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DSMC Approach for Rarefied Air Ionization during Spacecraft Reentry

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Abstract. The traditional DSMC method is extended to simulate three-dimensional (3D) rarefied ionization flows around spacecrafts during hypervelocity reentry. The electron mass amplification is utilized and the reaction rates involving electron are modified correspondingly. A weighting factor scheme for trace species is proposed, and its impacts on collision mechanism, the realization of chemical reactions as well as the calculations of macroscopic parameters are considered. The proposed DSMC algorithm is highly efficient in simulating weakly inhomogeneous flows, and its reliability is validated by the comparisons with aerodynamics force test of Shenzhou capsule model in low density wind tunnel, the electron number densities of RAM-C II and Stardust in rarefied transitional flow regimes. The introduction of rare species weighting factor scheme can significantly improves the smoothness of the number density contours of rare species, especially for that of electron in weak ionization case, while it has negligible effect on the macroscopic flow parameters. The ionization characteristics of the Chinese lunar capsule reentry process is analyzed for the first time at the altitudes of 80*km*, 85*km* and 90*km*, and the predicted communication blackout altitude agrees with the actual reentry flight data. The computation reveals that, for blunt body reentry with a speed larger than the second cosmic speed, the main ionization source is the direct collision ionization, and the electron number density is high enough to cause communication blackout in traditional rarefied flow regimes.

AMS subject classifications: 11K45, 35Q35, 60K40, 62P35

Key words: Spacecraft hypervelocity reentry, rarefied gas dynamics, DSMC, ionization reaction.

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1 Introduction

With rapid development of manned spaceflight, lunar and deep space exploration, spacecraft reentry speed has been increasing. Therefore, typical hypervelocity flow phenomena such as thermo-chemical nonequilibrium, ionization and communication blackout occur even in rarefied flows [1, 2]. For instance, the Chinese lunar exploration capsule launched in 2014 returned with a speed of $11.2\,km/s$, while the Stardust recorded the fastest man-made spacecraft reentry speed of $12.8\,km/s$ [3,4]. Under these typical hypervelocity conditions, the extremely strong bow shock around the vehicle leads to intensive physico-chemical nonequilibrium process, thus the atmosphere needs to be considered as an ionized gas mixture with vibrational excitation, dissociation and electronic excitation. To improve communication design of spacecraft during hypervelocity reentry, we need to accurately predict the electron number density distribution around the complex three-dimensional (3D) surface of spacecraft, which has been a long-standing research challenge [5, 6] to the field of rarefied gas dynamics.

At low altitude, the ionization effect is usually treated as the conventional chemical reaction using continuum flow models such as the Navier-Stokes equation [7, 8]. However, the continuum flow assumption for the Navier-Stokes equation becomes invalid for rarefied gas at high altitude. Ground test facilities can hardly reproduce the crucial non-equilibrium flows of extremely high-speed reentry in non-continuum atmospheric environment [9]. Although kinetic methods including the direct solver of kinetic models [10–12], the discrete velocity models [12–19], the gas-kinetic unified algorithm [20–23], the unified flow solver [24, 25], and the BGK-type discrete unified gas-kinetic schemes [26–28] describing non-equilibrium gas flows are still under development, they do not include the ionization process yet. Currently, only the most widely used method for rarefied hypersonic flows, the Direct Simulation Monte Carlo (DSMC) method [29, 30], which is essentially a statistical method, has the largest opportunity to overcome this rarefied atmosphere ionization challenge.

In 1987, Bird [31] utilized the DSMC method to simulate the rarefied air ionization for the first time, where the ionization process was treated using 11 molecular species and 41 chemical reactions, and the electrons were kept in close proximity to the ions in order to enforce charge neutrality. This pioneering work established a framework for simulation of ionization effect in rarefied flows. Carlson & Hassan [32] proposed a scheme to compute the electric field intensity, however, this scheme would suffer significant statistical fluctuation due to the scattering of charged particles. Both approaches have only been applied to one-dimensional stagnation problems because of the computational costs, thus it was difficult and unsuccessful to compare the DSMC results with flight experiment data [31, 33]. The surface geometry of aircraft will strongly influence its flow structure. The flow along the stagnation line can be significantly different for aircrafts with different configurations even if all other parameters were the same. Therefore, the real spacecraft geometries should be taken into account for accurate calculations of rarefied air ionization around 3D spacecraft with complex geometries.