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EFFECT OF NEGATIVE ION CONCENTRATION AND MAGNETIC FIELD ON ELECTRONEGATIVE PLASMA SHEATH

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ABSTRACT

Plasma is the ionized state of matter and is of interest as it has found applications in diverse fields. In all practical applications of plasma, it interacts with the material surface via non-neutral region that is formed between bulk plasma and surface known as the sheath, which plays a vital role in overall plasma properties. In this work, the characteristics of electronegative magnetized plasma sheath have been presented employing the kinetic trajectory simulation method based on kinetic theory. It is found that magnetic field and volumetric composition of negatively charged particles have significantly affected the characteristics of electronegative plasma sheath. Although the particle densities deplete towards the wall, the decreasing rate of negative charged particles is steeper than that of positive ions. The magnitude of electric field slowly increases close to the sheath entrance, whereas it sharply increases close to the wall. The positive ion density decreases in both cases when the concentration of negative ion is increased or when the magnetic field is increased. On increasing the magnetic field from 0 to 250 mT, the ion density reaching the wall decreases from 0.331 to 0.305 n_{ps}. The results are similar and agree with similar works following different models and our model provides a satisfactory basis for the study of electronegative plasma sheath.

Keywords: collisionless - cut-off distribution - kinetic theory - magnetized plasma

INTRODUCTION

Plasma is the ionized state of matter also known as the fourth state of matter that can exist over wide ranges of temperatures and densities, and has found applications in diverse fields, such as agriculture, materials processing, semiconductor devices, controlled thermonuclear fusion, electric propulsion and many more (Kouznetsov, Lichtenberg & Lieberman 1999, Aanesland, Meige & Chabert 2009, Boeuf, Hagelaar, Sarrailh, Fubiani & Kohen 2011). The plasma region near the wall has crucial role in determining the overall plasma characteristics. As the electrons are lighter and hence faster compared to the positive ions, the surface is negatively charged with respect to the surrounding plasma. Generally, a positive barrier is formed at the surface; however, it is also possible to produce negative charge barrier near to the positively biased electrode. In recent years, many experimental and theoretical works on electronegative plasma sheath with different models have been reported (Kono 2003, Hatami, Shokri & Niknam 2008, Shaw, Kar, & Goswami 2012, Jing-ju, Ma & Wei 2013, Basnet, Patel & Khanal, 2020, Dhawan & Malik 2020,Malik & Dhawan 2020, Paul, Adhikari, Moulick, Kausik & Saikia2020) but still, it is not fully understood. It has applications in diverse fields such as plasma etching, surface treatment, ion implantation, fabrication of semiconductor devices, etc. Li, Vyvoda, Dew, & Brett (2000) studied the sheath structure of electronegative plasma assuming cold positive ions and planer sheath configuration. Using a one-dimensional collisionless sheath model, it was found that the thickness of sheath region is strongly affected by the temperature ratio of electrons to negative ions. Kono (2003) presented the sheath edge conditions for the instability of plasma sheath in low-pressure electronegative plasma by using fluid model. It was found that the sheath is influenced by the positive and negative ion temperature, direction of positive ion flow, geometries of plasmas in low- pressure condition. Zheng-Xiong, Jin-Yuan, Xiu, Yue and Xiao-Gang (2003) investigated the electronegative plasma sheath structure at steady state assuming that the hot negative ions and cold positive ions, modified the Bohm criterion and ions sound velocity is obtained from the Sagdeev potential. The variation of electrostatic potential, space charge density and particle densities in the sheath are analyzed for different temperature ratio. They found that the real positive ion sound velocity changes drastically, potential fall and a peak distribution of net charge near the sheath edge. Xiu, Jin-Yuan, Zheng-Xiong, Ye and Xiao-Gang (2004) investigated the electronegative magnetized plasma sheath structure assuming hot electrons, negative ions and cold positive ions. Takizawa, Kono and Sasaki (2007) studied the variation of electric field in the plasma sheath in the presence of negative ions. The distribution of electric field in the sheath between electrode and electronegative Ar/SF6 plasma was analyzed based on laser-induced fluorescence-dip spectroscopy technique. Hatami, Shokri and Niknam (2008) numerically investigated a magnetized plasma sheath characteristic in the presence of negative ions. Shaw, Kar and Goswami (2012) studied the effect of positive ions temperature in electronegative magnetized plasma sheath having two species of positive ions. They found that with the increase in temperature of positive ions, the lighter ions density peaks that appear in the sheath region, increases and shifts toward the sheath entrance. In the presence of magnetic field, the particle density fluctuation increases at the sheath entrance. Huiping, Xiu and Minghui (2014) investigated the sheath formation criterion for the electronegative plasma in the presence of an oblique magnetic field consisting of hot electrons, hot ions and cold positive ions. They found that the Mach number, which is influenced by the magnitude and obliqueness of the applied external magnetic field, is relatively due to interaction between positive and negative ions. Dhawan and Malik (2020) presented the behavior of collisional electronegative plasma sheath using fluid model for planar probe geometry. It was found that the thickness of sheath region decreased significantly for the increase in collisional parameter and mass ratio of negative to positive ions. Also, the sheath thickness was significantly affected with the increment of negative ions temperature and concentration.

