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# Computer Modelling of Aerothermodynamic Characteristics for Hypersonic Vehicles

**Yuri Ivanovich Khlopkov, Anton Yurievich Khlopkov, Zay Yar Myo Myint**

Department of Aeromechanics and Flight Engineering, Moscow Institute of Physics and Technology, Zhukovsky, Russia
Email: khlopkov@falt.ru, zayyarmyomyint@gmail.com

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## Abstract

**The purpose of this work is to describe the suitable methods for aerodynamic characteristics calculation of hypersonic vehicles in free molecular flow and the transitional regimes. Moving of the hypersonic vehicles at high altitude, it is necessary to know the behavior of its aerodynamic characteristics for all flow regimes. Nowadays, various engineering approaches have been developed for modelling of aerodynamics of aircraft vehicle designs at initial state. The engineering method that described in this paper provides good results for the aerodynamic characteristics of various geometry designs of hypersonic vehicles in the transitional regime. In this paper present the calculation results of aerodynamic characteristics of various hypersonic vehicles in all range of regimes by using engineering method.**

## Keywords

**Aerodynamic Characteristics, Computational Aerodynamics, Hypersonic Technology, Rarefied Gas Dynamics; Engineering Method, Aerodynamics in Transitional Regime**

## 1. Introduction

Theoretical studies of hypersonic flows associated with the creation of "Space Shuttle" to transport people and cargo into Earth orbit began in the last century. Research had been focused mainly on the department of TsAGI named after N.Y. Zhukovsky (Central Aerohydrodynamic Institute). Practical work on the creation of aerospace systems 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 at height of 28-30 km from its back, manned orbital plane 10 ton (8 m long and 7.4 m span) was supposed to start.

The "Spiral" (**Figure 1**) was a response to the U.S. space program to create an interceptor reconnaissance bomber, the X-20 "Dyna Soar" (**Figure 2**). 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 vehicle programs are developed in many developed countries as the U.S. and the Soviet

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**Figure 1.** Russian project "Spiral".

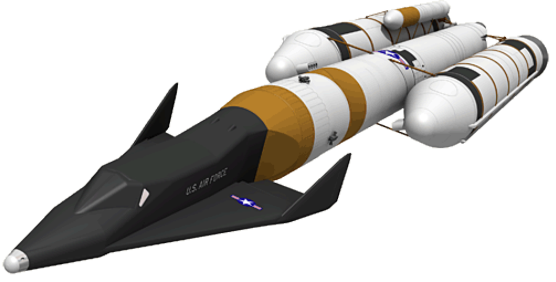

**Figure 2.** USA project "Dyna Soar".

Union. For example, in England "HOTOL" (**Figure 3**), Germany "Zenger" (**Figure 4**), France "Hermes" (**Figure 5**), Japan "Hope" (**Figure 6**), China "Shenlong" (**Figure 7**) and India "AVATAR" (**Figure 8**). Some of them have been folded.

Russia is developing new generation reusable spacecraft programs "Clipper", "RUS" 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 full-size test flight is in 2014, the first flight to the moon planned in 2020.

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 (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.

With the development of space and rocket technologies, it is required the reliable methods on the aerodynamic and aerothermodynamic characteristics modelling 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.

As we have 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].

**Figure 3.** HOTOL.

**Figure 4.** Zenger.

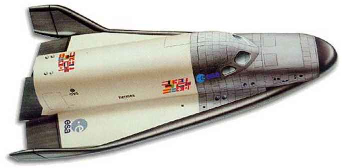

**Figure 5.** Hermes.

**Figure 6.** Hope.

**Figure 7.** Shenlong.

**Figure 8.** AVATAR.

To correctly simulate hypersonic flows, the flows must be understood and modeled correctly and this is 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 analyze the aerodynamic characteristics of hypersonic vehicles by using theoretical and experimental research in aerodynamics of hypersonic flows. Nowadays, the basic quantitative tool for study of hypersonic rarefied flows is direct simulation Monte Carlo method (DSMC) [3] [7]. DSMC method 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 provide 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 calculate aerodynamic characteristics of perspective space vehicle “Clipper” and hypersonic technology vehicle “Falcon HTV-2” by using engineering method. This engineering method is suitable to calculate with taking into account the various Reynolds number, and provide good results for various hypersonic vehicle designs.

