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Thermodynamics of electrons expanding in a magnetic nozzle

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Various processes of particle acceleration and momentum conversion in an expanding magnetic field have been discussed for a long time and are recently utilized to develop an electric propulsion device called a helicon-type magnetic nozzle rf plasma thruster [1], consisting of a helicon or inductive plasma source and a magnetic nozzle. In traditional electric propulsion devices, e.g., gridded ion and a Hall effect thrusters, the electric power is directly coupled with the ions accelerated by the externally applied electrostatic field, while the rf power mainly energizes the electrons in the helicon thruster, yielding the finite electron temperature and enhancement of the ionization of propellant gas. Therefore, it is important to understand how the thrust can be generated in such a system and how the electron energy can be converted into the thrust. The thrust is equal in magnitude and opposite in direction to the momentum flux exhausted from the system, which is given by a sum of static and dynamic pressures. In the non-equilibrium plasmas having the electron temperature larger than the ion temperature, the momentum flux is given by the electron pressure and the ion dynamic momentum [2].

A number of laboratory experiments have shown electrostatic ion acceleration by spontaneous electric fields, typically an ambipolar electric field or a current-free electric double layer [3,4]. Since the energy source of the electric field is the electron thermal energy [5], the structure plays a role in the energy conversion from the electron energy into the ion kinetic energy, while it does not increase the momentum flux. When the electric fields are formed in the plasma source, the ions are axially accelerated and sometimes deliver their momentum flux to the wall when they are lost to the wall, resulting in reduction of the thrust [6.7]. It has recently been demonstrated that the losses of the momentum flux and energy to the radial wall can be inhibited by applying the magnetic field [8]. In the magnetic nozzle region, an internal diamagnetic electric current is spontaneously induced, resulting in the Lorentz force due to the presence of the radial magnetic field [9,10]. Since the diamagnetic current originates from the electron pressure gradient in the magnetic field, the thrust enhancement process can be understood as the momentum conversion from the radial electron pressure to the axial plasma momentum. Further downstream of in the magnetic nozzle, the electrons have to be detached from the magnetic field lines to exhaust the plasma into space. A recent experiment has observed that the plasma flow can stretch the magnetic nozzle when the plasma flow velocity exceeds a few tens of percent of the Alfven velocity, which can be qualitatively explained with a magnetohydrodynamic model [11]. As mentioned above, the electron energy or momentum conversion processes are significantly important in the magnetic nozzle, where no heating source is applied to the electrons, i.e., the electrons expand adiabatically. A new application of the thruster to space debris removal has also been proposed [12].

When the electrons do work on their surrounding (magnetic nozzle for this case) in an adiabatic situation, the internal energy of the electron is reduced if following the first law of the thermodynamics. On the other hand, the electron temperature in the system is likely to be uniform in most of the laboratory plasmas even when the electrons adiabatically expand in the magnetic nozzle [13]. Since the electrons are generally trapped in the laboratory system by the positive plasma potential due to the ambipolar electric field and the sheath at the wall, they can move back and forth in the system and thermalized along the magnetic field lines. Therefore, the non-local effect of the electric field trapping the electrons seems to apparently make them isothermal [14]. In order to investigate the polytropic index of the electrons along the magnetic nozzle with the absence of the non-local effect of the electric field, a special experiment removing all the electric field is constructed, resulting in the nearly zero plasma potential in the diffusion chamber. On the other hand, the high plasma potential can also be formed by applying the positive voltage to the electron beam source. The experiment clearly shows the polytropic index approaching to 5/3, i.e., the adiabatic expansion, when interacting with only the magnetic nozzle, while it is close to unity, i.e., the isothermal expansion for the high potential case [15]. Furthermore, the magnetic field strength can be changed while maintaining the zero plasma potential. The thermodynamic behavior of the electron gas for various magnetic field strength will be shown in the presentation.

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