Numerical Simulation of Weakly-Ionized Rarefied Arc-Jet Flowing Supersonically along Diverging Magnetic Field

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We are studying characteristics of supersonic helium plasma flowing along a diverging magnetic field. Its plasma parameters are measured by a Langmuir probe and Mach probe. The plasma is initially generated by arc discharge under atmospheric pressure, followed by a supersonic expansion into a weak uniform longitudinal magnetic channel in a rarefied gas wind tunnel as a plasma expansion chamber, and finally, expanded along the diverging magnetic field. It was experimentally found that the ion Mach number has its maximum ~ 3 at 1 cm downstream after passing the magnetic nozzle. We also found that the ion Mach number turned to decrease, and that the plasma potential dropped along the diverging magnetic field [1, 2].

We make an attempt to simulate the behavior of the expanding plasma along the open magnetic field, i.e., supersonic acceleration followed by deceleration and electric potential drop. Since the Knudsen number of the ion flow is larger than 0.01, the plasma flow has to be treated as a particle model. It is found that the ionization degree of the plasma is about 0.01 at most. Consequently, we should solve the kinetics of neutral particles simultaneously by a particle model. However, since the Debye length is in the order of 10^{-6} m, PIC scheme requires too fine discretization. As a result, we chose hybrid simulation, i.e., Direct Simulation Monte Carlo (DSMC) method for neutral particles and ions, and fluid method for electrons. Residual molecules in the vacuum chamber are also included as particles.

By the present numerical simulation, we find the velocity increase just after passing the open magnetic field line, followed by deceleration due to collisions with residual molecules. We also find the temperature increase during the deceleration. In this acceleration-deceleration phenomenon, the velocity difference between neutrals and charged species are found, which also changes the electric potential. We discuss the mechanisms of potential formation along the plasma flow mainly by the pressure difference and the friction force between the charged particles and neutral species. The numerical results are, at least qualitatively, consistent with our previous experimental results.

[1] K. Yoshida T. Kanuma, H. Ichii, A. Nezu, H. Matsuura and H. Akatsuka, *IEEJ Trans. Elec. Electron. Eng*., **4**, 416 (2009).
[2] K. Yoshida, T. Shibata, A. Nezu, H. Matsuura and H, Akatsuka, *IEEE Trans. Plasma Sci.*, **37**, 1414 (2009).