EFFECTS OF COLLISION FREQUENCY AND ION MACH NUMBER ON ELECTRO-NEGATIVE MAGNETIZED PLASMA SHEATH

A Dissertation

Submitted to the Dean Office, Institute of Science Technology Tribhuvan University, Kirtipur in the Partial Fulfillment for the Requirement of Master's Degree of Science in Physics

By

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RECOMMENDATION

It is certified that **Mr. Ishwor Datt Bhatt** has carried out the dissertation work entitled **"EFFECTS OF COLLISION FREQUENCY AND ION MACH NUMBER ON ELECTRO-NEGATIVE MAGNETIZED PLASMA SHEATH"** under our supervision and guidance.

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EVALUATION

We certify that we have evaluated this dissertation entitled **"EFFECTS OF COLLISION FREQUENCY AND ION MACH NUMBER ON ELECTRO-NEGATIVE MAGNETIZED PLASMA SHEATH"** submitted by **Mr. Ishwor Datt Bhatt** and in our opinion, it fulfills all the specified criteria, in the scope and quality, as a dissertation for the partial fulfillment of the requirement for the degree of Master of Science in Physics at Tribhuvan University.

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Abstract

We have studied the effects of ion Mach number and collision frequency in electro-negative magnetized plasma sheath having two species of positive (H^+) and negative (Cl^-) using fluid model. It assumed that both ions are singly ionized and thermal equilibrium, and the electrons obey Boltzmann distribution. The compiled set of fluid equations are solved for the given boundary conditions. On increasing the collisional frequency, ions accumulation point and current saturation point shift towards the sheath entrance (away from the wall). Incrementof ion Mach number also affects potential, velocity, space charge density, current density and kinetic energy profile. Our work signifies that the collision frequency and ion Mach number greatly affect the electro-negative magnetized plasma sheath parameters.

List of Figures

Contents

Chapter 1

Introduction

1.1 Motivation and Background

During the last few decades, the generation of magnetic fields has been studied in different areas of physics, such as in cosmic environments (e.g. supernova remnants, gamma-ray bursts), and in laser produced plasmas. Many studies have been conducted on magnetized plasma sheaths, which are important in semiconductor processing, material surface modification, ion acoustic wave excitation, hypersonic flow control, and ion implantation. In this work, we have investigated the effect of collision frequency and ion Mach number on electro-negative magnetized plasma sheath. The obtained results are compared with the previous work for validation and consistency and results are useful in dry, etching and thin-film deposition processing, and in plasma technology.

The atoms decompose into negatively charged electrons and positively charged ions when the temperature of a gaseous object rises to or above the atomic ionization energy. These charged particles are no longer bonded and can now move independently of their individual thermal velocity. However, their motion is strongly affected by each others electromagnetic field. Such a state of matter is called "plasma", and the natural occurrence of plasmas at high temperatures is the reason for the designation, 'the fourth state of matter'. It was Sir William Crookes who first identified the fourth state of matter in 1879. It has often been said that about 99 % of the matter in the Universe is in plasma state. We live in the remaining 1 % of the Universe in which plasmas do not occur naturally. The stellar interiors and atmospheres, gaseous nebula, interstellar hydrogens, solar winds are plasmas [1].

In the early 1920s, while working on the development of vacuum tubes for large currents, Irving Langmuir and collaborators were the first to study plasma phenomena, and Irving Langmuir (1929) was the first to use the term plasma to describe the state of matter in the positive column of a glow discharge tube [2] . There does not appear any definite reason for the use of the term 'plasma'. However, his colleagues who worked with him at the general electric research laboratory has acknowledged his relating the term to blood plasma for the similarity in carrying particles [3]. Plasma is well defined as the quasineutral gas of charged and neutral particles that exhibit collective behavior. Quasineutrality of plasma implies that the electron and ion densities are nearly equal ($n_i = n_e =$ n, where n is the plasma density) but not so neutral that all the interesting electromagnetic forces vanish. If a deviation from neutrality occurs, the strong electrostatic interaction between negative and positive charges lead to currents, which restore neutrality [1].

In ordinary gases, particles interact only through collision. For most of the time a gas atom fly on a straight path independent of other atoms. This is quite different in plasma. It is a set of charged particles with free electric charge carriers and so it is conductive and reacts strongly to electric and magnetic fields. This means that each plasma particles interacts with a large number of other particles. Therefore, in plasma particles show a simultaneous response to an external influences. In this sense plasma show collective behavior, which means that the macroscopic result to an external influences is the cooperative response of many plasma particles [4].

The most important property of plasma is its ability to shield out any external electric potentials that are applied to it. This phenomena is called Debye shielding. In plasma the applied external potentials are shielded out within a very small radius of sphere called Debye sphere and the thickness (radius) is called "Debye length" [5]. The expression for the electron Debye length with electron temperature T_e and common density n_e is written as:

$$\lambda_{De} = \sqrt{\frac{\epsilon_0 k_B T_e}{e^2 n_e}} \tag{1.1}$$

Thus, three conditions an ionized gas must satisfy to be called a plasma are:

(a) The electron Debye length should be very smaller than the length of the system, i.e $\lambda_D << L$.

(b) The number of particles in a Debye sphere should be very large, i.e. $N_D >> 1$.

(c) If ω be the frequency of plasma oscillation and τ is the mean time between the collision with neutral atoms, then $\omega\tau > 1$.

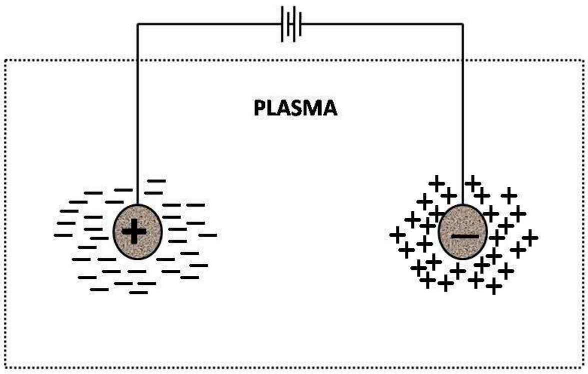

Figure 1.1: Debye shielding

1.2 Sheath

In all practical plasma devices, the plasma is contained in a vacuum chamber of finite size. When a plasma is in contact with the material such as electrodes or wall, the surface becomes negatively charged due to the absorption of fast moving electrons. The initial condition electrons flux into the wall is larger in comparison with the ion flux due to the electron being lighter particles and have high mobility. Because of the fast moving electrons, the wall develops a negative potential, repelling electrons but attracting ions, which are attracted to the surface and form a positive space charge region in front of the material surface. To balance the electron and ion losses, a non-neutral zone is formed at plasma boundary called plasma sheath as shown in Figure 1.2. The plasma will have a positive potential relative to the wall, but the wall potential ϕ_w will be negative. This potential can't be distributed throughout the plasma, because of the Debye shielding, the potential variation will be limited to a layer of a few Debye lengths in thickness. The purpose of the sheath is to create a potential barrier so that more mobile species, such as electrons, are electrostatically bound [6]. The sheath is also often called as 'Debye sheath' as it's dimension is equal to dimension of Debye length, or the 'ion sheath' as it is a positive space charge region. The height of the potential barrier continues to grow as long as there is net flux of negative charge into the wall. After attaining the maximum potential, electron starts to repel and ions get accelerated towards the wall that results in the decrease of the wall potential in magnitude and again electron tends to move towards the wall.

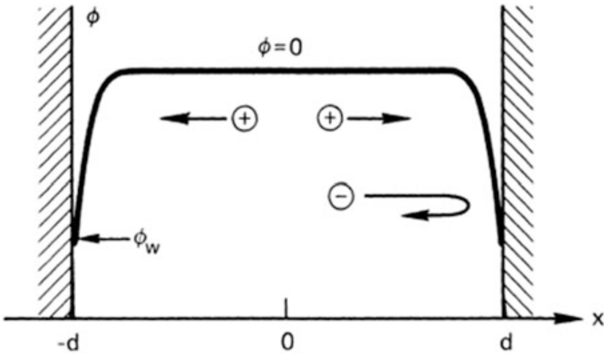

Figure 1.2: Plasma sheath [5]

Clearly, sheath region is non-neutral region. However, the plasma is quasineutral at the sheath edge. The sheath creation is responsible for particle and energy flow towards the wall, and it may also have an impact on bulk plasma behavior [7, 8]. Plasma is significantly non-neutral in the sheath region and practically quasineutral at the sheath edge. If we move very close to the walls, the potential falls of rapidly. The electric field is strong and the motion of particles is dominated by electric force rather than magnetic force.

1.3 Presheath

The sheath region is unable to shield out the wall potential completely due to the exponential decay of negative potential of the wall so that a residual electric field penetrates beyond the sheath edge into the bulk plasma. This electric field is responsible for acceleration of ions and entering to sheath region is called presheath as shown in Figure 1.3. Ions are accelerated towards the sheath entrance by residual electric fields in the presheath area to satisfy the “Bohm sheath criteria”, which is required for the creation of a stable sheath.

$$u \geq c_s \tag{1.2}$$

where

$$c_s = \sqrt{\frac{k_B(\gamma_i T_i + \gamma e T_e)}{m_i}} \tag{1.3}$$

is the ion-acoustic velocity. The ion and electron polytropic constants are γ_i and γ_e respectively, and the ion and electron temperatures are T_i and T_e respectively, at the presheath side of the sheath edge. The Bohm sheath criteria says that ions must enter the sheath region with a velocity greater than the acoustic velocity, which cannot be generated by thermal motion of ions. Presheath has two separate zones in the presence of an oblique magnetic field: magnetic presheath and collisional presheath. The electron pressure gradient accelerates electrons along magnetic field lines in the magnetic presheath next to the main plasma, resulting in an electric field that accelerates the ion. In the collisional presheath adjacent to the sheath, the electric field is strong enough to deflect the ions from their motion along the magnetic field. The above Bohm criteria is the special case when magnetic field is absent or magnetic field is perpendicular to the wall. In the presence of oblique magnetic field, Bohm-Chodura condition at magnetic presheath entrance [9] is

$$u_n \geq c_s cos\theta \tag{1.4}$$

where θ is angle made by magnetic field with the normal to the wall.

