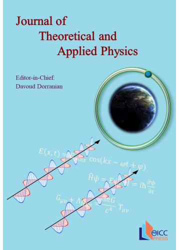

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Effect of collisions, ionisation and non-extensivity in an electronegative warm plasma associated with electron emission from the wall

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Abstract:
The effect of collisions, ionisation and non-extensivity is studied numerically in an electronegative warm plasma associated with electron emission from the wall. Electrostatic potential, space charge density, net negative charge density and emitted electron beam density are plotted with the normalised distance to see the effects of aforesaid parameters The negative ion is described with fluid equations to see it's effect of the mass ratio (negative ion to positive ion) on emitted electron beam density inside the sheath. The three types of electronegative plasma taken are CF_4, O_2 and C_60. The emitted beam electron density is more in number at the wall for higher collisional and ionisation case and less in higher mass ratio. For super-extensive case the emitted beam electrons is lesser than compared to the Boltzmann distributed electrons. The sheath thickness is found to be more in higher mass ratio, emitted beam electrons and super -extensive case while for higher collisional and ionisation case the sheath thickness is less.

Keywords: Warm plasma; Collisions; Ionization; Non-extensivity

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1. Introduction

The plasma and material interaction results in the formation of a sheath which is very crucial for application point of view in the areas of plasma processing, [1], plasma-based treatment [2, 3] etching, sputtering [4–6] electric space propulsion [7], nitriding [8, 9] and microelectronics [10]. The sheath characteristics depend on various parameters like electronegativity [11, 12], collisions between the ions and neutrals [13–19], ionization [20–22], magnetic field [22], temperature of the charged species [23]. The sheath characteristics also depends upon the electrons emitted from the wall. Electron emission from the wall may takes place due to various reasons like bombardment of electrons with wall this type of emission is basically called secondary electron emission [24,25]. The primary electrons in the plasma having energy greater then 30 eV can produces the secondary electrons [26–28]. The positive ions can also produce secondary electrons from the wall but for this emission the positive ion must have energy have greater than 1 keV. There is also in some case the emission is due to heating of electrode due to applying of high voltage to the electrode or due to heating of wall by the plasma itself present in the container as in the fusion plasma [29–32]. The emitted electrons from the wall significantly put impact on electron velocity distribution function (EVDF) and it reduces the electrostatic potential of the sheath which increases the heat flux to the wall and more and more electrons are produced from the wall. The emission affects the ion implantation, particle/energy transport, and sputtering. Various theoretical model [33–38] is given to explain the sheath with emitted electrons. Few of researchers explained the electron emission in the electronegative plasma [39] but they have considered the Boltzmann distribution of electrons and negative ion the plasma. In reality there exist some system where particles deviate from the Boltzmann distribution [40, 41]. The use of Maxwellian distribution in Boltzmann-Gibbs statistics is valid till the system is in equilibrium. While for system where a non-equilibrium stationary state exists and the long-range interaction occurs just like plasma and gravitational system, the Maxwellian distribution is inadequate for the description of the system. For such a system, generally the Tsallis or non-extensive statistics is applied and the entropy is given by

$$S_q = k_B\left(\frac{1-\Sigma_i^w P_i^q}{q-1}\right) \tag{1}$$

where q=degree of non extensivity, w=total number of microstates, P_i=probability of the i^th microstate and k_B=Boltzmann constant. This entropy is non-additive in nature. Suppose we have two independent systems a and b and if P_a and P_b be the corresponding probabilities of the two system. The total entropy of their composed system $S_q(a+b)$ is given by

$$S_q(a+b) = S_q(a)+S_q(b)+\frac{(1-q)}{k_B}S_q(a)S_q(b) \tag{2}$$

Which is not just the sum of the individual entropies of the two system. For $q>1$ the system is called as sub-extensive and if $q<1$ the system is called as super-extensive. As $q\to 1$ in Eq. (1) the Boltzmann-Gibbs entropy is obtained, i.e., now the entropy is extensive in nature.

