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Effect of Ion Temperature Variation in Two-Ion Species Magnetized Plasma Sheath

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Abstract: For all practical applications of plasma, it has to be confined and in all such cases a sheath is formed at the material wall, which plays an important role in the properties of overall plasma wall transition region. The effect of ion temperature in a magnetized plasma sheath, which consists of two species of positive ions, has been studied using kinetic theory. The profile of ion densities, electron density, total charge density, potential is obtained by self-consistent solution to a non-neutral, collisionless, time independent plasma sheath. The physical parameters change slowly near the sheath entrance but exhibit steep gradient near the wall. The effect of applied magnetic field is more on ions whereas the electrons are almost non responsive and they are not influenced directly. In presence of magnetic field, the ion density is slightly lower compared to the case without magnetic field. The ion density increases on increasing ion temperature due to increase in their thermal velocity. On increasing the ion temperature, the total charge density at the wall increases and hence the potential decreases in magnitude. The result is useful in understanding and hence controlling the particles in plasma wall transition region especially in cases of two-ion species magnetized plasma sheath.

Key words: Plasma sheath, magnetized plasma sheath and kinetic trajectory simulation.

1. Introduction

All practical plasmas are separated from confining walls by a sheath, the properties of which determine the energy and flux of ions and electrons reaching the wall. Sheath is one of the oldest problems in plasma and its nature is complicated for various situations of magnetic field. Its nature not only changes drastically in absence and presence of an external magnetic field it also shows different properties for changing strength and obliqueness of the field. The study of magnetized plasma sheath started with Chodura [1] who modified the criterion of sheath formation and showed that the potential distribution in the presence of an oblique magnetic field consists of two different scaled structures. Closing to the wall is the usual electrostatic sheath, also known as the Debye sheath and the magnetic presheath, known as the Chodura sheath near the plasma boundary. Various approaches have been proposed to explain the properties of plasma sheath and are still a subjected of interest [2-11].

Multi-component plasma has been investigated by using hydrodynamic model under different conditions and few authors have studied the unmagnetized plasma sheath in multi-component plasmas [12-15]. Furthermore, using the kinetic and fluid models, it is shown that ions have interesting behaviors in the presence of magnetic field in a plasma sheath structure [1, 10, 16-18]. Franklin [3] described a plasma sheath in active plasma containing two species of positive ions including the effect of collisions. Hatami et al. [4] studied the collisional effect in magnetized plasma with two species of positive ions and they have shown that, by increasing the ion-neutral collisional frequency, the amplitude of ion density fluctuation and velocity increases. There is a significant effect of heavier ion on the density distribution, velocity and kinetic energy of the lighter ions. Liu et al. [5] studied the plasma sheath properties (ion temperatures,

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plasma densities and magnetic field strength) in a strong magnetic field using a steady state two-fluid model. The motion of ions is affected heavily by strong magnetic fields and the effect of ion temperature cannot be neglected, which is established theoretically using fluid model. Khoramabadi et al. [6] have studied the ion temperature effect on magnetized dc plasma sheath having single species ion and they have shown that the ion temperature strongly affects the sheath properties, i.e., increase of the ion temperature leads to increase of the sheath width and decrease of potential at the sheath edge. Shaw et al. [8] studied two ion species magnetized plasma sheath for varying ion temperature, magnitude of magnetic field and its orientation by using fluid model. The ion (both lighter and heavier positive ions, and negative ions) densities, the ion velocities, and electric potential inside the sheath are investigated. It is observed that, with increase of positive ion temperature, the lighter positive ion density peak increases at the sheath edge and shifts toward the wall for both absence and presence of magnetic field. For heavier positive ions, the density peak increases at the sheath edge for both unmagnetized and magnetized cases.

