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Analysis of Local Engineering Methods for Determining the Aerodynamic Characteristics of High-speed Vehicles in the Transitional Regime

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Abstract

In present day, there are many local engineering methods for solving the aerodynamics problems of the high-speed flows in the transitional regime. These methods are based on the experimental and theoretical data. In this paper present the local engineering methods for calculating aerodynamic characteristics in the transitional regime. These methods would be useful for realizing new generation high-speed vehicle designs.

Keywords: hypersonic technology, rarefied gas flow, engineering methods, transitional regime.

Introduction

The difficulties in the development of high-speed vehicle systems are caused by quite number of problems, for example, problem of modeling full-scale flight conditions in the wind tunnels. This is the reason to use computer simulation and to create approximate engineering methods. Multi-parametric calculations can be performed only by using an approximation engineering approach [1-11]. Computer modeling allows to quickly analysis the aerodynamic characteristics of high-speed vehicles by using theoretical and experimental research in aerodynamic of high-speed flows.

The purpose of this research is to analysis engineering methods for determining the aerothermodynamic characteristics of high-speed vehicles in the transitional regime. In this paper present the calculation results of the coefficients of drag force C_x, lift force C_y and heat transfer coefficient C_h for new generation high-speed vehicles.

Local engineering methods (Approximate engineering methods)

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, Knudsen number Kn, Reynolds number Re:

$$\mathrm{M}_\infty = \frac{V_\infty}{a_\infty}, \quad \mathrm{Kn} = \frac{\lambda_\infty}{L_{ref}}, \quad \mathrm{Re}_\infty = \frac{\rho_\infty V_\infty L_{ref}}{\mu_\infty}$$

where, λ_∞ - the mean free path, L_{ref} - reference length of vehicle, μ_∞ - the viscosity coefficient.

Traditionally, Newton method can be use for calculating pressure coefficient in hypersonic flow

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

The modified Newton method is

$$C_p = C_{p_0}\cos^2\theta$$

$$C_{p_0} = C_{p_\infty}\left[\frac{(\gamma+1)\mathrm{M}_\infty^2}{2}\right]^{\gamma/(\gamma-1)}\left[\frac{\gamma+1}{2\gamma\mathrm{M}_\infty^2-(\gamma-1)}\right]^{1/(\gamma-1)}$$

C_{p0} - pressure at the stagnation point on the body surface. For $\mathrm{M}_\infty \to \infty$, $C_{p0} = 0.920$ at $\gamma = 1.4$.

One of these approaches consists of the construction of the approximation function at well known values, corresponding to a free-molecular flow $C(0)$ and a flow in the regime of continuum medium $C(\infty)$, which is usually determined through the Newton method

$$f(C, \mathrm{Re}, G, t_w, \gamma, \mathrm{M}, \ldots) \approx \frac{C(\mathrm{Re}) - C(\infty)}{C(0) - C(\infty)}$$

The function f depends on the gas properties, parameters of the incident flow, surface geometry, etc.

We can use the expressions for the elementary pressure forces and friction forces are applied in the form described in [2, 3, 5].

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

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

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

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

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

$$R = \mathrm{Re}_0 \left(0.75 t_w + 0.25\right)^{-0.67}$$

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

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

where h is a relative lateral dimension of the apparatus, which is equal to the ratio of its height to its length. In the previous research papers [12-18] described the results of aerodynamic characteristics of various hypersonic vehicles by using local engineering method.

Using the local bridging method to calculate aerodynamics and heat flux coefficients for hypersonic vehicles in transitional regime is suitable and no need large number of computer memory. In the free molecular regime, to determine the heat transfer coefficient equation can write analytically [6]

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

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

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 [21, 22]

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

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

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

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

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

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.

