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Effects of Atomic Processes on Sheath Formation

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Abstract

Effects of sheath formation due to atomic processes were calculated using simplified MHD equations involving collision effects. The results showed that even a small rate of atomic processes has an effect on sheath depth and length, causes the sheath and presheath boundary to be smooth. Assuming the Boltzmann distribution of electron density, ionization and charge exchange processes increase ion density, and thus stabilize sheath formation. On the other hand, recombination processes prevent sheath formation. When there is a large rate of charge exchange, the ion velocity does not exceed sound velocity at the wall (here the current density is assumed to be zero at the wall).

Consequently, in this paper, the condition of sheath formation was calculated by simple MHD equations. Therefore, the effects of pressure gradient and/or electron temperature gradient will be the next problem to solve in the near future due to the spatial profile of atomic reaction rates.

Keywords:

atomic process, sheath boundary, potential depth, ion velocity, two fluids model

1. Introduction

Much research has been done with regard to sheath formation at various conditions [1-10]. Recently K.U. Riemann has investigated the charge exchange process on sheath formation [1]. X.P. Chen has also studied the condition of sheath formation involving the charge exchange process [2]. However, few considered the ionization and recombination processes in the above studies [3]. Since, in general, atomic processes, except charge exchange, indeed change local electron temperature and density, the assumption of the constant electron temperature is no longer valid, especially when neutral density is large. Therefore, it is believed that the treatment of sheath formation by conventional methods is not sufficient.

It is worthy to note, electron-electron collision frequency is larger than that of ions in most cases. Therefore, the Boltzmann distribution regarding electron density would be valid because of thermal equilibrium dependent on the local electron temperature. If the sheath region and/or presheath region were not wide with respect to the typical length of the electron temperature spatial profile, it would be important the effects of atomic processes on sheath formation assuming that electron temperature remains constant.

In this paper, the effects of sheath formation due to the ionization, recombination, and charge exchange processes are calculated by simple MHD equations.

2. Governing Equations

To simplify the calculation of the above-mentioned processes, one-dimensional two fluids MHD equations were used with no consideration to the magnetic field. The ion and neutral fluids are assumed to be cold in all regions, with the ion having a small drift velocity to the wall from the beginning. The electron density is assumed to be Boltzmann distribution. The conservation laws of ion particles and ion momentum, and Poisson equation required to be solved.

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$$\frac{dn_i}{dt} + \frac{dn_i V}{dx} = S_i \quad (1)$$

$$\frac{dn_i m_i V}{dt} + \frac{dn_i m_i VV}{dx} = n_i eE - S_m \quad (2)$$

$$\varepsilon_0 \frac{d^2\Phi}{dx^2} = -(n_i - n_e)e \quad (3)$$

$$n_e = n_{e0} \exp(\frac{e\Phi}{kT_e}) \quad (4)$$

$$S_i = n_e n_0 K_{ION} - n_e n_i K_{RR} - n_e^2 n_i K_{CR} \quad (5)$$

$$S_m \cong m_i V n_i n_0 \langle \sigma V \rangle_{CX} + m_i V (n_e n_i K_{RR} + n_e^2 n_i K_{CR}) \quad (6)$$

In above equations, n_i, V and m_i are the ion density, velocity and mass respectively. n_e and T_e are electron density and temperature respectively. S_i and S_m are the ion particle source and momentum source respectively due to the atomic processes. S_i includes the electron impact ionization rate K_{ION} and all recombination rates (i.e. radiative recombination rate K_{RR}, dielectronic recombination rate K_{CR}, etc.). S_m includes the charge exchange rate $\langle \sigma V \rangle_{CX}$ and all recombination rates. E is the electric field and Φ is the potential. The neutral density profile $n_0(x)$ is needed to solve these above equations. The profile of neutral density is assumed as constant in this calculation.

