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Engineering Methods to Calculate Heat Transfer Coefficients on the Surface Body in High-Speed Flow

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Abstract

The development of rocket and space technology is very important for any countries for two categories: construction high-speed passenger plane and reusable aerospace vehicle. It's required continuous improvement of the research of processes of heat and mass transfer, and heat transfer theory development. Modeling research allows to quickly analysis the aerodynamic and heat exchange processes of high-speed aircrafts by using theoretical and experimental research. Well known method - Direct simulation Monte Carlo method (DSMC) is the basic quantitative tool for study of high-speed rarefied gas flow. These methods remain the most reliable approach, together with the local engineering methods, that provides good results for the global aerothermodynamics coefficients. Engineering methods are required small amount of computer resources (i.e. memory) and expensive at the initial stage of aircraft design and trajectory analysis. There are many engineering methods to calculate aerothermodynamics in hypersonic flow. In this paper described the analysis of the engineering methods to predict heat transfer coefficient on the surface of high-speed aircraft at high-altitude.

Keywords

High-Speed Aircraft, Bridging Methods, Transitional Flow Regime, Rarefied Gas Dynamics, Heat Transfer in Boundary Layer

1. Introduction

The development of high-speed aircraft construction in the atmosphere at altitudes of up to 40-60 km with an airframe type as an airplane, which will allow us to talk about the construction of reusable supersonic passenger plane. The construction of a reusable reentry vehicle is similar to reusable transport systems such as the Space Shuttle with the use of innovative technologies for constructing thermal protection. Every countries have their national projects concerning with the high-speed aircrafts construction, for example, "Dragon" in China; "HEXAFLY" in ESA; "Hermes" in France; "Hopper" in Germany; "USV" in Italy; "AVATAR" in India; "Hope X" in Japan; "Clipper", "Rus", "Baikal" in Russia; "X-51", "Orion", "WaveRider", "Falcon HTV-2" in USA; "Hyper X", "HOTOL" in UK; etc.

The analysis of the aerodynamic and heat transfer coefficient characteristics for high-speed aircraft at high-altitude requires numerous numerical calculations [1-3]. High-speed flow 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 high-speed aircrafts by using theoretical and experimental research in aerodynamic of high-speed flows. Direct simulation Monte Carlo method (DSMC) is the basic quantitative tool for study of high-speed rarefied flows [4]. The Monte Carlo method remains the most reliable approach, together with the local engineering methods, that provides good results for the global aerodynamic coefficients. 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 [5-15].

The purpose of this work is to calculate heat transfer coefficient on surface of high-speed aircrafts. Bridging methods are suitable to calculate for taking into account the influence of Reynolds number, and provide good results for various high-speed aircrafts designs.

2. Bridging Methods

Many empirical engineering formulas are proposed to estimate the heat transfer coefficient at the stagnation point. The heat transfer coefficient is calculated as

$$C_h = \frac{2(Q_i - Q_r)}{\rho V_\infty^3 S_{ref}},$$

Q_i, Q_r – the amount of heat brought by the flow and the amount of heat entrained by the flow from the body surface respectively.

Dependencies of the heat flux coefficients (Stanton number *St*) on the Reynolds number Re, can be used in the first order of self-similar interpolation [16]:

$$St = \frac{1}{\sqrt{St_{fm}^{-2} + \mathrm{Re}_0\, St_{con}^{-2}}},$$

$$St = \begin{cases} St_0 & \mathrm{Re}_0 \to 0 \\ St_\infty / \sqrt{\mathrm{Re}_0} & \mathrm{Re}_0 \to \infty \end{cases}.$$

In this work described the formulas to predict heat transfer coefficient which described in the work [17]. In the free molecular flow regime, the Stanton number has a constant value of 1.0 independent of the body shape and can described:

$$St_{fm} = \frac{\dot{Q}}{\frac{1}{2}\rho_\infty V_\infty^3 A_{ref}} = 1.0$$

In the continuum flow regime it depends on the Reynolds number Re_0 and the body shape. According to the Lee's theory [18] and some experimental data, the Stanton number of a sphere can be wrote

$$St_{con} = \frac{2.1}{\sqrt{\mathrm{Re}_0}}$$

Continuum heating is related to the local inclination θ of the surface element

$$St_{con} = \frac{2.1}{\mathrm{Re}_0}(0.1 + 0.9\cos\theta)$$

$$\mathrm{Re}_0 = \frac{\rho_\infty V_\infty R_N}{\mu(T_0)}$$

where R_N is the effective nose radius of the object and $\mu(T_0)$ is the stagnation point viscosity. The power law viscosity ω = 0.72 dependence on the temperature $(T_0/T_\infty)^\omega$.

