MODELLING OF AERODYNAMIC CHARACTERISTICS FOR RE-ENTRY VEHICLE IN FREE MOLECULAR FLOW

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Abstract— Experimental determination of aerodynamic data for high altitudes is difficult not only with technical, but also from an economic point of view. Therefore, the main tools for the study of aerodynamic characteristics of re-entry vehicles are numerical methods of rarefied gas dynamics. The development of numerical methods in rarefied gas dynamics is primarily due to the use of direct simulation method (Monte Carlo). In this paper present algorithm of the Monte Carlo method and the various gas-surface interaction models. The results of the aerodynamic characteristics of re-entry vehicles obtained by Monte Carlo method at different gas-surface interaction models are described.

Keywords— Monte-Carlo method, rarefied gas dynamics, gas-surface interaction models, Maxwell model, Cercignani-Lampis-Lord model, space vehicle, high-altitude aerodynamics.

I. INTRODUCTION

While the aircrafts are moving in an upper atmosphere where it's necessary to take into account the molecular structure of gas, kinematic models are applied (such as the Boltzmann equation and corresponding numerical simulation methods). In the case of high-altitude (such as free molecular flow regime) the integral of collisions in the Boltzmann equation becomes zero and its general solution is a function of distribution, which remains constant along the paths of particles [1]. The basic quantitative tool for the study of rarefied gas flow is direct simulation Monte Carlo method (DSMC) [2, 3]. In order to determine the forces and heat exchange of the gas on the body, it's sufficient to know local exchanges of coefficients of impulse and energy. In kinetic theory, the gas-surface interaction is a main form of a boundary condition between the gas molecules and solid surface. Although various gas-surface interaction models have been proposed over the last century, the validity of these models remains an important fact in rarefied gas dynamics.

In several works [4-21] investigated the aerodynamics characteristics of aerospace vehicles using DSMC methods, the use of three gas-surface interaction models, and engineering method.

The aim of this paper is to predict aerodynamic characteristics of aerospace vehicles using Direct Simulation Monte Carlo (DSMC) method by taking into account various gas-surface interaction models.

II. METHOD

The numerical statistical methods in rarefied gas dynamics developed in three directions: the use of the Monte Carlo methods to evaluate the collision integrals in the regular finite difference schemes for solving the kinetic equations; the direct statistical simulation of physical phenomena, which is subdivided into two approaches: the simulation of trajectories of test particles by the Haviland method and the simulation of the evolution of the ensemble of particles by the Bird method; the construction of a stochastic process using the Ulam–Neumann procedure corresponding to the solution of the kinetic equation.

The dynamics of rarefied gas is described by the Boltzmann integro-differential kinetic equation for the single-particle distribution density like as

$$\frac{\partial f}{\partial t} + \xi \nabla f = \int (f' \cdot f_1' - f \cdot f_1) g b db d\varepsilon d\xi_1 = J(f)$$

Here, $f = f(t, x, y, z, \xi_x, \xi_y, \xi_z)$ is the distribution density. f, f_1, f', f_1', correspond to the molecules with the velocities ξ, ξ_1 and ξ', ξ_1', before and after the collision, g is the relative velocity of the molecules in binary collisions $|g| = |\xi - \xi_1| = |\xi' - \xi_1'|$, and b and ε are the impact parameter and the azimuth angle for the collision.

The algorithm of the Monte Carlo method is as follows:

1. Constant data entry.
2. Defining the boundaries of entry of the molecule in the computational domain.
3. Calculating the coordinates of the point of entry and the velocities of molecules.
4. Calculating the coordinates of an intersection of the trajectory of the molecule with the surface of the body and calculating the momentum transfer.
5. Calculating the rate of the reflected molecules and calculating the reactive pulse.
6. Implementation of steps 4-5 to escape molecule from computational domain.
7. Data Averaging.