Simplifying eq. (2) by subtracting eq. (1) and using a steady state formula (i.e. $d/dt = 0$), after normalization process, we get :

$$\frac{d(\hat{n}_i U_i)}{d\hat{x}} = \hat{S}_i, \quad \hat{S}_i = \hat{n}_e \hat{n}_0 \hat{K}_{ion} - \hat{n}_e \hat{n}_i \hat{K}_{rec} \quad (7)$$

$$U_i \frac{dU_i}{d\hat{x}} = -\frac{d\varphi}{d\hat{x}} - \hat{S}_m, \quad \hat{S}_m = \hat{n}_e \hat{n}_0 \hat{K}_{ion} + \hat{n}_i \hat{n}_0 \langle \hat{\sigma} U_i \rangle_{CX} \quad (8)$$

$$\frac{d^2\varphi}{d\hat{x}^2} = -(\hat{n}_i - \exp\varphi), \quad \varphi = \frac{e\Phi}{kT_e} \quad (9)$$

where $\hat{S}_i$ is the normalized particle source, and $\hat{S}_m$ is the normalized momentum source. It is noteworthy that recombination rates are included in only $\hat{S}_i$, whereas the ionization rate is included in not only $\hat{S}_i$ but also $\hat{S}_m$. U_i is the normalized ion speed by ion sound velocity, and $\hat{n}_i$, $\hat{n}_e$ and $\hat{n}_0$ are the normalized ion, electron and neutral density by initial ion density. We have freedom to choose the potential absolute value; then the initial potential φ is set to zero. The ionization and recombination rates represent the rate of increase of $\hat{n}_i U_i$ by unit length, and the ionization and charge exchange rates represent the rate of decrease of U_i^2 by unit length.

If the atomic process is zero, these equations represent the collision-less sheath theory.

3. Calculational Results and Discussion

The initial values of the calculation are set to be $n_{i0} = n_{e0} = 10^{19}$ m^{-3}, $n_0 = 0.1\ n_{i0}$, $T_e = 100$ eV, $\varphi = 0$, $d\varphi/dx = 0$, $U_i = 0.01$, and deuterium plasmas. The normalized ionization and charge exchange rates are the range of 1×10^{-3} to 1×10^{-7} corresponding to the edge plasma parameters in tokamaks. The calculational results with atomic processes are shown in Fig.1 (a), (b). These initial values could be set arbitrarily; however, if the atomic process is neglected, nothing will happen in this calculation. Fig.1 (a), (b) show how the atomic process forms the sheath, in particular if charge exchange rate is huge, even the ion velocity is smaller than sound velocity, sheath formation occurs. Also, when recombination processes exceed the ionization process, the sheath formation is unstable in this calculation (not shown). To understand this situation, the momentum loss must be set to zero, and recombination rates must not be zero. In this case, the ion density decreases in the first step, and does not change, (i.e. electron density becomes greater than that of the ions). At this point, the sheath is not formed any longer.

Due to the negative effects of recombination rates on sheath formation, we will investigate the ionization and charge exchange processes independently and more in-depth. The parameter scan of ionization (*io*) rates and charge exchange (*cx*) rates are shown in Fig.2–4. The boundary of sheath and presheath is ambiguous in this calculation due to the continual solution. We can then define the boundary as being the point where the value of electron density is half that of the initial density that meet collision-less sheath theory. And we define the wall where the current density is zero.

Figure 2 shows wall potential dependence on the *io* and *cx* rates. When the *io* rate is greater than the *cx* rate, potential depth does not change. However, where the *cx* rate is greater than the *io* rate, the potential depth increases drastically. On the other hand, ion velocity does not change under these parameters. Figure 3 shows the sheath length (i.e. from beginning to the wall) within the parameters of *io* and *cx* rates. In these parameters range, sheath length increase with decrease of *io* and *cx*

rates. Figure 4 shows the results of ion velocity at the boundary (half-n_{e0} point) within the parameters of *io* and *cx* rate. It is clear that ion velocity is close to sound velocity where the *io* rate is greater than the *cx* rate. This region looks collision-less.