$$S_1 = -k_B\Sigma_i^w P_i \ln P_i \tag{3}$$

When the particles are not in thermodynamic equilibrium, they usually deviate from the Boltzmann distribution. For example, in space plasmas [42–44] there are larger number of particles present in the tail which have higher values in the velocity distribution function. Experimentally [45] and theoretically [46–50] researchers have shown this behaviour. Tsallis [51] have explained the non-extensive case in the system. Also, negative ion in the high pressure do not follow Boltzmann distribution as the nature of negative ion is just similar to that of positive ions i.e., the mobility of negative ions is same as that of positive ion. This behavior of negative ion is considered in the model of Dhawan et al., [52]. Also, in the model [39] they have considered the cold plasma and neglected the collisions between neutrals and ions. Effect of ionization was also not present in their model. In experiments, it is generally found that the positive ions have finite temperature and there is ionization and collisions present in the plasma which affect the sheath properties. These days mostly use of electronegative plasma is preferable for all the plasma processing applications as it helps in to control the potential of electrode. The non-extensivity in the plasma is observed for the system which is distant from thermodynamic equilibrium. Hence, it is very important to take all these parameters in the model for a better understanding of the sheath formation mechanism. In this paper, a mathematical model is developed to study the characteristics of the sheath which takes all the parameters like collisions between neutral and positive /negative ions, ionization, non-extensivity in the plasma and electron emission from the wall. The fluid equation is written for negative ions to see the effect of mass ratio (negative to positive ion) on electrostatic potential, sheath thickness and the density of emitted electrons at the wall. The effect of emitted beam electrons, non- extensivity on the electrostatic potential, net space charge densities, net negatively charged species and sheath thickness is investigated.

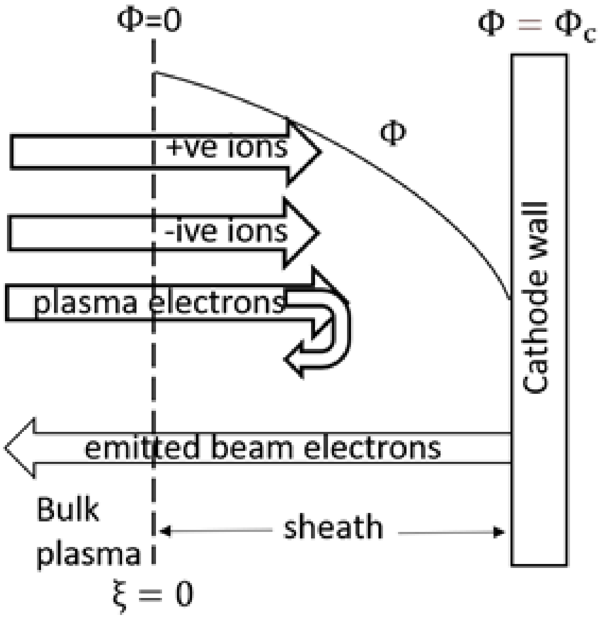

Figure 1. Schematic diagram depicting sheath associated with cathode wall emitting beam electrons.

2. Theoretical model

The position of imaginary plane at $\xi=0$ corresponds to the position where the quasi-neutrality holds sheath is started as depicted in figure 1. The continuity equations and momentum transfer equations are written to describe the ions (positive and negative) and beam electrons (emitted from the wall). The plasma electrons are described by their non-extensive distribution. The Poisson's equation relates the density with electric potential and distance from the edge of the sheath ($\xi=0$) towards the wall.