In low temperature plasma, where mainly the surface properties are modified using plasma techniques, sheath plays an important role in delivering appropriate particle and energy fluxes to the substrate (wall). In high temperature plasma, sheaths determine the details of wall heating, erosion, and wall material recycling. Thus, the knowledge of sheaths is important to understand plasma wall interactions, Langmuir probe characteristics, plasma etching, spacecraft charging, etc. [9]. Not a single work based on kinetic theory which describes two or multi-species ions are reported so far. Most of the works either follow fluid approach or deal with single ion species. In this work we use KTS (kinetic trajectory simulation) model [10] to study the effect of ion temperature variation in a magnetized plasma sheath consisting of two-species of positive ions. The motivation for the present work was triggered by similar works based on the fluid approaches [1, 8, 11].

This paper is organized as follows: In Sec. 2, basic theory of KTS is presented, in Sec. 3, our magnetized plasma sheath model is presented and in Sec. 4, result and discussion will be presented and finally, summary and conclusions are presented in Sec. 5.

2. Basic Theory of KTS

In KTS method the distribution function of particle species (in our case two positive ion species) is calculated directly by solving the related kinetic equations along the collisionless particle trajectory [10]. To obtain the distribution function $f(\vec{r},\vec{v},t)$ at any point $\vec{r},\vec{v},t$ of phase space, we trace the related trajectories of the phase space to the point where the distribution function is known or given. Here we assume that distribution function of ions and electron at the sheath edge to be cut-off Maxwellian in such a way that the most important requirements of the presheath-sheath transition are satisfied, i.e. quasineutrality, the sheath-edge singularity condition, continuity of the first three moments of each species and the kinetic Bohm-Chodura criterion. The species-*s* velocity distribution function describes the Boltzmann equation:

$$\frac{\mathrm{d}f^s}{\mathrm{d}t} \equiv \left[\frac{\partial}{\partial t} + \vec{v}\cdot\nabla + \vec{a}^s\cdot\frac{\partial}{\partial\vec{v}}\right] f^s = C^s \quad (1)$$

where,

$\vec{a}^s(\vec{r},\vec{v},t) = \frac{q^s}{m^s}\left[\vec{E}(\vec{r},t) + \vec{v}\times\vec{B}(\vec{r},t)\right]$ is the macroscopic acceleration of species-*s* particles and $\vec{E}(\vec{r},t)$ and $\vec{B}(\vec{r},t)$ are the macroscopic electric & magnetic field, and C^s is the species-*s* collision term. For collisionless cases the distribution function at every point along the trajectory can be obtained if it's value at one point (i.e., at the boundary) is known.

The electron and ion densities are obtained using

$$n^s(\vec{r}) = \int_{-\infty}^{\infty} d^3v\, f^s(\vec{r},\vec{v}) \quad (2)$$

and space charge density is given as,

$$\rho(\vec{r}) = \sum_s q^s n^s \tag{3}$$

The electrostatic potential $\varphi(\vec{r})$ is calculated using Poisson's equation

$$\nabla^2\varphi(\vec{r}) = -\frac{\rho(\vec{r})}{\varepsilon_0} \tag{4}$$

and the electric field is given by,

$$E(\vec{r}) = -\nabla\varphi(\vec{r}) \tag{5}$$

For an initial guess to the potential profile the system is iterated unless a final self-consistent state is reached [10].

3. The Magnetized Plasma Sheath Model

The 1*d*3*v* model of our magnetized plasma sheath is shown in Fig. 1.

The region of interest is bounded by two parallel planes situated at $x = 0$ and $x = L$ and the plasma consists of electrons, protons and singly charged boron. The "sheath entrance" at $x = L$ which separates the non-neutral, collisionless sheath region ($0 < x < L$) from the quasineutral collisional presheath region ($x > L$). The wall ($x = 0$) is assumed to be perfectly absorbing and the magnetic field lies in the *x-y* plane such that

$$\vec{B} = B_0[\cos\theta\hat{x} + \sin\theta\hat{y}] \tag{6}$$

Since the wall does not emit any particles and that both boundaries are perfectly absorbing, the electron velocity distribution function is given by,

$$f^e(x,v) = A^e e^{-\left(\frac{v_x^2+v_y^2+v_z^2}{v_t^{e2}}\right)+\frac{e\varphi(x)}{\mathrm{kT}^e}}\,\Theta(v_c^e(x) - v_x) \tag{7}$$