In this work, we study the influence of magnetic field and volumetric concentration of negative ions on electronegative magnetized plasma sheath via kinetic trajectory simulation (KTS) method. The collisionless electronegative magnetized plasma consists of singly charged positive ions (He+), negative oxygen ions (O-) and electrons in which the distribution of particles at the injection boundary (right-hand boundary) follow the cut-off half Maxwellian distribution. The effect of magnitude of magnetic field and negative ion concentration on plasma sheath properties: particle densities profile, space charge density profile and electric field profile are systematically investigated. In the absence of negative ion concentration, the obtained results are compared with previous work (Chalise & Khanal 2015) and found to be qualitatively similar, although quantitatively different.

KINETIC THEORY AND SHEATH MODEL

The KTS method is based on kinetic theory, which is a statistical approach that can be used to study various bounded plasma problems and yield results that are more accurate compared to the fluid approach (Khanal 2003).In the presence of collision term, the velocity distribution function for the particle species-*s* obeys the Boltzmann equation,

$$\frac{df^s(\boldsymbol{r},\boldsymbol{v},t)}{dt} = \left[\frac{\partial}{\partial t} + \boldsymbol{v}.\nabla + \frac{\boldsymbol{F}^s}{m^s}.\nabla_v\right] f^s(\boldsymbol{r},\boldsymbol{v},t) = \left(\frac{\partial f^s}{\partial t}\right)_{coll} \tag{1}$$

which for collisionless case takes the well-known form of the Vlasov equation

$$\left[\frac{\partial}{\partial t} + \boldsymbol{v}.\nabla + \frac{\boldsymbol{F}^s}{m^s}.\nabla_v\right] f^s(\boldsymbol{r},\boldsymbol{v}) = 0 \tag{2}$$

where $s = (e,i,n)$ in which m^s is the mass of the particle species-*s* and the term $F^s = q^s\,[E+v \times B]$ is the macroscopic force acting on the particle species-*s*. The densities of positive ions, negative ions and electron at sheath entrance are obtained as (Chalise & Khanal 2012 & 2015).

$$n^s = \int\int\int d^3\boldsymbol{v} f^s(x = L, \boldsymbol{v}) \tag{3}$$

The space charge density is given by,

$$\rho(x) = \sum_s q^s n^s(x) \tag{4}$$

Solution of the Poisson's equation yields the electrostatic potential:

$$\nabla^2\phi = \frac{-\rho}{\epsilon_0} \tag{5}$$

where ϵ_0 is the electric permittivity for the free space.