The flux and energy of the emitted beam electrons inside the sheath are given as follow

$$n_b = \frac{j_b}{ev_b} \tag{4}$$

$$\frac{1}{2}m_e \mathrm{v}_b^2 = e(\mathrm{V}-\mathrm{V}_C) \tag{5}$$

Eq. (4) and Eq. (5) together give Eq. (3)

$$n_b = \frac{j_b}{e}(\frac{m_e}{2e})^{\frac{1}{2}}(\mathrm{V}-\mathrm{V}_C)^{-\frac{1}{2}} \tag{6}$$

Continuity equation for the positive and negative ions are

$$\frac{d}{dx}(n_p\mathrm{v}_p) = v_{iz}n_e \tag{7}$$

$$\frac{d}{dx}(n_n\mathrm{v}_n) = v_{att}n_e - v_{det}n_n \tag{8}$$

Momentum transfer equation for both the ions read

$$M_p n_p \mathrm{v}_p\frac{d\mathrm{v}_p}{dx} = -Z_p e n_p\frac{d\mathrm{V}}{dx} - k_B T_p\frac{dn_p}{dx} - M_p n_p \mathrm{v}_p v_p \tag{9}$$

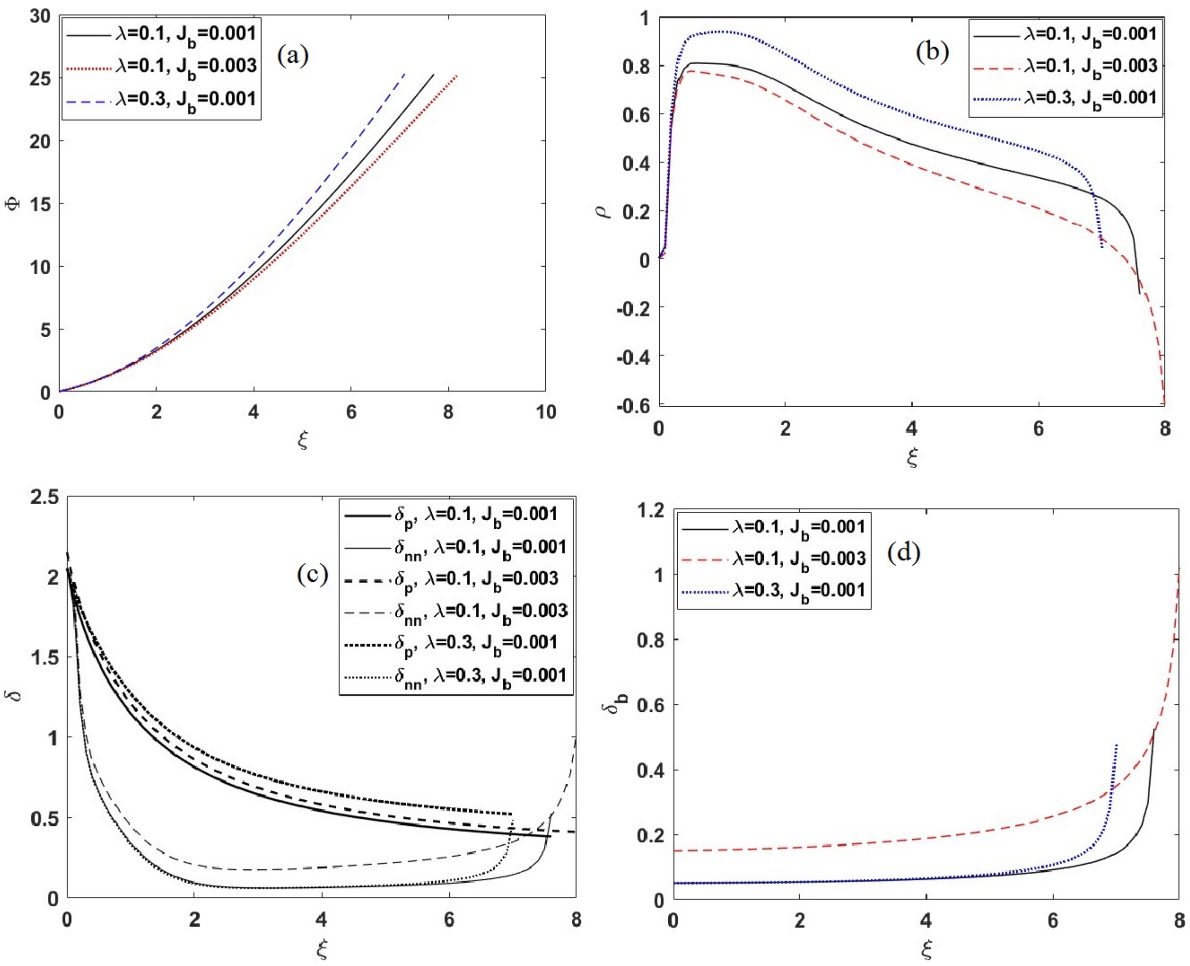

Figure 2. (a) Variation of normalised electrostatic potential (b) net space charge density (c) positive and net negative charged species (d) emitted electron beam density as a function of normalized distance for different values of J_b and λ when M_p=69, M_n=19, γ_p=10, γ_n=10, δ_{n0}=1, q=0.99, A=0.0005, D=0.0015, r=0.005, Φ_c=25, m=0, Z_p=1 and Z_n=1.

$$M_n n_n \mathrm{v}_n \frac{d\mathrm{v}_n}{dx} = -Z_n e n_n \frac{d\mathrm{V}}{dx} - k_B T_n \frac{dn_n}{dx} - M_n n_n \mathrm{v}_n \nu_n \quad (10)$$

Non-extensive distribution of the electrons is given by

$$n_e = n_{e0}\left(1+(q-1)\frac{e\mathrm{V}}{k_B T_e}\right)^{\frac{(q+1)}{2(q-1}} \quad (11)$$

Poisson's equation

$$\frac{d^2V}{dx^2} = -\frac{e}{\varepsilon_0}(Z_p n_p - Z_n n_n - n_e - n_b) \quad (12)$$