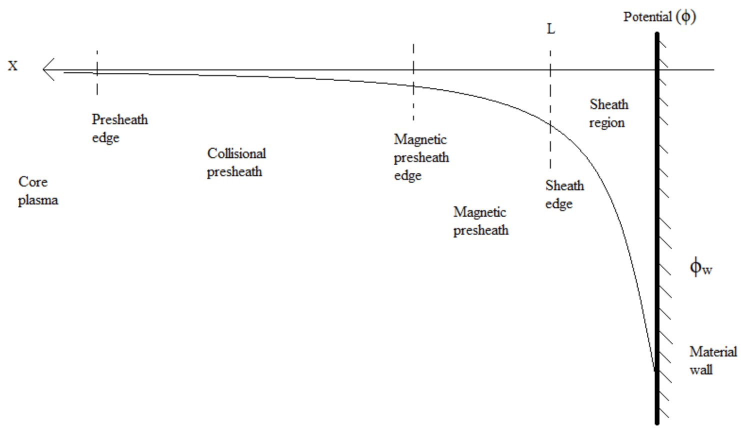

Figure 1.3: Schematic potential variation in plasma sheath.

1.4 Magnetization

Magnetized plasma has a magnetic field **B** strong enough to influence the velocity of the charged particles. Magnetized plasmas are anisotropic, anisotropic plasmas refer to situations where the velocity distribution functions of the various particle species are non isotropic (in particular non Maxwellian). Such a regime requires Coulomb collisions to be sufficiently weak. Many astrophysical plasmas are magnetized and weakly or even almost non collisional. While electric fields in plasma are usually small due to high conductivity, the electric field **E** associated with a plasma moving with a velocity **v** in a magnetic field is given by **E** = -**v** × **B**, and it is not affected by Debye shielding. Charged particles in the presence of a magnetic field experience the Lorentz force **F** = q(**v**× **B**), which causes them to move in a circular motion in the plane perpendicular to **B** and so follow a helical path. As the strength of the field increases, the resulting helical orbits becomes more tightly wound, effectively tying particles to magnetic field lines [10, 11].

1.5 Collision in Plasma

Collision is one of the most critical factors that determines the sheath properties in plasma. The collisions between the particles can be elastic or inelastic, therefore there is always a transfer of momentum between them.

Collisions in weakly ionized plasma are caused by interactions between charged particles and neutral particles, as well as between short-range neutral particles. The charged particles maintain a long-range Coulomb interaction with one another. As a result, in the situation of weakly ionized plasma, we must examine both short and long range interactions. Particle interactions in completely ionized plasma are only owing to the long-range Coulomb force. Due to such long range interaction, particles get subjected to continuous deflection in the time of their motion [12].

Collisions in the sheath are not the same as collisions in the core plasma. In comparison to the presheath region, the sheath region is ion-rich and non-neutral. The only collision that occurs is among the ions which is also small as the ion density in the sheath region is low. Collision is thus proportional to density and velocity of the ions and the collision force ($\vec{F}$) for non-neutral collision frequency (ν_i) is given by;

$$\vec{F} = m_i n_i \nu_i v_i \tag{1.5}$$

where m_i , n_i , and v_i are mass, density and relative velocity of ion, respectively.

1.6 Mach Number

In fluid dynamics, the Mach number is a dimensionless quantity representing the ratio of velocity of ion (u_0) at boundary x = 0 to the ion acoustic velocity (c_s). It is denoted by M and is given by;

$$M = \frac{u_0}{c_s} \tag{1.6}$$

By definition Mach number equal to 1 implies the ion velocity becomes equal to its acoustic velocity. The Mach number depends upon the speed of particles and speed of particles depend upon the type of particles and temperature of the particles.

(1) If M $<$ 1, the flow speed is lower than speed of sound and in this case the speed is subsonic.

(2) If M = 1, the flow speed equals to speed of sound and in this case the speed is transonic.

(3) If M $>$ 1, the flow speed is greater than the speed of sound and in this case the speed is supersonic.

Therefore, Mach number is used for analysing the fluid flow dynamics problems. Moreover, Mach number is used to describe an airplane's speed in terms of the speed of sound. In plasma the Mach number of ion species becomes crucial especially when it comes in contact with a material wall. As given by the Bohm criterion a stable, and hence a stable plasma is possible only when the Mach number is beyond a certain value, otherwise the plasma can not sustain for a long time [13].

Chapter 2

Literature Review

2.1 Literature Review

The formation of plasma sheath at the material wall has great importance for almost all plasma applications. Hence, the study of plasma sheath is of great interest in the field of plasma physics. In case of electro-negative plasma the negative ion density introduces some complications in the plasma analysis. The properties of the plasma sheath in the presence of negative ions and magnetic field have been studied by many researchers but still this phenomena is not fully understood. Some of the relevant works are reviewed here.

I. Langmuir [2] introduce the interaction of electron and positive ion space charges in cathode sheaths. In this work the potential distribution in the plasma and near the sheath edge for a particular case is studied and conclusion is drawn that the velocities of the the ions that enter the sheath can be calculated from the electron temperature if the geometry of the source of ionization is given. In 1949, Bohm formulated and interpreted the sheath formation condition explicitly [14]. Beilis et al. investigated the effect of magnetic field on the plasma-wall transition layer using two-fluid approximation. With neutral particles present and a magnetic field parallel to the confining walls, they investigated the quasineutral presheath. They demonstrated that the electron density distribution in the presheath may not follow the Boltzmann distribution [15].

Franklin and Snell investigated the low-pressure positive column in electronegative gases while taking space charge effects into consideration. They demonstrated that in low pressure plasma comprising positive and negative ions and electrons, matching plasma and sheath is possible using a fluid model. In addition, they found that the shapes of potential distributions differ markedly from those when negative ions were absent. By orders of magnitude, the transition from plasma to sheath is sharper, and the penetration of the wall electrical fields into the plasma is less [16]. Kono investigated the conditions at sheath edge that could lead to instability in the plasma-wall boundary in low pressure electronegative plasma. He found the relevant range of the ratio of the negative ion density to electron density at the sheath edge and showed that it is affected by the positive and negative ion temperature direction of positive ion flow, geometries of plasma and by the effect of ionization and momentum transfer collision [17].

Masoudi investigated collisional sheath using external magnetic field by considering collision between ions and neutral gas atoms under various pressure. He demonstrated that when there is a collision, the ion density increases, and when there is no collision, the ion density decreases. The influence of the magnetic field was also dominated by collision in the sheath close to the wall [18]. Khoramabadi et al. numerically investigated the ion temperature effects on magnetized plasma sheath. He discovered a direct relationship between ion temperature and ion flux toward the wall. He noticed that as the ion temperature increased, the thickness of the sheath reduced while the space charge grew [19]. Yasserian et al. investigated the structure of presheath-sheath in magnetized electronegative plasma. They found that under high values of electronegativity and for sufficiently cold negative ions, different magnetic field values constitute three types of discharge structure [20].

Hatami and Shokri investigated the sheath formation criterion in a weakly magnetized electronegative plasma. Using some boundary conditions, they discovered the upper and lower limits for positive ions velocity entering the sheath region. The ion Mach number M must be within a certain range for sheath formation; otherwise, the reduction of positive ion density distribution will not be monotonic. Presence of magnetic field affects both of these limits [21]. Liu et al. researched sheath criterion for electronegative plasma. They discovered that negative ions and an external magnetic field had an effect on the sheath criterion. They get to the conclusion that the ion Mach number is low due to coulomb attraction between positive and negative ions in electronegative plasma [22].

Basnet and Khanal studied effects of collision and ion Mach number on magnetized plasma sheath with two species of positive ions. They discovered that the ion Mach number has a significant influence on sheath properties [13]. Acharya studied the effect of magnetic field on plasma sheath by using fluid model. The final self consistent ion density, electron density, space charge, electric potential and ion velocity of entire sheath region are analyzed. The result shows that the magnetic field has significant effect on plasma sheath. It is found that on increasing the magnetic field strength and its obliqueness increase the perpendicular component of magnetic field which results on increasing the positive space charge and decreasing the sheath thickness [23].

Rai studied the sheath properties of magnetized electronegative plasma consisting two species of positive ions (lighter and heavier). She found that the electrostatic sheath potential at the sheath region increases and density distribution of electrons and both positive ions species decreases by increasing the electronegativity. She concluded that the density of lighter ion is significantly affected by the obliqueness of magnetic field [24]. Basnet studied the multicomponent magnetized plasma sheath and seen the effect of an oblique magnetic field and ion densities ratio. He also found that the lighter ion is more affected by obliqueness of magnetic field [25]. Pokhrel studied the effect of magnetic field in a cylindrical plasma sheath for both collisional and collisionless cases. He found that the sheath profile changes for different orientation [26]. Poudel also studied the sheath properties and ion dynamics in a magnetized plasma sheath by taking collision effect too [27].