A geometrical model of magnetized plasma sheath for collisionless plasmas that interacts with the wall is shown in Figure 1, where $x = L$ is the plasma side (designed as a sheath entrance) and $x = 0$ represents the material surface. The plasma consists of singly charged positive helium ions (He^+), negative oxygen ions (O^-) and electrons. These two positive and negative ions are in thermal equilibrium such that $T^i_{ps} = T^n_{ps}$. The uniform external magnetic field ***B*** acts in the *xy*-plane, which makes an angle θ with direction normal to the injection plane. The simulation region of interest is taken as 10 λ_{De} ; where $\lambda_{De} = \sqrt{\frac{\epsilon_0 k_B T_{ps}^e}{n_{ps} e^2}}$ is the electron Debye length with n_{ps} is the plasma density.

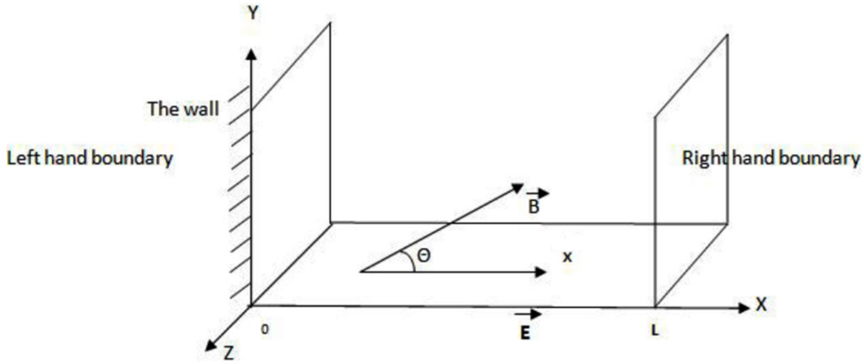

Figure 1: Magnetized plasma sheath model.

Due to negative wall potential, the electrons is considered to be cut-off half Maxwellian as

$$f^e(x,\boldsymbol{v}) = A^e exp\left[\frac{-\left(v_x^{e2}+v_y^{e2}+v_z^{e2}\right)}{v_t^{e2}} + \frac{e\phi(x)}{T^e}\right]\Theta\left(v_{cL}^e(x)-v_x^e\right) \tag{6}$$

where A^e is the amplitude of distribution function, $v_t^e = \sqrt{\frac{2K_B T^s}{m^s}}$ is the thermal velocity of a particle species-*s*, Θ is the Heaviside step function and $v_c^e = \sqrt{\frac{2e(\phi(x)-\phi)}{m^e}}$ is the cut-off velocity of electrons at *x*. The ion velocity distribution functions for the ion species are (Chalise & Khanal 2012 & 2015).

$$f^i(x=L,\boldsymbol{v}) = A^i exp\left[\frac{-\left(v_x^{i\,2}+v_y^{i\,2}+v_z^{i\,2}\right)}{v_t^{i2}}\right]\Theta\left(v_{cL}^i(x)-v_x^i\right) \tag{7}$$

and

$$f^n(x=L,\boldsymbol{v}) = A^n exp\left[\frac{-\left(v_x^{n2}+v_y^{n2}+v_z^{n2}\right)}{v_t^{n2}}\right]\Theta\left(v_{cL}^n(x)-v_x^n\right) \tag{8}$$

where A^i, and $A^n$are the amplitudes of the positive and negative ion distribution functions, v_{cL}^i and v_{cL}^n are the cut-off and the Maxwellian maximum velocities of the positive and negative ions at $x = L$.

RESULTS AND DISCUSSION

The compiled kinetic equations have been solved for the given boundary conditions and the details of simulation method were presented in the previous work (Chalise & Khanal 2012, 2015, Basnet, Deuja & Khanal 2021). The physical input parameters considered in the present work are: magnetic field B (0, 100 mT and 250 mT), obliqueness of magnetic field $\theta = 45^0$, $T^e_{ps} = 5.0$ eV, $T^i_{ps} = T^{\mathrm{n}}_{\mathrm{ps}} = 0.02\ T^e_{ps}$ and plasma density $n_{\mathrm{ps}} = 10^{18}$ m^{-3}.