The quasi-neutrality condition reads

$$Z_p n_{p0} = Z_n n_{n0} + n_{e0} + n_{b0} \quad (13)$$

Here the subscripts p and n stand for positive and negative ions, respectively, subscripts b and e stand for beam electrons and plasma electrons, respectively, M is the mass of ions and q is used to denote the non-extensivity parameter. V is potential inside the sheath with respect to edge, V_c is the potential applied at the cathode, v_{att} is the attachment rate, v_{det} is the detachment rate, k_B is the Boltzmann constant, v is the velocity, n is the density and T is the temperature.

Using normalization parameters as n_{e0}, k_BT_e/e, C_{sp}, λ_{de}, C_{sp}, v_{iz} and j_c, the various physical quantities used in Eq. (4) to Eq. (13) are normalised. The normalized quantities appear to be

$$\delta_p = \frac{n_p}{n_{e0}},\ \delta_n = \frac{n_n}{n_{e0}},\ \delta_e = \frac{n_e}{n_{e0}},\ \delta_b = \frac{n_b}{n_{e0}}$$

$$u_p = \frac{\mathrm{v}_p}{C_{sp}},\ u_n = \frac{\mathrm{v}_n}{C_{sp}},\ \xi = \frac{x}{\lambda_{de}},\ \Phi = -\frac{e\mathrm{V}}{k_B T_e}$$

$$\Phi_c = -\frac{e\mathrm{V}_c}{k_B T_e},\ \gamma_p = \frac{T_e}{T_p},\ \gamma_n = \frac{T_e}{T_n},\ \lambda = n_g \sigma_s \lambda_{de}$$

$$r = \frac{\lambda_{de}}{\Lambda},\ A = \frac{v_{att}}{v_{iz}},\ \lambda_{de} = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_{e0} e^2}},\ \Lambda = \frac{C_{sp}}{v_{iz}}$$

$$J_b \frac{j_b}{j_c} \quad \text{where} \quad J_c = n_{e0} e \left(\frac{k_B T_e}{m_e}\right)^{\frac{1}{2}} (2\mathrm{V}_C)^{\frac{3}{2}}$$