## 2. Calculation Methods

### 2.1. Method for Hypersonic Aerodynamics in the Free Molecular Flow Regime

The problem of determination of the aerodynamic characteristics in free molecular flow is set in a usual way. In the case of hypersonic flow, the values of pressure $p$ and tangential $\tau$ forces and heat flux $q$ for the element of a surface look as below

$$p = \frac{\rho V^2}{2}\left[(2-\sigma_n)2\sin^2\theta + \sigma_n\sqrt{\frac{\gamma-1}{\gamma}\frac{T_w}{T_\infty}}\pi\sin\theta\right]$$

$$\tau = \frac{\rho V^2}{2}\sigma_\tau 2\sin\theta\cos\theta$$

$$q = \frac{\rho V^2}{2}\sigma_\tau\left(1-2\frac{\gamma-1}{\gamma}\frac{T_w}{T_\infty}\right)\sin\theta$$

where $\sigma_\tau$—accommodation coefficient, $\gamma$—specific heat ratio, $T_w$, $T_\infty$—surface temperature and flow temperature respectively . The experiment provides the most reliable results for the formulation of a connection between the flow as like the oncoming particles characteristics and the reflected particles through the coefficients of accommodation. The results of aerodynamic characteristics of semi-sphere, cone with the various semi-angles by a vertex, blunted semi-cones, and blunted semi-cones with wings are presented in [12].

### 2.2. Method for Hypersonic Aerodynamics in the Transitional Regime

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

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

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

where, coefficients $p_0$, $p_1$, $\tau_0$ (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 $\mu_0$ is calculated at stagnation temperature $T_0$. Except Reynolds number the most important parameter is the temperature factor $T_w/T_0$, where $T_0$, $T_w$ are the stagnation temperature and surface temperature respectively.

The dependency of the coefficients of the regime in the hypersonic case must ensure the transition to the free-molecular values at $Re_0 \to 0$, and to the values corresponding to the Newton theory, methods of thin tangent wedges and cones, at $Re_0 \to \infty$. On the basis of the analysis of computational and experimental data, the empirical formulas are proposed [15-17]

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

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

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

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

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

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

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

The technique 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 $M_\infty \sin\theta >> 1$.

This locality method for 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 [13,15-19] described the results of aerodynamic characteristics of various hypersonic vehicles by using this method.

## 3. Results

The results of the calculation of the coefficients of drag force $C_D$, lift force $C_L$, pitching moments $M_Z$ with value of angle of attack $\alpha$ from 0 to 90 deg for Russian perspective space vehicle "Clipper, TsAGI model" (**Figure 9**) [14] and USA perspective hypersonic technology vehicle "Falcon HTV-2" (**Figure 10**) are presented.

The calculation has been carried out through the method described on the above section within the range of angles of attack $\alpha$ 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 $T_w/T_0 = 0.01$; Reynolds number $Re_0 = 0, 10, 100, 10000$; velocity ratio = 15.

The dependencies of $C_D(\alpha)$, $C_L(\alpha)$ and $M_Z(\alpha)$ are presented in **Figures 11-13**. It can be seen from these results that when the Reynolds number increased, the drag coefficients $C_D$ of vehicle diminished which can be ex-

