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Modern Trends in the Development of Reusable Aerospace System

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ABSTRACT— ***The purpose of this work is to analysis the history and future development of hypersonic vehicles all over the world and to determine the aerodynamic and aerothermodynamic characteristics of prospective hypersonic vehicles by using engineering methods at all range of flow regimes (free-molecular, transitional and continuum regimes). In this paper present the calculation results of aerodynamic and aerothermodynamic characteristics of prospective hypersonic vehicle.***

Keywords— space transportation system, reusable space vehicles, computational aerothermodynamic, hypersonic technology, rarefied gas dynamics, DSMC, engineering methods, transitional regime.

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1. INTRODUCTION

The purpose of this paper is related to the development of reusable hypersonic vehicle system. History has shown that hypersonic vehicle programs proposed in developed countries over the last 20 years. The motivations for high-speed flight have based on military and civilian needs. Several important factors that motivate the consideration of hypersonic or reusable launch system solutions for those missions are: potential reductions in operational cost to accomplish the mission (space launch system), the ability to enable a unique capability based on the hypersonic speed (high-speed transportation system), potential improvements in operational flexibility for accomplishing the mission (military missions).

Theoretical studies of hypersonic flows associated with the creation of “Space Shuttle” to transport crews and cargo into Earth orbit in the Soviet Union began in the last century. Research mainly focused on one of the departments of TsAGI named after N.Y. Zhukovsky (Central Aerohydrodynamic Institute). Practical work on the creation of aerospace systems was had been instructed engineering centre of the experimental design bureau named after A.I. Mikoyan. Air Force Research Institute has developed an original concept of space system, which efficiently integrated the ideas of the aircraft, rocket plane and space object in 1960.

The project was called “Spiral” and represented as a complex system. Powerful hypersonic aircraft (weight 52 tons, length 38 m, wingspan 16.5 m), which was dispersed to six times the speed of sound (Mach = 6), then from its back at height of 28-30 km was supposed to start 10 ton manned orbital plane (8 m long and 7.4 m span).

The "Spiral" was a response to the U.S. space program to create an interceptor reconnaissance bomber, the X-20 "Dyna Soar". As shown, the implementation of project "Dyna Soar" is not successful as a "Spiral". In the end both projects have been folded, although at different stages of development [1].

Since 1980 aerospace plane programs are developed in many developed countries as the USA and the Soviet Union. For example, in England "HOTOL" (Fig. 3), Germany "Zenger" (Fig. 4), France "Hermes" (Fig. 5), Japan "Hope" (Fig. 6), China "Shenlong" (Fig. 7), India "AVATAR" (fig. 8), the National Aerospace Plane (NASP) and several recent NASA X-vehicle programs including the X-33, X-34, X-30, X-43B/C.

Figure 1: Russian project "Spiral"

Figure 2: USA project "Dyna Soar"

In the present, Russia is developing new generation reusable spacecraft "Clipper", "RUS" programs to deliver crews and cargo to low Earth orbit and the space station since 2000. The first flight is expected in 2015. United States is developing a new spacecraft "Orion" to deliver crew and cargo to low Earth orbit and back. First manned flight is planned in 2014, the first flight to the moon in 2020.

Figure 3: HOTOL

Figure 4: Zenger

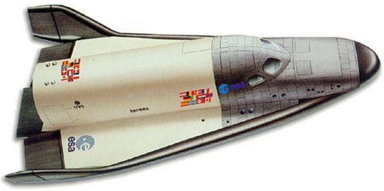

Figure 5: Hermes

Figure 6: Hope

Figure 7: Shenlong

Figure 8: AVATAR

Figure 9: Russian perspective project **"**RUS"

Figure 10: USA perspective project **"**Orion"

The DARPA (Defense Advanced Research Projects Agency) is developed “Falcon” (Force application and launch from continental United States) since 2003. The Falcon Hypersonic Technology Vehicle (Falcon HTV-2) is a multiyear research and development effort to increase the technical knowledge base and advance critical technologies to make long-duration hypersonic flight a reality. Falcon HTV-2 is an unmanned, rocket-launched, maneuverable aircraft that glides through the Earth’s atmosphere at incredibly fast speeds -Mach 20.

