

RAREFIED AERODYNAMICS OF THE CLIPPER REENTRY VEHICLE

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The orbit of advanced space vehicles lies at altitudes of about 300-400 km. During their reentry to the Earth, the vehicles first experience the action of the free-molecular flow, then enter the transitional regime, and finally, beginning from an altitude of 80 km, descend in the continuum flow. For successful reentry of the vehicle to the Earth, it is necessary to know the behavior of its aerodynamic characteristics in all flow regimes.

Computation of aerodynamic characteristics of reentry vehicles in the free-molecular flow does not involve many difficulties because theoretical approaches have been developed for simple shapes and the DSMC method can be readily used for more complicated shapes. Methods for computing aerodynamic characteristics in the continuum flow have also been adequately developed.

The study of aerodynamic characteristics in the transitional flow regime ($0.001 < Kn < 100$) is a rather complicated problem. The Navier-Stokes equations fairly suitable in the continuum medium, yield, strictly speaking, incorrect results in the transitional regime and require special modifications for taking into

account flow slipping. The Direct Statistical Monte Carlo (DSMC) method provides rather accurate values of aerodynamic characteristics with allowance for physical and chemical processes but requires large amounts of computer memory and performance, which hinders the use of this method. There are several software systems that allow simulation of gas flows in the transitional regime (e.g., SMILE, DAC), but their application at the initial stage of spacecraft design and trajectory analysis is unreasonably expensive because it is necessary to compute a large number of variants for different angles of attack and sideslip and for different flow parameters. The method for solving this problem is to use approximate engineering methods, which offer acceptable accuracy with a short computation time. For instance, the existing aerodynamic software system Ramses [1] includes an engineering method based on local bridging interpolation between the free-molecular and continuum flow regimes to obtain aerodynamic characteristics in the transitional regime.

Accuracy evaluation of engineering methods is difficult because of the lack of ex-

perimental data on aerodynamic characteristics of modern spacecraft in the transitional regime. One possible way is a comparison with the complicated but accurate DSMC method. The aerodynamic characteristics of the promising reentry capsule Clipper (see Figs. 1) were examined in the present paper.

Geometrical model and flow parameters

The Clipper is shaped as a lifting body that provides an effective aerodynamic lifting force during the reentry into the atmosphere. As a result, the vehicle is able to conduct side maneuvers during its return to Earth, unlike a traditional reentry capsule. This vehicle is planned to replace the ‘‘Soyuz’’ capsule used today. As compared to the ‘‘Soyuz’’ capsules, the spacecraft considered ensures higher maneuverability and lower overloading during its reentry. The length of the Clipper vehicle is 6 m, and area 3.53 m² were used as reference parameters.

For geometric models of space vehicles to be used in computations, their surface is represented as a set of triangular panels. The total number of panels depends on the size and curvature of spacecraft elements.

The aerodynamic characteristics of reentry capsules were considered along the initial part of the reentry trajectory to an altitude of about 80 km. Depending on the degree of rarefaction of the incoming flow, the number of molecules simulating the flow in DSMC (SMILE system) computations around the capsules was varied. The free-molecular flow was simulated using approximately 10⁵

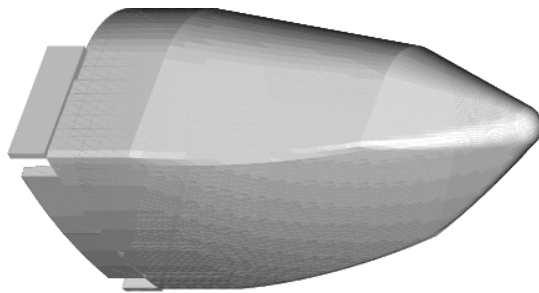


Fig.1

model molecules in computations. In near-continuum flows, the number of model molecules was increased to 30·10⁶. For gas-surface interaction, the diffuse reflection model with complete energy accommodation was used.

Numerical investigation methods

Two local bridging methods and the DSMC method were used to compute aerodynamic characteristics of the Clipper vehicle.