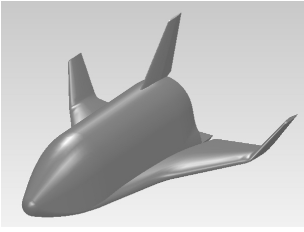

**Figure 9.** Geometry view of space vehicle "Clipper".

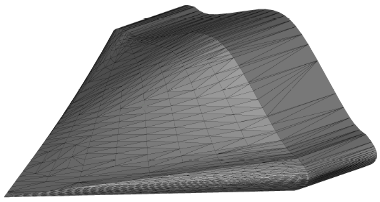

**Figure 10.** Geometry view of hypersonic vehicle "Falcon HTV-2".

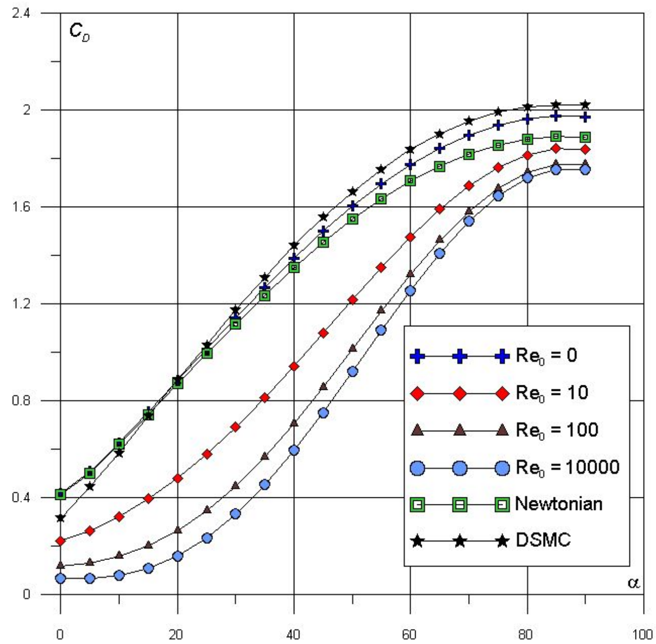


**Figure 11.** Drag coefficients $C_D$ for space vehicle "Clipper".

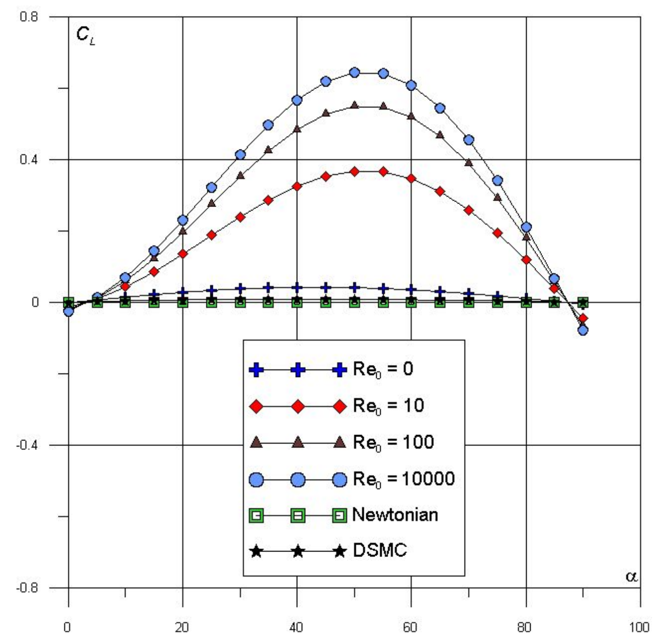


**Figure 12.** Lift coefficients $C_L$ for space vehicle "Clipper".

plained by the decrease of normal and tangent stresses. 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 $M_Z$ 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 and Newtonian methods.

The dependencies of $C_D(\alpha)$, $C_L(\alpha)$ and $M_Z(\alpha)$ of hypersonic vehicle "Falcon HTV-2" are presented in **Figures 14-16**. In **Figure 14**, 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.