The development of space and rocket technologies require reliable data on the aerodynamic and aerothermodynamic characteristics of hypersonic vehicles in the whole range of flow regimes, i.e., from the continuum flow regime up to the free-molecular regime. During de-orbiting, the spacecraft passes through the free molecular, then through the transitional regime and the finalized 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 [2].

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 [2-3]. On the transition interval between the free molecular and continuum regimes numerical methods of solving the Boltzmann equation and its model equations are being used with success [4].

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 [5].

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 [6]. 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 aerodynamics of hypersonic flows. The basic quantitative tool for study of hypersonic rarefied flows is direct simulation Monte Carlo method (DSMC) [7], [3]. DSMC method is required large amount of computer memory and unreasonable expensive at the initial stage of vehicle design and trajectory analysis. The solution for this problem is the approximate local engineering methods [8-11]. 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 early work of [3] indicated that local engineering methods could have significant effect on aerodynamic characteristics of various hypersonic vehicles. 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 [3].

The purpose of this work is to compute aerothermodynamic characteristics of perspective aerospace vehicle “Clipper” and hypersonic technology vehicle “Falcon HTV-2” by using local engineering method. This engineering method is suitable to calculate for taking in account the influence of Reynolds number, and provide good results for various hypersonic vehicle shapes.

2. METHOD FOR DESCRIPTION THE SURFACE OF VEHICLES

One of the basic technology questions of aerodynamic characteristics calculation of the arbitrary apparatus shape is the rational choice of way to describe of surface geometry. Methods for describing of complex surfaces can be divided into two main groups: mathematical approximation of a surface and space distribution of large number surface points which restored the system of surface element. The main disadvantage of the first group of methods are usually related to approximation of complex mathematical problems, essentially nonlinear surfaces on small number of control points, and the second - difficulty preparation of initial data. In the given work, these both methods are used: due to comparative simplicity and universality of the task of control points, and finally restore surface on the control points, the modeled body is divided into number of specific parts (wing, fore part, bottom-most part of fuselage, etc.), for each of those is conducted square-law interpolation on control points [12].

For each part introduces the axis (x, y', z'), which are the axes of the symmetric coordinate system. Axis divided into a finite number of characteristic points defined by the parameters x_i, y_i, z_i. These points in a cylindrical coordinate system are given by section: φ_j, R_{ij}; φ_{yi}, R_{yij}; φ_{zi}, R_{zij}. Depending on the shape of the cross section, it can be defined as a discrete and in analytical form.

For qualification the surface of the passing points provides an interpolation procedure. Intermediate points on the axes and the angles are according to the formulas of the linear interpolation,

$$x_i = \frac{1}{2}\left(x_{i-\frac{1}{2}} + x_{i+\frac{1}{2}} \right), \varphi_j = \frac{1}{2}\left(\varphi_{j-\frac{1}{2}} + \varphi_{j+\frac{1}{2}} \right)$$

Radius value by use of Lagrange polynomial interpolation is interpolated twice – by φ и x:

$$R(a) = \sum_{i=1}^{3} R(a_i) \prod_{j \neq 1} \frac{a - a_j}{a_i - a_j}$$

where $a_{i,\,,j}$ - correspond to the values of φ и x in the interpolation points.

Thus, with the required accuracy are given by the initial points on the surface. The question remains, how is spanned by the available core surface of the streamlined apparatus. As already noted, the aim is suitable linear approximation, so in the capacity of basic will consider the linear element, correspond triangle, which was build by nearest three points. Vertices of triangles in rectangular coordinates for the different parts are defined by formula.

For fuselage

$$r = \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x_i \\ R_{ij} \cos \varphi_j \\ R_{ij} \sin \varphi_j \end{pmatrix}$$

For wing

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x_0 + z_i \cos \alpha_z - R_{zij} \cos \gamma_{zi} \\ y_0 + z_i \sin \alpha_z + R_{zij} \sin \varphi_{zj} \\ z_0 + z_i \cos \alpha_z \cos \beta_z - R_{zij} \cos \varphi_{zj} \sin \gamma_{zi} \end{pmatrix}$$

Where (x_0, y_0, z_0) - initial coordinates of the axis of the wing z', α_z – angle of slope of axis of the wing to the surface $y = 0$, β_{zi} - angle of slope of the axis of the wing to the axis z, γ_{zi} - the angle of slope defined by sections on the axis z'. For full definition of elements it is necessary to determine its orientation and surface area.

