SIMULATION TECHNIQUES IN HYPERSONIC LOW-DENSITY AERODYNAMICS

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Hypersonic rarefied flows near a wedge, disk, plate, and sphere were studied under the conditions of wind-tunnel experiments [1-8] and hypersonic flights. The direct simulation Monte-Carlo (DSMC) method [9] is used to study the influence of similarity parameters on aerodynamic coefficients in He, Ar, N_2, and CO_2. It is found that, for conditions approaching the hypersonic stabilization limit, the Reynolds number Re_0 and temperature factor t_w are primary similarity parameters. The influence of other parameters (specific heat ratio γ, Mach number M_∞, and viscosity parameter) becomes significant at $Re_0 < 10$ and values of the hypersonic similarity parameter $M_\infty\theta < 1$. The numerical results are in a good agreement with experimental data, which were obtained in a vacuum chamber at $0.1 \le Re_0 \le 200$. The effect of nonequilibrium processes on flows over blunt bodies is studied by solving the Navier-Stokes equations [10] and the thin-viscous-shock-layer (TVSL) equations [11]. The nonequilibrium, equilibrium and “frozen” flow regimes were examined for various physical processes in air and N_2, including rotational relaxation, chemical reactions and ionization. It is found that the binary similitude law is satisfied for blunt bodies in the transitional flow regime.

The Reynolds number Re_0, in which the viscosity coefficient is calculated by means of stagnation temperature T_0, can be considered as the main similarity parameter for modeling hypersonic flows in continuum, transitional and free-molecular regimes [5]. Using Re_0, γ, and M_∞, it is possible to perform other well-known parameters, such as χ and V for pressure and skin-friction approximations [8]. The Re_0 values can be changed by relocation of a probe along the free-jet axis at different distances x from a nozzle exit ($Re_0 \sim x^{-2}$). Due to this method [1, 2, 5], fundamental laws of hypersonic streamlining of bodies were discovered and valuable experimental data on aerothermodynamics of various probes was collected [6-8].

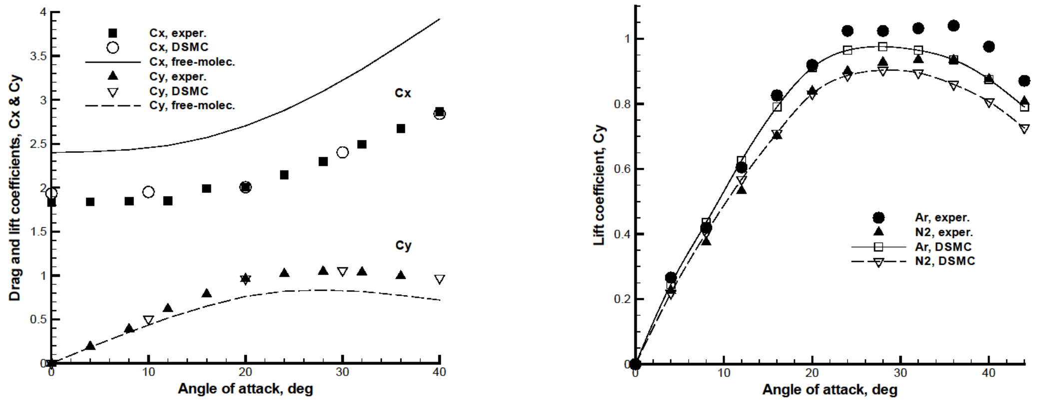

Fig. 1 *Left*: Drag and lift coefficients c_x, c_y for a wedge (2θ = 40 deg) in He at $Re_0 = 4$ and $M_\infty = 11.8$. *Right*: Lift coefficient c_y of the wedge at $Re_0 = 3$ in Ar and N_2. DSMC from data [9].

The role of similarity parameters γ and t_w is studied here. The testing was performed in underexpanded jets of He, Ar, N_2, and CO_2 in a vacuum wind tunnel [6-8] at T_0 = 295 K and 950 K. Plates, wedges, and disks were selected as probes. The presence of a nonuniform field in the expanding flow and experimental errors (5-8%) were evaluated [6-8]. The dependency of drag and lift coefficients c_x and c_y of the wedge (2θ = 40 deg) on the angle of attack was examined in He at $Re_0 = 4$ ($Kn_{\infty,L} = 0.3$), $t_w = 1$, and $M_\infty = 11.8$. The comparison of the testing data with DSMC results [9] is shown in Fig. 1 (*left*). The results indicate the advantages of the probe flight at transitional conditions in comparison with the free-molecular data (curves) [12]. The transitional-regime lift is bigger than the free-molecular lift by a factor of 1.25.