Kshetry studied the effect of electric and magnetic fields on ion velocity at presheath-sheath boundary. Electric field doesnt not affect the particle which are gyrating along perpendicularly but it affects the parallel component velocity [28]. Sapkota investigated the ion dynamics on collisional magnetized plasma sheath. He found that the space charge density and net current density increase with increasing value of ion temperature and magnetic field and its peak shifted towards the sheath edge [29]. Bashyal studied sheath properties and ion Mach number for magnetized electronegative plasma. It is observed that the presence of oblique magnetic field can significantly reduce the ion flow velocity along the sheath entrance and hence increases the wall potential. The presence of oblique magnetic field has significant effect on the velocity and potential profile of electro negative plasma is found and ion Mach number rises with the increasing value of magnetic field strength and its obliqueness [30]. Using a fluid model, Jha evaluated the influence of ion Mach number on electro-negative magnetized plasma sheath. He noticed that the ion Mach number has a big impact on sheath characteristics [31].

2.2 Objectives

To investigate the effect of collision frequency and ion Mach number on potential, velocity, density, space charge density, current density and kinetic energy of ions of electro-negative magnetized plasma sheath.

Chapter 3

Methodology

3.1 Fluid Model

Single particle theory, kinetic theory and fluid theory are three different approaches to studying plasma behavior.

The simplest way to describing plasma phenomena is the fluid model, which is based on average quantities, such as moment of distribution functions. It derives the equations of current density and plasma density only on the basis of minimum informations of the particle distribution. A typical plasma density might be 10^{18} ion-electron pairs per m^3. If each of these particles follows a complicated trajectory and it is necessary to follow each of these, predicting the plasma's behavior would be a hopeless task. Fortunately, this is rarely necessary because, unexpectedly, the bulk of plasma events observed in real tests, perhaps as much as 80 %, can be explained by a fluid model. This model is used in fluid mechanics; in which the identity of the individual particles is neglected, and only the motion of fluid elements is taken into account. Of course, in case of plasma the fluid contents electric charges. In an ordinary fluid, frequent collisions between particles that keep the particles in a fluid elements moving together. So this model can describe plasma properties such as transport properties, instabilities, plasma waves and oscillation.

Using fluid theory, the state of plasma is described by using:

- Continuity Equation
- Momentum Transport Equation
- Boltzmann Relation
- Poisson's Equation

3.2 Continuity Equation

Consider a fluid having volume V enclosed by surface S. Let $\mathbf{dS} = \hat{n}ds$ be an element of area on this surface, with the unit normal vector $\hat{n}$ in outward direction as shown in figure. The average number of particle that leaves the volume V through the elements of area d**S** per unit time with velocity **u** is

$$n\mathbf{u}.\mathbf{ds} \tag{3.1}$$

The number of particles that leave the volume V through whole closed surface S is obtained by integrating equation (3.1) over the whole surface

$$\oint_s n\mathbf{u}.\, d\mathbf{s} \tag{3.2}$$

On the other hand, the total number of particles contained in V at any time is,

$$\int_v n\, dV \tag{3.3}$$

If we consider that there are no production or loss of particles inside the volume V, the number of particles leaving volume V must be equal to the rate of decrease of the number of particles inside V. We have,

$$-\frac{\partial}{\partial t}\int_v ndv = \oint_s n\mathbf{u}.\, d\mathbf{s} \tag{3.4}$$

From Gauss Divergence theorem, we can write

$$\oint_s n\mathbf{u}.\, d\mathbf{s} = \int_v \nabla.(n\mathbf{u})\, dV \tag{3.5}$$

Using equation (3.5) in equation (3.4) we get,

$$\int_v \nabla.(n\mathbf{u})\, dV = -\frac{\partial}{\partial t}\int_v ndv \tag{3.6}$$

$$\therefore \int_v [\frac{\partial n}{\partial t} + \nabla.(n\mathbf{u})]\, dV = 0 \tag{3.7}$$

This result must be valid for any arbitrary volume V, therefore,

$$\frac{\partial n}{\partial t} + \nabla.(n\mathbf{u}) = 0 \tag{3.8}$$

This is the continuity equation and it describes the conservation of charge. Any source and sinks of particles are to be added to the right hand side of equation (3.8).

3.3 Momentum Transport Equation

The equation of motion for charge particles in an electromagnetic field moving with average velocity **u** is,

$$mn\frac{\partial \mathbf{u}}{\partial t} = qn(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \tag{3.9}$$

where n is the number density, m is the mass of the particle, q is the charge of particle, **E** is the electric field and **B** is magnetic field.

Let us consider **G**(**x**,t) be property of field element in one dimensional x-space. The rate of charge of G as seen by observer moving with field is;

$$\frac{d\mathbf{G}}{\partial t} = \frac{\partial \mathbf{G}}{\partial t} + u_x \frac{\partial \mathbf{G}}{\partial x} \tag{3.10}$$

Here the first term of right hand side represent change of **G** at a point fixed in a space. The second term of right side represent the change of **G** due to motion of an observation with the fluid at different point in space. The result generalizing in 3-dimensional is;

$$\frac{d\mathbf{G}}{\partial t} = \frac{\partial \mathrm{G}}{\partial t} + (\mathbf{u}.\nabla)\,\mathbf{G} \tag{3.11}$$

This is called convection derivative. therefore equation (3.9) can be written as;

$$mn[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}.\nabla)\mathbf{u}] = qn[\mathbf{E} + \mathbf{u} \times \mathbf{B}] \tag{3.12}$$

When thermal motion are taken into account, a pressure gradient force has to be add to be added to the right hand side of equation (3.9), the resulting field equation of motion,

$$mn[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}.\nabla)\mathbf{u}] = qn[\mathbf{E} + \mathbf{u} \times \mathbf{B}] - \nabla p \tag{3.13}$$

Where ∇p=$\nabla(nk_BT)$ be the pressure gradient force arises from the random motion of particles in and out of a fluid element and does not apper in the equation for a single particle.

If plasma have a neutral fluid, the charge fluid will exchange momentum it through collisions. The momentum lost per collision will be proportional to the relative velocity **u** - $\mathbf{u}_0$. Where $\mathbf{u}_0$ is the velocity of the neutral fluid. If τ is the mean free time between collisions, the resulting collisional force can be written as; $-mn\frac{(\mathbf{u}-\mathbf{u}_0)}{\tau}$. The fluid equation of motion can be generalized to include anisotropic pressure and neutral collision as follows,

$$mn[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}.\nabla)\mathbf{u}] = qn[\mathbf{E} + \mathbf{u} \times \mathbf{B}] - \nabla p - mn\frac{(\mathbf{u} - \mathbf{u}_0)}{\tau} \tag{3.14}$$

3.4 Boltzmann Relation

The x-component of fluid equation of motion is;

$$mn[\frac{\partial u_x}{\partial t} + (\mathbf{u}.\nabla)u_x] = qnE_x - \frac{\partial p}{\partial x} \tag{3.15}$$

The convective term $(\mathbf{u}.\nabla)u_x$ is much smaller than the term $\frac{\partial u_x}{\partial t}$ so we can nehlect this term. Thus, equation (3.15) becomes,

$$\frac{\partial u_x}{\partial t} = \frac{q}{m}E_x - \frac{\gamma k_B T}{mn}\frac{\partial n}{\partial x} \tag{3.16}$$

This shows that the fluid is accelerated along the field direction ($\mathbf{B}$) under combined electrostatic and pressure gradient forces. Now, taking limit for electron $m \to 0$, $q \to -e$, $\mathbf{E} = -\nabla\Phi$, and consider cases in which u_x is spatially uniform, then

$$e\frac{\partial \Phi}{\partial x} = \frac{\gamma k_B T_e}{n}\frac{\partial n}{\partial x} \tag{3.17}$$

For isothermal process we take $\gamma = 1$ and integrating equation (3.17), we get

$$e\Phi = k_b T_e \ln n + C \tag{3.18}$$

Using the boundary condition when $\Phi = 0$, n = n_0, then

$$C = -k_B T_e \ln n_0 \tag{3.19}$$

$$n = n_0 \exp\frac{e\Phi}{k_B T_e} \tag{3.20}$$

This is Boltzmann distribution relation for electrons.

3.5 Poisson Equation

As we know that the electric field is the gradient of a scalar potential Φ, i.e.

$$\mathbf{E} = -\nabla\Phi \tag{3.21}$$

Gauss law can be written as;

$$\nabla.\mathbf{E} = \frac{\rho}{\epsilon_0} \tag{3.22}$$

Where ρ is the total volumn charge density. Thus, combining equations (3.21) and (3.22), we get

$$\nabla^2\Phi = \frac{\rho}{\epsilon_0} \tag{3.23}$$

This is called poission equation.

3.6 The Plasma Sheath Model

We consider a planar collisional magnetized plasma sheath bounded by x = 0 and x = L as shown in Figure 3.1.

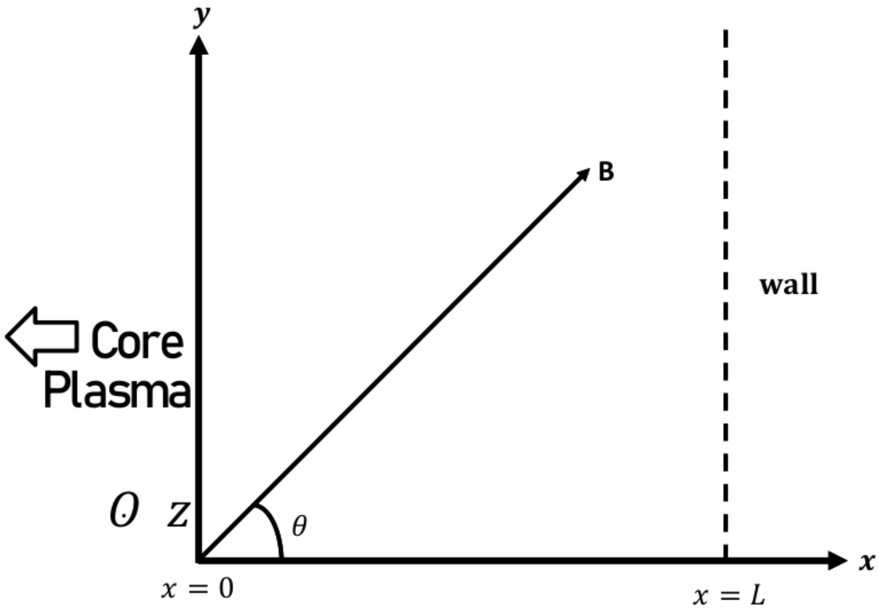

Figure 3.1: Plasma sheath model.