Let $\mathbf{a} = r_2 - r_1$, $\mathbf{b} = r_3 - r_1$, generating elements of the vector. Then element of the area

$$\mathrm{S} = \frac{1}{2}(\mathbf{a} \times \mathbf{b})$$

and normal to the surface

$$\mathbf{n} = (\mathbf{a} \times \mathbf{b}) / (|\mathbf{a} \times \mathbf{b}|)$$

An estimate error for approximation by linear elements in the process for free molecular flow regime gives good results. So, for the approximation in calculation the resistance of cone accurate within 5% (average error of statistical methods) should be about 10 elements, and for approximation of the sphere – 100, single application of the interpolation procedure reduces the error by an order [12].

3. METHODS TO COMPUTE AERODYNAMIC CHARACTERISTICS IN HYPERSONIC FLOWS

Various local interaction models have been known for a long time and widely used in many fields of mechanics and physics both in theoretical research and practical calculations [9]. Some of them used in gas dynamics and aeromechanics are described below. To be applied for hypersonic flows, the Newton model for calculating pressure on the exposed leading part of the body surface is widely used.

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

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]

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

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

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

where γ - specific heat ratio and M_∞ – Mach number. It can assumed that a fraction of particles $(1-\alpha_\tau)$ is reflected mirror-like from the surface and α_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 [3, 9, 11].

$$p = p_0\sin^2\theta + p_1\sin\theta$$
$$\tau = \tau_0\ \sin\theta\ \cos\theta$$

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

$$p_0 = p_\infty + [p_\infty(2-\alpha_n) - p_\infty]p_1/z$$
$$p_1 = z\exp[-(0.125+0.078t_w)\mathrm{Re}_{0eff}]$$
$$\tau_0 = 3.7\sqrt{2}[R+6.88\exp(0.0072R-0.000016R^2)]^{-1/2}$$
$$z = \left(\frac{\pi(\gamma-1)}{\gamma}t_w\right)^{1/2}$$
$$R = \mathrm{Re}_0\left(\frac{3}{4}t_w+\frac{1}{4}\right)^{-0.67},$$
$$\mathrm{Re}_{0eff} = 10^{-m}\,\mathrm{Re}_0, \qquad m = 1.8(1-h)^3$$

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 $M_\infty \sin\theta >> 1$ [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 [13-19] described the results of aerodynamic characteristics of various hypersonic vehicles by using engineering method.

4. METHOD TO COMPUTE HEAT TRANSFER COEFFICIENTS FOR HYPERSONIC VEHICLE IN TRANSITIONAL REGIME

The most suitable method to compute heat transfer coefficient of hypersonic vehicle relies on bridging formulae. Many bridging formulae have been seen in the work [20]. In the free molecular regime, to determine the heat transfer coefficient equation can write analytically [2]

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

$$\chi(x) = e^{-x^2} + \sqrt{\pi} x \left(1 + \operatorname{erf}(x)\right), \ \operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-x^2} dt$$

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 [21]

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

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

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

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

$$F_{b,1} = \frac{1}{2}\left(1 + \operatorname{erf}\left(\frac{\sqrt{\pi}}{\Delta \mathrm{Kn}_1} \cdot \lg\left(\frac{\mathrm{Kn}_0}{\mathrm{Kn}_m}\right)\right)\right), \quad F_{b,2} = \frac{1}{2}\left(1 + \operatorname{erf}\left(\frac{\sqrt{\pi}}{\Delta \mathrm{Kn}_2} \cdot \lg\left(\frac{\mathrm{Kn}_0}{\mathrm{Kn}_m}\right)\right)\right)$$

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.

5. CALCULATION RESULTS OF HYPERSONIC AEROSPACE VEHICLES

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*" (Fig. 11) and USA perspective hypersonic technology vehicle "Falcon HTV-2" (Fig. 12) 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 $\mathrm{Re}_0 = 0, 10, 10^2, 10^4$.