In the rarefied transition flow regime a bridging formula is

$$St_{bridging} = \frac{St_{con}}{\sqrt{1 + (St_{con} / St_{fm})^2}}$$

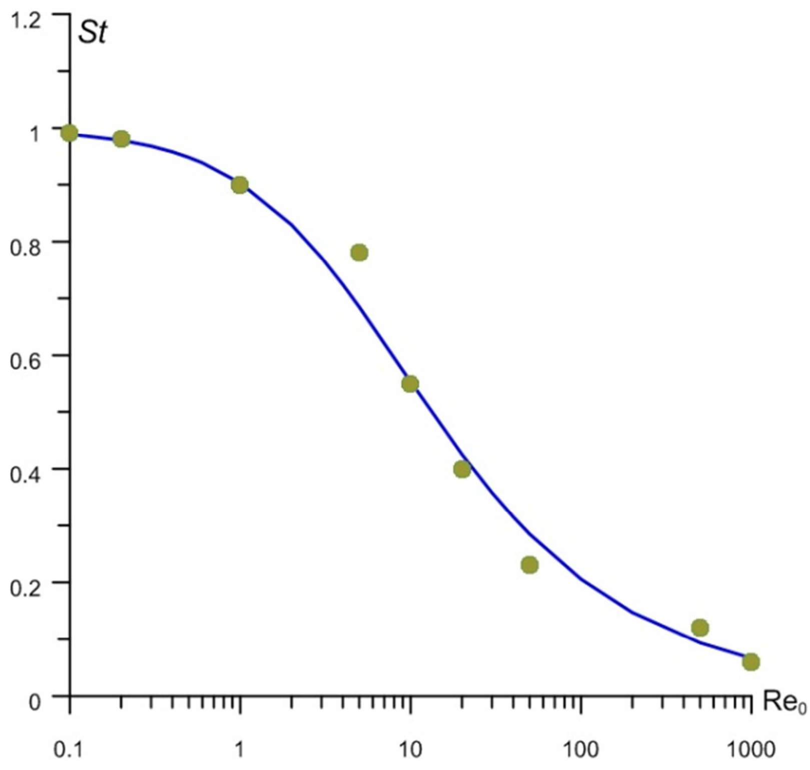

Figure 1. *Stanton number vs. Reynolds number (symbol – results from [19]).*

In the free molecular regime, to determine the heat transfer coefficient equation can write analytically [1]

$$C_h = \alpha_e \frac{1}{2\sqrt{\pi} s^3}\left\{\left(s^2 + \frac{\gamma}{\gamma-1} - \frac{1}{2}\frac{\gamma+1}{\gamma-1} t_w\right)\chi(s\sin\alpha) - \frac{1}{2} e^{-s^2\sin^2\alpha}\right\} \chi(x) = e^{-x^2} + \sqrt{\pi} x(1+\mathrm{erf}(x)),\quad \mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-x^2} dt$$

where, α_e – energy accommodation coefficient on surface, s - speed ratio, T_w, T_∞ - surface temperature and flow temperature respectively. To calculate heat transfer coefficient in continuum regime, equation can described as follow [20, 21]

$$C_h(s,\theta) = C_{h0} \cdot \frac{1}{\sqrt{\dfrac{s/r + \dfrac{1}{s/r+1}}{1+\dfrac{\gamma+3}{\gamma+1}\dfrac{\gamma}{2}M_\infty^2\cos^2\theta / 1+\dfrac{\gamma+3}{\gamma+1}\dfrac{\gamma}{2}M_\infty^2}}} \qquad C_{h0} = \frac{2^{k/2}}{2}\mathrm{Pr}^{-2/3}\sqrt{\frac{\gamma+1}{\gamma-1}\sqrt{\frac{\gamma-1}{\gamma}}}\frac{1}{\sqrt{\mathrm{Re}_{\infty,r}}}\left(\frac{\gamma-1}{2}M^2\right)^{\omega/2}$$

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 [22, 25]

$$C_h = (C_{h,fm} - C_{h,con})F + C_{h,con},\quad F_1 = \frac{1}{2}\left(1+\mathrm{erf}\left(\frac{\sqrt{\pi}}{\Delta \mathrm{Kn}_1}\cdot\lg\left(\frac{\mathrm{Kn}_0}{\mathrm{Kn}_m}\right)\right)\right),\quad F_2 = \frac{1}{2}\left(1+\mathrm{erf}\left(\frac{\sqrt{\pi}}{\Delta \mathrm{Kn}_2}\cdot\lg\left(\frac{\mathrm{Kn}_0}{\mathrm{Kn}_m}\right)\right)\right).$$

Where, $C_{h,fm}$ – heat transfer coefficient in free molecular regime and $C_{h,con}$ - heat transfer coefficient in continuum regime. If $\mathrm{Kn}_0 < \mathrm{Kn}_m$, should be used the function F_1 and in opposite reason F_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.