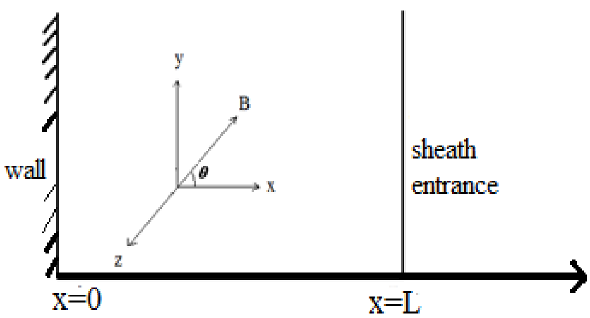

Fig. 1 The magnetized plasma sheath model.

where, k is the Boltzmann constant, $v_c^e(x) = \sqrt{\frac{2e\varphi(x)-\varphi_0}{m^e}}$ is the electron cut-off velocity at x and $v_t^s = \sqrt{\frac{2\mathrm{kT}^s}{m^s}}$ is the species-*s* (ion and electron) thermal velocity. The ion velocity distribution function at $x = L$ is given by,

$$f^i(L,v) = A^e e^{-\left(\frac{\left(v_x-v_{\mathrm{mL}}^i\right)^2+v_y^2+v_z^2}{v_t^{i2}}\right)}\Theta\left(v_{\mathrm{cL}}^i(x) - v_x\right) \tag{8}$$

where, v_{mL}^i is the ion "Maxwellian-maximum" velocity at $x = L$ and v_{cL}^i is the ion cut off velocity at $x = L$.

4. Results and Discussion

The sheath region is considered to be of size 10 electron-Debye lengths and having plasma density of 10^{18} m^{-3} with proton and singly charged boron in the ratio of 9:1. The electron temperature is considered to be constant at 1 eV and both the ions are at equal temperatures (three different cases of ion temperatures 0.02 eV, 0.04 eV and 0.06 eV are considered). The results obtained are plotted with the x-axis as the distance from the wall normalized with respect to the electron-Debye length and the magnetic field is kept constant (13 mT at 30° with respect to the normal to the wall).

Fig. 2 shows the total ion density profile which shows the number density of ion decreases slowly close to the sheath entrance up to about 6 Debye lengths and has sharp gradient towards wall. On increasing the ion temperature, the density of ions reaching the wall increases due to the fact that the increased temperature causes increased particle fluxes reaching the wall. Not only the ions but also the density of electron increases with increase in ion temperature as shown in Fig. 3, however, the rate of increment is different.

Figs. 4 and 5 show the density profiles of heavier and lighter ions, respectively, for different ion temperatures. Both the ion densities decrease continuously towards wall and on increasing the ions temperature, density of both species increases.