In the present case, the plasma consists of positive ions (H^+), negative ions (Cl^-) and electrons, which are considered as fluid in the phase space of a one dimensional spatial coordinate x and three dimensional velocity space v_x, v_y and v_z. The external magnetic field **B** is in the x-y plane and form angle θ with the normal to the wall. We assume that the plasma is non-isothermal $T_e \neq T_i$, where T_e and T_i are electrons and ions temperature, respectively. The numerical calculation is done by using fluid equations for ions. We solved these equations by using Boltzmann relation for electron and negative ion and Poisson's equation too.

3.7 The Set of Fluid Equations

(1) Boltzmann relation

The external magnetic field is assumed to be small, and the low-pressure plasma is not very electronegative. As a result, the Boltzmann distribution governs the negative ion density. Furthermore, because the wall potential is a floating potential, the electron density follows the Boltzmann distribution. Thus,

$$n_e = n_{e0} \exp(\frac{e\phi}{k_B T_e}) \tag{3.24}$$

$$n_n = n_{n0} \exp(\frac{e\phi}{k_B T_n}) \tag{3.25}$$

where n_e, n_n are the electron and negative ion densities in the sheath region. T_e, T_n are the temperatures of electron and negative ion. n_{e0}, n_{n0} are electron and negative ion densities in the plasma region.

(2) The Continuity Equation

The steady state ion continuity equation in the absence of any source and sink is;

$$\nabla.(n_i \mathbf{v}_i) = 0 \tag{3.26}$$

Now in 1d3v considering the properties to change only in x -direction.

$$\frac{d}{dx}(n_i v_{ix}) = 0 \tag{3.27}$$

where n_i and v_{ix} are the ion density and ion velocity, respectively.

(3) The Momentum Equation

The momentum transport equation for ion in account of pressure gradient force and collision force is,

$$m_i n_i (\mathbf{v}_i.\nabla)\mathbf{v}_i = q n_i (\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) - m_i n_i \nu_i \mathbf{v}_i \tag{3.28}$$

where m_i, n_i and ν_i are ion mass, ion density and non- neutral collision frequency, respectively.

(4) The Poisson's Equation

The Poisson's equation for plasma having electron, positive ion and negative ion is;

$$\nabla^2 \phi = -\frac{e}{\epsilon_0}(n_i + n_e - n_n) \tag{3.29}$$

where ϵ_0 is the electric permitivity of free space.

We have from quasi neutrality condition

$$n_{i0} = n_{e0} + n_{n0} \tag{3.30}$$

It is assumed that the wall is infinitely long in the y and z direction, the quantities change only in the x-direction normal to the wall, i.e.

$$\nabla \rightarrow \hat{x}\frac{\partial}{\partial x} \tag{3.31}$$

In order to solve the set of fluid equations introducing the dimensionless variables as follows;

$\xi = \frac{x}{\lambda_{De}}$, the normalized distance.

$\Phi = -\frac{e\phi}{k_B T_e}$, the normalized potential.

$\mathbf{u}_i = \frac{\mathbf{v}_i}{C_{is}}$, the normalized velocity of ion.

where $C_{is} = \sqrt{\frac{k_B T_e}{m_i}}$ is the ion acoustic velocity.

$N_i = \frac{n_i}{n_{e0}}$ be the normalized positive ion density.

$N_e = \frac{n_e}{n_{e0}}$ be the normalized electron density.

$N_n = \frac{n_n}{n_{n0}}$ be the normalized negative ion density.

$\sigma = \frac{T_e}{T_n}$ be the electron to negative ion temperature ratio.

$T = \frac{T_i}{T_e}$ be the normalized ion temperature.

$\delta = \frac{n_{n0}}{n_{e0}}$ be the positive ion and electron density ratio at x = 0.

$\gamma = \frac{\omega_{ic}}{\omega_{pi}}$ be the ratio of positive ion cyclotron frequency to the ion plasma frequency.

$\omega_{ic} = \frac{eB}{m_i}$ be the positive ion cyclotron frequency.

$\omega_{pi} = \sqrt{\frac{n_{i0}e^2}{\epsilon_0 m_i}}$ be the ion plasma frequency.

$\alpha = \frac{n_{n0}}{n_{i0}}$ be the density ratio of negative ions to the positive ions.

Then from quasi neutrality condition;

1 - $\alpha = \frac{n_{e0}}{n_{i0}}$ is the density ratio of electron to positive ions.

Using dimensionless variables, equation (3.24) and (3.25) becomes

$$N_e = \exp(-\Phi) \tag{3.32}$$

$$N_n = \exp(-\sigma\Phi) \tag{3.33}$$

Using dimensionless variables, equation (3.27) becomes,

$$\frac{d}{d\xi}(N_i u_i) \tag{3.34}$$

$$\frac{dN_i}{d\xi} = -\frac{N_i}{u_i}\frac{du_i}{d\xi} \tag{3.35}$$

We have,

$$\frac{d}{dx}(n_i v_{ix}) = 0 \tag{3.36}$$

$$(\frac{n_i}{n_{i0}})(\frac{v_{ix}}{c_{is}}) = (\frac{v_{ix0}}{c_{is}}) \tag{3.37}$$

Using dimensionless variables, we get

$$N_i u_{ix} = M.(\delta + 1) \tag{3.38}$$

where, $M = \frac{v_{ix0}}{c_{is}}$ is ion Mach number at the sheath entrance.

Now, x -component of the equation (3.28) gives,

$$m_i n_i v_{ix}\frac{\partial v_{ix}}{\partial x} = -en_i\frac{\partial \phi}{\partial x} - en_i B v_{iz} sin\theta - m_i n_i v_{ix}\nu_i \tag{3.39}$$

Using dimensionless variables, then

$$u_{ix}\frac{du_{ix}}{d\xi} = \frac{d\Phi}{d\xi} - \gamma u_{iz} sin\theta - \nu u_{ix} \tag{3.40}$$

where $\nu = \frac{\nu_i \times \lambda_{De}}{c_s}$ is the normalized collision frequency.

Again, y-component of the equation (3.28) gives;

$$m_i v_{ix}\frac{dv_{iy}}{dx} = eBv_{iz} cos\theta - \nu_i v_{iy} \tag{3.41}$$

Using dimensionless variables, then

$$u_{ix}\frac{du_{iy}}{d\xi} = \gamma u_{iz} cos\theta - \nu u_{iy} \tag{3.42}$$

and the z -component of equation (3.28) gives;

$$m_i v_{ix}\frac{dv_{iz}}{dx} = eB(v_{ix} sin\theta - v_{iy} cos\theta) - \nu_i m_i v_{iz} \tag{3.43}$$

Using dimensionless variables,

$$u_{ix}\frac{du_{iz}}{d\xi} = \gamma(u_{ix} sin\theta - u_{iy} cos\theta) - \nu u_{iz} \tag{3.44}$$

Now, from equation (3.29);

$$\frac{d^2\phi}{dx^2} = -\frac{e}{\epsilon_0}(n_i + n_e - n_n) \tag{3.45}$$

Using dimensionless variables, then

$$\therefore \frac{d^2\Phi}{d\xi^2} = N_i - N_e - N_n\delta \tag{3.46}$$

3.8 The Boundary Conditions

The set of a fluid equation are compiled and solved numerically for the given initial and boundary condition to investigate the potential, velocity, density, space charge density and net current density of the magnetized plasma sheath with collisional plasma. We have considered the electro-negative magnetized plasma that consists of positive ions of hydrogen atom, negative ions of chlorine atom, electrons and some neutral particles. The physical parameters are B = 0.137 T, $\theta = 30$, $\nu = 0.01$, $\sigma = 25$ and $\delta = 0.1$.

All normalized equations are solved by using Runge-Kutta method in Matlab with following initial conditions:

$u_{ix}(\xi = 0) = (\mathrm{M}, 0, 0)$

$\Phi(\xi = 0) = 0$

$\frac{d\Phi}{d\xi}(\xi = 0) = 0.01$

Here we take the electrostatic potential Φ is zero but to valid plasma approximation we assume that $\frac{d\Phi}{d\xi}(\xi = 0)$ takes infinitesimally small values, i.e. $\frac{d\Phi}{d\xi}(\xi = 0) = 0.01$. The results are obtained by solving set of fluid equations, and we investigate the potential profile, ion density profile, ion velocity profile, space charge density profile, current density profile and kinetic energy profile.

3.9 The Runge-Kutta Method

In this section, we discuss the numerical method which we have been used to solve the set of fluid equations. Runge and Kutta, two well known German mathematicians, devised this method around 1900. This method of numerically integrating ordinary differential equations involves employing a trial step at the midpoint of an interval to cancel out the lower order error term. The function's increments are calculated once and for everyone using formulae in this case. The initial increment is calculated in the same way as every other increment. Below are the formulas for numerous different forms of differential equations [32]. For our work we have used one member of the family of Runge-Kutta method referred to as 'RK4', 'Classical Runge-Kutta method' or simply as 'the Runge-Kutta method'. The method is briefly described below.

Let an initial value problem be

$\dot{y}$ = f(x, y), y(0) = y_0

Here, y is an unknown function (scalar or vector) of x which we would like to approximate using the given initial value.