Effect of magnetic field on plasma sheath

The variation of positive ion density in the electronegative plasma sheath region at constant obliqueness of magnetic field (450) for three different magnitudes of magnetic field (0 mT, 100 mT and 250 mT) and 10 % concentration of negative ions is shown in Figure 2. From the figure, it is found that the density of positive ions decreases continuously from the sheath entrance towards the wall for all the cases. With the increase in magnitudes of magnetic field, the decreasing rate of positive ions is faster and hence the density of positive ions reaching at the wall decreases. The effect of magnetic field is prominent in the magnetic presheath region and its effect fade away towards the wall due to strong gradient in electric potential. This causes to accelerate the positive ions and hence its density decreases towards the wall. When the magnetic field gets increased from 0 to 250 mT, the density of positive ions at the wall reduced from about 0.331 to 0.305 nps.

The variation of negatively charged particles density in the sheath region at constant obliqueness of magnetic field (450) of the three different magnitude of magnetic fields (0 mT, 100 mT and 250 mT) and 10% concentration of negative ions is shown in Figure 3. From the figure, it is observed that the negatively charged particles density decreases gradually from the sheath entrance to acquire its minimum at the wall. The sharp gradient of electric potential decelerates the negatively charged particles and comparing with positive charged particles, the density of negatively charged particles is much less at the wall. Also, it is found that the effect of magnetic field on density of negatively charged particles is not significant due to having sharp gradient of electrostatic potential close to the wall (i.e., about 2 electron Debye lengths from the wall).

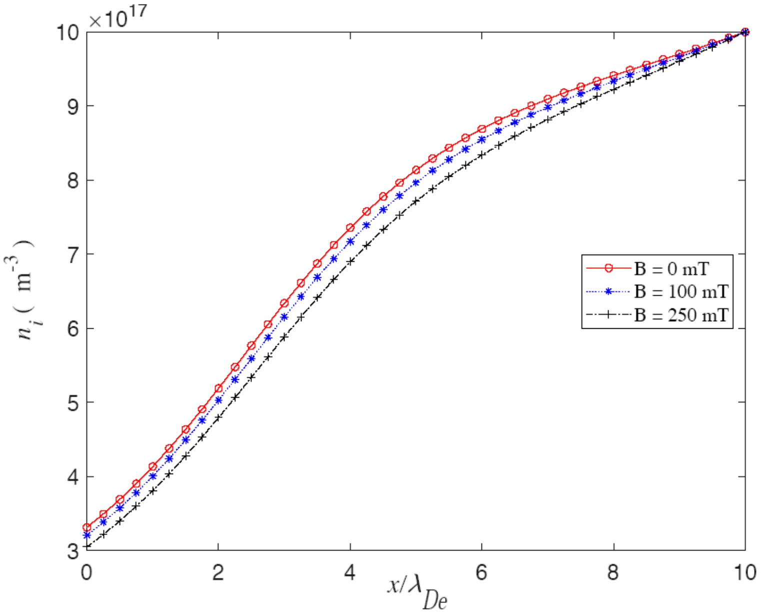

Figure 2: Positive ion density versus normalized distance for three different magnitudes of magnetic field.

