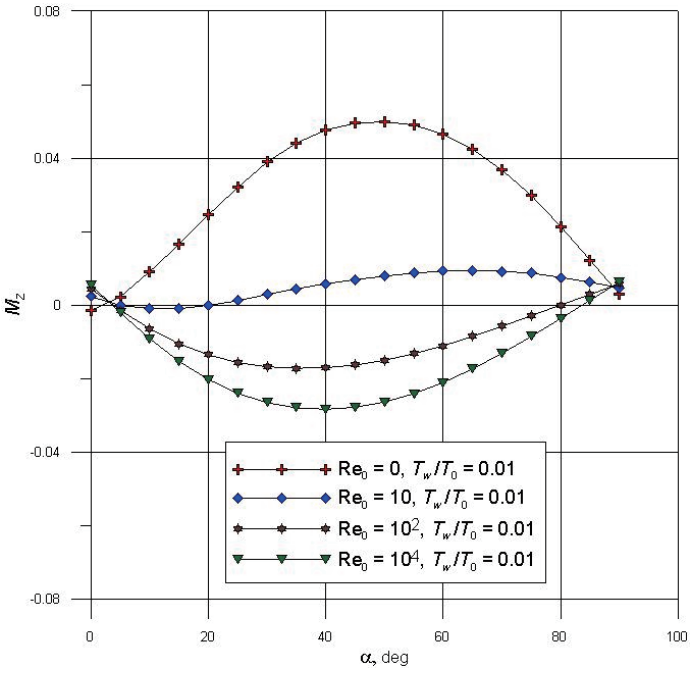

Fig. 9. Dependencies of pitching moment coefficients M_Z (α) for "Clipper" on various Reynolds number

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4. Conclusions

The analysis of different approaches to calculate aerodynamic characteristics of prospective spacecraft vehicles in rarefied gas flow were performed. The engineering method to calculate hypersonic aerodynamics in the transitional regime is described. The calculation results of aerodynamic characteristics for a spacecraft vehicle by the engineering method in transitional regime with various Reynolds numbers are presented. Comparison to Newton's method and the DSMC method are described. We can reduce calculation errors in vehicle design projects by multiple calculations using this method. The above engineering method in transitional regimes gives a good result for a wide range of bodies. The obtained data can be applied in the future for hypersonic vehicle design.

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