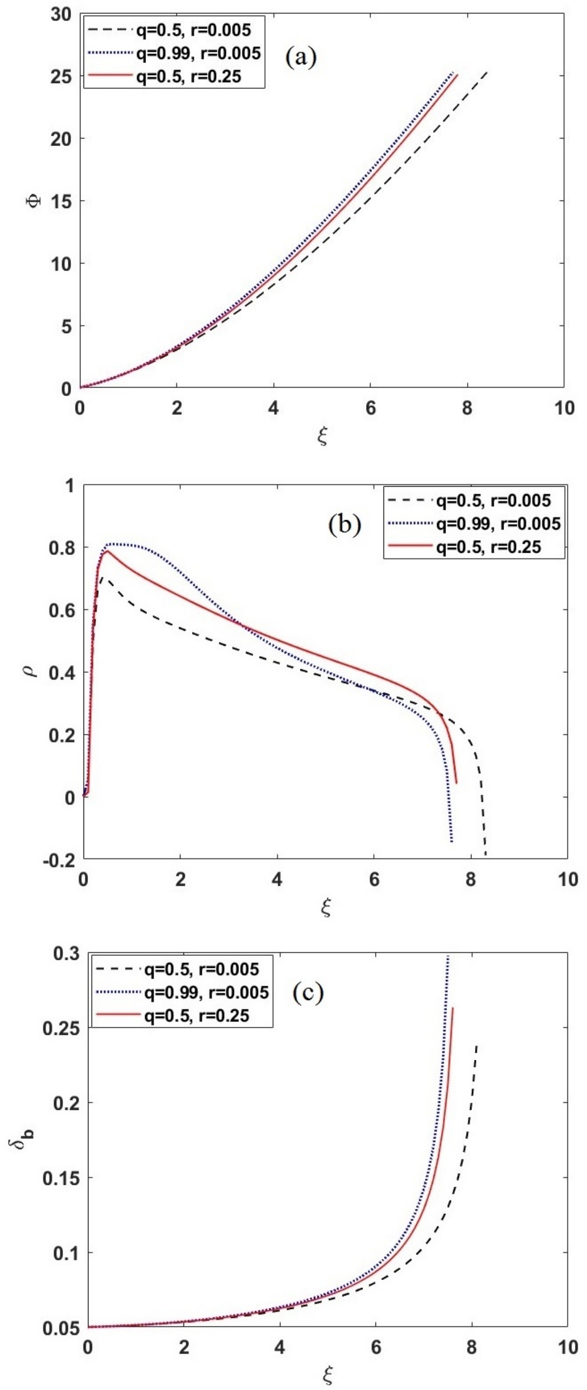

Figure 3. (a) Normalized electric potential (b) net space charge density (c) emitted electron beam density as a function of normalized distance for different values of q and r when M_p=69, M_n=19, δ_{n0}=1, γ_p=10, γ_n=10, A=0.0005, D=0.0015, Φ_c=25, J_b=0.001, Z_p=1 and Z_n=1.

Here λ is the collisionality parameter and λ_{de} is the Debye length. The normalized equations are as follows

$$\delta_b = \frac{J_b(2\Phi_C)^{\frac{3}{2}}}{(2\Phi_C - 2\Phi)^{\frac{1}{2}}} \tag{14}$$

$$\acute{\delta}_p u_p + \acute{u}_p \delta_p = r\delta_e \tag{15}$$

$$\acute{\delta}_n u_n + \acute{u}_n \delta_n = rA\delta_e - rD\delta_n \tag{16}$$

$$\acute{u}_p = \frac{\gamma_p u_p}{(\gamma_p u_p^2 - 1)}\left(Z_p\acute{\Phi} - \frac{r\delta_e}{\gamma_p \delta_p u_p} - \lambda u_p^{(m+2)}\right) \tag{17}$$