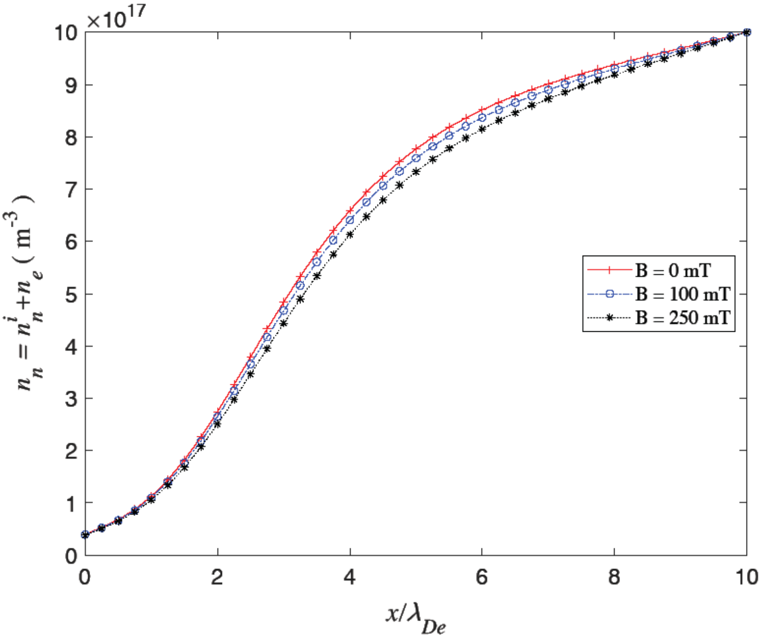

Figure 3: Negative charged particle density versus normalized distance for three different magnitudes of magnetic field.

The effect of magnetic fields (0 mT, 100 mT and 250 mT) on space charge density profile for constant obliqueness of magnetic field (450) and 10% concentration of negative ions is depicted in Figure 4. From the figure, it is clearly observed that the space charge density is zero at the sheath entrance being plasma quasineutral and then it gradually increases towards the wall for all cases. The space charge density attains its maximum value close to the wall about 1 electron Debye length from the wall and then after it decreases towards the wall. This is because the charge separation occurs beyond the sheath entrance i.e., $n_i > n_e$, which results in increment of space charge density towards the wall. As the magnetic field increases, space charge density decreases due to its gyrating effect on the particles that leads to decrease in both positive and negative charges as shown in Figures 2 and 3 respectively. The bump nature that appears near the wall gets decreased for the increase in magnitude of magnetic field.

Figure 5 shows the variation of electric field as the function of normalized distance at constant obliqueness of magnetic field (45^0) for three different magnetic fields (0 mT, 100 mT and 250 mT) and 10% concentration of negative ions. The negative sign in the electric field represents its direction towards the wall. From the figure, it is found that the magnitude of electric field increases towards the wall and acquiring its maximum value at the wall. The increasing rate is slow in the sheath entrance up to four electron Debye lengths from the right-hand boundary ($x = L$), and after that it sharply increases towards the wall. In the magnetic field dominant region, the magnitude of electric field increases with the increase in magnetic field, although its magnitude decreases after eight electron Debye lengths from the right-hand boundary ($x = L$). Therefore, we can say that the motion of charged particles close to the wall is governed by the electric field rather than magnetic field.

Effect of concentration of negative ions on plasma sheath

The effect of negative ion concentration on particle densities as the function of normalized distance at constant magnetic field (100 mT) and its obliqueness (45^0) is shown in Figure 6. From the figure, it is seen that the density of positive ions decreases continuously from the sheath entrance towards the wall for all cases; however, the decreasing rate of positive ions density is faster with the increase in concentration of negative ions. When the volumetric concentration of negative ions increase, the positive ion density decreases up to about one electron Debye length from the wall and then it has no effect on positive ion density profile. On the other hand, the negative charged particles decrease continuously towards the wall from the sheath entrance for all cases. For $n_n^i = 0$, i.e., it is similar to ordinary electron-ion plasma sheath, the result is qualitatively similar with earlier work (Chalise & Khanal 2012). For the increase in volumetric concentration of negative ions, the negative charged particle density profile decreases up to 7.5 electron Debye length from the right-hand boundary and after that its rate of decrement and nature changes.