Sheath formation, the condition of $\hat{n}_i > \hat{n}_e$,

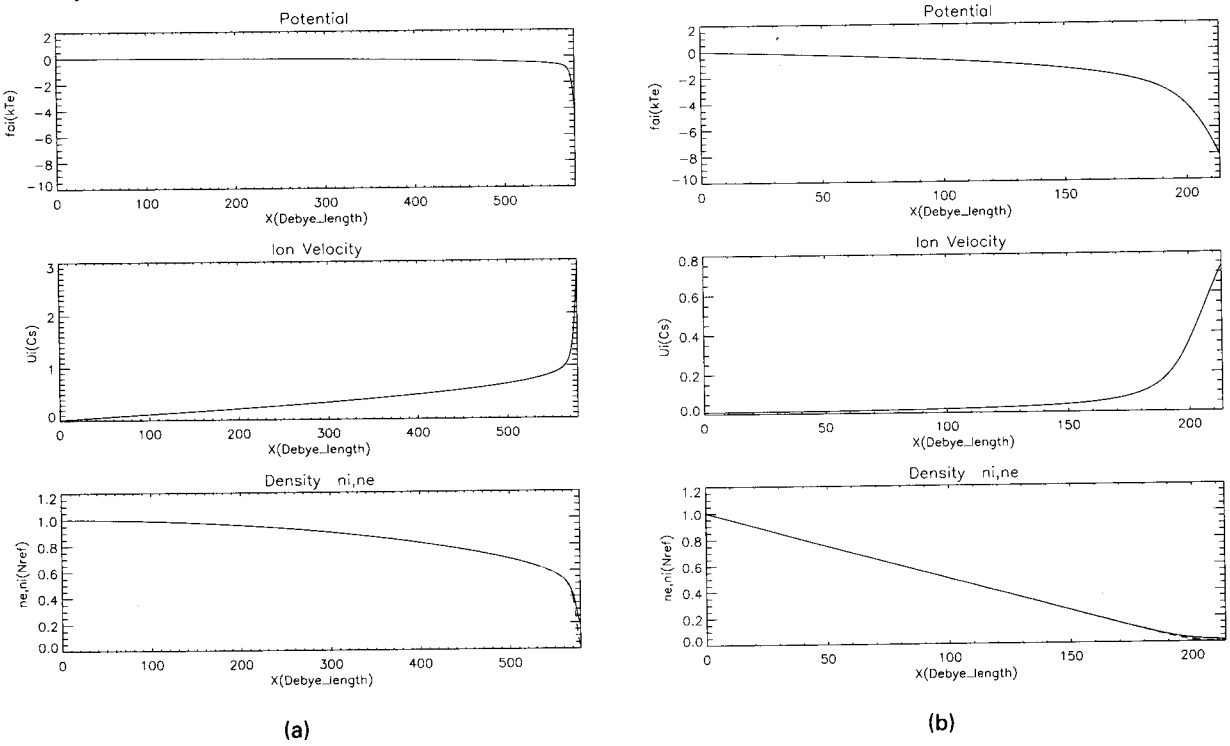

Fig. 1 Typical results of calculation including the atomic processes.
Horizontal axis represents the length by Debye length; upper shows the potential; middle shows the ion velocity; lower shows ion and electron densities; (a). normalized ionization rate = 1×10^{-2}, and the other atomic processes are set to zero. (b). normalized charge exchange rate = 5, and the other atomic processes are set to zero.

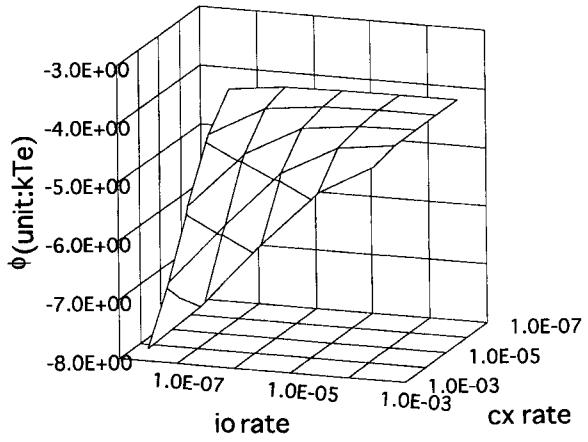

Fig. 2 Wall potential versus io rate and cx rate.
Io rate means normalized ionization rate, and cx rate means normalized charge exchange rate. Wall potential drastically changes in the region where the cx rate is greater than the io rate.