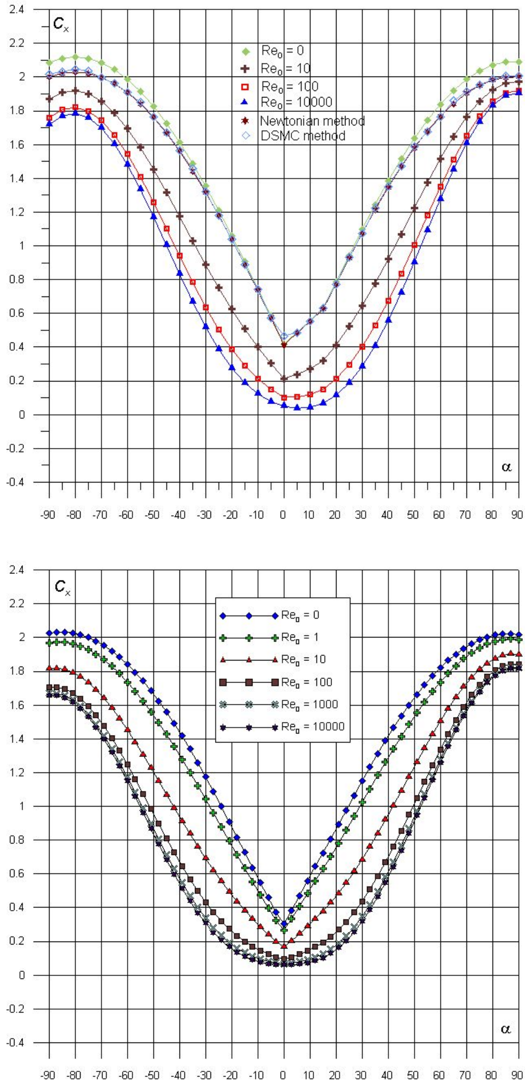

Figure 1: Dependencies of C_x (α) for high-speed vehicles using local engineering method

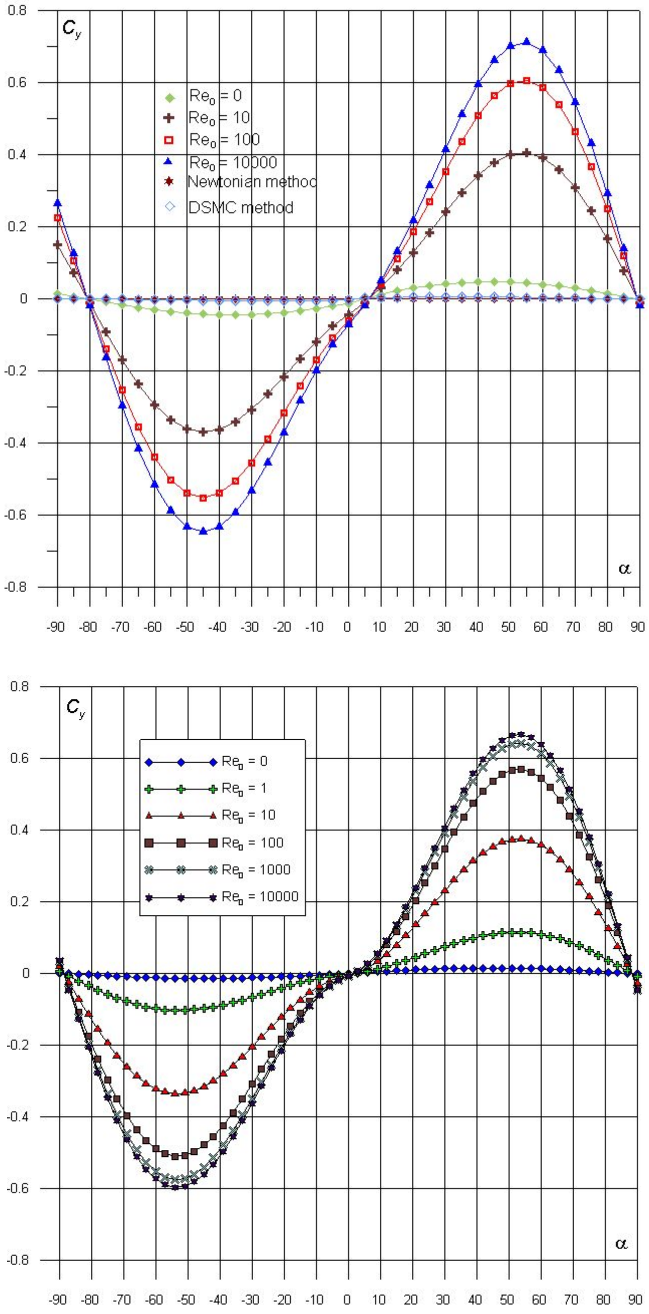

Figure 2: Dependencies of C_y (α) for high-speed vehicle using local engineering method