1. Local bridging method.

This engineering local bridging method employs the following formulas for determining the influence of the flow onto the surface:

$$P = P_0 + P_1 w_n + P_2 w_n^2$$

$$T = T_0 w_t + T_1 w_n w_t$$

Here, P and T are the pressure and friction components of the aerodynamic force; w_n and w_t are the normal and tangential components of the velocity vector to the surface. The parameters P_0, P_1, P_2, T_0 and T_1 are calculated using the following formulas:

$$P_0 = P_0^{id} + (P_0^{fm} - P_0^{id}) F_{P_0}$$

$$P_1 = P_1^{fm} F_{P_2}$$

$$P_2 = P_2^{id} + (P_2^{fm} - P_2^{id}) F_{P_2}$$

$$T_0 = T_0^{fm} F_{T_0}$$

$$T_1 = T_1^{fm} F_{T_1}$$

The superscripts ‘‘fm’’ and ‘‘id’’ mean free-molecular and ideal continuum parameters; F_P, F_T are bridging functions for pressure and friction.

The free-molecular pressure and friction are computed using the formulas:

$$P_0^{fm} = \frac{2 - \sigma_n}{\gamma M^2} (1 + \operatorname{erf}(z)) + \frac{\sigma_n}{\gamma M} \sqrt{t_w \frac{\gamma - 1}{2}} e^{-z^2}$$

$$P_1^{fm} = \frac{\sigma_n}{2} \sqrt{t_w \frac{\pi(\gamma - 1)}{\gamma}} (1 + \operatorname{erf}(z)) + \frac{2 - \sigma_n}{M} \sqrt{\frac{2}{\pi\gamma}} e^{-z^2}$$

$$P_2^{fm} = (2 - \sigma_n)(1 + \operatorname{erf}(z))$$

$$T_0^{fm} = \sigma_t e^{-z^2} \frac{1}{M} \sqrt{\frac{2}{\pi\gamma}}$$

$$T_1^{cm} = A_3(1 + \operatorname{erf}(z))$$

$$z = \sqrt{\frac{\gamma}{2}} M \sin \alpha_{loc}$$

The continuum formulas are based on the modified Newton method:

$$P_0^{id} = \begin{cases} 0, & \text{for } \sin \alpha_{loc} \geq 0.73 \\ P_\alpha \left(1 - \frac{\sin \alpha_{loc}}{0.73}\right), & \text{for } 0 \leq \sin \alpha_{loc} \leq 0.73 \end{cases}$$

$$P_\alpha = \begin{cases} \frac{8}{(\gamma + 1)(\gamma + 3)M^2}, & \text{for cone} \\ \frac{1}{(\gamma + 1)M^2}, & \text{for wedge} \end{cases}$$

$$P_2^{id} = \begin{cases} C_p & \sin \alpha_{loc} \geq 0.73 \\ C_p + (P_k - C_p) \left(1 - \frac{\sin \alpha_{loc}}{0.73}\right) & 0 \leq \sin \alpha_{loc} \leq 0.73 \end{cases}$$

$$P_k = \begin{cases} \frac{2(\gamma + 1)(\gamma + 7)}{(\gamma + 3)^2} & \text{for cone} \\ \gamma + 1 & \text{for wedge} \end{cases}$$

C_p is the stagnation pressure coefficient:

$$C_p = \frac{\gamma + 1}{\gamma} \left(\frac{(\gamma + 1)^2 M^2}{4\gamma M^2 - 2(\gamma - 1)} \right)^{\frac{1}{\gamma - 1}} - \frac{2}{\gamma M^2} T$$

the bridging coefficients for pressure are

$$F_{P_0} = \frac{1}{\alpha \sqrt{\operatorname{Re}_0} + \exp(-b \operatorname{Re}_0)}$$

$$\alpha = \frac{(\gamma - 1) \sqrt{t_w} + M^{-1} \sqrt{2(\gamma - 1)}}{(0.56 + 1.2 t_w) M + 2.15}$$

$$b = 0.35 + 0.005 M$$

$$F_{P_1} = F_{P_2} = \exp\left(- (0.125 + 0.078 t_w) \operatorname{Re}_0 \cdot 10^{-1.8(1 - \sin \alpha_{loc})^2}\right)$$