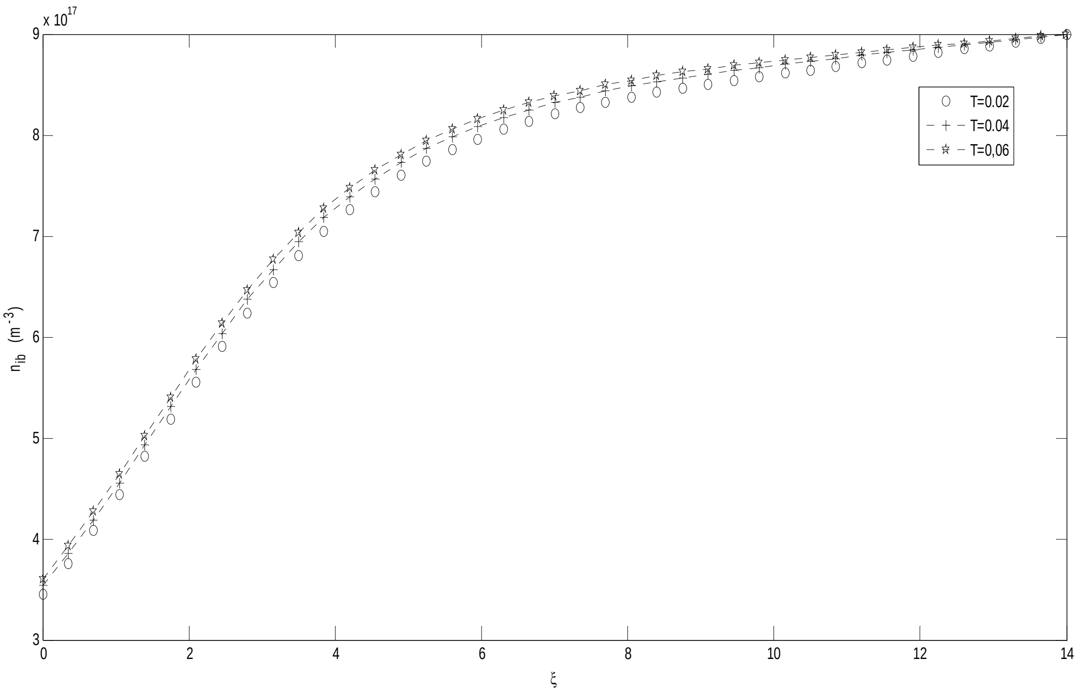

Fig. 2 Total ion density profile for different ion temperatures.

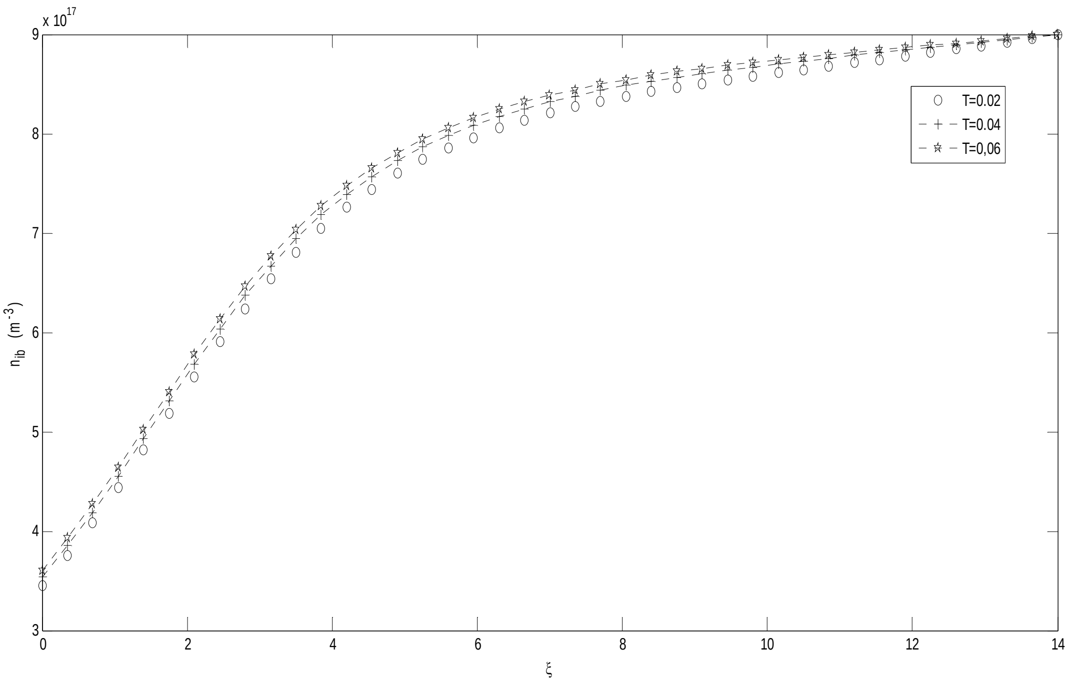

Fig. 3 Electron density profile for different ion temperature.