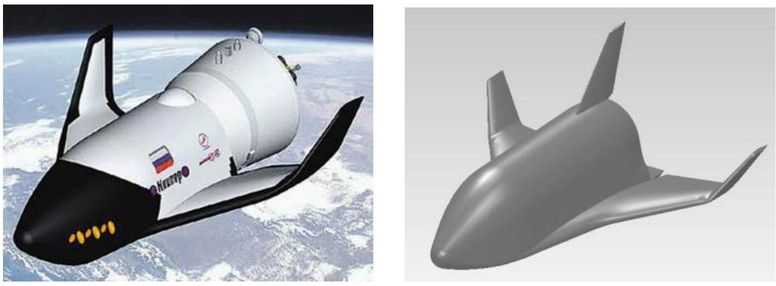

Figure 11: Geometry view of aerospace vehicle "Clipper"

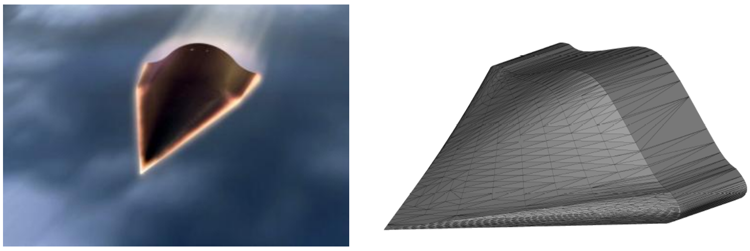

Figure 12: Geometry view of hypersonic vehicle "Falcon HTV-2"

The dependencies of $C_D(\alpha)$, $C_L(\alpha)$ and $M_Z(\alpha)$ for aerospace vehicle "Clipper" and hypersonic vehicle "Falcon HTV-2" are presented in Figs. 13-15. 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.

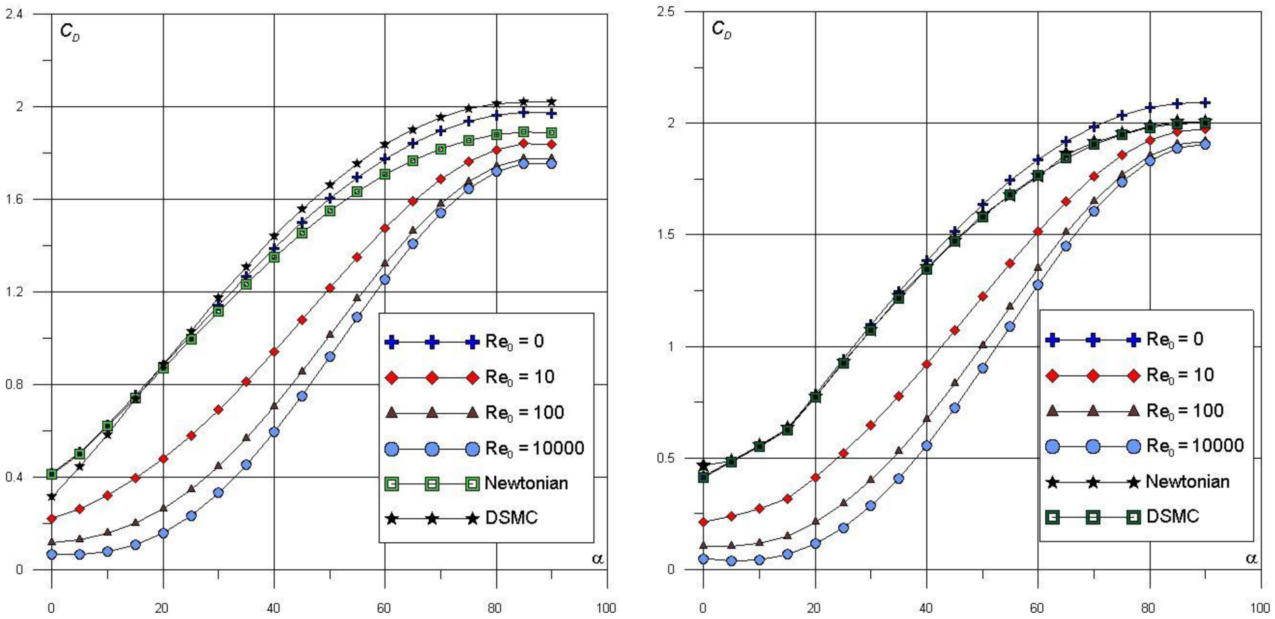

Figure 13: Drag coefficients C_D for aerospace vehicle "Clipper" and hypersonic vehicle "Falcon HTV-2"

At high Reynolds number $Re_0 \geq 10^6$, characteristics almost not changed. 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 for "Clipper" are quite sensitive to the variation of Re_0 and 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.