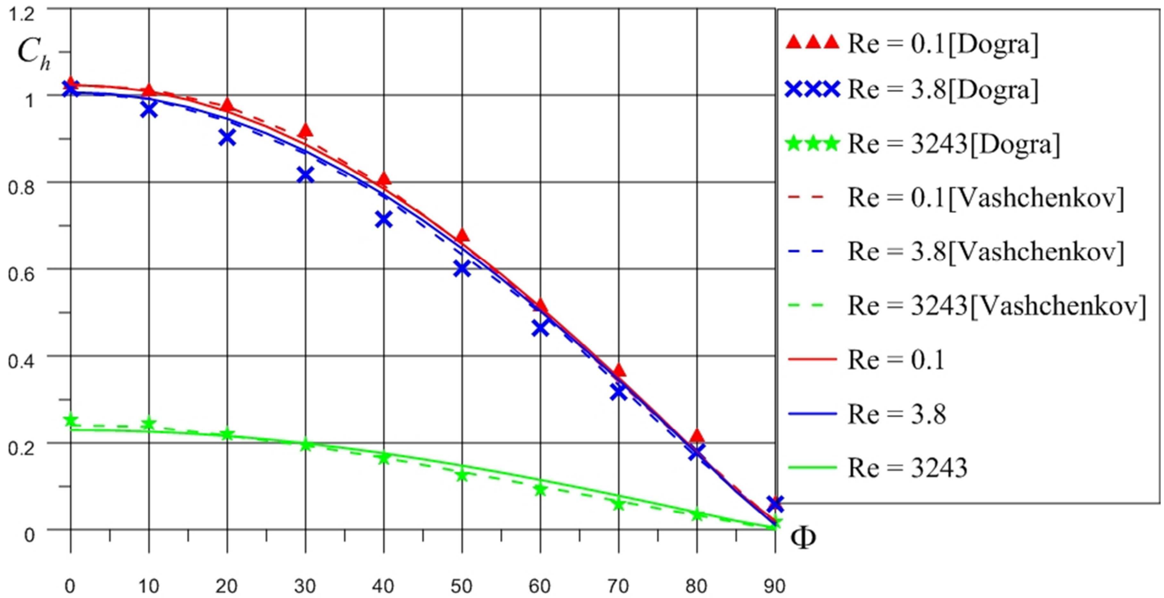

Figure 2. *C_h (α) on sphere.*

Table 1. *Standard Atmosphere.*

H, km	n_∞, 1/cm³	ρ_∞, kg/m³	T_∞, K	Kn_∞
250	2.8210×10^{15}	9.4248×10^{-11}	1124	111
200	8.9996×10^{15}	3.2829×10^{-10}	1026	34.80
150	5.3055×10^{16}	2.1383×10^{-9}	733	5.90
100	1.1898×10^{19}	5.5824×10^{-7}	194	0.0263
95	2.9047×10^{19}	1.3800×10^{-6}	189	0.0108
85	1.6540×10^{20}	7.9550×10^{-6}	181	0.0019
75	9.0130×10^{20}	4.3350×10^{-5}	200	0.0003

3. Heat Fluxes for Laminar and Turbulent Flow Regime

Engineering methods to calculate heat transfer coefficient on the surface of high-speed aircrafts in boundary layer is presented in the work [23]. In this paper described to solve problems of heat fluxes for a laminar and turbulent flow regime. Heat flux formula at the stagnation point in laminar flow [24]:

