

DIRECT MONTE CARLO SIMULATION OF A RAREFIED IONIZED FLOW ABOUT A REENTRY VEHICLE

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Key Words: *DSMC method, high-altitude aerothermodynamics of space vehicles, real gas effects, ionization, thermal nonequilibrium .*

The Direct Simulation Monte Carlo (DSMC) method¹ is traditionally used to study high-enthalpy flows with a significant level of thermochemical nonequilibrium. The main area of application of this method is investigations of high-altitude aerothermodynamics of space vehicles. For flight altitudes above 80 km, where the mean free path of molecules becomes commensurable with the vehicle size, conventional methods of computational fluid dynamics based on Navier-Stokes equations cannot be applied, and the DSMC method actually becomes the only feasible tool for numerical simulations. Even for altitudes below 80 km, the effects of rarefaction and nonequilibrium can be still pronounced, so numerical investigations of reentry flows by the DSMC method are required.

The allowance for real gas effects is extremely important in studying high-altitude aerothermodynamics of space vehicles. A high-temperature viscous shock layer is formed behind the bow shock wave. Typical features of this shock layer are the excitation of vibrational degrees of freedom of molecules and nonequilibrium chemical reactions, which appreciably affect the aerothermodynamic characteristics of the vehicle. The sizes of the relaxation zones (of rotational and vibrational energy) and the chemical reaction zone are comparable with the characteristic length scale of the flow. The differences in temperatures of translational, rotational, and vibrational modes substantially complicate the flow structure and significantly affect rates of chemical reactions. There are also associative ionization reactions in the gas; and the most probable of these reactions is $N + O \rightarrow NO^+ + e$. The degree of gas ionization at high altitudes during orbital reentry is usually smaller than one percent; the ionization processes weakly affect the aerothermodynamic characteristics of the vehicle and are of major interest in determining trajectory segments with communication blackout².

For the above-mentioned reasons, an appropriate choice of adequate physicochemical models is of principal importance when the DSMC method is used to study such flows. In the present work we investigate a flow for conditions of RAM-C II flight experiments with the SMILE++ software system designed for studying rarefied gas flows by the DSMC method³. In contrast to previous research^{4,5}, the present study is performed for a wide range of flight altitudes in order to validate models of real gas effects for the DSMC method against the RAM-C II plasma measurements. In particular, the significant attention is paid to the model of

nonequilibrium dissociation and its effect on the plasma density in the shock layer. The following three molecular dissociation models are examined: the Total Collision Energy (TCE) model⁶, the Quantum Kinetic (QK) model⁷ and the Kuznetsov-based State Specific (KSS) model⁸. A comparative analysis of these three models was started in Ref. 9 where DSMC predictions were compared with experimental data on strong shock wave structure in oxygen. The RAM-C II in-flight measurements is another example of experimental data on chemically reacting thermally nonequilibrium flows which is suitable for DSMC chemistry models validation.

Analysis of the axisymmetric computational results for altitudes between 71 and 81 km has revealed good qualitative agreement with the measured values of the electron density in the shock layer. The results of these comparisons prove high sensitivity of the calculated electron density in the shock layer to the model of nonequilibrium dissociation used. The full-length paper will also include assessment of the uncertainties associated with chemical rates data, ambipolar diffusion modeling and thermal nonequilibrium effects on the dissociative recombination. Weighting factors for charged species will be implemented to reduce the statistical scatter in plasma modeling for high altitudes (more than 80 km) where degree of ionization is extremely low. 3D computations will be performed for small angles of attack in order to examine the sensitivity of computational results to this parameter.

The study is supported by the RFBR Grant 14-08-01251 and SB RAS Interdisciplinary Integration Projects Nos. 39 and 47. This support is gratefully acknowledged.

REFERENCES

- [1] Bird, G. A., *Molecular Gas Dynamics and the Direct Simulation of Gas Flows*, Clarendon Press, Oxford, 1994.
- [2] Grantham, W. L., "Flight Results of a 25,000 Foot per Second Reentry Experiment Using Microwave Reflectometers to Measure Plasma Electron Density and Standoff Distance," NASA TN D-6062, 1970.
- [3] Ivanov, M.S., Kashkovsky, A.V., Vashchenkov, P.V., and Bondar, Ye.A. AIP Conf. Proc. 1333. – 2011. – PP. 211-218.
- [4] Bird G. A., "Nonequilibrium Radiation During Re-entry at 10 km/s," AIAA Paper 87-1543, 1987
- [5] Boyd I.D., Modeling of associative ionization reactions in hypersonic rarefied flows, *Phys. Fluids* 19, 096102 (2007)
- [6] G.A. Bird, "Monte-Carlo simulation in an engineering context," In *Rarefied Gas Dynamics*, ed. S. Fisher, *Progr. Astronaut. Aero.*, 1981, Vol. 74, pp. 239-255.
- [7] G.A. Bird, "A Comparison of Collision Energy-Based and Temperature-Based Procedures in DSMC," 26th Intern. Symp. on Rarefied Gas Dynamics, in AIP Conf. Proc., 2008, Vol. 1084, pp. 245-250.
- [8] Ye.A. Bondar and M. S. Ivanov. "DSMC Dissociation Model Based on Two-Temperature Chemical Rate Constant," AIAA Paper 2007-0614, 2007.
- [9] S. Gimelshein, I. Wysong, Y. Bondar, M. Ivanov, "Accuracy Analysis of DSMC Chemistry Models Applied to a Normal Shock Wave," in AIP Conf. Proc., 2012, Vol 1501, pp. 637-643.