The bridging coefficients for friction are

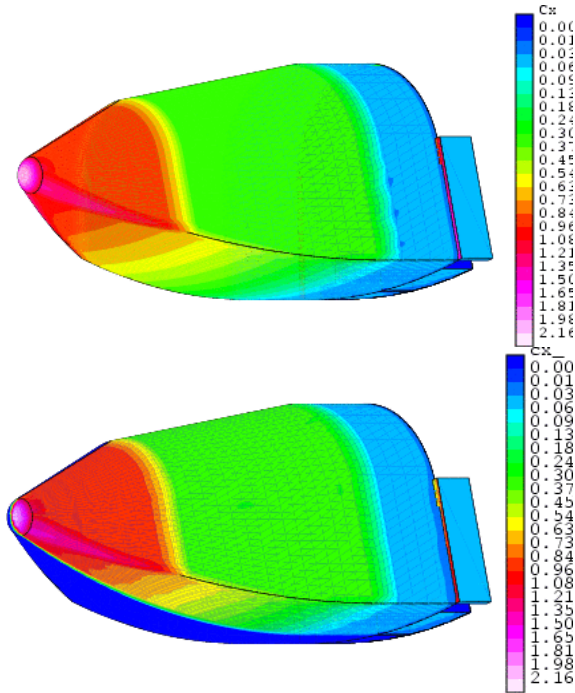


Fig. 2

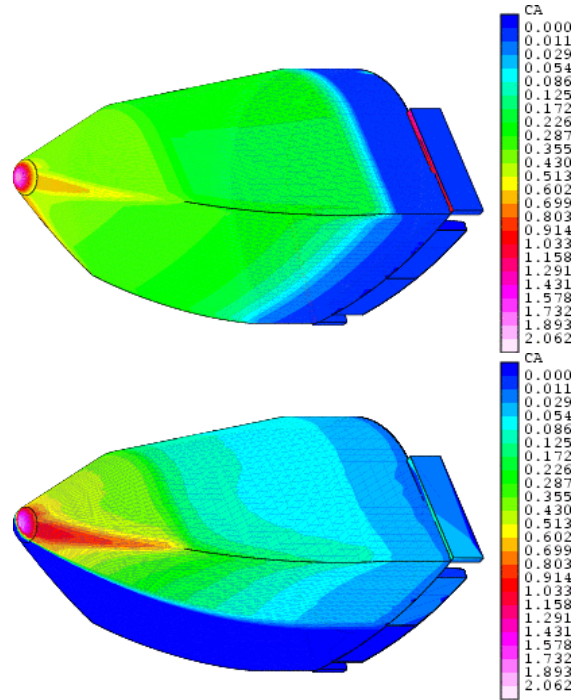


Fig. 3

$$F_{T_0} = [\alpha_1 \text{Re}_0 + \exp(-b_1 \text{Re}_0)]^{-3/4}$$

$$\alpha_1 = \frac{\gamma - 1}{2} \left[\sqrt{\frac{\pi\gamma}{2}} M(0.208 + 0.341t_w) \right]^{-3/4}$$

$$b_1 = 0.213 - 0.133 t_w$$

$$F_{T_1} = [0.145R + \exp(7.2 \cdot 10^{-3} R - 1.6 \cdot 10^{-5}) R^2]^{-1/2}$$

$$R = (0.75 t_w + 0.25)^{-2/3} \text{Re}_0 \cdot 10^{-2.4(1 - \sin\alpha_{loc})^3}$$

The aerodynamic parameters are computed separately for each panel composing the body with allowance for shadowing of some spacecraft elements by other (more forward) elements. The resultant action of the flow on the space vehicle is found as a sum of actions on each panel.

2. **DSMC method.** DSMC computations were produced using the SMILE software system [2]. This system allows simulation of complex 2D and 3D nonequilibrium rarefied gas flows by the DSMC method. The number of collisions was calculated by the majorant frequency technique. The collisions of mole-

cules were computed using the variable hard sphere (VHS) model. The internal degrees of freedom were taken into account by the Larsen-Borgnakke model. For rather high Knudsen numbers (approximately $\text{Kn} > 0.1$), the DSMC method does not require a large number of model particles; hence, the requirements to computer resources are not severe. Such computations were performed on single-processor computers. In problems with a rather dense incoming flow, it is necessary to introduce a large number of model particles and divide the computational domain into many cells (on the average, about 10^6 of cells and $5 \cdot 10^6$ model particles). Such flows around the capsules were simulated by the parallel version of the SMILE code.

The geometric size of the computational domain was varied for different degrees of rarefaction of the free-stream flow. The reason is that the influence of the body on the external flow at high Knudsen numbers is extended to a greater distance than in the case of a denser