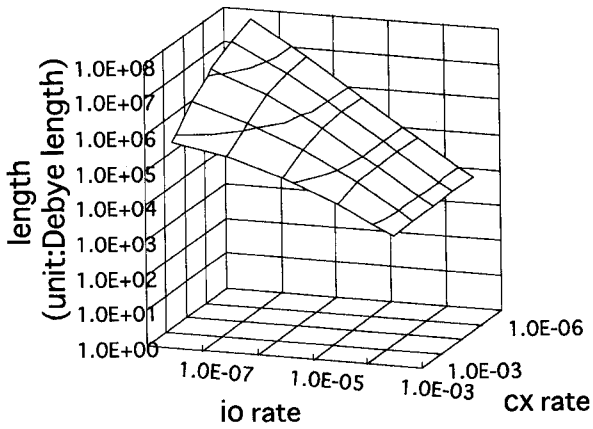

Fig. 3 Sheath length versus ionization (io) rate and charge exchange (cx) rate.
Sheath will become large with io rate where the cx rate is greater than the io rate.

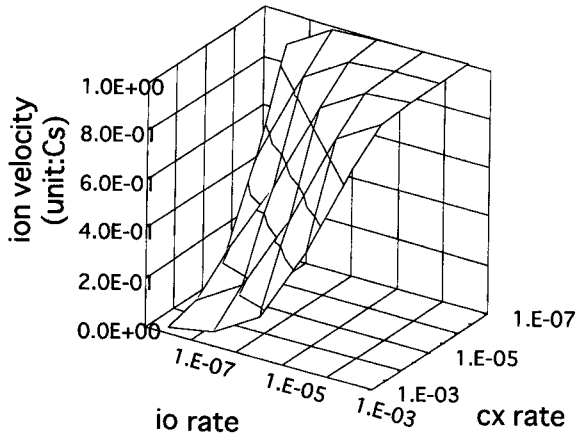

Fig. 4 Ion velocity at half-n_{e0} point
Ion velocity seems to be sound velocity where the ionization (io) rate is greater than the charge exchange (cx) rate. It looks collision-less.

therefore, the increase of U_i and $\hat{n}_i$ or the increase of U_i and the decrease of $\hat{n}_e$ satisfies the stable sheath condition. In eq. (7) the io rate affects the $\hat{n}_i U_i$ increment, but the cx rate does not. In eq. (8) both rates relate the U_i^2 decrement. However, in eq. (9) $\hat{n}_i$ increase means $d\varphi/dx < 0$, which overcomes the decrement due to the io rate, U_i^2 will increase gradually. On the other hand, *cx* rate decrease only U_i^2, and does not change $\hat{n}_i U_i$. Therefore, $\hat{n}_i$ increase gradually, and then $d\varphi/dx$ will be negative more gradually than that of *io* rate case. Therefore, in the parameter range of both rates of 1×10^{-3} to 1×10^{-7}, the *cx* rate mainly determine sheath depth. In general, however, it is noted that this results depend on the initial neutral density spatial profile, ion drift velocity. Moreover, in this calculation, we neglect electron temperature spatial profile and pressure term. Even though, it is clear that atomic processes really do affect sheath formation near the wall.

4. Conclusion

The effects of atomic processes on sheath formation were investigated. The results of calculations show that the ionization and charge exchange processes permit the sheath formation, whereas on the other hand, the recombination process inhibits the sheath formation. The boundary of the sheath and presheath region is not clear in the existence of atomic processes. It is natural to define the point where electron density is half of the initial value as the boundary, which satisfies the collision-less theory.

Within the parameter range of ionization and charge exchange rates of 1×10^{-3} to 1×10^{-7}, it is concluded that when the charge exchange rate is greater than ionization rate, the potential depth increases with the charge exchange rate; whereas on the other hand, the wall potential and sheath structure seem to meet the requirement of the collision-less theory when the ionization rate is greater than the charge exchange rate.

The effects of pressure gradient and/or electron temperature gradient will be the next problem to solve in the near future due to the spatial profile of atomic reaction rates.

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