$$\acute{u}_n = \frac{M_n\gamma_n u_n}{(M_n\gamma_n u_n^2 - M_p)}\Bigg(- \frac{M_p}{M_n} Z_n\acute{\Phi} - \frac{Ar\delta_e M_p}{\gamma_n \delta_n u_n M_n} + \frac{DrM_p}{\gamma_n u_n M_n} - \lambda u_n^{(m+2)}\left(\frac{M_n}{M_p}\right)^{\frac{m}{2}}\Bigg) \tag{18}$$

$$\delta_e = [1 - (q-1)\Phi]^{\frac{(q+1)}{2(q-1)}} \tag{19}$$

$$\acute{\acute{\Phi}} = (Z_p\delta_p - Z_n\delta_n - \delta_e - \delta_b) \tag{20}$$

$$Z_p\delta_{p0} = 1 + Z_n\delta_{n0} + 2J_b\Phi_c \tag{21}$$

In the above equations, the first derivative is denoted by single prime and second derivative is denoted by double prime. Equations (14) – (20) are coupled equations which are solved by numerical method. Researchers have used numerical methods for solving different existing problems [53–56]. We use Runge-Kutta (ODE 45) to solve these coupled equations. The initial conditions for solving the equations is similar to our previous work [57].

3. Results and discussion

For different values of J_b and λ, the normalised electrostatic potential, net space charge density, positive and net negative charged density for different values of collisional parameter and electron beam current density are plotted as a function of normalised distance in figure 2. As J_b increases the net space charge density gets decreased near the wall (figure 2(b)) which is due to the increase in net negative charged species inside the sheath (figure 2(c)) and hence there is a reduction in the slope of the electrostatic potential (dotted line in figure 1). Under this situation, the sheath thickness gets increased. This behavior matches with the work of other researchers [39] where they have obtained the larger thickness with the increase in emitted electron beam current density (from the wall).

For increase in the collisions between the positive/negative ions with the neutral atoms, there is an increase in the slope of electrostatic potential. This is because of the increased positive charge density in the presence of higher collisions (dotted line in figure 2(c)); this increases the net space charge density inside the sheath (dotted line in figure 2(b)). The sheath thickness gets decreased for this case.

On increasing the value of J_b, the normalised electron beam density inside the sheath and at the sheath edge (ξ=0) get increased which results in the enhanced total negative charged species density inside the sheath (shown in figure 2 (b)). Hence, the net space charge density decreases and the slope of the electrostatic potential also decreases, as shown in figure 2(a). As collisions between positive/negative ions increases, the emitted electrons are more in number near the wall (blue dotted line in figure. 2(d)) because the slope of the potential gets increased (figure 2(a)) i.e., the electric field gets increased and the emitted electrons experience a greater force.

The effect of non-extensivity and the ionization rate on electrostatic potential and the net space charge density is plotted in figure 3(a) and figure 3(b) respectively. It is observed that