The coefficients of drag force C_x, lift force C_y and pitching moment m_z which are calculated according to equations as below

$$C_i = \frac{F_i}{\frac{1}{2}\rho_\infty V_\infty{}^2 S_{ref}} \quad i = x, y,$$

$$m_Z = \frac{M}{\frac{1}{2}\rho_\infty V_\infty{}^2 L_{ref} S_{ref}}$$

L_{ref}, S_{ref} – references length and surface; F_i M – resultant force acting on the vehicle and moment, respectively.

III. MODELS

Boundary conditions for Boltzmann equation are the conditions relating the distribution function of incident and reflected molecules. The most popular gas-surface interaction model for kinetic theory is specular (mirror) and diffuse reflection model developed by Maxwell (1879) [1]. This model is based on the assumption that the portion $(1 - \sigma_\tau)$ of molecules reflected specularly from the surface, and the rest part σ_τ of the molecule diffusely. The density of distribution of reflected molecules is set as follows:

$$f_r(\mathbf{x}_w, \xi_r) = (1-\sigma_\tau) f_i\left(\mathbf{x}_w, \xi_r - 2(\xi_r \cdot \mathbf{n})\mathbf{n}\right) + \sigma_\tau n_r \pi^{-3/2} h_r^{3/2} \exp\left(-h_r \xi_r^2\right), \ (\xi_r \cdot \mathbf{n}) > 0$$

and the scattering kernel has form

$$K(\xi_i \to \xi_r) = (1-\sigma_\tau)\delta\left[\xi_i - 2\left(\xi_r \cdot \mathbf{n}\right)\mathbf{n}\right] - \sigma_\tau \frac{2h_r^2}{\pi} \exp\left[-h_r \xi_r^2\right] \cdot \left(\xi_i \cdot \mathbf{n}\right),$$

$$h_r = \frac{m}{2kT_r}$$

Here, ξ_r –velocity vector of the reflected molecules, δ – Dirac delta-function, $\mathbf{n}$ –outward unit normal to the surface $\mathbf{x}_w$, h_r - most probable velocity of molecules at temperature T_w. Indexes i and r denote the quantities for the incident and reflected fluxes, and an index w - the value corresponding to diffuse reflection at a temperature of wall T_w. Parameter $0 \le \sigma_\tau \le 1$ in Maxwell model defines accommodation coefficient for the tangential momentum. For complete specular reflection $\sigma_\tau = 0$, for complete diffuse reflections $\sigma_\tau = 1$. Popularity of Maxwell model is due to its simplicity and with the fact that it satisfies the principle of detailed balance. Maxwell's model proved suitable for low speed experiments and low rarefaction environments.

Vector velocity components at diffuse reflection are modelled in a local spherical coordinate system which axis is directed along outward unit normal to the surface, by means of expressions [22]

$$|\xi_r| = h_r^{-1/2}\sqrt{-\ln(\alpha_1\alpha_2)}\ , \ \cos\theta = \sqrt{\alpha_3}\ , \ \varphi = 2\pi\alpha_4$$

Where α_1, α_2, α_3, α_4 - the independent random numbers uniformly distributed between 0 and 1. θ, φ - polar and azimuthal angles. The Accommodation coefficient of kinetic energy is defined in terms of incident and reflected fluxes as follows

$$\sigma_E = \frac{E_i - E_r}{E_i - E_w} = \frac{\xi_i^2 - \xi_r^2}{\xi_i^2 - h_w^{-1}}$$

Here E_w - energy which would be carried out the reflected molecules if gas is in equilibrium with a wall, i.e., when $T_r = T_w$. Expression for the velocity of the reflected molecule corresponding to not full accommodation of kinetic energy looks like

$$|\xi_r| = k h_r^{-1/2}\sqrt{-\ln(\alpha_1\alpha_2)}$$

where, $k = \sqrt{(1-\sigma_E)\xi_i^2 h_r + \sigma_E}$

In work [22] is proposed phenomenological model of Cercignani-Lampis (CL) which also satisfies the principle of reciprocity and is reported improvement of the Maxwell models [1]. The model is based on the introduction of two parameters which represent accommodation coefficient of kinetic energy connected with normal momentum $\sigma_n = \sigma_{En}$, and tangential momentum accommodation coefficients σ_τ, respectively.