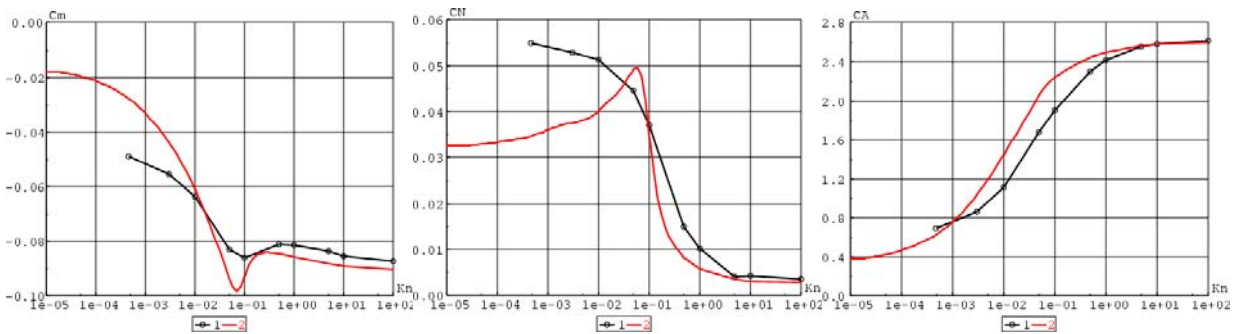


Fig. 4

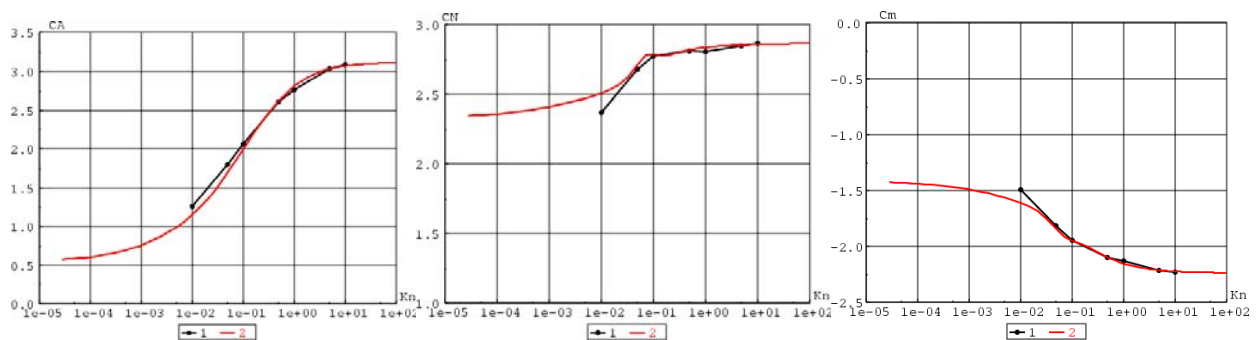


Fig. 5

flow with the same other parameters of the free-stream flow. The total number of cells in the computational domain was also variable to ensure the necessary spatial resolution.

Results

Figures 2 and 3 show the surface distribution of the axial force coefficient for Knudsen numbers 10 and 0.01. The upper and lower fields are computed by the engineering method and by the DSMC method, respectively. The engineering method is seen to accurately reproduce the load distributions on each panel for high Knudsen numbers, but the computations in the transitional regime are affected by the fact that this method takes into account only the local inclination of the triangular panel to the free-stream flow and ignores the changes in flow parameters in the boundary layer. It is visible on the almost flat rear part of the vehicle for $Kn = 0.01$: the panels located in the middle part of the body experience the same loads as the panels at the edges of the lower surface at places where it joins the lateral surfaces, while the DSMC computations predict some changes in the distribution of C_A in these regions. Nevertheless, despite some differences in the detailed distribution of the axial force coefficient over the surface, the local bridging method still reproduces the integral value of C_A with an admissible error. It is seen in Fig. 4, which shows the behavior of the aerodynamic coefficients C_A, C_N, C_m of the Clipper capsule at zero incidence as a function of the free-stream Knudsen number, which were calculated by the DSMC method (black line 1) and by the local bridging method (red line 2). The distribution $C_A(Kn)$ predicted by the engineering method has some error, but the distributions of the normal force C_N and pitching moment C_m display good qualitative agreement with the DSMC results.

Figure 5 shows the distributions of the aerodynamic characteristics for the Clipper reentry vehicle at an angle of attack equal to

40° . In this case, the maximum deviation of the aerodynamic parameters calculated by the engineering method from the DSMC results is about 5%.

As the engineering method ignores chemical reactions, which will proceed during Clipper reentry when the air density becomes rather high, it is necessary to find out at which altitude the real properties of air start to be noticeably manifested and to which extent this affects the aerodynamic characteristics. For this purpose, additional computations were performed by the DSMC method with allowance for chemical reactions at altitudes of 90 and 80 km (Knudsen numbers equal to $6.3 \cdot 10^{-3}$ and $9.55 \cdot 10^{-4}$, respectively).

