Reconsideration of Electron Temperature of Plasmas with Non-Maxwellian EEDF Based on Statistical-Thermodynamical Discussion

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Generally, the electron energy distribution function (EEDF) F becomes far from Maxwellian in a weakly-ionized plasma. Some research reports discuss the definition of rigorous electron temperature T_e even for the plasma with non-Maxwellian EEDF. For instance, Alvarez *et al.* applied the BOLSIG+ and reported a common relationship $T_e \equiv [\partial S/\partial U]^{-1} = [2/(3k)]U$, for any discharge species, where k, S and U are the Boltzmann constant, the entropy and the electron internal energy, respectively [1]. However, it should be remarked that the software BOLSIG+ does not consider the variation in the counterparts of the electron collision [2]. The objective of the present study is to reconsider "T_e" of the plasma with non-Maxwellian EEDF.

We choose a model of oxygen plasma, where the dissociation degree is taken into accounr [3]. We set the parameters of the oxygen plasma in a cylindrical tube of 2.6 cm$^{\phi}$, its discharge pressure 1 Torr, and the constant electron density $N_e = 2 \times 10^{11}$ cm^{-3}. The internal energy of electron U is simply calculated as a mean energy of electrons:

$$U \equiv \langle \epsilon \rangle = \int_0^{\infty} \epsilon F(\epsilon) \mathrm{d}\epsilon, \text{ with } \int_0^{\infty} F(\epsilon) \mathrm{d}\epsilon = 1. \tag{1}$$

Meanwhile, S is obtained from the Gibbs entropy formula:

$$S = -k \int_0^{\infty} F(\epsilon) \ln [F(\epsilon)] \,\mathrm{d}\epsilon. \tag{2}$$

Equations (1)-(2) enable us to calculate S and U as functions of E/N under the given parameters. On the other hand, the first law of thermodynamics is described as follows for a closed system:

$$\left(\frac{\partial S}{\partial U}\right)_{V,N} = \left(\frac{1}{T_e}\right), \tag{3}$$

where T_e in Eq. (3) is hereafter referred to as the thermodynamic electron temperature T_e^{th}.

The thermodynamic temperature should be compared with other candidates of the electron temperature. For example, the electron kinetic temperature T_e^{k} is frequently defined as follows [1]:

$$T_e^{\mathrm{k}} \equiv \frac{2U}{3k}, \tag{4}$$

which exactly agrees with T_e for the equilibrium plasma. We should also discuss the difference between T_e^{th} and the ones determined as a slope in electron energy space, defined as $f(\epsilon) \equiv F(\epsilon)/\epsilon$.

Figure 1 shows a comparison between various temperatures defined to the oxygen plasma. It should be remarked that $T_e^{\mathrm{th}} \neq T_e^{\mathrm{k}}$, which does not agree with Alvarez *et al.* [1]. It should be noted that T_e^{th} is more close to T_1, the electron temperature of the bulk component, than T_e^{k} is. Further statistical-thermodynamic discussion is necessary to understand the physical meaning of each temperature.

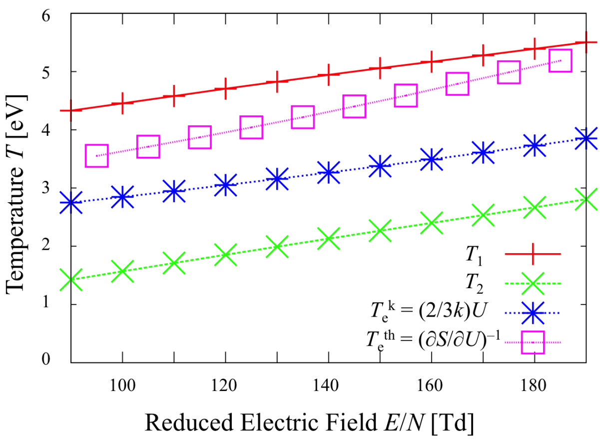

Figure 1: Comparison between various electron temperatures defined in the present study for the oxygen plasma. T_1 is that of the bulk component, T_2 is that of high-energy tail component, while T_e^{th} and T_e^{k} are defined in Eqs. (3) and (4), respectively.

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[2] G. J. M. Hagelaar and L. C. Pitchford: Plasma Sources Sci. Technol. **14** (2005) 722.
[3] J. Konno, A. Nezu, H. Matsuura and H. Akatsuka: Tech. Meeting PST, IEE Japan, (2013) PST-13-63.