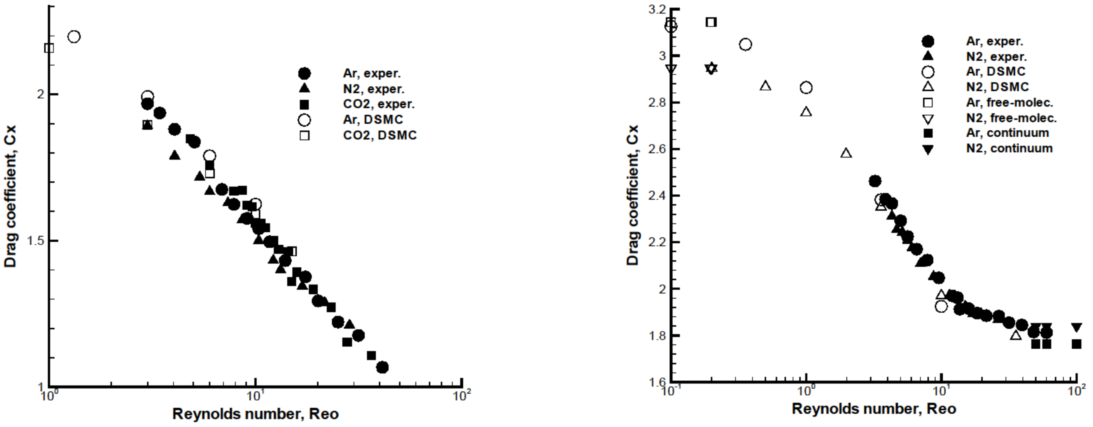

Fig. 2 Drag coefficient c_x for a wedge ($2\theta = 40$ deg) (*left*) and for a disc at $\alpha = 90$ deg (*right*) for various gases vs. the Reynolds number Re_0. DSMC data from [9].

In the free-molecular regime [12], aerodynamic characteristics of bodies depend on the normal component of the momentum of the reflected molecules, which depends on γ. The drag of thin bodies is proportionate to ($\gamma + 1$) at the regime of hypersonic stabilization [7]. The same conclusion is derived from tests conducted with Ar, N_2, and CO_2. The dependencies of c_x for a wedge ($2\theta = 40$ deg) are shown in Fig. 2 (*left*) at various Re_0 and γ. Testing data are compared with DSMC data [7, 9]. At $Re_0 \rightarrow 0$, a small increase of c_x is observed as γ grows. Identical dependency (5%) is found in the testing for transitional regime at $Re_0 < 10$.

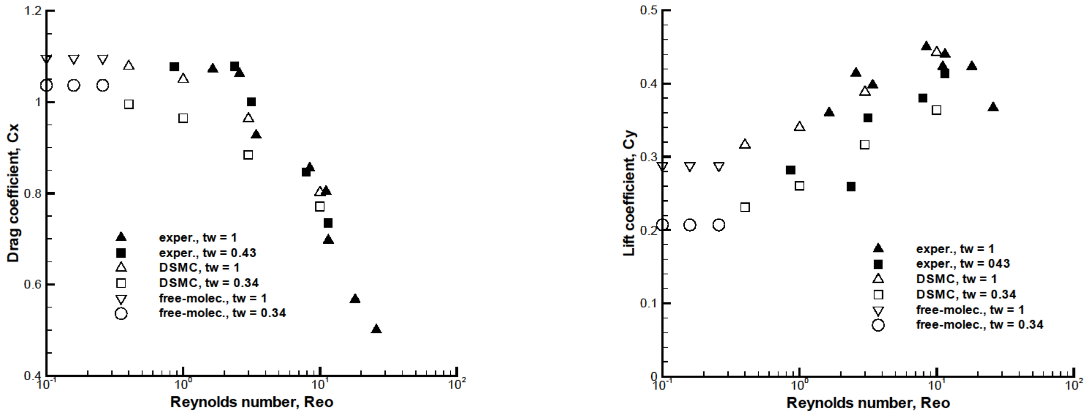

Fig. 3 Drag (*left*) and lift (*right*) coefficients c_x, c_y for the blunt plate ($\delta = 0.1$) vs. Reynolds number Re_0 in N_2 at $\alpha = 20$ deg and various temperature factors t_w. DSMC data from [9].

