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Effect of concentration in two ion magnetized plasma sheath

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ABSTRACT

The plasma sheath forms at the material wall surface in all practical plasma applications and plays a crucial role in the plasma-wall transition region. The influence of ion concentration in a magnetized plasma sheath containing two species of positive ions has been investigated using kinetic trajectory simulation. The study reveals that ion density, electron density, potential, and electric field decrease as they approach the wall, while the total charge density increases. An increase in ion concentration leads to a rise in ion density, electron density, total charge density, and potential, whereas the electric field decreases. Additionally, concentration variation in the plasma system affects the parametric values at the wall. Mathematically, ion density and total charge density exhibit exponential growth, while the electric field follows a parabolic function.

Keywords: Plasma Sheath, ion density, electron density, charge density, potential profile

Introduction

Plasma appears in nature in various forms and is widely utilized in science and technology. It is a distinct state of ionized gas consisting of neutrals, electrons, and positive ions. Matter transitions through different states when subjected to heat, changing from solid to liquid and then from liquid to gas. If the gas is heated beyond a certain threshold, the thermal energy causes it to enter the plasma state. Irving Langmuir was the first to use the term plasma to describe the ionized state of matter observed in a positive column glow discharge tube. The word "plasma" (Langmuir 1928), derived from Greek, means fabricated or molten, reflecting the nature of plasma. However, Sir William Crookes initially introduced the concept in 1879.

The universe is primarily composed of dark energy, followed by dark matter and normal matter. All visible celestial bodies and radiation originate from normal matter, which predominantly exists in the plasma state. When a gaseous substance is heated to sufficiently high temperatures, it becomes ionized and transitions into plasma. A substance can be transformed into plasma by increasing its temperature until a significant fraction of its particles become ionized. The degree of ionization in plasma is closely related to electron temperature under thermodynamic equilibrium. This relationship is mathematically defined by the Saha equation (Chin, 1984).

$$\frac{n_i}{n_n} \approx 2.4\text{x}10^{21} \frac{T^{3/2}}{n_i} e^{\frac{-U}{KT}}$$

Criteria of Plasma

- Debye length is too short compared to the dimension of the plasma system i.e. $\lambda_D << L$
- Debye shielding is valid only if there are many particles in the Debye sphere (charge cloud) i.e. $N_D >>> 1$
- The mean time between collisions of ions is usually long in comparison with the period of plasma oscillation (Chin, 2016) i.e. $\omega\tau > 1$

Debye Shielding

When an external test charge is introduced into an unperturbed plasma the outside charge causes the plasma to become disturbed. Here, opposite polarity charges are drawn to one another, same polarity charges are swapped out and a cloud of spheres forms. There is a potential created by this charge particle. The potential in plasma is protected within a very tiny area known as the Debye Length. The electron Debye Length has the following relation.

$$\lambda_D = \sqrt{\frac{\varepsilon_0 K_B T}{ne^2}}$$

Sheath

Materials in contact with plasma will be negatively charged about the plasma potential because electrons in the plasma are far more movable than ions and as a result, have much higher fluxes. Electrons are repelled from the negatively charged surface while ions are drawn to it. Only in the sheath region will the negative potential of a solid surface have the strongest effect due to the shielding effect of the plasma. The plasma is essentially non-neutral but as we approach the wall, the potential rapidly decreases and becomes nearly quasi-neutral. The behavior of bulk plasma is influenced by the flow of particles and energy towards the wall which is caused by the sheath structure (Kuhn et al., 2006).

Presheath

When there is a magnetic field present in the plasma, the potential profile near the wall changes. There will be different regions created from the potential region. For a quasi-neutral plasma, the presheath region is the area of the bulk plasma where the potential tends to zero. Additionally, there are two regions within the sheath: the collisional presheath, also known as the collision-dominant region. The Debye sheath, which has the potential to be dominant, is the other section. Figure (1-3) shows the various divisions of the plasma sheath region. When an oblique magnetic field is present the area following the collisional sheath is further separated into the Debye sheath and the magnetized sheath within the Debye length order. To stream the ions in the sheath region from the bulk plasma for ion acoustic velocity Cs will

