24Ca07

発散磁場中を膨張する電子のポリトロープ指数
Polytropic index of electrons expanding in a divergent magnetic field

高橋和貴[1]， Charles Christine[2], Boswell Rod W[2]
Kazunori TAKAHASHI[1], Christine CHARLES[2], and Rod W BOSWELL[2]

[1]東北大院工，[2]オーストラリア国立大 SP3
[1]Dept. Electrical Eng., Tohoku Univ., [2]SP3, The Australian National Univ.

Various processes of particle acceleration and momentum conversion in an expanding magnetic field are associated to plasma dynamics in space and astrophysical objects. The phenomena are recently utilized to develop an electric propulsion device called a helicon-type magnetic nozzle rf plasma thruster, consisting of a helicon or inductive plasma source and a magnetic nozzle [1]. The rf power mainly energizes the electrons in the helicon thruster, yielding the finite electron temperature and enhancement of the ionization of propellant gas. The thrust is the reaction force of the momentum exhausted from the system per unit time. 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 energy. The thrust is equal in magnitude and opposite in direction to the momentum flux exhausted from the system.

The thrust component exerted to the magnetic nozzle by the electrons induces the displacement of the system in space, implying the electrons do work on the magnetic nozzle. In terms of the thermodynamics, the relation between the change in the internal energy ΔU, the added heat Q, and the work W done by surroundings can be simply given by

$$\Delta U = Q + W.$$

When the system is adiabatic (Q = 0) and does work on surroundings ($W < 0$), the internal energy should decrease ($\Delta U < 0$). This relation can be more conveniently described by using a polytropic relation as

$$pV^{\gamma} = \mathrm{const},$$

where p, V, γ are the pressure, the volume, and the polytropic index. It is well known that $\gamma = 1$ for isothermal and $\gamma = (N+2)/N$ for adiabatic conditions, respectively.

The assessment of the polytropic index near the Sun's surface has shown $\gamma \sim 1$, suggesting the presence of the heating source (added heat) [2]. However, a number of the laboratory experiments in the magnetic nozzle have shown the nearly isothermal γ despite the adiabatic conditions, suggesting a non-local effect of the electric field in the system, e.g., ambipolar, sheath, and current-free double layer electric fields.

To verify if the polytropic index of electrons shows the adiabatic value when simply expanding in the magnetic nozzle with no interaction with the electric field, all the electric fields are removed from the system by injecting electrons. This can be demonstrated by the measurement of the plasma potential showing nearly zero value. In such a situation, all the electrons created by the source flow in the magnetic nozzle, escape from the opposite side wall, and never turn back to the source. Therefore, it might simulate the electrons in space and astrophysical object.

The assessment of the polytropic index clearly show $\gamma \sim 1$ for the high potential plasma, where almost of the electrons are trapped in the system, while it approaches $\gamma \sim 5/3$ for the zero potential condition. The results clearly demonstrate that the polytropic relation based on the thermodynamics can well describe the cooling of the electrons expanding in the magnetic nozzle [3]. Furthermore, $\gamma \sim 1$ and $\gamma \sim 5/3$ are observed for weak and strong magnetic fields. In the former, the electrons diffuse across the magnetic field lines and have no interaction with the magnetic nozzle, approaching the expansion in vacuum. For the latter, the electrons have interaction with the magnetic nozzle via an electron diamagnetic current and do work on the magnetic nozzle [4]. These observations might give some insight into the electron cooling in space and astrophysical objects.

[1] K. Takahashi, Rev. Mod. Plasma Phys. **3**, 3 (2019).
[2] T.V. Doorsselaere et al., Astrophys. J. Lett. **727**, L32 (2011).
[3] K. Takahashi *et al.*, Phys. Rev. Lett. **120**, 045001 (2018).
[4] K. Takahashi *et al.*, Phys. Rev. Lett. **125**, 045001 (2020).