Model CL well corresponds to the results of laboratory researches with high-speed molecular beams. Although a comparison is limited by laboratory conditions, CL model has theoretically justified and relatively simple. Later, there were modification of scattering kernel of CL model; however, they give slight improvement in comparison with laboratory experiments. Generally the interaction model has some arbitrary physical parameters that allow to achieve the reasonable agreement with results of laboratory researches in a range of conditions. In this sense, original model CL is enough physically and suitable for theoretical research. The universal model should use the scattering kernel received on the basis of physical experiment in a wide range of Knudsen numbers and velocity of the stream. In CL model, the diffusion kernel of velocity of surface normal has the following form

$$K(\xi_{ni} \to \xi_{nr}) = \frac{2\xi_{nr}}{\sigma_n} I_0\left(2\sqrt{1-\sigma_n}\frac{|\xi_{ni}|\xi_{nr}}{\sigma_n}\right) \exp\left[-\frac{\xi_{nr}^2 + (1-\sigma_n)\xi_{ni}^2}{\sigma_n}\right]$$

$$I_0(x) = \frac{1}{2\pi}\int_0^{2\pi} \exp(x\cos\phi)d\phi$$

Here I_0 –first type Bessel function, ξ_{ni}, ξ_{nr} – molecular velocities of surface normal for the incident and reflected molecules, rating as $h_w^{-1/2}$. A scattering kernel is written as follows

$$K(\xi_{\tau i} \to \xi_{\tau r}) = \frac{1}{\sqrt{\pi\sigma_\tau(2-\sigma_\tau)}} \exp\left[-\frac{\left(\xi_{\tau r} - (1-\sigma_\tau)\xi_{\tau i}\right)^2}{\sigma_\tau(2-\sigma_\tau)}\right]$$

Here $\xi_{\tau i}$, $\xi_{\tau r}$ – molecular velocities of tangent to surface for the incident and reflected molecules, rating as $h_w^{-1/2}$.

Twenty years after the creation CL model have been published the algorithm of its realization based on some transformation with the limits of the direct statistical simulation method [23]. The model in this form is called as Cercignani-Lampis-Lord model (CLL). Usage of CL model transformation expands to account for rotational energy exchange between gas and surface. Then, updating CLL model in the form of [23] is to account for vibrational energy exchange and extend range of states of the scatted molecule. CLL model is widely recognized examples of its application are presented in multiple works [24-29].

IV. ANALYSIS AND DISCUSSIONS

The calculation has been carried out through the method described in the previous section within the range of angles of attack α from – 90 deg 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 $t_w = T_w/T_0 = 0.04$; velocity ratio $M_\infty = 20$, energy accommodation coefficient $\sigma_n = 0.5$, 0.9, 1, momentum accommodation coefficient $\sigma_\tau = 0.5$, 0.9, 1.

In the figures 2-4 presented the results of the calculation of the coefficients of drag force C_x, lift force C_y with value of angle of attack α from 0 deg to 30 deg for reentry vehicle (fig. 1) by using DSMC method with the use of three gas-surface interaction models (Maxwell, Cercignani-Lampic-Lord).

From these results, we can explain, the drag and lift coefficient results of CLL model less than the Maxwell model as expected. The Maxwell model and CLL model predict the same lift, drag when the accommodation coefficients are equal to zero or one. In fact, for $\alpha_\tau = 1$ in Maxwell model and $\alpha_\tau = \alpha_n = 1$ in the CLL model, the two models give precisely the same. For accommodation coefficients not equal to zero or one, the CLL model gives higher aerodynamic forces than the Maxwell model for the same value of their respective accommodation coefficients.