This phenomenon takes place in the case of streamlining of the wedge ($2\theta = 40$ deg) at $0 < \alpha \leq 40$ deg and $Re_0 = 3$. The experimental data for Ar and N_2 and the DSMC results [9] are shown in Fig. 1 (*right*). The correlation of the data for different γ demonstrates a significant difference (10%) in the values of c_y. The dependencies of c_x of the disc in Ar and N_2 are shown in Fig. 2 (*right*) for a wide range of Re_0. The experimental data obtained for Ar and N_2 are compared with DSMC data [9] and their limits in free-molecular and continuum regimes, which demonstrate different signs of γ-influences in the regimes.

Compared to other similarity parameters, the temperature factor ($t_w = T_w/T_0$) is the most important one [5-8]. The experimental data for c_x and c_y of a blunt plate ($\delta = 0.1$) is shown in Fig. 3 for wide range of Re_0. The lift changes non-monotonically from continuum to free-molecular flow regime. Maximum values occur in the transitional flow regime (see Fig. 3, *right*). The influence of t_w can be estimated as 35% for the lift-drag ratio. The DSMC results [9] correlate well with the experimental data at $Re_0 \leq 10$. Decreasing t_w decreases the pressure at the body surface in comparison with the tangential stresses [7, 8].

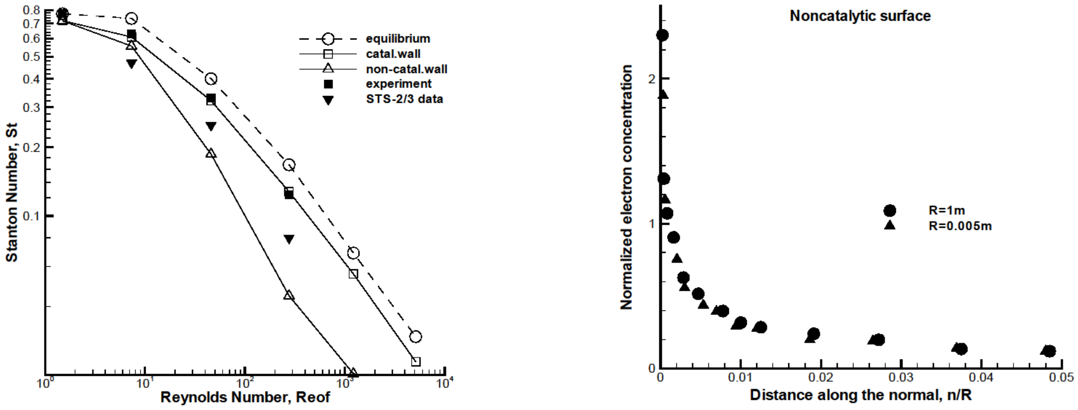

Fig. 4 *Left*: Stanton numbers *St* vs. Reynolds numbers Re_0 for a sphere along the Space Shuttle trajectory and different medium models. *Right*: electron concentration $N_e R \cdot 10^{-14}$ m^{-2} at the stagnation streamline of a sphere at $Re_0 = 7.33$, $U_\infty = 7.9$ km/sec, $\rho_\infty R = 5.35 \cdot 10^{-7}$ kg/m^2.

Calculations were carried out for descent flight conditions of a blunt body in the Earth atmosphere at altitudes $110 \geq h \geq 60$ km and Reynolds numbers $1.49 \leq Re_0 \leq 5130$ per 1 m. The values of the Stanton number *St* in the critical point of a sphere ($R = 1$ m) along the Space Shuttle trajectory are shown in Fig. 4 (*left*). The surface catalysis significantly influences heat flux *q*. The values of *q* under the flight conditions at 80 km ($Re_0 = 230$, $U_\infty = 7.9$ km/sec) differ by factor of three for various catalytic surfaces due to the nonequilibrium chemical processes in the TVSL [11]. This fact is confirmed by the STS-2/3 flight data (▼). At $h = 67.5$ km this difference reaches 240%. Numerical results show that parameters in the TVSL are “frozen” at $Re_0 < 20$; recombination processes are negligible, and the binary-scaling similitude law [11], $\rho_\infty R = \text{const}$, can be applied at $U_\infty = \text{const}$ (Fig. 4, *right*).

Methods used in this study allow the user to acquire information that could be effectively used in predicting aerothermodynamic characteristics of hypersonic vehicles at low-density flight conditions in atmospheres of the Earth, Mars, Venus, and other planets.

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