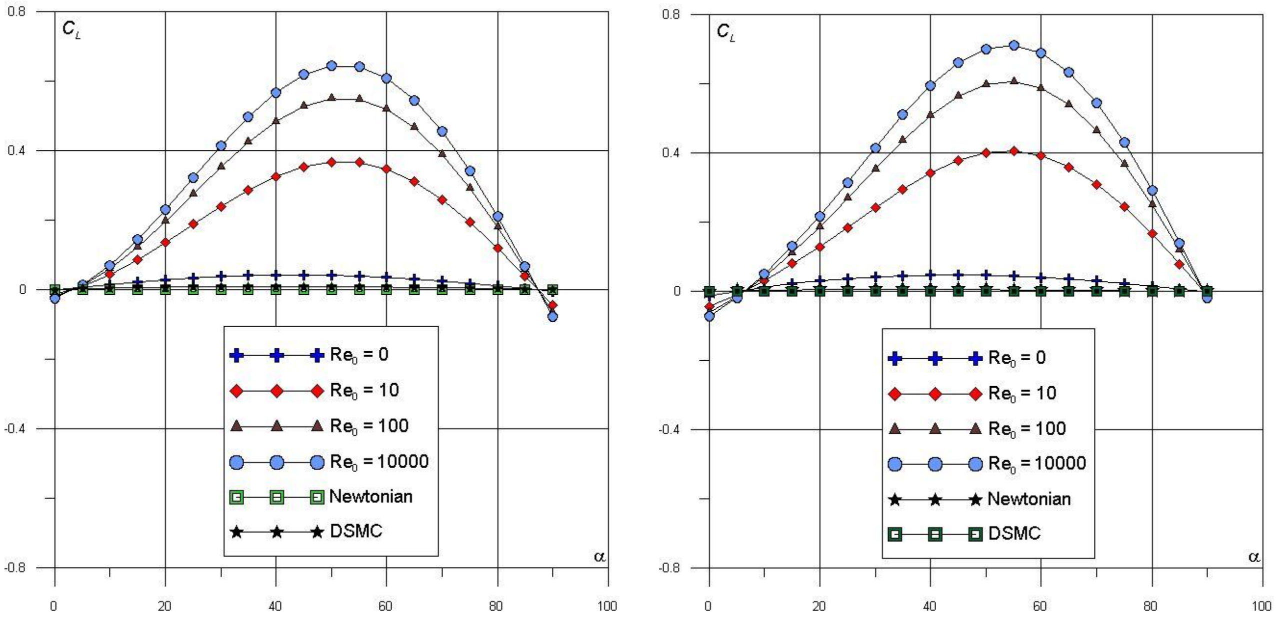

Figure 14: Lift coefficients C_L for aerospace vehicle “Clipper” and hypersonic vehicle “Falcon HTV-2”