Now, let us pick a step-size $h > 0$, and define

$y_{n+1} = y_n + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4)$

and $x_{n+1} = x_n + h$

for n = 0, 1, 2, 3,...

where $k_1 = f(x_n, y_n)$

$k_2 = f(x_n + \frac{h}{2}, y_n + \frac{1}{2}k_1 h)$

$k_3 = f(x_n + \frac{h}{2}, y_n + \frac{1}{2}k_2 h)$

$k_4 = f(x_n + h, y_n + k_3 h)$

Here y_{n+1} is the RK4 approximation of $y(x_{n+1})$ and the next value y_{n+1} is determined bythe present value y n plus the weighted average of four increments, where each increment is the product of the size of the interval 'h', and an estimated slope specified by function f' the right-hand side of the differential equation.

- k_1 is the increment based on the slope at the beginning of the interval, using y;
- k_2 is the increment based on the slope at the midpoint of the interval, using $y + \frac{h}{2}k_1$;
- k_3 is again the increment based on the slope at the midpoint, but now using $y + \frac{h}{2}k_2$;
- k_4 is the increment based on the slope at the end of the interval, using $y + hk_3$;

In averaging the four increments, greater weight is given to the increments at the midpoint. If the weights are chosen such that if f is independent of y, so that the differential equation is equivalent to a simple integral, then RK4 is Simpson's rule.

The RK4 method is a fourth-order method, meaning that the local truncation error is on the order of $O(h^5)$, while the total accumulated error is order $O(h^4)$. Using this method we can solve the differential equations up-to fourth order.

3.10 Introduction of ode45 in MATLAB

Ode45 is one of the solver of the ordinary differential equations in MATLAB. It solves non-stiff differential equations implementing Runge-Kutta method with medium order accuracy [33].

Syntax:

$[X, Y] = ode45(odefun, xspan, y_0)$

Here,

- 'odefun' is a function handle that evaluates the right side of the differential equations of the form $\dot{y}$ = f(x, y).
- 'xspan' is a vector specifying the interval of integration, $[x_0, x_f]$. The solver imposes the initial condition at xspan(1), and integrates from xspan(1) to xspan(end). For xspan vectors with two elements $[x_0, x_f]$, the solver returns the solution evaluated at every integration step. For xspan vectors with more than two elements, the solver returns solutions evaluated at the given points. The position values must be in order, either increasing or decreasing.
- 'y_0' is a vector of initial conditions.
- x is column vector of position points.
- y is the solution array. For a scalar X and a vector Y, odefun(x, y) must return a column vector corresponding to f(x, y). Each row in Y corresponds to the solution at a position returned in the corresponding row of X.

Example:

$[t, x] = ode45(@ishwor, [0 : 0.1 : 20], [00.1001], [], gamma, alpha, theta, M);$

$u_1 = spline(t, x(:, 3), 0 : 0.1 : 20);$

$plot(t, u_1);$

Here, $[0 : 0.1 : 20]$ is the tspan or linspace and "ishwor"is the function file. Running this command file will give solution of equations define in function file "ishwor". Once the solution is obtained a plot of x(:, 3), i.e. x-component of ion velocity versus distance will be displayed.

Chapter 4

Results and Discussion

In this section, we present the numerical results obtained by solving the set of nor- malized fluid equations compiled in the section 3.7 by using Runge-Kutta method. The boundary conditions at the sheath edge ($\xi = 0$) discussed in the section 3.8 are used to solve the equations. The physical parameters like external magnetic field and its obliqueness, ion and electron temperature, collision frequency are considered to be uniform throughout the plasma sheath region. In order to investigate the effect of collision and ion Mach number on electro-negative magnetized plasma sheath, potential profile, ion density profile, ion velocity profile, space charge density profile, net current density profile and kinetic energy profile are plotted and analysed.

4.1 Effect of Ion Mach Number

4.1.1 Potential Profile

The normalized potential (Φ) versus normalized distance (ξ) for uniform magnetic field B = 0.137 T and its obliqueness $\theta = 30^0$ and collisional frequency $\nu = 0.01$ for different values of ion Mach number is shown in Figure 4.1. It is seen that the electrostatic potential, which has zero magnitude at the sheath edge as the plasma is quasineutral, increases towards the wall for all cases. For all scenarios, it can be shown that the potential grows rapidly towards the wall. This corresponds to decrease in real potential as we move towards the wall which is in accordance to the Debye shielding. As the Mach number increases, the magnitude of potential also increases at the wall. This is because the effect of collision force and Lorentz force increases at the sheath edge with the increase in ion Mach number and hence the potential increases. The magnitude of potential at the wall increases from 31 to 49 as the ion Mach number increases from 1.0 to 1.5. As the Mach number rises, the wall potential rises, implying that the sheath thickness increases as well.

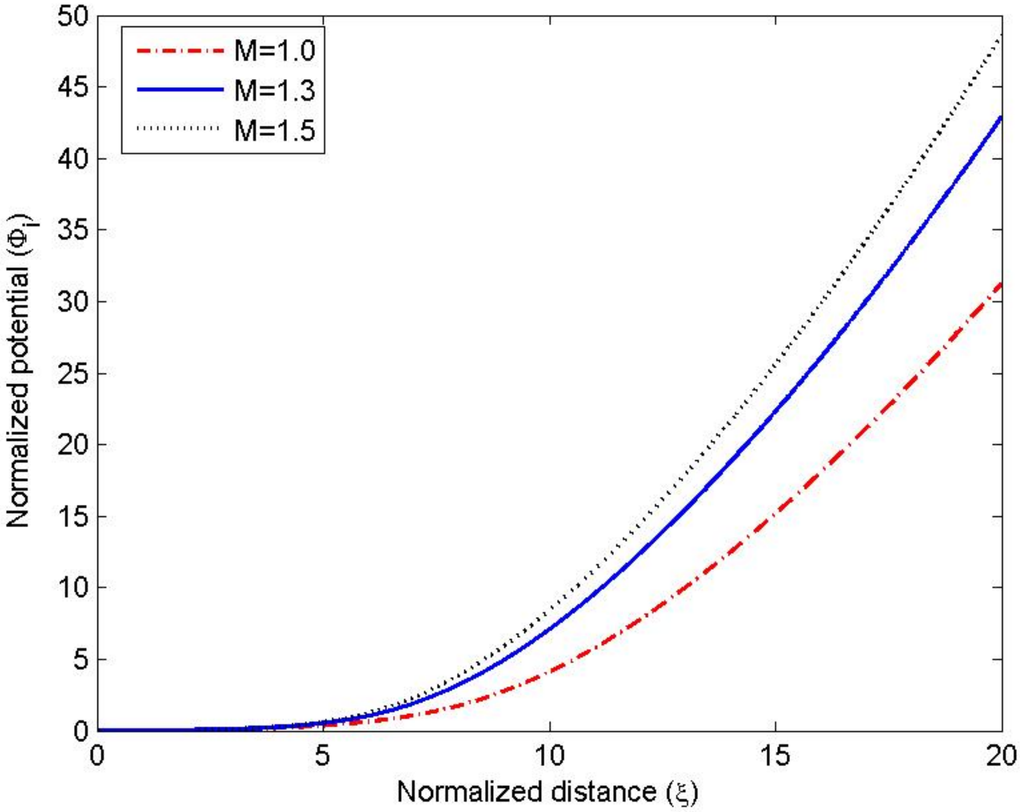

Figure 4.1: Normalized potential (Φ) as the function of normalized distance (ξ) for the different values of ion Mach number.

4.1.2 Ion Density Profile

The normalized ion density (N_i) versus normalized distance (ξ) for uniform magnetic field B = 0.137 T and its obliqueness $\theta = 30^0$ and collisional frequency $\nu = 0.01$ for different values of ion Mach number is shown in Figure 4.2. It is seen that ion density maximum at the sheath edge and then gradually declines towards the wall for all cases. In the sheath edge, ion density maximum due to the prominent effect of Lorentz force and collision force that causes charged particles to spent more time at the sheath edge. As the ions move towards the wall, the electric field is dominant and hence the velocity of ion increases towards the wall. Thus, according to conservation of ion flux towards the sheath region, the density of ions decreases towards the wall.

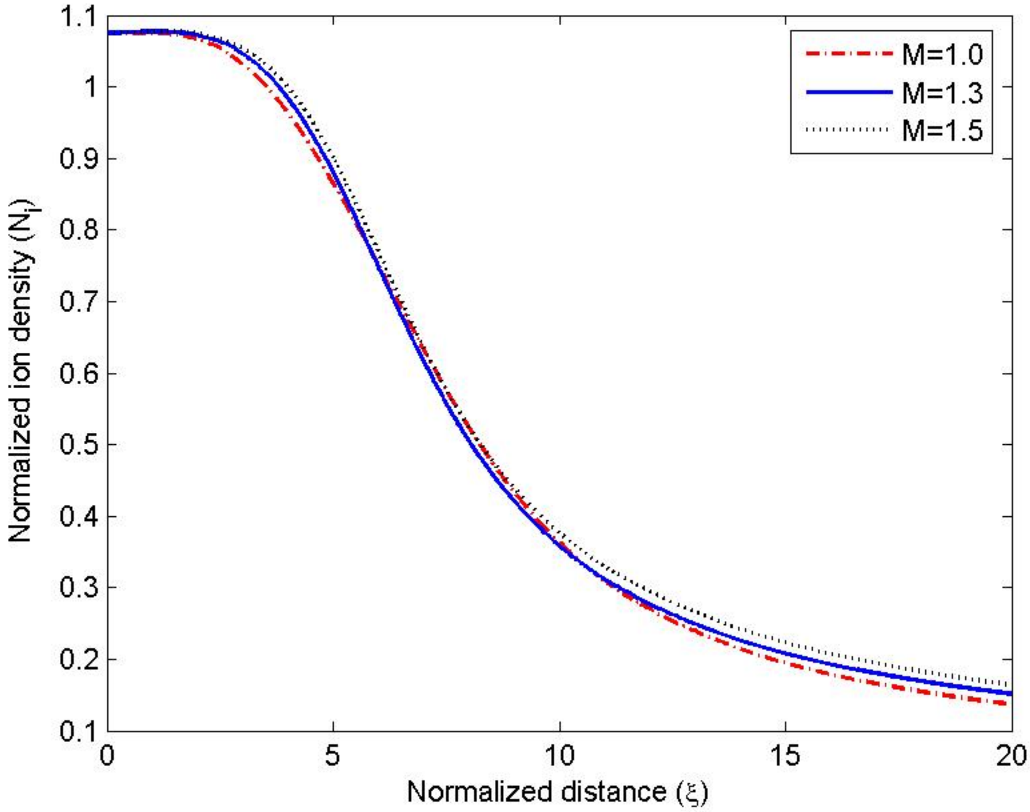

Figure 4.2: Normalized ion density (N_i) as the function of normalized distance (ξ) for the different values of ion Mach number.