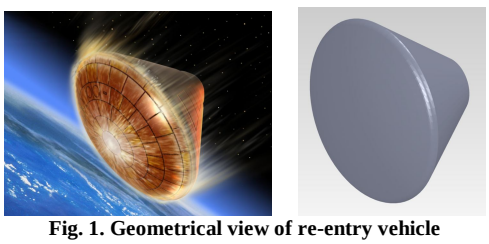


Fig. 1. Geometrical view of re-entry vehicle

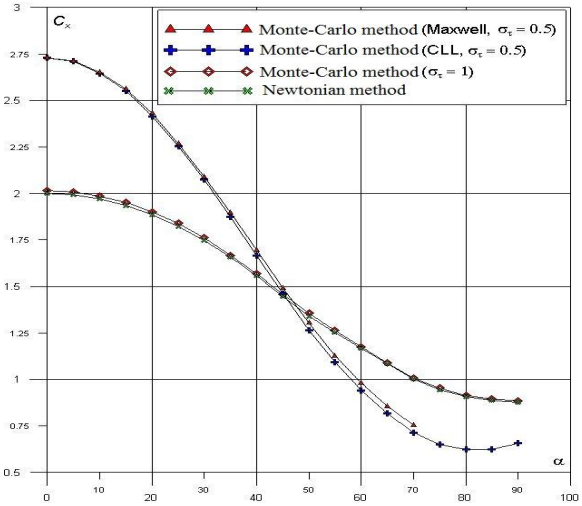


Fig. 2. Dependencies of C_x (α) for re-entry vehicle

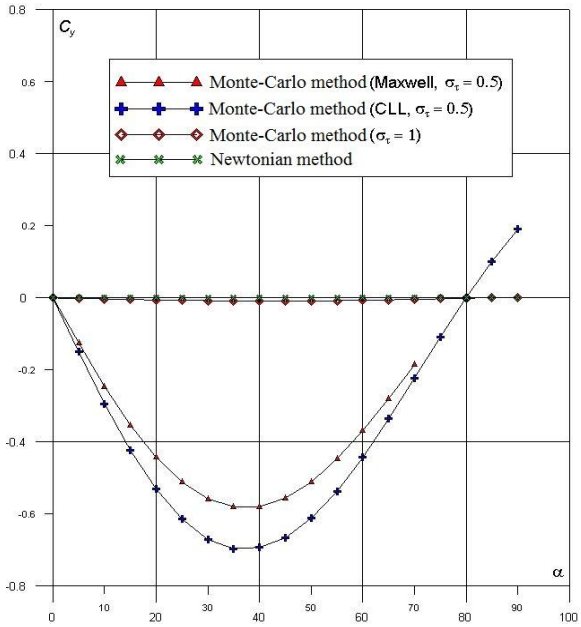


Fig. 3. Dependencies of C_y (α) for re-entry vehicle

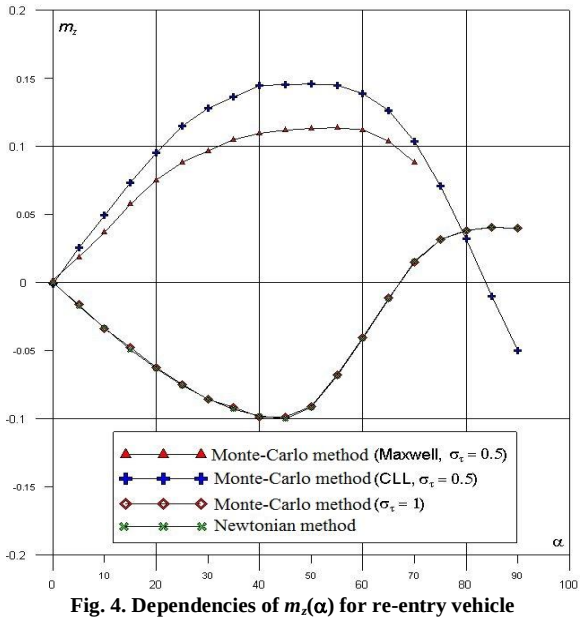


Fig. 4. Dependencies of m_z(α) for re-entry vehicle

V. CONCLUSION

The Investigation provided better understanding of the effects of gas-surface interaction models in DSMC calculations and ultimately a better understanding of the accommodation coefficients of materials and gases for orbital flight. The gas-surface interaction models have fundamental differences, they give similar predictions of aerodynamic forces on various vehicle design. The calculations with normal, tangential accommodation coefficients are provided more sensitivity of the aerothermodynamics quantities of aerospace technologies.