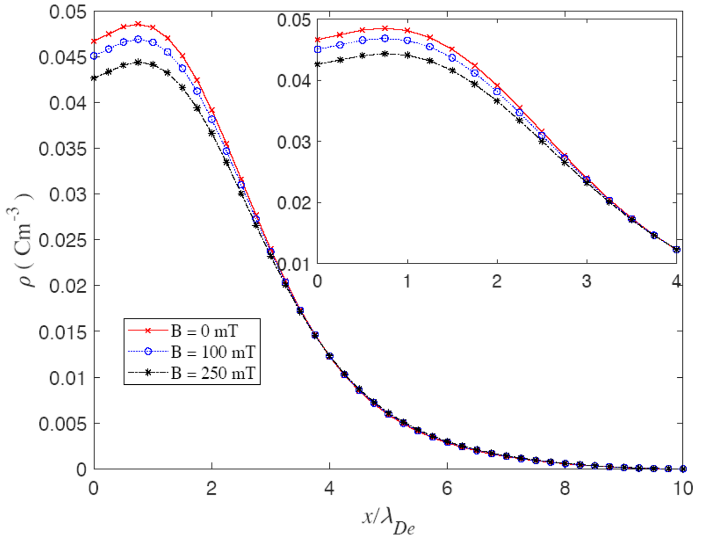

Figure 4: Space charge density versus normalized distance for three different magnitudes of magnetic field.

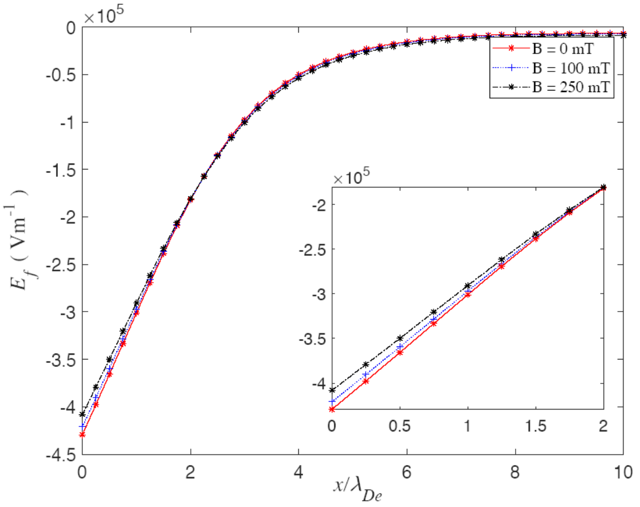

Figure 5: Electric field versus normalized distance for three different magnitudes of magnetic field.

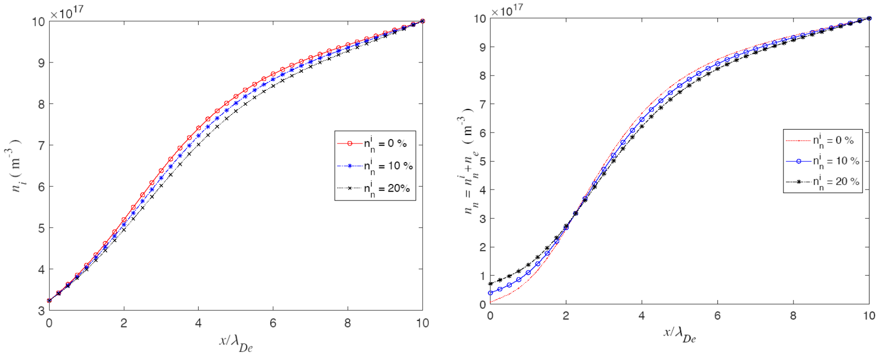

Figure 6: Particle density versus normalized distance for three different concentrations of negative ions.