4.1.3 Ion Velocity Profile

The normalized ion velocity (u_i) versus normalized distance (ξ) for uniform magnetic field B $= 0.137$ T and its obliqueness $\theta = 30^0$ and collisional frequency $\nu = 0.01$ for different values of ion Mach number is shown in Figure 4.3. It is found that ion velocity decreases at the sheath edge and increases towards the wall for all cases. At sheath edge, the prominent nature of collisional force and Lorentz force causes to increase the ion density. Therefore, according to continuity equation the ion velocity decreases to conserve the fluxes of ions. The velocity of ions increase at the wall from 7.9 to 9.9 for the increasing ion Mach number from 1.0 to 1.5. Hence, it is concluded that the velocity of ions is higher at the walls for those ions having high ion Mach number.

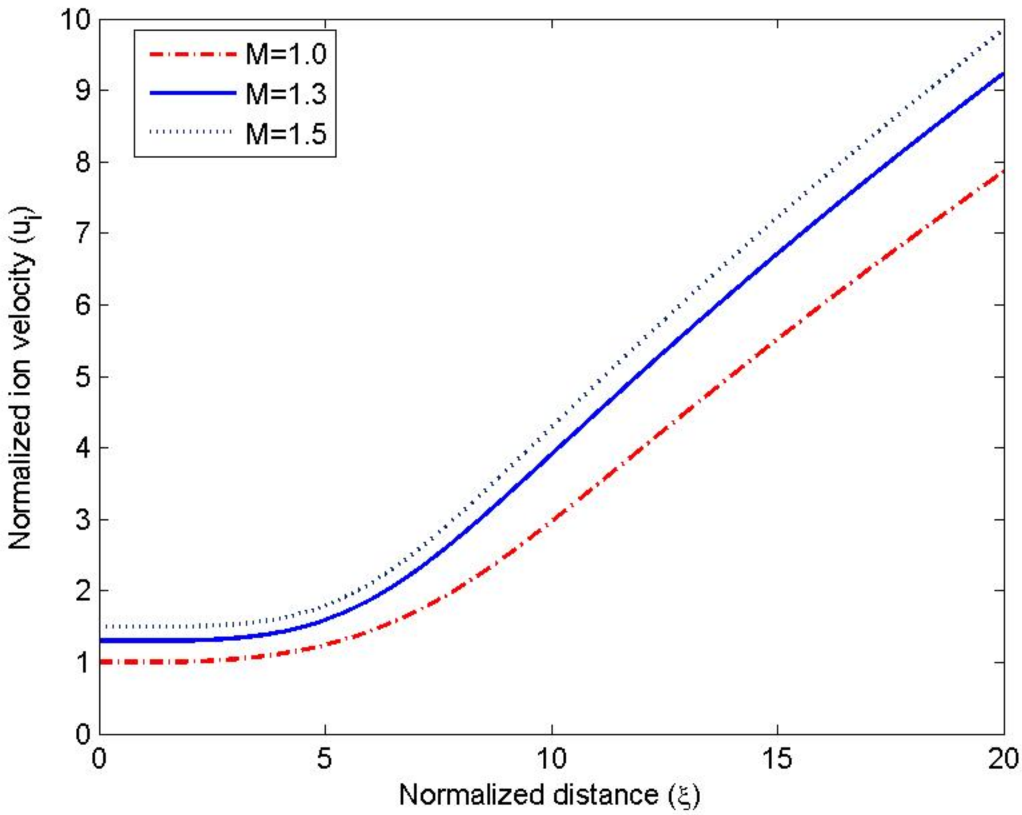

Figure 4.3: Normalized Ion velocity (u_i) as the function of normalized distance (ξ) for the different values of ion Mach number.

4.1.4 Space Charge Density Profile

The space charge density (ρ) versus normalized distance (ξ) for uniform magnetic field B = 0.137 T and its obliqueness $\theta = 30^0$ and collisional frequency $\nu = 0.01$ for different values of ion Mach number is shown in Figure 4.4. It is seen that space charge density is maximum near the sheath edge and then decreases towards the wall for all cases. The peak of space charge density increases with the increase in ion Mach number which represents the high ion density near the sheath edge. It can also be seen that the fluctuation of space charge density increases with increasing ion Mach number. The increase in space charge density represents that the number of shielding particles increases that makes the stationary sheath stable. Therefore, the number of shielding particles increases because of the increase of sheath thickness.

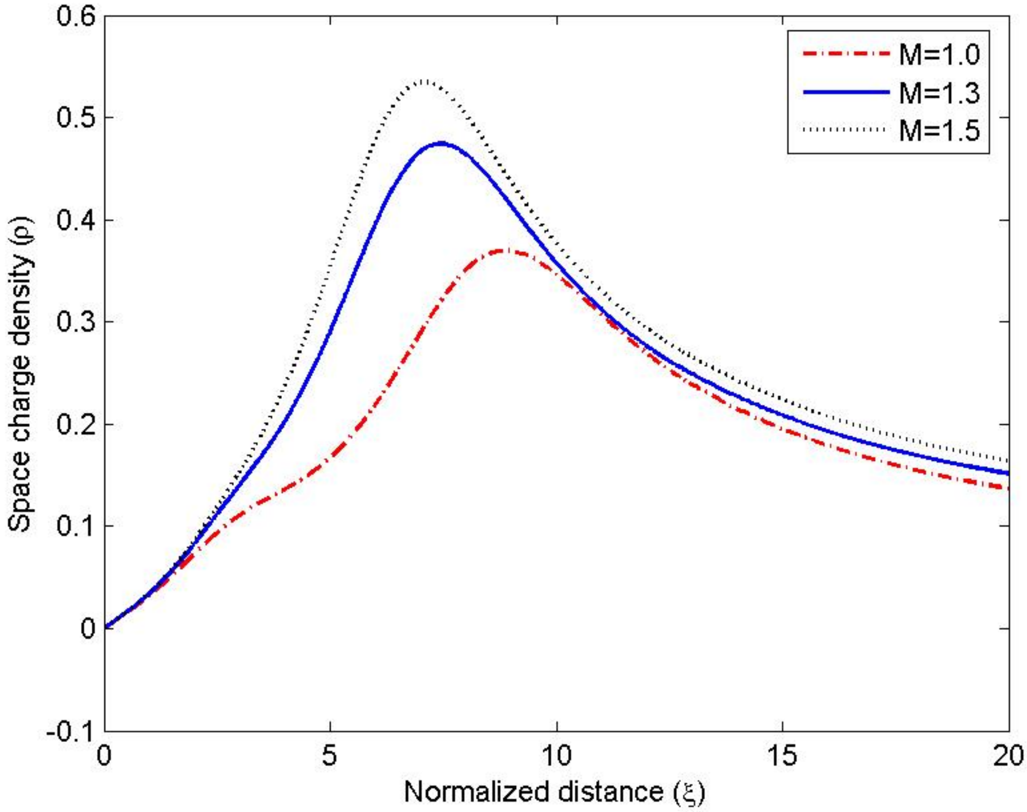

Figure 4.4: Space charge density (ρ) as the function of normalized distance (ξ) for the different value of ion Mach number.

4.1.5 Net Current Density Profile

The net current density (J_n) versus normalized distance (ξ) for uniform magnetic field B = 0.137 T and its obliqueness $\theta = 30^0$ and collisional frequency $\nu = 0.01$ for different values of ion Mach number is shown in Figure 4.5. It is seen that the net current density increases towards the wall and gets saturated for all cases. At the sheath entrance, the net current density is the lowest, indicating that the current due to negatively charged particles is greater than the current due to ions. Around 8 electron Debye lengths, the net current density reaches saturation, indicating that the fluxes of positively and negatively charged particles are equal. The saturation point moves closer to the sheath entrance as the ion Mach number increases.