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REFERENCES

[1] Kogan, N. M., 1969, "Rarefied Gas Dynamic," Plenum Press, New York.

[2] Bird G.A., 1994, "Molecular Gas Dynamics and the Direct Simulation of Gas Flows", Oxford: Clarendon Press.

[3] Belotserkovskii, O. M., and Khlopkov, Yu. I., 2010, "Monte Carlo Methods in Mechanics of Fluid and Gas," World Scientific Publishing Co. Ltd. Singapore, New Jersey, Hong Kong.

[4] Khlopkov, Yu. I., 2006, "Statistical Modeling in CFD," MIPT Press, Moscow. (in Russian)

[5] Khlopkov, Yu. I., Chernyshev, S. L., and Zay Yar, Myo Myint, and Khlopkov, A. Yu., 2013, "Introduction to Specialty II. High-speed Aircraft Vehicles," MIPT Press, Moscow. (in Russian)

[6] Votta, R., Schettino, A., and Bonfiglioli, A., 2011, "Advanced Models for Prediction of High Altitude Aero-Thermal Loads of a Space Re-entry Vehicle," AIP Conference Proceedings, 1333, 1, pp. 1343–1348.

[7] Zay Yar Myo Myint, and Khlopkov, A. Yu., 2010, "Aerodynamic Characteristics of an Aircraft with a Complex Shape Taking into Account the Potential of Molecular Flow Interaction with a Surface," TsAGI Science Journal, 41(5), pp. 551-566.

[8] Vaganov, A. V., Drozdov, S., Kosykh, A. P., Nersesov, G. G., Chelysheva, I.F., and Yumashev, V. L., 2009, "Numerical Simulation of Aerodynamics of Winged Reentry Space Vehicle," TsAGI Science Journal, 40(2), pp. 131-149.

[9] Zay Yar Myo Myint, Khlopkov, Yu. I., and Khlopkov, A. Yu., 2013, "Aerothermodynamics Investigation for Future Hypersonic Aerospace System," Proc. 4th International Conference on Science and Engineering. 9-10 December 2013, Yangon, Myanmar.

[10] Khlopkov, Yu. I., Zharov, V. A., Zay Yar Myo Myint, and Khlopkov, A. Yu., 2013, "Aerodynamic Characteristics Calculation for New Generation Space Vehicle in Rarefied Gas Flow," Universal Journal of Physics and Application, 1(3), pp. 286-289.

[11] Khlopkov, Yu. I., Chernyshev, S. L., Zharov, V. A., Zay Yar Myo Myint, Khlopkov, A. Yu., Polyakov, M. S., Kyaw Zin, 2014, "Modern Trends in the Development of Reusable Aerospace System," Asian Journal of Applied Sciences 2(1).

[12] Khlopkov, Yu. I., Chernyshev, S. L., and Zay Yar Myo Myint, 2014, "Hypersonic Aerothermodynamic Investigation for Aerospace System," Proc. 29th Congress of the International Council of the Aeronautical Sciences, 7-12 September, St. Petersburg, Russia.

[13] Koppenwallner G., Frittsche B., Lips T., "Aerodynamic and Aerothermal Analysis: Tech. rep," Hypersonic Technology Gottingen, 2004.

[14] Khlopkov Yu.I., Chernyshev S.L., Zay Yar Myo Myint, Khlopkov A.Yu., 2015, "Notable Achievements in Aviation and Aerospace Technology", Open Science Publishers, New York.