$$\langle \frac{1}{v^2} \rangle \leq \langle \frac{1}{c_s^2} \rangle, \text{ where } Cs = \sqrt{\frac{K_B\left(\gamma^i T_{ps}^i + \gamma^e T_{ps}^e\right)}{m^i}} \text{ ,}$$

where $\gamma^i$and γ^e are polytropic constants and T_{ps}^e are the ion and electron temperature in the presheath side be the Bohm sheath criteria are used. The polytropic constants are the presheath side ion and electron temperatures. The angle formed by the oblique magnetic field along the electric field is $v_s \geq c_s\cos\beta$ and the modified Bohm sheath relations for magnetized sheath plasma are as follows (Riemann, 1997). Chodura (1982) studied the effect of a magnetic field on the transition layer between plasma and an absorbing wall. The transition layer proves to have a double structure comprising a quasi-neutral magnetic presheath preceding the electrostatic Debye sheath. The magnetic presheath scales with the ion gyro radius at the sound speed and with the angle of the magnetic field. The overall electric potential drop between the wall and plasma turns out to be relatively insensitive to the magnetic fields angle and strength. Khanal (2003) developed and presented in detail a kinetic model for accurate studies of bounded plasmas. Chalise and Khanal (2015) developed and studied in detail a kinetic trajectory simulation model for magnetized plasma sheath. They observed that the magnetic effect is prominent near the sheath entrance and has almost no effect at the wall. Hatami et al. (2009) have studied the collisional effect in the magnetized plasma with two species of positive ions. They have demonstrated that there is a substantial impact of ions on the density distribution velocity and kinetic energy of the lighter ions and that the amplitude of ion density fluctuations and velocity increases with an increase in the ion-neutral collisional frequency. Mishra (2007) had studied a space charge sheath adjacent to an absorbing wall with sheath plasma on the other side, which she assumed to be described by a two-fluid solution.

Materials and Methods:

Principle of Kinetic Trajectory Simulation

Through the solution of the associated kinetic equations along the corresponding collisionless particle trajectories, the velocity distribution function of the particle species involved is directly computed in the Kinetic Trajectory Simulation (KTS) (Khanal, 2003). To find the distribution function at any point in the phase space, we trace the corresponding phase space trajectories where the distribution function is provided. Here, we assume cut-off Maxwellian distribution functions for the electron and ion velocities at the sheath edge. In a given bounded spatial region, time-independent self-consistent kinetic plasma states can be numerically determined using the iterative KTS technique. The plasma states are generally characterized by:

- The velocity distribution function $f((\vec{x}, \vec{v}, t)$
- The electric field $\vec{E}(\vec{x})$
- The magnetic field $\vec{B}(\vec{x})$

- The given boundary conditions

Results and discussion

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The subsequent section will showcase the various plasma parameter profiles for varying ion plasma concentrations, including 1×10^{17} m^{-3}, 2×10^{17} m^{-3} and 3×10^{17} m^{-3} for fixed magnitude (13 mT) and obliqueness (θ=45°) of the magnetic field as well as the best fit of those parameters at the wall.

Ion density profile

Figure 1 shows how the ion density changes with the normalized sheath distance from the wall for varying ion plasma concentrations. We observe that the decrease in ion density when normalized sheath distance increases. Ion density is observed to decrease sharply up to 12 Debye length when moving away from the wall then steadily up to 4 Debye length before flattening out as we get closer to the wall. We know that as ion concentration rises so does ion density. In contrast to low concentration, it is discovered that the ion density reaching the wall increases with concentration. This occurs because of an increase in ion concentration which causes an increase in ion velocity and a subsequent decrease in ion density.