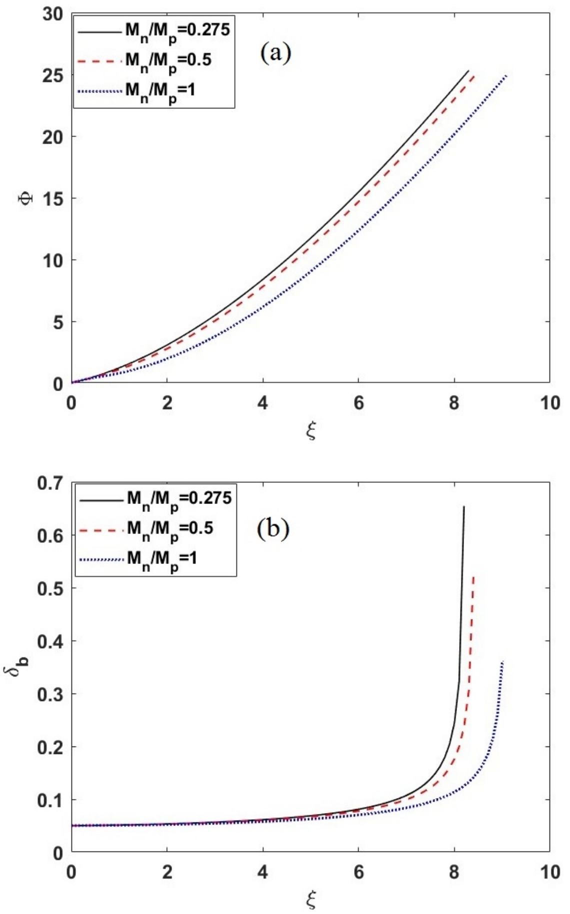

Figure 4. (a) Normalised electric potential (b) normalised electron beam density as a function of normalized distance for different ratio (mass of negative ion to positive ion M_n/M_p) when γ_p=10, γ_n=10, A=0.0005, D=0.0015, r=0.05, Φ_c=25, J_b=0.001, δ_{n0}=1, m=0 and q=0.5.

as the value of extensivity changes from q=0.5 to q=0.99 from non -extensive distribution of electrons to Boltzmann distribution there is lesser number of electrons inside the sheath and the net space charge density is more inside the sheath as shown in figure 3(b) and hence the electrostatic potential gradient gets increased. This also depicts that the sheath thickness gets reduced. This result matches with the observation of [48] Also, with the increase in the ionization rate there is more production of positive ions and electrons. The positive ions get attracted towards the wall (since applied potential to the wall is negative) and hence the sheath thickness gets reduced which is observed in the figure 3(a) and the electrostatic potential gradient gets increased. Due to increase of this potential gradient the force on the emitted beam electrons increases and the density gets increase inside the sheath and hence more emitted beam electrons are observed in the sheath (in figure 3 (c)) for the case of Boltzmann distributed electrons (dotted line) and high ionisation (solid line) as compared to the non-extensive distributed electrons (dashed line).

The three types of electronegative plasma taken are CF_4, O_2 and C_60 so that the effect of mass ratio of negative ion to positive ion on the electrostatic potential and the density of emitted beam electrons can be understood. As it is shown in the figure 4. The gradient of electrostatic potential decreases with the increase in the negative ion to positive ion (mass ratio) as shown in figure 4 (a). And hence there is increase in the thickness of the sheath. This result is consistent with the result of [52]. The density of emitted beam electrons decreases inside the sheath as shown in figure 4 (b) as the negative ion to positive ion (mass ratio) is increased this is because the electric field is lesser for the higher mass ratio so lesser force is experience by the emitted beam electrons hence lesser density is found.

4. Conclusion

In the presence of electron beam current density, the net negative charge density increases while the net space charge density and the slope of electrostatic potential reduce. There is an increase in the sheath thickness for the larger electron beam current density. For increasing collisions between the ions and neutrals, there is an increase in the positive charge density and the net space charge density. These result in larger slope of the electrostatic potential. The sheath thickness gets decreased for the higher collisions. For non-extensive case the gradient in the electrostatic potential, net space charge density and the emitted electron beam density is less while these values get increased with the consideration of Boltzmann distributed electrons and higher ionization rate. The sheath thickness is greater for the non-extensive case while it is lesser for Boltzmann distribution and high ionization. For higher mass ratio (negative to positive) the gradient in the electrostatic potential and the emitted electron beam density is smaller while the thickness in the sheath is larger. Our model is very much useful in the field of plasma processing (etching) where there is presence of negative ions which has a considerable effect. Also, the negative ion's mass plays a crucial role on the thickness of the sheath and other's sheath parameters. Also during the plasma processing the effect of collision, ionization and the non-extensivity in the plasma can be explained by using our model. Our model is also useful to control the electrode potential, where the emission of secondary electrons or thermionic electrons takes place from the electrode and the electrostatic potential and the thickness of sheath gets affected. The results may find other interesting applications in negative ion sources and film depositions.

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Conflict of interest statement:
The authors declare that they have no conflict of interest.

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