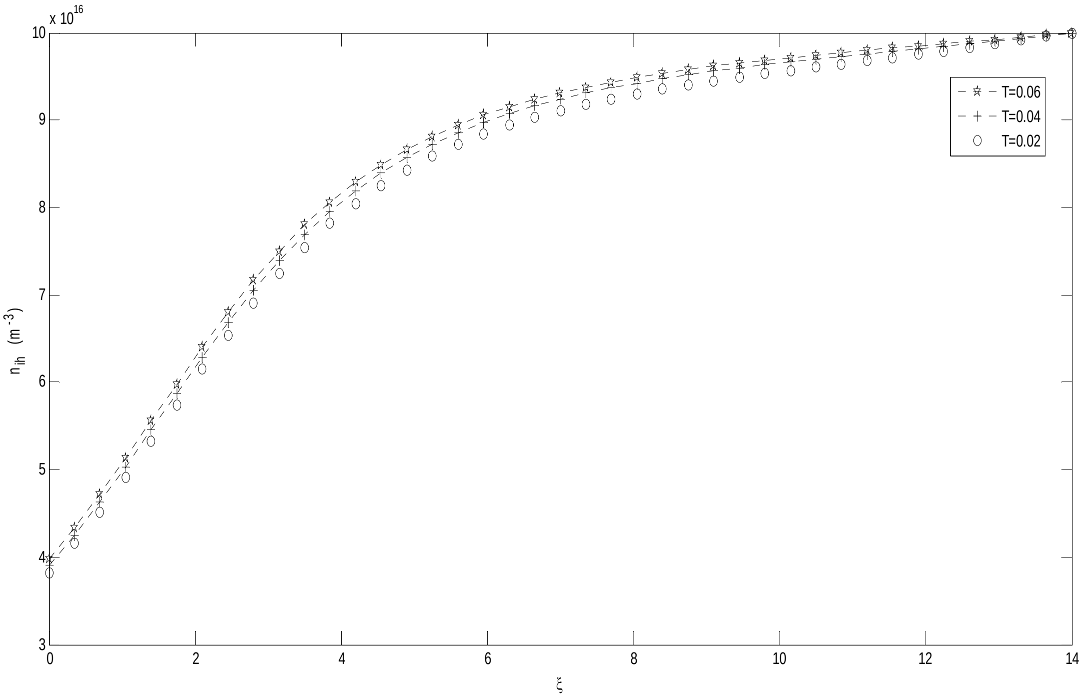

Fig. 4 Heavier ion density profile for different ion temperatures.