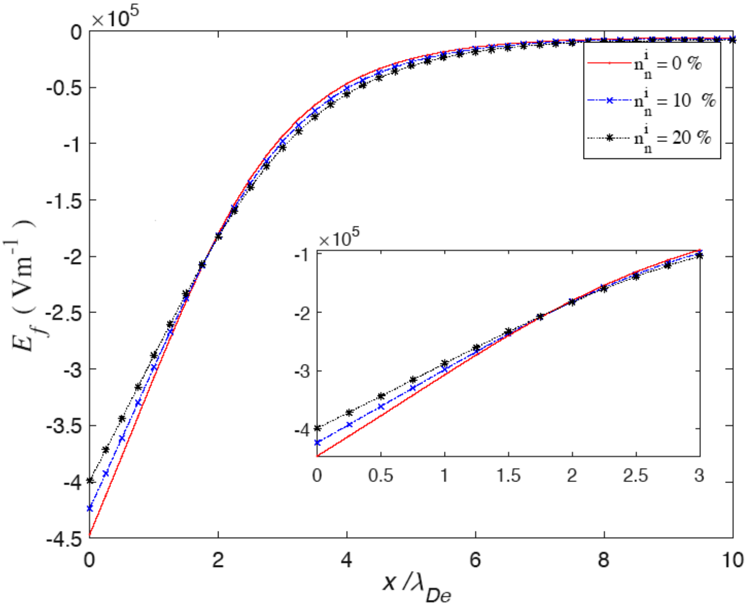

Figure 7: Electric field versus normalized distance for three different concentrations of negative ions.

Figure 7 shows the self-consistent electric field profile at constant magnetic field (100 mT) and its obliqueness (450) for three different volumetric concentrations of negative ions. It is found that the magnitude of electric field continuously increases from the sheath entrance towards the wall. The increasing rate is slow up to six electron Debye lengths from the right-hand boundary and after that its magnitude sharply increases towards the wall. As the concentration of negative ion increases, the magnitude of electric field decreases from about 2.5 electron Debye lengths from the wall. In the present work, we have considered the positive and negative ions can reach sheath boundary with individual sound speed, which may lead to the obtained results is qualitatively different from the previous work (Basnet, Deuja & Khanal 2021).

CONCLUSION

Using kinetic trajectory simulation method, the characteristics of electronegative magnetized plasma sheath has been investigated. It is assumed that the plasma sheath is collisionless as the ion-neutral collision mean free path is larger than that of dimension of plasma sheath and also, the distribution of particles is best represented by cut-off half Maxwellian distributions at the injection plane. It is found that the magnetic field and volumetric composition negatively charged particles affect the electronegative plasma sheath properties: particle densities profile, space charge density profile and electric field profile are systematically presented. The particle densities deplete towards the wall; however, the depletion rate of negatively charged particles is much steeper than that of positive ions for the increase in magnetic field. The peak appears on the space charge density profile and magnitude of electric field close to the wall gets decreased for higher magnitude of magnetic field. Two distinct regions; magnetic field dominant region lying near to the sheath entrance and electric field dominant region near to the wall are prominently observed in all cases. Similarly, concentration of negative ion also plays vital role in the sheath region. The concentration of negative ion affects the magnetic presheath region in all cases.

REFERENCES

Aanesland, A., Meige, A. & Chabert, P. (2009). Electric propulsion using ion-ion plasmas. *Journal of Physics: Conference Series*, **162**(1): 2009-2013. https://doi.org/10.1088/1742-6596/162/1/012009

Basnet, S., Patel, A. & Khanal, R. (2020). Electronegative magnetized plasma sheath properties in the presence of non-Maxwellian electrons with a homogeneous ion source. *Plasma Physics and Controlled Fusion,* **62**(11): 5011-5012. https://doi.org/10.1088/1361-6587/abb0f7

Basnet, S., Deuja, A. & Khanal, R. (2021). Kinetic-theory-based investigation of electronegative plasma–wall transition with two populations of electrons. *Plasma Science and Technology*, **23**(3): 5002-5011. https://doi.org/10.1088/2058-6272/abde1d

Boeuf, J. P., Hagelaar, G. J. M., Sarrailh, P., Fubiani, G. & Kohen, N. (2011). Model of an inductively coupled negative ion source: II. Application to an ITER type source. *Plasma Sources Science and Technology*, **20**(1): 5002-5015. https://doi.org/10.1088/0963-0252/20/1/015002

Chalise, R. & Khanal, R. (2012). A kinetic trajectory simulation model for magnetized plasma sheath. *Plasma Physics and Controlled Fusion*, **54**(9): 5006-5012. http://stacks.iop.org/PPCF/54/095006

Chalise, R. & Khanal, R. (2015). Self-consistent one dimension in space and three dimension in velocity kinetic trajectory simulation model of magnetized plasma wall transition. *Physics of Plasmas*, **22**(11): 3505-3510. http://dx.doi.org/10.1063/1.4934601