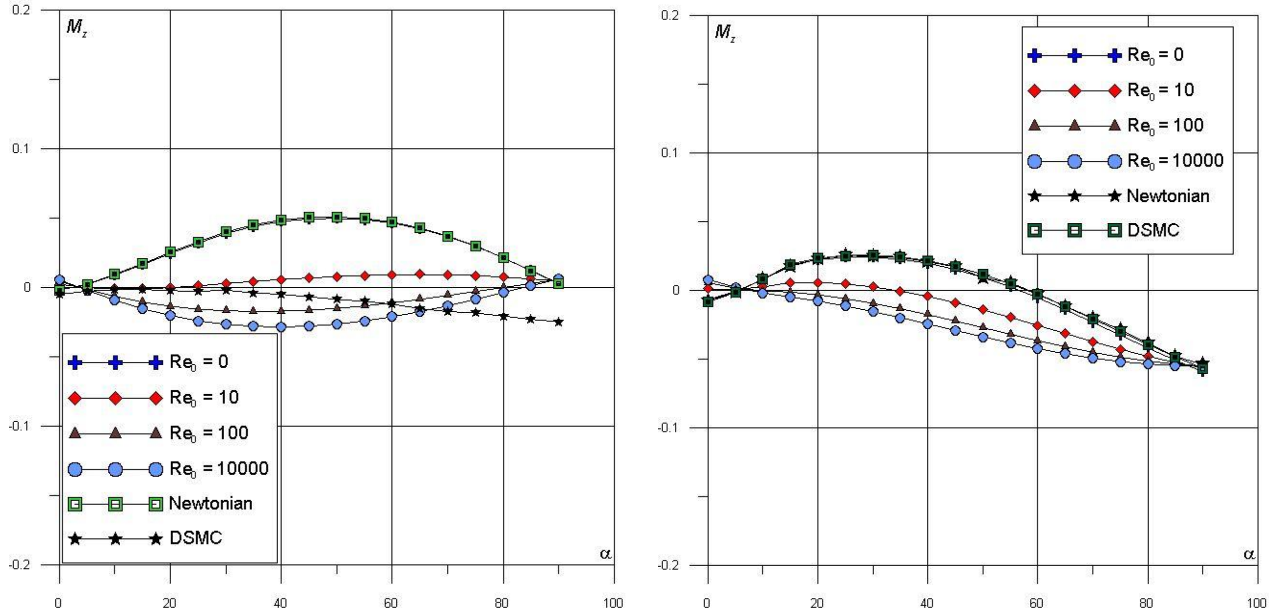

Figure 15: Pitching moment coefficients M_Z for aerospace vehicle “Clipper” and hypersonic vehicle “Falcon HTV-2”

Drag coefficients C_D of “Falcon” more than “Clipper”. The dependency $C_L(\alpha)$ for “Falcon HTV-2” is increased, and the value is reached to 0.54 at $Re_0 \sim 10^4$. The values of M_Z for “Falcon” are quite sensitive to the variation of Re_0, changes its sign at $\alpha \sim 5$ deg. Results by using local engineering method are compared with the results obtained by DSMC method and Newtonian method.

The dependencies of $C_h(\alpha)$ for hypersonic vehicles are in Figs. 16 with the use of bridging functions. It can see that the values of “Falcon HTV-1” 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.

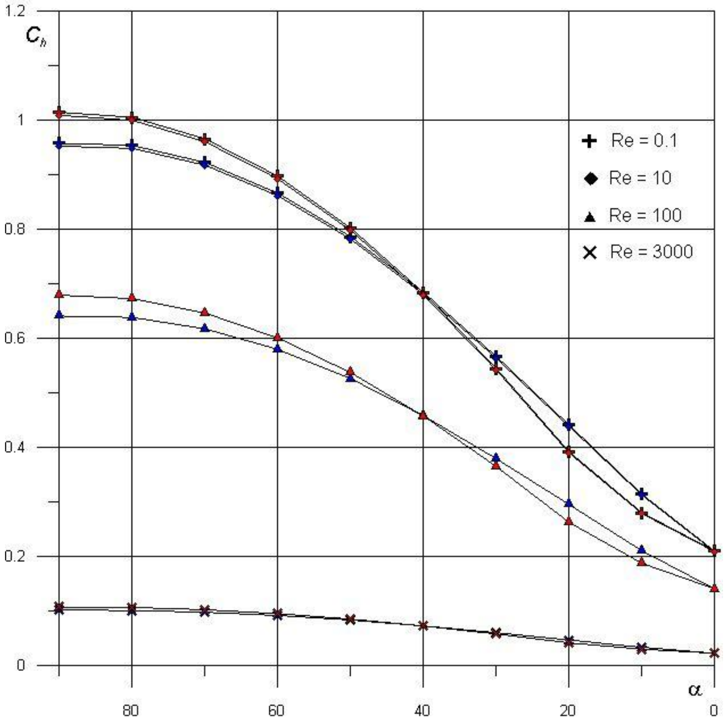

Figure 16: Heat transfer coefficients C_h for "Clipper" (blue) and "Falcon HTV-2" (red)

6. CONCLUSIONS

The history and modern trends in development of hypersonic technology all over the world are discussed. The different local engineering methods to calculate aerodynamic and aerothermodynamic characteristics of perspective hypersonic vehicles in rarefied gas flow are carried out. 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 method are compared with the DSMC and Newtonian method.

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7. ACKNOWLEDGEMENT

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