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Numerical Study of Effect of Background Pressure on Plasma Flowing Supersonically through Open Field Lines
開放端磁場の超音速プラズマに対する背景圧力の影響に関する数値研究

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We numerically study the effect of background pressure on supersonically flowing plasma through open field lines. Ions and neutrals are treated by particle-based Direct Simulation Monte Carlo (DSMC) method, while electrons are treated as a fluid in order to save memory and calculation time. We find that the ion temperature and velocity profile are different from those of neutral particles. The number density and temperature of residual gas affect on ion's temperature and velocity profiles.

1. Introduction

Expanding arc-jet is applied to various engineering fields, for example, ion implantation in material processing, electric thrusters for artificial satellites, etc. In these applications, open field lines are expected to control the arc-jet plasma characteristics because the open field lines act as a magnetic nozzle for these plasmas flowing with sonic velocity [1]-[3].

Yoshida *et al.*'s experiment showed supersonic velocity of ions of helium plasma up to Mach ~ 3 and the electric potential drop at the end of the hollow magnets [4].

To understand physical properties of the plasma flow quantitatively, we should carry out numerical modeling of the supersonic plasma flow at the open field lines. For this purpose, we should describe the system by the Boltzmann equations, because the Knudsen number of the system is larger than 0.01 or sometimes becomes up to 1.0, where the fluid dynamic treatment is not appropriate. Ions and neutrals are treated by the Direct Simulation Monte Carlo (DSMC). However, electrons must be treated as a fluid in order to save memory and CPU time [5].

2. Description of the model

The simulation area is cylindrically symmetrical as shown in Fig. 1. In the figure, the plasma flow comes in from the left side through magnetic line in hollow electro-magnets with about Mach number Ma ~1.2. In this simulation we treat a cold helium plasma with low-ionization degree ~ 1%, with its electron temperature T_e ~ 0.5eV and electron density N_e ~10^{12} cm^{-3} in the most upstream region A.

2.1 *Domain Considered and Discretization*

We discretized the entire domain uniformly by the mean free path of heavy particles at the entrance of the domain considered for the simulation, 4 mm, as already shown in Fig. 1. The supersonic plasma flows along the magnetic field to the downstream direction, and finally goes outside of the domain. Meanwhile, the step Δt was set to be 0.05 times of the mean free time, 0.1 μsec, which also corresponds to the value calculated at the entrance of the domain considered.

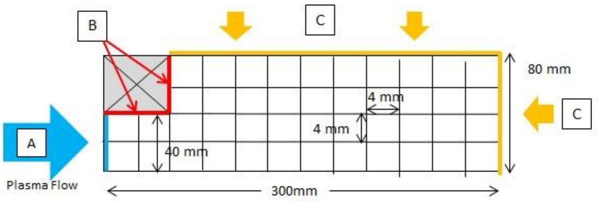

Fig. 1. Schematic diagram of domain considered and discretization in present study. "A" is the entrance of the plasma flow, "B" is the wall of the hollow magnet made of dielectric material, and "C" is the boundary with the incoming flux of residual gas.

2.2 *Magnetic Field*

Because of small magnetic Reynolds number [6], the plasma flow has no effect on the applied external magnetic field. It shows that we can assume steady-state magnetic field in this field. Six hollow magnets are set coaxially with their gap 1 cm, each of which is of 30 turns with its inner diameter D = 8 cm and thickness 6 cm, where the magnitude of the field inside the magnets is found to be 0.16 T with magnet current 300 A [4].

2.3 *Boundary Conditions*

At the cross section "A", the entrance of the domain in Fig. 1, electron, ion and neutral have the same temperature 0.5 eV. The flow velocity is 6.45 km/s (Ma ~1.2). We assumed the ionization degree at “A” to be 1.0%. We set the electric potential at the cross sectional area “A” to be the reference as zero voltage.

At the surface “B” in Fig. 1, the particles reflect at the surface of walls. We assume that the ion and the neutral are randomly reflected. The temperature of the wall is assumed to be 300 K. We set the potential on the surface of the magnet “B” to be zero by neglecting the charge up effect.

Meanwhile, there is also incoming flux of neutrals as background residual gas molecules from the downstream boundary, at the section “C” in Fig. 1. In this study we fix the pressure and change the temperature and density of incoming neutrals. We consider that the residual gas is thermodynamically equilibrated with vacuum chamber. The velocity distribution of residual gas is assumed to be Maxwellian justifiably [5].

3. Results and Discussion

Figures 2 and 3 present the magnitude of the flow velocity of the ions and neutrals, respectively, on the axis $r = 0$, under several temperatures at the background (neutral densities are adjusted to keep background pressure constant).

We find the ion’s profiles are different from the neutral’s profiles in velocity and temperature. First, we explain neutrals. In velocity profile, the higher the temperature of residual gas, the lower the flow velocity and the higher the neutral temperature.

Meanwhile, the velocity profile of ions shows the same behavior as neutral at first. After the temperature of residual gas is increasing, the velocity of ions is increasing. However, it is not monotonic. For a certain temperature the velocity of ions is decreasing again. The temperature profile and the velocity profile have inverse relation because of conservation of energy.

We find the ion temperature, when residual gas temperature is 300 K, is similar to ion temperature, when residual gas temperature is 750 K. The magnitude of velocity of ions, however, dramatically becomes high.

It is considered that a cold residual gas cools the ion initially. When the temperature of residual gas increases, the high-energy residual gas molecules make the ion’s temperature increases. However, the density of background pressure becomes lower. The frequency of collision becomes lower, too. It makes the temperature of ions, when residual gas temperature is 750 K is similar to 300 K.

4. Conclusion

We carried out numerical study of weakly-ionized helium arc-jet flowing supersonically along an open magnetic field line to understand the effect of background pressure in terms of residual gas temperature.

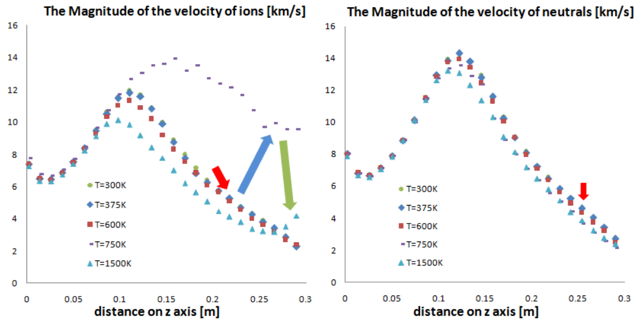

Fig.2. The magnitude of flow velocity on z

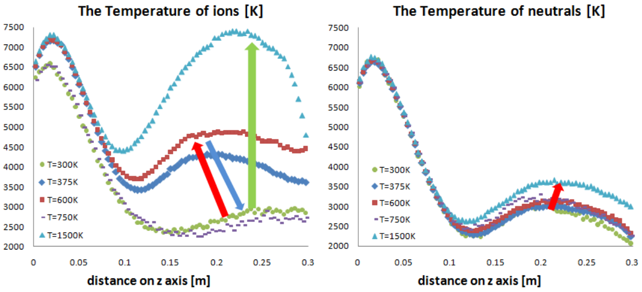

Fig.3. The temperature of ion and neutral on z

In this study, ions and neutrals were treated with the DSMC method. On the other hand, electrons were treated by the fluid model.

We found the velocity and temperature profiles of ions are quite different from neutral. The ions are affected in terms of temperature and number density of residual gas.

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