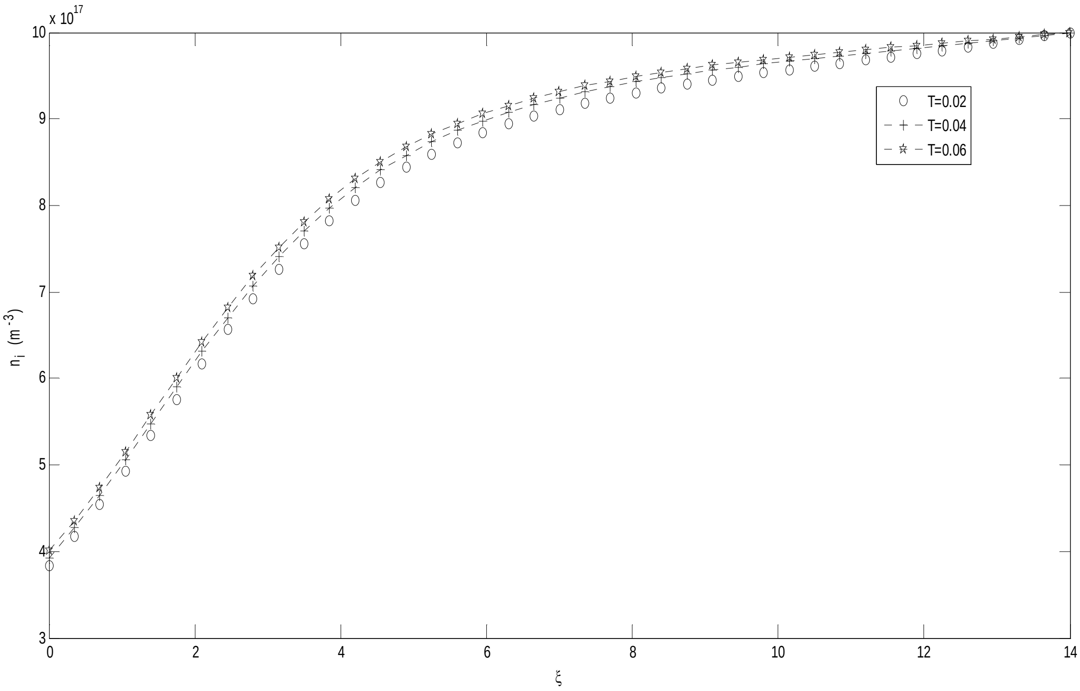

Fig. 5 Lighter ion density profile for different ion temperatures.

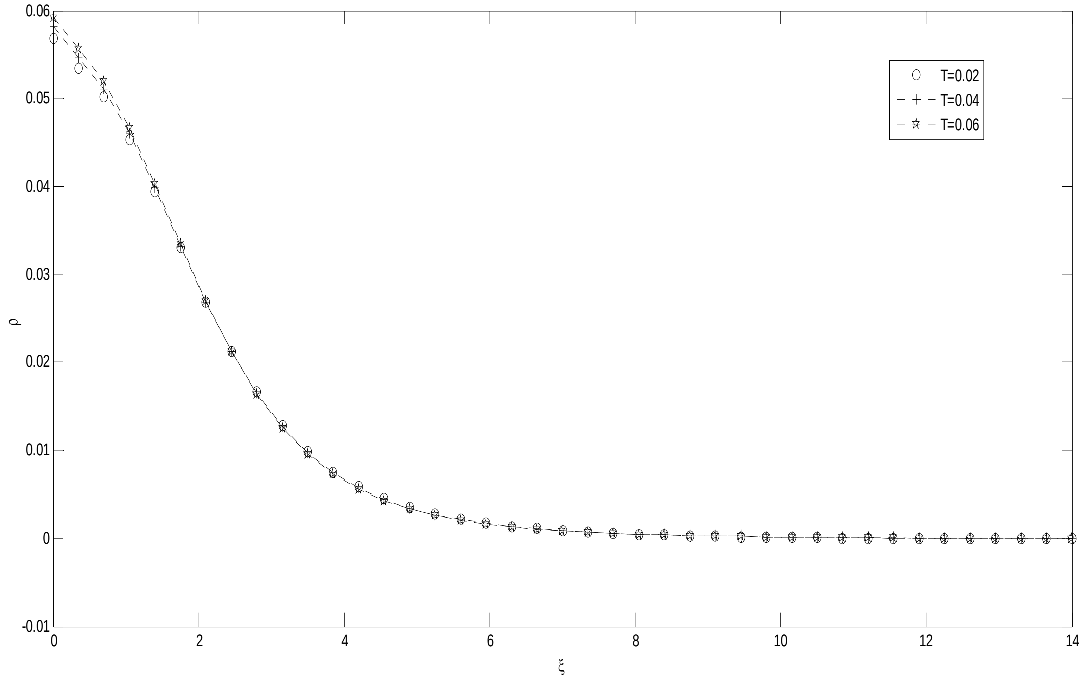

Fig. 6 Charge density profile for different ion temperatures.