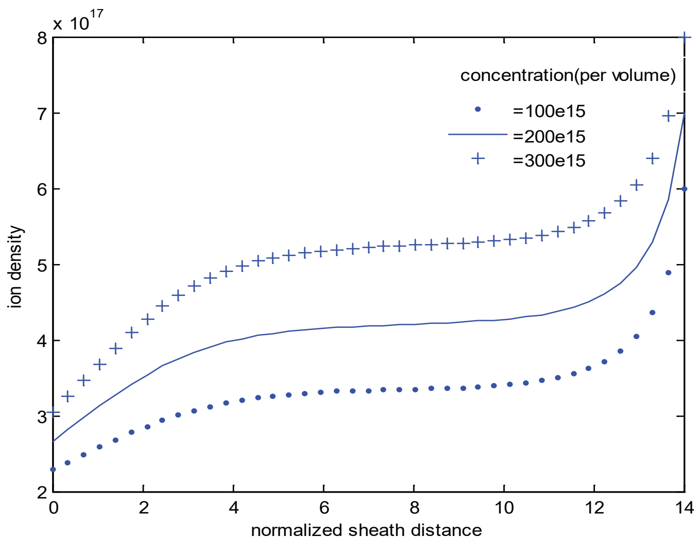

Figure 1: Variation of ion density versus normalized sheath distance for different concentrations

Figure 2 shows the clear change in ion density at the wall as the plasma concentration changes. In the specified concentration range the ion density at the wall is steadily rising and is best fitted as an exponential function. Ion density and concentration are directly correlated, which explains this.

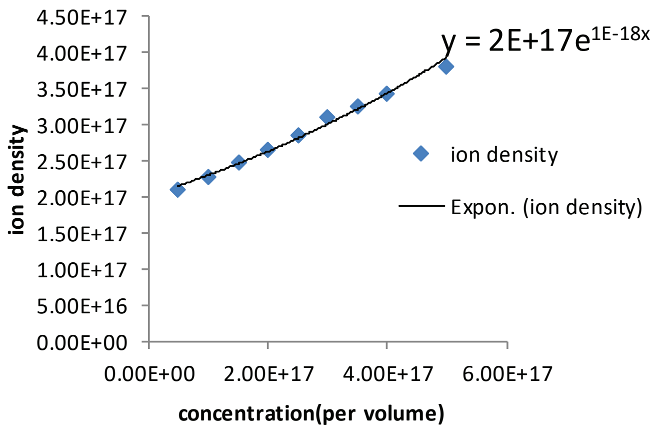

Figure 2: Variation of ion density at the wall in different concentrations

Electron Density Profile

Figure 3 illustrates how the normalized sheath distance and electron density change at varying plasma concentrations. Although the profile's nature is nearly identical to that of ion, a more abrupt decline is seen toward the wall. As the concentration rises, the number of electrons close to the wall and boundary is significantly less impacted. As the normalized sheath distance from the wall increases, the electron number density falls. The electron density increases as the concentration rises but the wall and boundary do not noticeably change. The coulomb repulsion of electrons with the negative wall potential causes the electron density to decrease towards the wall, allowing for high-velocity electrons.

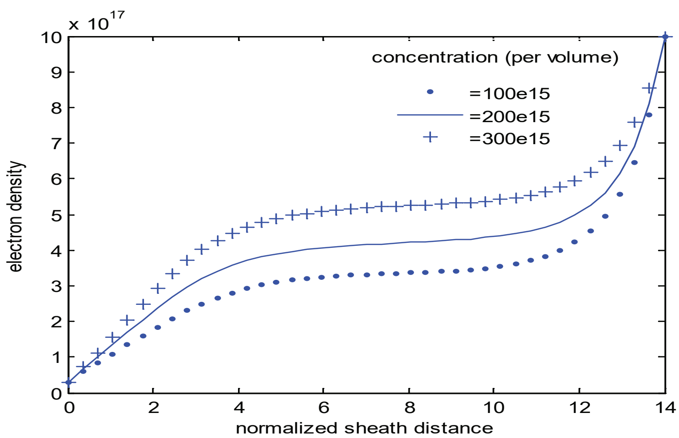

Figure 3: Variation of electron density versus normalized distance for different concentrations

Total charge density

Figure 4 shows the variation of total charge density versus normalized sheath distance at different sheath plasma. The total charge density increases as it moves towards the wall but the slope of the increment near the wall and sheath boundary is sharper which becomes flat in the midway. For an increase in concentration of plasma, there is a decrease in the total charge density profile which is dominant in the sheath entrance sides. On moving towards the wall, ion acceleration increases, and electron acceleration decreases as the wall has a negative potential, resulting in a different rate while receiving.