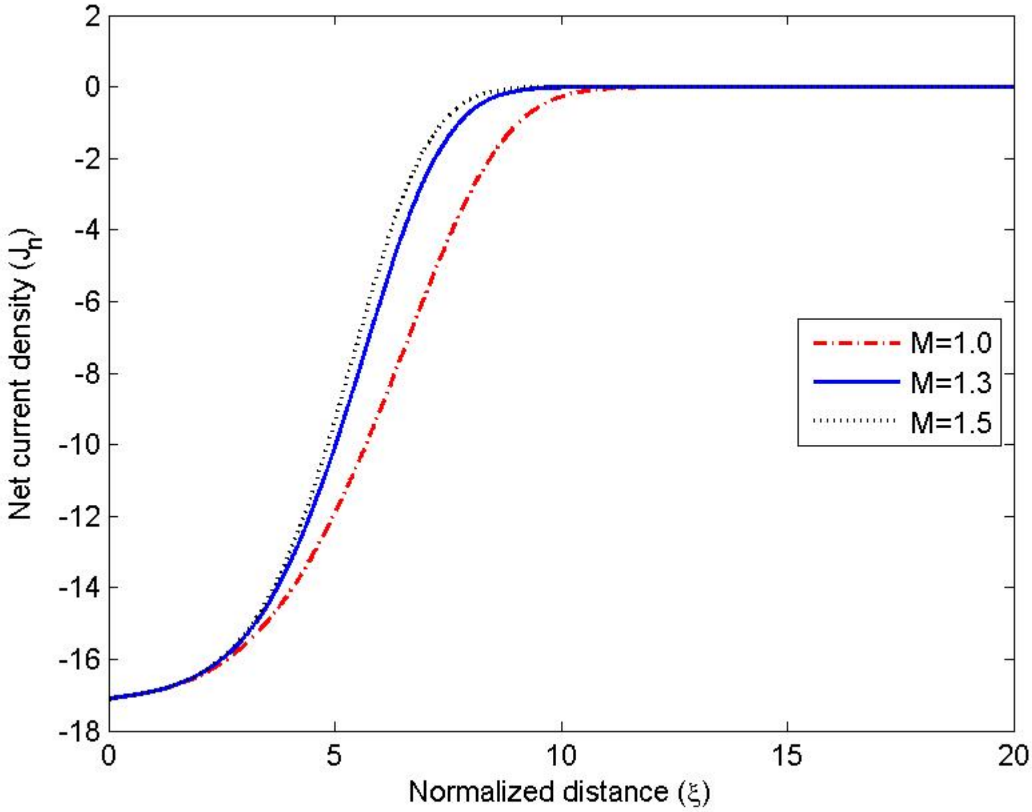

Figure 4.5: Net current density (J_n) as the function of normalized distance (ξ) for the different values of ion Mach number.

4.1.6 Kinetic Energy Profile

The kinetic energy (E_k) versus normalized distance (ξ) for uniform magnetic field B = 0.137 T and its obliqueness $\theta = 30^0$ and collisional frequency $\nu = 0.01$ for different values of ion Mach number is shown in Figure 4.6. It is seen that the kinetic energy at the sheath edge is minimum and its magnitude is uniformly increased towards the wall for all cases. Since ion Mach number increases the velocity of ions increases towards the wall, the kinetic energy of ions also increases towards the wall. The normalized kinetic energy of ions increases at the wall from about 61 to 98 for the increase in ion Mach number from 1.0 to 1.5.

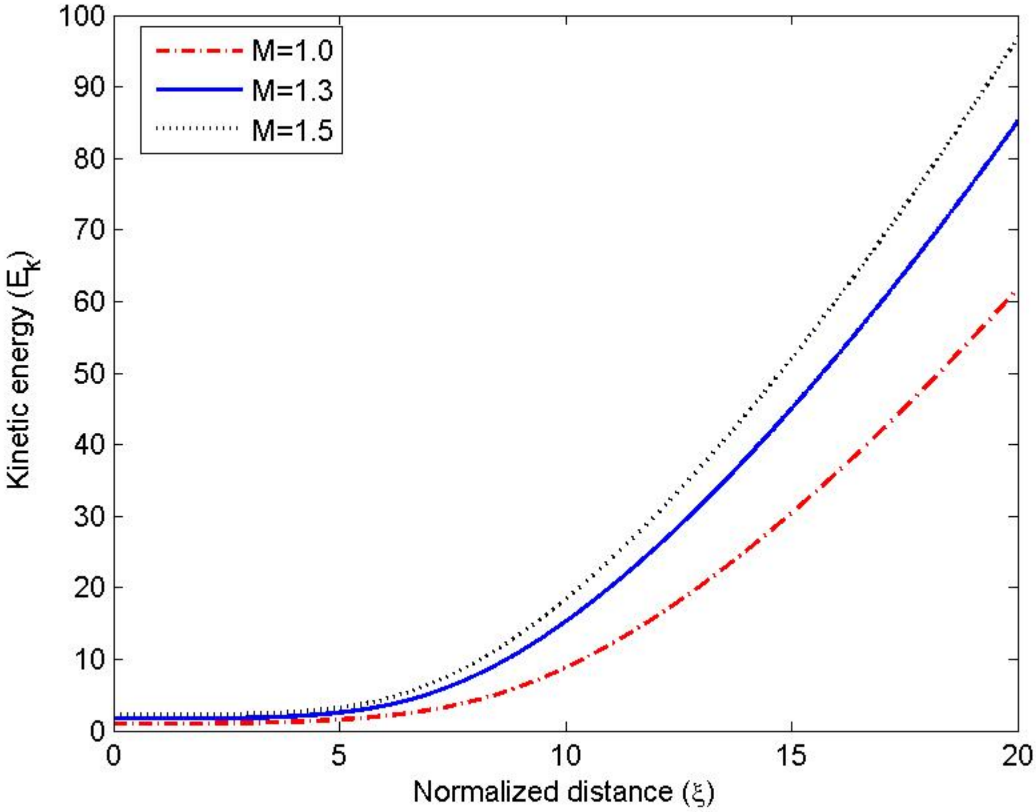

Figure 4.6: Kinetic energy (E_k) as the function of normalized distance (ξ) for the different values of ion Mach number.

4.2 Effect of Collision Frequency

4.2.1 Potential Profile

The normalized potential (Φ) verses normalized distance (ξ) at constant magnetic field B $= 0.137$ T and its obliqueness $\theta = 30^0$ for three different values of collision is shown in Figure 4.7. In all conditions, the electrostatic potential increases towards the wall, which is zero at the sheath edge because the plasma is quasineutral. As the collision increases, the magnitude of potential also increases at the wall. This is because Lorentz force gyrates the charged particle and spend more time near to the sheath edge ($\xi = 0$). As the particles move towards the sheath region, the velocity of particle decreases after collision, which causes to increase the magnitude of potential to satisfy the Bohm condition near the magnetic presheath entrance. The magnitude of normalised wall potential increases from

29 to 42 for the increasing value of collision frequency from 0.00 to 0.03.

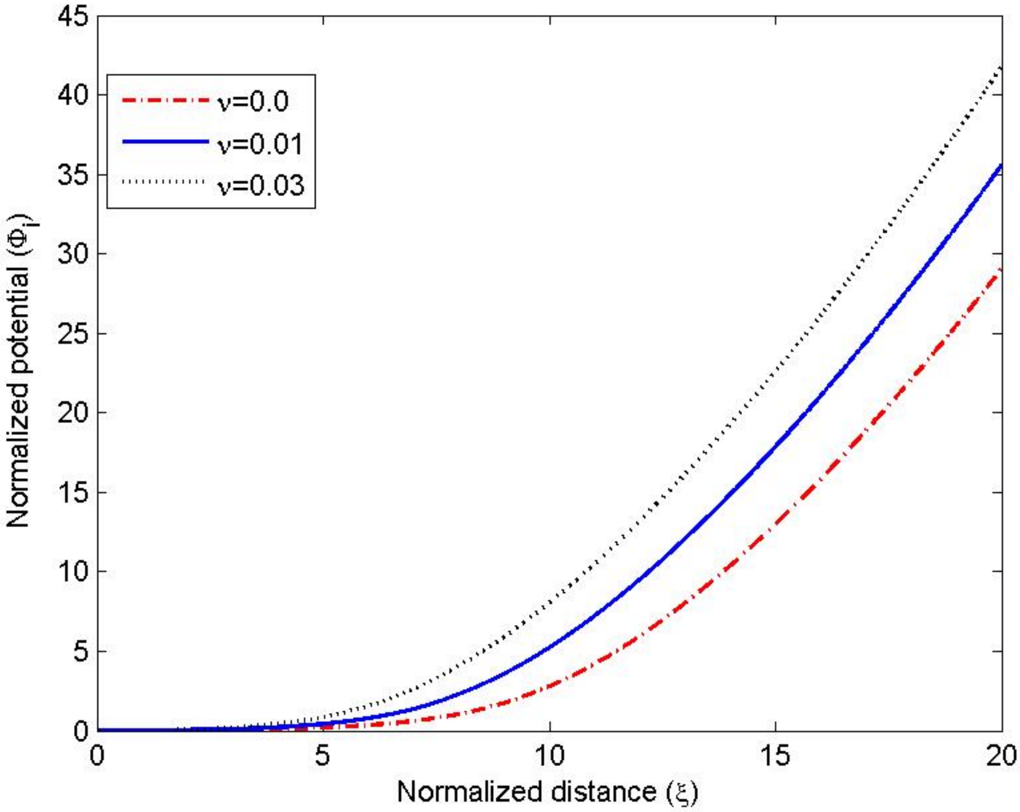

Figure 4.7: Normalized potential (ϕ) as the function of normalized distance (ξ) for the different values of collision frequency.

4.2.2 Ion Density Profile

The normalized ion density (N_i) versus normalized distance (ξ) for uniform magnetic field B $= 0.137$ T and its obliqueness $\theta = 30^0$ for three different values of collision is shown in Figure 4.8. In all situations, ion density increases near the sheath edge and subsequently drops monotonically towards the wall. The bump nature occurs on the density profile at the sheath edge due to the prominent Lorentz and collision force effects, which lead charged particles to spend longer time at the sheath edge. As the ions move towards the wall, the electric field is dominant and hence the velocity of ion increases towards the wall. Thus, according to conservation of ion flux towards the sheath region, the density of ions decreases towards the wall.