In the figures 1 and 2 present the coefficients of drag coefficient for aerospace vehicle “Clipper” (model of TsAGI) and hypersonic technology vehicle “Falcon HTV-2” with taking into account various Reynolds number Re using local engineering method which described above. The calculation has been carried out through the methods described in the previous section. The parameters of the problem are the following: ratio of heat capacities $\gamma = 1.4$; temperature factor $T_w/T_0 = 0.001$, $T_w/T_\infty = 0.1$; velocity ratio $S = 15$; Reynolds number $\mathrm{Re}_0 = 0 – 10000$; accommodation coefficients = 0.5, 0.75, 0.9, 1.

It can be seen from these results that when the Reynolds number increased, the drag coefficients C_x 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. The dependency $C_y(\alpha)$ 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 $\mathrm{Re}_0 \sim 10^2$. At $\mathrm{Re}_0 \sim 10^4$, the value of $m_z = - 0.03$ at the angle of attack is reached at $\alpha \approx 40$ deg. The dependency $C_y(\alpha)$ for “Falcon HTV-2” is increased, and the value is reached to 0.54 at $\mathrm{Re}_0 \sim 10^4$. The values of m_z are quite sensitive to the variation of Re_0, changes its sign at $\alpha \sim 5$ deg. Results by using local engineering method are compared with the results obtained by DSMC method and Newtonian method.

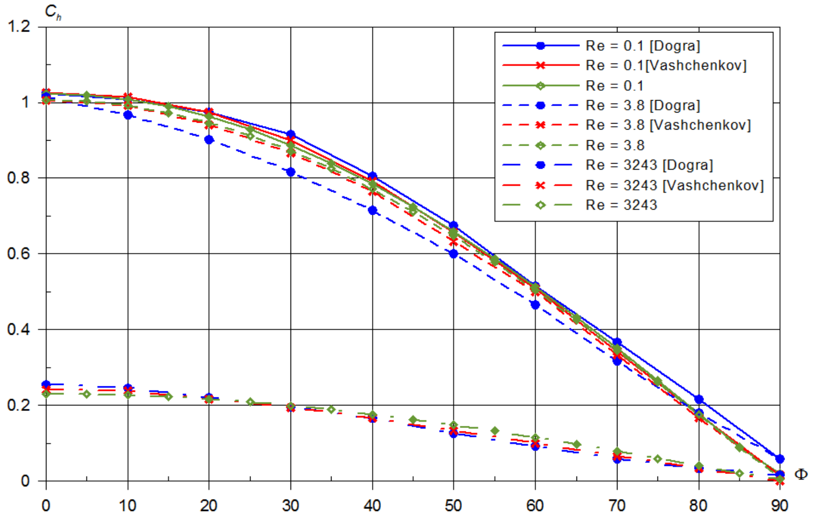

Figure 3: Distribution of heat transfer C_h on sphere

In the figure 3 present the distribution of heat transfer coefficient C_h on sphere and results are compared with the result of *Dogra, Wilmoth, Moss* [22] *and Vashchenkov* [19]. These local engineering methods described above are very suitable for calculating aerothermodynamic characteristics for high-speed vehicles at the initial stage of the vehicle design [18].

Conclusions

The approximate engineering methods to determining the aerodynamic characteristics and heat transfer coefficients for high-speed vehicles in rarefied gas flows are described. The calculation results by these methods are presented. These methods give good and qualitatively right results for a wide range of vehicle design.

The obtained results by local engineering methods are compared with the DSMC and Newtonian method.

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