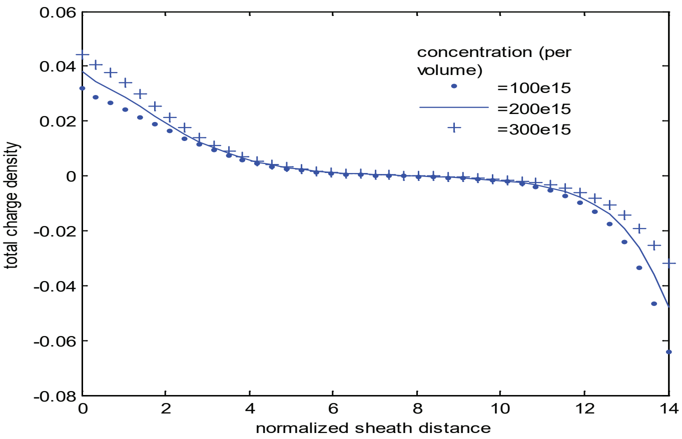

Figure 4: Variation of total charge density (C/m^3) versus normalized distance for different concentrations

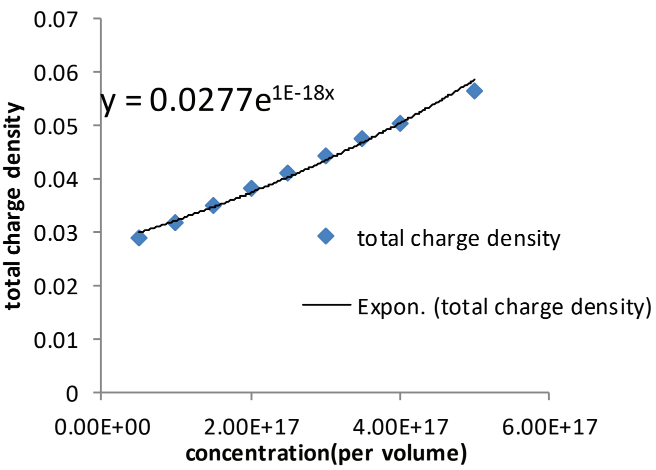

Figure 5: Variation of total charge density at wall in different concentration

Potential profile

Figure 6 shows the potential versus normalized sheath distance variation. It is not dispersed equally throughout the area, even though the concentration increase lowers the potential. The coulomb nature profile of the plasma negative potential wall is what causes this growing variation as we get closer to the wall. Additionally, different media have uniform variations in the potential at the wall.

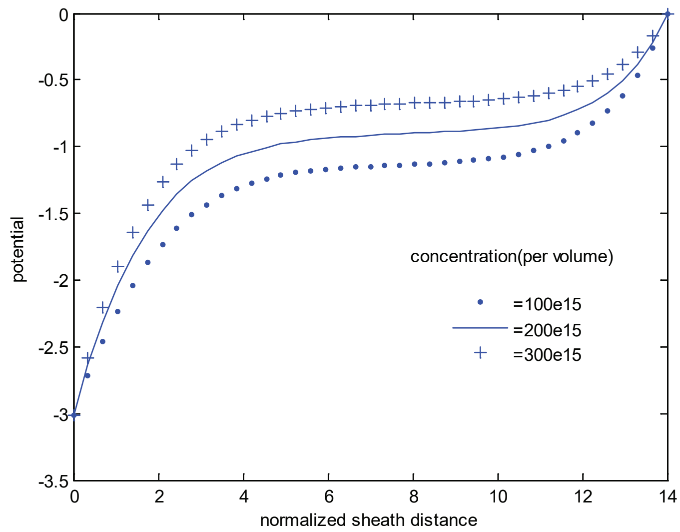

Figure 6: Variation of potential (in volts) versus normalized sheath distance for different concentrations