Dhawan, R. & Malik, H. K. (2020). Sheath formation criterion in collisional electronegative warm plasma. *Vacuum*, **177**(10): 9354-9364. doi.org/10.1016/j.vacuum.2020.109354

Dhawan, R. & Malik, H. K. (2020). Behaviour of sheath in electronegative warm plasma. *Journal of Theoretical and Applied Physics*, **14**: 121-128. https://doi.org/10.1007/s40094-020-00369-2

Hatami, M. M., Shokri, B.,& Niknam, A. R. (2008). Numerical investigation of the magnetized plasma sheath characteristics in the presence of negative ions. *Physics of Plasmas*, **15**(12): 3501-3507. http://dx.doi.org/10.1063/1.3028306

Huiping, L., Xiu, Z. & Minghui, Q. (2014). Sheath criterion for an electronegative plasma sheath in an oblique magnetic field. *Plasma Science and Technology*, **16** (7): 633-636. https://iopscience.iop.org/article/10.1088/1009-0630/16/7/01

Jing-ju, L., Ma, J. X. & Wei, Z. (2013). Sheath and boundary conditions in a collisional magnetized warm electronegative plasma. *Physics of Plasmas*, **20** (6): 3503. http://dx.doi.org/10.1063/1.4811479

Khanal, R. (2003). *A kinetic trajectory simulation (KTS) model for bounded plasmas.* (PhD dissertation). Austria: Innsbruck University, Innsbruck.

Kono, A. (2003). Intrinsic sheath edge conditions for sheath instability in low-pressure electronegative plasmas. *Journal of Physics D: Applied Physics,* **36** (5): 465-472. http://stacks.iop.org/jd/36/465

Kouznetsov, I. G., Lichtenberg, A. J. & Lieberman, M. A. (1999). Internal sheaths in electronegative discharges. *Journal of Applied Physics*, **86**(8): 4142-4153. https://doi.org/10.1063/1.371339

Li, M., Vyvoda, M. A., Dew, S. K. & Brett, M. J. (2000). Sheath structure of an electronegative plasma with cold positive ions. *IEEE Transaction on Plasma Sci*ence **28**(1): 248-252. https://doi.org/10.1109/27.842914

Malik, H. K. & Dhawan, R. (2020). Sheath Structure in Electronegative Plasma Having Cold Ions: An Impact of Negative Ions' Mass. *IEEE Transactions on Plasma Science*, **48**(7): 2408-2417. https://doi.org/10.1109/TPS.2020.2998717

Paul, R., Adhikari, S., Moulick, R., Kausik, S. S. & Saikia, B. K. (2020). Magnetized plasma sheath in the presence of negative ions. *Physics of Plasmas*, **27**(6): 063520. https://doi.org/10.1063/5.0004796.

Shaw, A. K., Kar, S. & Goswami, K. S. (2012). The positive ion temperature effect in magnetized electronegative plasma sheath with two species of positive ions. *Physics of Plasmas*, **19**(10): 2108-2116. http://dx.doi.org/10.1063/1.4759460

Takizawa, K., Kono, A. & Sasaki, K. (2007). Distribution of electric field in the sheath of an electronegative plasma. *Applied Physics Letters*, **90**(): 1503-1506. https://doi.org/10.1063/1.2429026

Xiu, Z., Jin-Yuan, L., Zheng-Xiong, W., Ye, G. & Xiao-Gang, W. (2004). Electronegative plasma sheath structure in a magnetic field. *Chin Physics Letters*, **21**(8): 1572-1574. http://cpl.iphy.ac.cn/Y2004/V21/I8/1572

Zheng-Xiong, W., Jin-Yuan, L., Xiu, Z., Yue, L. & Xiao-Gang, W. (2003). Sheath structure of an electronegative plasma. *Chin Physics Letters*, **20**(9): 1537-1539. http://cpl.iphy.ac.cn/Y2003/V20/I9/1537