$$q_w^{lam} = 6.12\times10^{-9}\cdot\sqrt{\frac{\rho}{R_N}}\cdot V^{3.25}$$

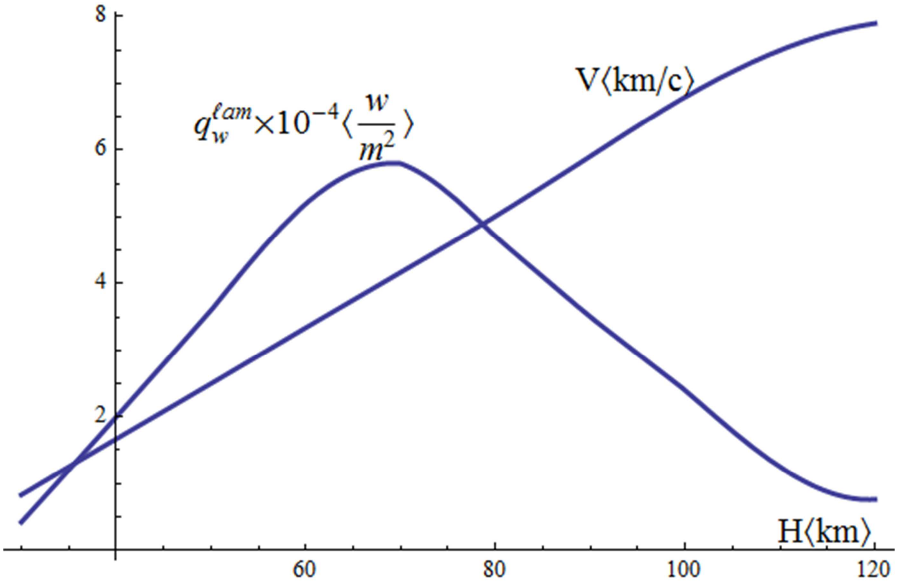

Figure 3. *Heat flux* q_w^{lam} *at the stagnation point on sphere in laminar flow* (R_N *– 6.0350 m).*

Heat flux formula at the stagnation point in turbulent flow:

$$q_w^{turb} = 1.01\times10^{-7}\cdot\frac{\rho^{0.8}}{R_N^{0.2}}\cdot V^{3.19}$$

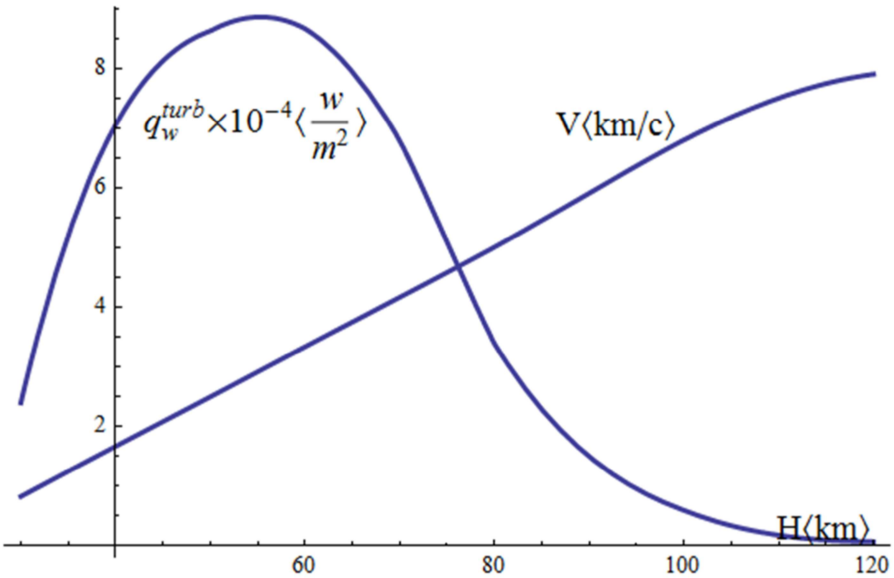

Figure 4. *Heat flux* q_w^{turb} *at the stagnation point on sphere in turbulent flow* (R_N *– 6.0350 m).*

4. Results and Discussions

The calculation results of the heat transfer C_h coefficients with value of angle of attack α from -90 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 γ = 1.4; temperature factor T_w/T_0 = 0.001, 0.01; velocity ratio s = 15, Reynolds number Re_0 = 0.1, 3.8, 3000.