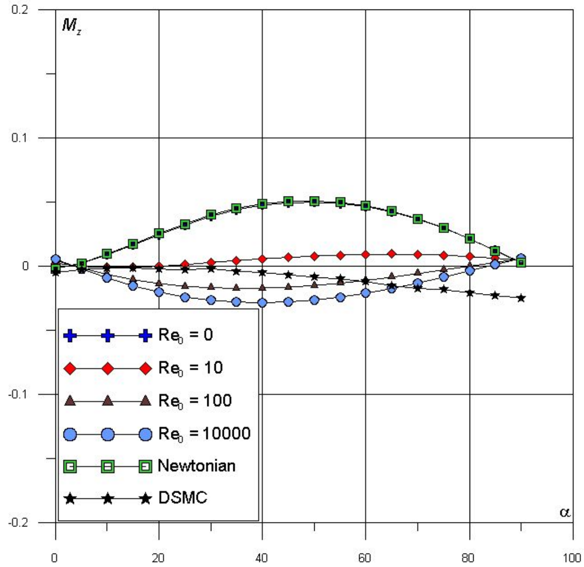


**Figure 13.** Pitching moment coefficients $M_Z$ for space vehicle "Clipper".

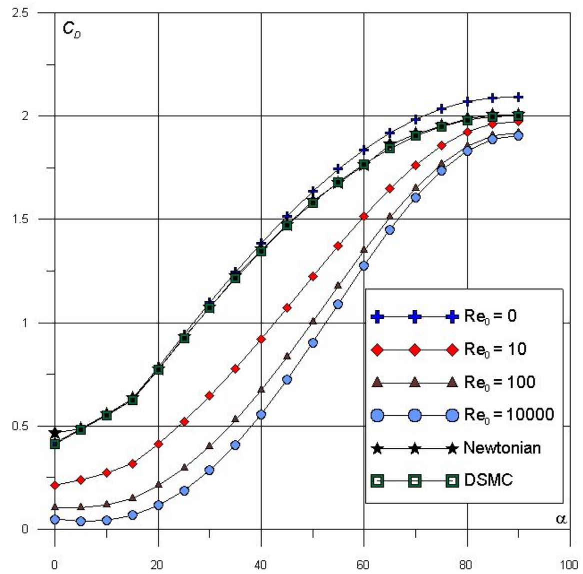


**Figure 14.** Drag coefficients $C_D$ for hypersonic vehicle "Falcon HTV-2".

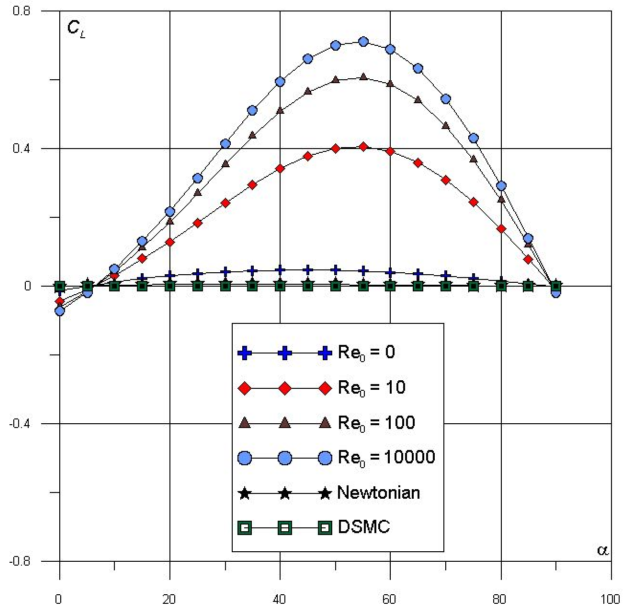


**Figure 15.** Lift coefficients $C_L$ for hypersonic vehicle "Falcon HTV-2".

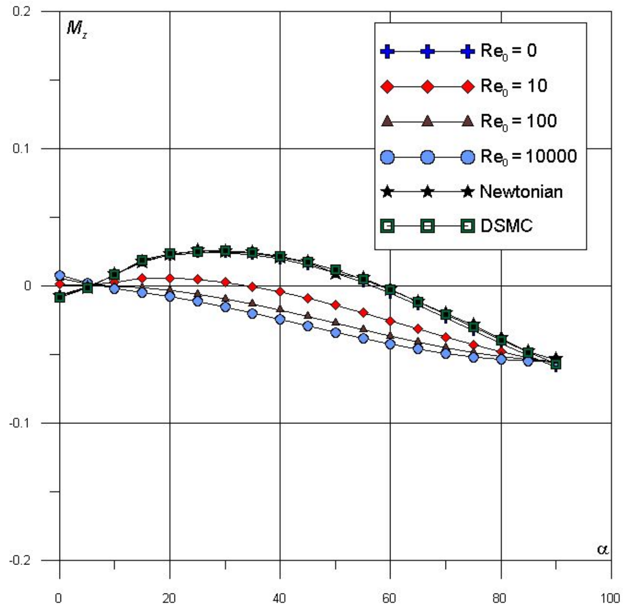


**Figure 16.** Pitching moment coefficients $M_Z$ for hypersonic vehicle "Falcon HTV-2".

## 4. Conclusions

Many analytical and numerical methods to estimate the aerothermodynamics of hypersonic vehicles were appeared with the development of space launch technologies. This paper presents different methods to calculate aerodynamic characteristics of various perspective hypersonic vehicles in rarefied gas flows. With the use of this engineering method, it had been calculated aerodynamic characteristics for various hypersonic vehicle design in rarefied gas flow. Results are compared with the DSMC and traditional Newtonian method. Methods which described above give good results and suitable to calculate aerodynamics for various hypersonic vehicle designs. The reported study was partially supported by RFBR (research project No. 11-07-00300-a).

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