Electric field profile

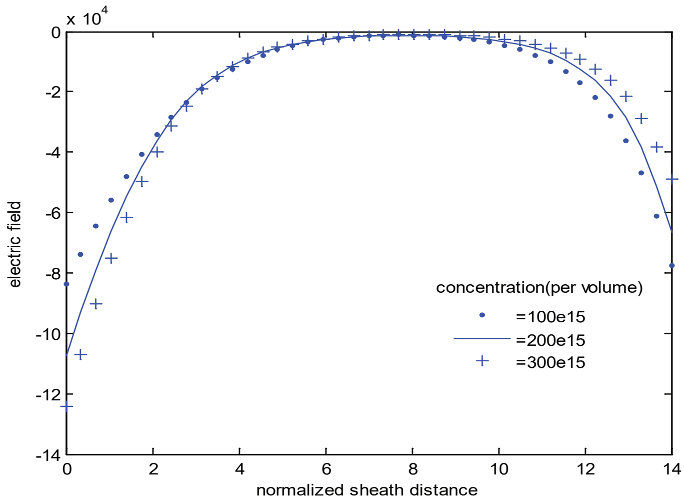

Figure 7: Variation of electric field versus normalized distance for different concentrations

Figure 7 shows the effect of plasma becoming most prominent near the wall which is also the dominant region of an electric field as compared to others. The increment of concentration of plasma increases the electric field but is also not uniform throughout the region. Since the electric field is defined as the negative space rate of change of potential. As we know the space variation of potential and effects of plasma in the screening process of ions in the negative wall potential are sharper nearer than other regions, so such type of electric field profile is reasonable with the previously estimated one. The distinct variation of the total charge density at a wall with the variation of concentration of plasma is shown in Figure 5. The functional profile of the total charge density at the wall is well estimated by best fitting a linear curve which is continuously decreasing in the given range of concentrations as shown in figure 8.

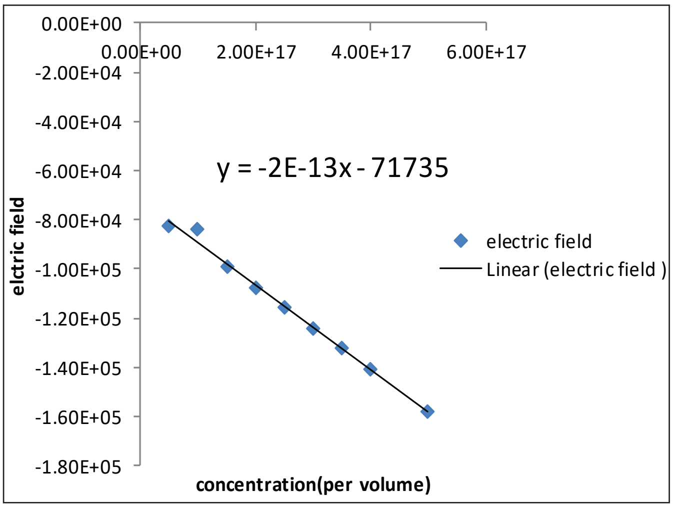

Fig. 8: Electric field variation at wall in varying concentration

Conclusion

This study aims to understand the impact of concentration variations on the characteristics of a magnetized plasma sheath consisting of two species of positive ions. Using the kinetic trajectory simulation method, a self-consistent solution to a non-neutral, collision less, and time-independent plasma sheath is obtained, providing profiles of ion densities, electron densities, potential, charge densities, and electric fields. It is well known that as ion concentration increases, the flux number rises, while the potential and field strength remain unchanged. The ion profile, electron profile, potential profile, and electric field decrease as they approach the wall. In contrast, the total charge density profile continues to increase in proximity to the wall. Additionally, as ion concentration increases, the electric field decreases, whereas ion density, electron density, total charge density, and potential all increase.

Variations in plasma system concentration also influence the mathematical behavior of these parameters. Ion density and total charge density follow exponentially increasing functions, while the electric field exhibits a linearly decreasing trend. The findings of this study align with previous research, demonstrating consistency in plasma sheath behaviour. The simulation of different plasma parameters using the kinetic trajectory simulation method in the plasma-wall transition region provides accurate and comparable density profiles of ions and electrons. This advanced and innovative approach enhances the understanding of plasma-wall transition phenomena.

Conflict of Interest

There is no conflict of interest in publishing this article.

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