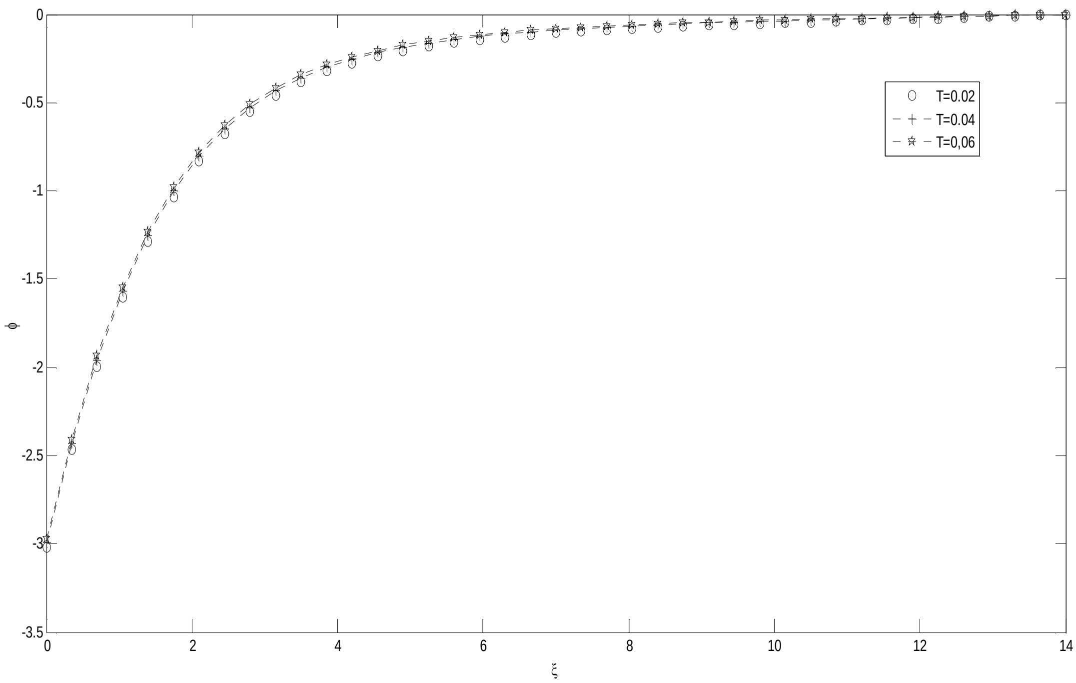

Fig. 7 Potential profile for different ion temperatures.

Figs. 6 and 7 show the charge density and potential profile respectively. The total charge density is almost constant near the sheath entrance up to about 4 Debye lengths and has steep gradient towards the wall. The charge density at the wall increases with the ion temperature because of increased density of ions. In fact densities of both ion and electrons increases for higher ion temperature, however, the increment in total ion density is more than that of electrons. This will cause the potential to increase thereby resulting in decrease of its magnitude as the wall is always in a negative potential.

5. Summary and Conclusion

Here, a magnetized plasma sheath having two positive ion species was studied using the kinetic trajectory simulation method. Particle densities, charge density and potential profile were analyzed by varying ion temperature keeping all other parameters constant. Increase in ion temperature causes all the particle densities (both species of ions and electrons) to increase which in turn increases the total charge density and wall potential. Keeping all other parameters same, when the ion temperature is changed from 0.02 eV to 0.06 eV, the heavier and lighter ion densities reaching the wall change from 3.45×10^{17} m^{-3} to 3.61×10^{17} m^{-3} and 3.82×10^{16} m^{-3} to 3.99×10^{16} m^{-3} respectively. This shows that the densities, charge density and potential can be controlled by varying the ion temperatures. This work is expected to provide better insight of various plasma parameters in a magnetized two-ion species plasma sheath region and may be useful in prediction as well as controlling the particle fluxes reaching to a wall. This is expected to be of importance in various applications of material treatment, sputtering, thin film deposition and ion implantation.

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