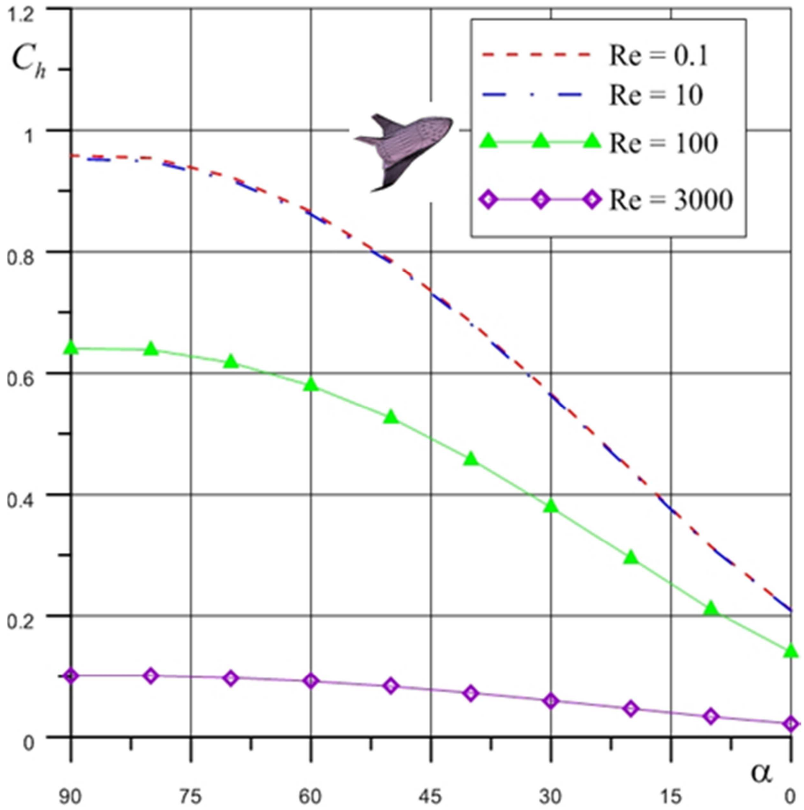

Figure 5. *C_h (α) for "Clipper".*

The dependencies of C_h (α) for "Clipper" and "Falcon HTV-2" are presented in figures 5 and 6 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 ($40 \le \alpha \le 90$). The values at Re = 0.1 and 10 are not very significant, but when the Re more than 10 the values are significant.

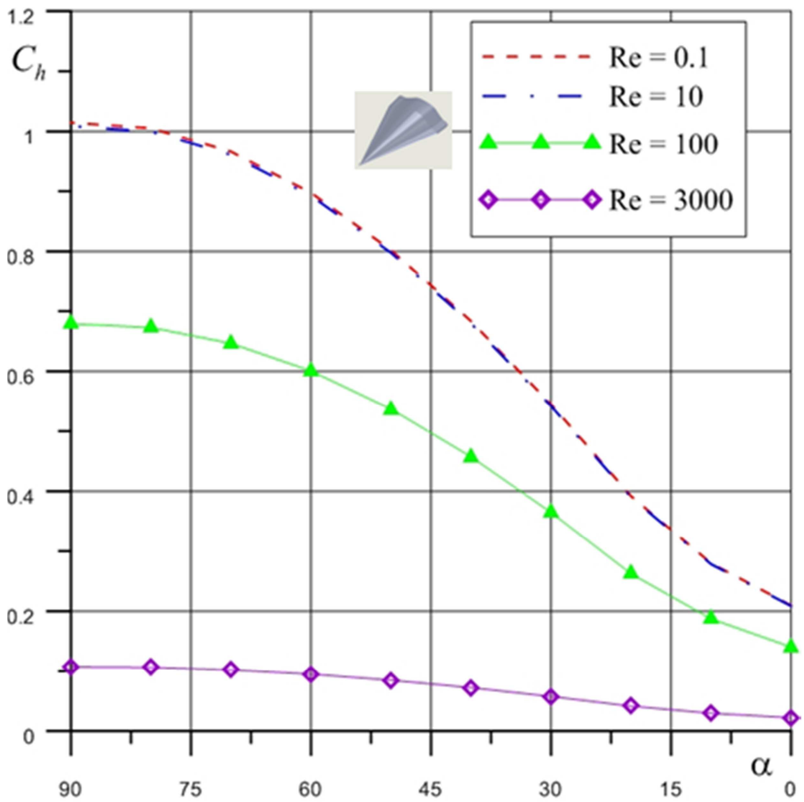

Figure 6. *C_h (α) for "Falcon HTV-2".*

5. Conclusions

The bridging methods to predict heat transfer coefficient on the surface of high-speed aircrafts in transitional regime are described. The results of calculation of heat transfer characteristic for new generation high-speed aircrafts by bridging methods in rarefied gas flow with various Reynolds numbers are presented. These bridging methods give good and qualitatively right results for a wide range of bodies. Results and methods can be used to calculate aerothermodynamics for new generation high-speed aircrafts. Also presented some methods to solve the problems of heat fluxes for a laminar and turbulent flow regime.

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