[15] Viviani A., Pezzella G., 2015, Aerodynamic and Aerothermodynamic Analysis of Space Mission Vehicles Springer International Publishing, Switzerland.

[16] Viviani A., Pezzella G., Golia C., 2010, "Aerothermodynamic analysis of a space vehicle for manned exploration missions to Mars," In the proceeding of 27th International Congress of the Aeronautical Sciences. 19-24 Sept 2010. Nice, France.

[17] Khlopkov Yu.I., Zay Yar Myo Myint, Khlopkov A.Yu., 2013, "Aerodynamic Investigation for Prospective Aerospace Vehicle in the Transitional Regime," International Journal of Aeronautical and Space Sciences, Vol. 14, N. 3, pp. 215-221.

[18] Khlopkov Yu.I., Khlopkov A.Yu., Zay Yar Myo Myint, Tian Van Vyong, 2014, "Monte-Carlo Methods in Applied Mathematics and Computational Aerodynamics," Proceeding of 29th Congress of the International Council of the Aeronautical Sciences, St. Petersburg, September 7-12, 2014.

[19] Khlopkov Yu.I., Zay Yar Myo Myint, Khlopkov A.Yu., 2015, "Analysis of Local Engineering Methods for Determining the Aerodynamic Characteristics of High-speed Vehicles in the Transitional Regime," International Journal of Applied Engineering Research. V. 10, N. 6. pp. 14227-14234.

[20] Khlopkov Yu.I, Zharov V.A., Khlopkov A.Yu., Zay Yar Myo Myint, 2014, "Development of Monte Carlo Methods in Hypersonic Aerodynamics // Universal Journal of Physics and Application. Vol. 2, No. 4. pp. 213-22.

[21] Khlopkov Yu.I., Khlopkov A.Yu., Zay Yar Myo Myint, 2014, "Computer Modelling of Aerothermodynamic Characteristics for Hypersonic Vehicles," Proceeding of 2014 Spring World Congress on Engineering and Technology (SCET 2014), Shanghai, China, (April 16-18), Journal of Applied Mathematics and Physics, Vol. 2, pp. 115-123.

[22] Cercignani, C., and Lampis, M., 1971, "Kinetic Models for Gas-Surface Interactions", Transport Theory and Statistical Physics, Vol. 1, No. 2, 1971, pp. 101-114.

[23] Lord, R., G., "Application of the Cercignani-Lampis Scattering Kernel to Direct Simulation Monte Carlo Calculations", In the proceeding of 17th Int. Symp. on Rarefied Gas Dynamics, pp. 1427-1433.

[24] Padilla, J., F., 2008, "Assessment of Gas-Surface Interaction Models for Computation of Rarefied Hypersonic Flows", Ph.D. Dissertation, University of Michigan.

[25] Santos, W., F., N., 2007, "Gas-Surface Interaction Effect on Round Leading Edge Aerothermodynamics", Brazilian Journal of Physics, Vol. 37, No. 2.

[26] Wadsworth, D., C., Van, Glider, D., B., and Dogra, V., K., 2003, "Gas-Surface Interaction Model Evaluation for DSMC Applications", In the proceeding of 23rd Int. Symp. on Rarefied Gas Dynamics, pp. 965-972.

[27] Kussoy, M., I., Stewart, D., A., and Horstman, C., C., 1972, "Hypersonic Rarefied Flow over Sharp Slender Cones", NASA Technical Note, D-6689.

[28] Voronich, I., V., and Zay Yar Myo Myint, 2010, "Feature Influence of Gas-surface Interaction on the Aerodynamic Characteristics of Aerospace Vehicle", Electronic magazine of MAI, Vol. 17, No. 3, pp. 59-67. (in Russian)

[29] Khlopkov Yu.I., Chernyshev S.L., Zay Yar Myo Myint, Khlopkov A.Yu., 2016, "Effects of Gas-surface Interaction Models on Spacecraft Aerodynamics," International Journal of Aeronautical and Space Sciences, Vol. 17, N. 1. pp. 112-118.

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