The temperature fields and the surface distributions of the heat-transfer coefficient C_h obtained in computations with and without allowance for chemical reactions are plotted in Figs. 6 and 7. The free-stream parameters in Figs. 6 and 7 refer to altitudes of 90 and 80 km, respectively. The upper figures show the computation results with a chemically nonreacting gas, and the lower figures were computed with allowance for chemical reactions. Allowance for chemical reactions is seen to change the surface distributions of the heat-transfer coefficient and the temperature field. As it could be expected, the real gas effects are manifested more profoundly on the front part of the vehicle. It is seen from Tables 1 and 2, however, that the values of aerodynamic parameters remain almost unaffected if chemical reactions are taken into account.

Thus, we can conclude that the engineering method ensures acceptable accuracy of aerodynamic characteristics for a rather wide range of Knudsen numbers.

Table 1.

	C_A	C_N	C_m	C_h
Chemically reacting	0.859	0.055	0.055	0.150
Non-reacting	0.852	0.051	0.054	0.154

Table 2.

	C_A	C_N	C_m	C_h
Chemically reacting	0.805	0.055	0.049	.095
Non-reacting	0.817	0.056	0.055	.134

Conclusions

Results of using engineering methods for approximate computations of aerodynamic characteristics of reentry vehicles in a hypersonic flow are presented. Comparisons with results obtained by a complicated and expensive DSMC method prove the adequacy of results. It is shown that the local bridging method can reproduce aerodynamic characteristics of spacecraft in wide range of Knudsen number. This local bridging method employs bridging functions based on the analysis of experimental data. It can be reasonably used at the initial stage of design of spacecraft of the lifting-body type for approximate estimates of a large number of different geometries or flow parameters, choosing the optimal spacecraft configuration, and other aerodynamic problems.

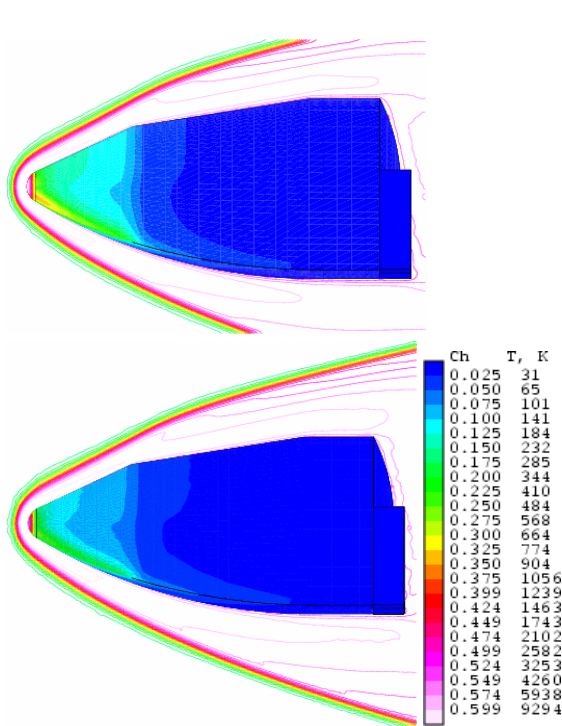


Fig. 6

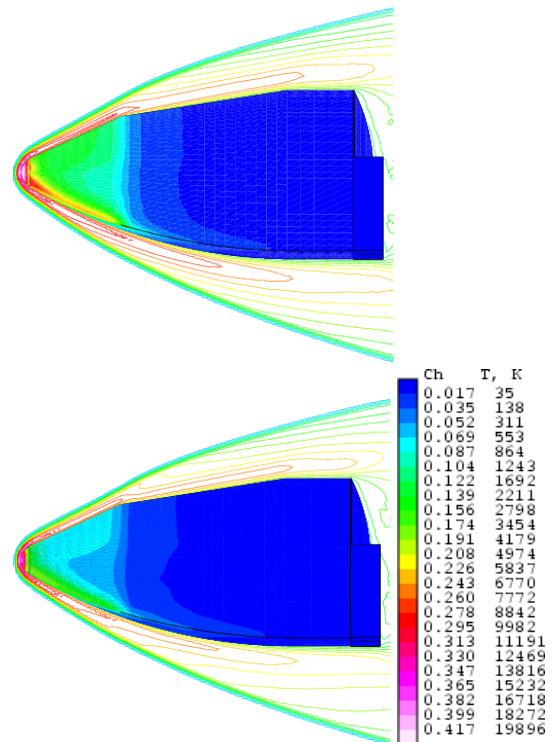


Fig. 7

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