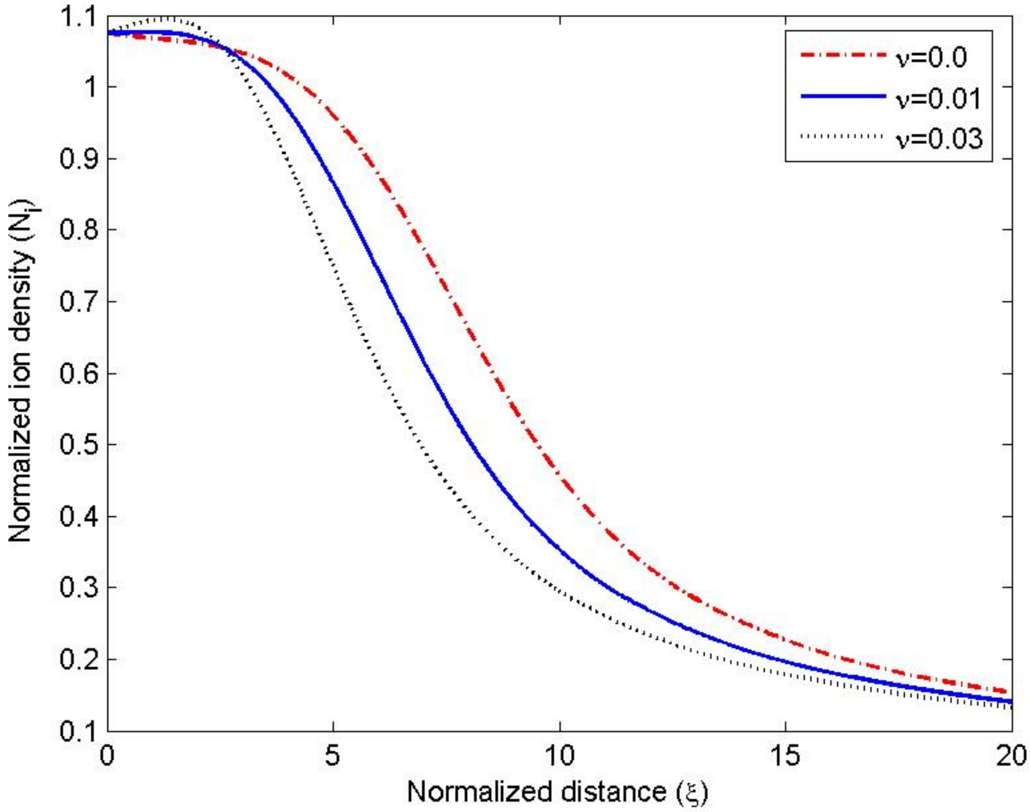

Figure 4.8: Normalized ion density (N_i) as the function of normalized distance (ξ) for the different values of collision frequency.

4.2.3 Ion Velocity Profile

The normalized ion velocity (u_i) versus normalized distance (ξ) at constant magnetic field B $= 0.137$ T and obliqueness $\theta = 30^0$ for three different values of collision frequency is shown in Figure 4.9. It is seen that the ion velocity decreases at the sheath edge and increases towards the wall for all cases. The dominating nature of magnetic Lorentz force and collision causes the velocity of ions to drop towards the sheath edge; however its effect fade away as the particles move towards the sheath region. Therefore, the velocity of ions gets increased towards the wall. The normalized velocity of ions increases at the wall from about 7.8 to 9 for the increase in collision frequency from 0.00 to 0.03.

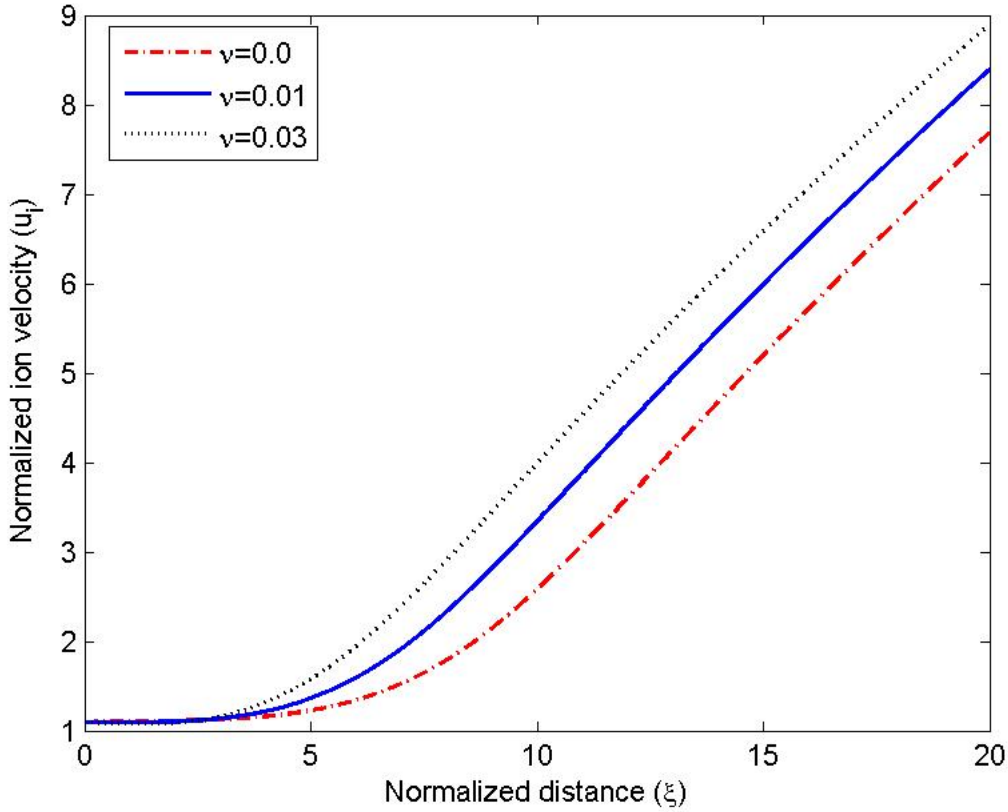

Figure 4.9: Normalized ion velocity (u_i) as the function of normalized distance (ξ) for the different values of collision frequency.

4.2.4 Space Charge Density

The space charge density (ρ) versus normalized distance (ξ) at constant magnetic field B = 0.137 T and obliqueness $\theta = 30^0$ for three different values of collision frequency is shown in Figure 4.10. On increasing the collision frequency, the net positive space charge density also increases and shift towards the sheath edge. This is because, at sheath edge, collision force adding up with Lorentz force increases the fluctuation of ion velocity (i.e. decrease the ion velocity) which leads to increase in ion density. Therefore, the number of shielding particles increases because of the increase of sheath thickness.

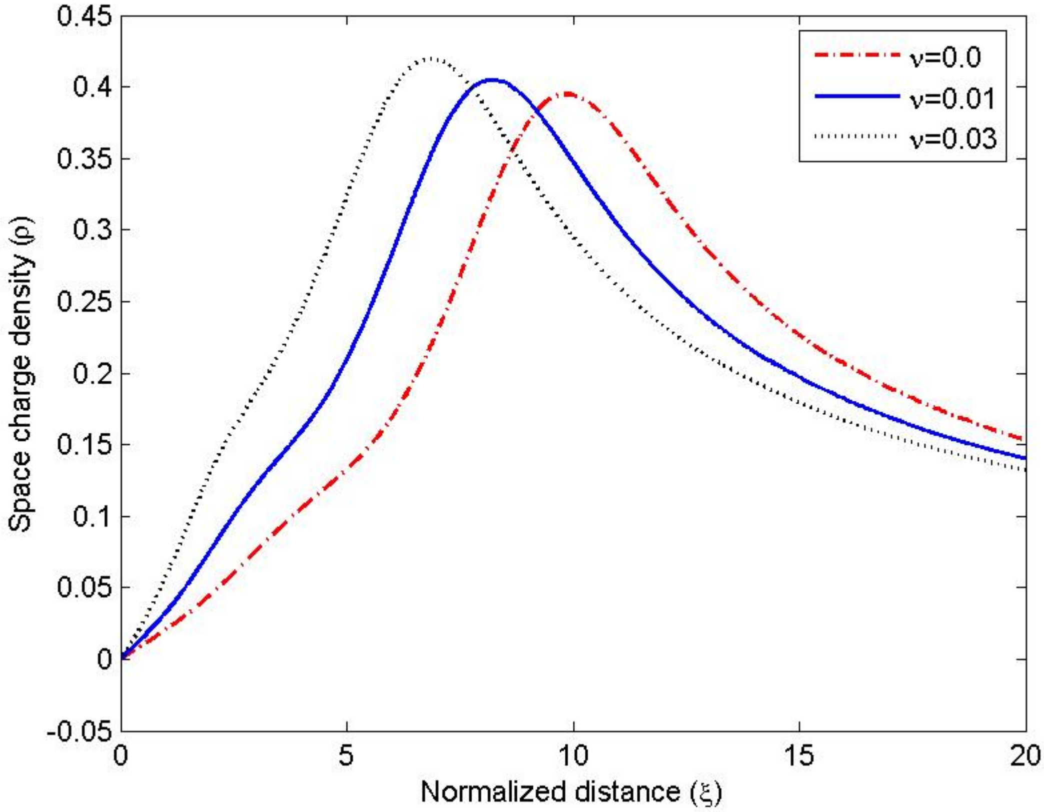

Figure 4.10: Space charge density (ρ) as the function of normalized distance (ξ) for the different values of collision frequency.

4.2.5 Net Current Density Profile

The net current density (J_n) versus normalized distance (ξ) at constant magnetic field B = 0.137 T and obliqueness $\theta = 30^0$ for three different values of collision frequency is shown in Figure 4.11. The net current density increases towards the wall and gets saturated. The saturation point shifts towards the sheath entrance with the increasing values of collisional frequency. As the particles move towards the wall from the sheath entrance, ion flux dominates electron flux and the current density increases towards the wall. After moving few Debye lengths from sheath entrance, both fluxes are equal and hence net current density gets saturated.

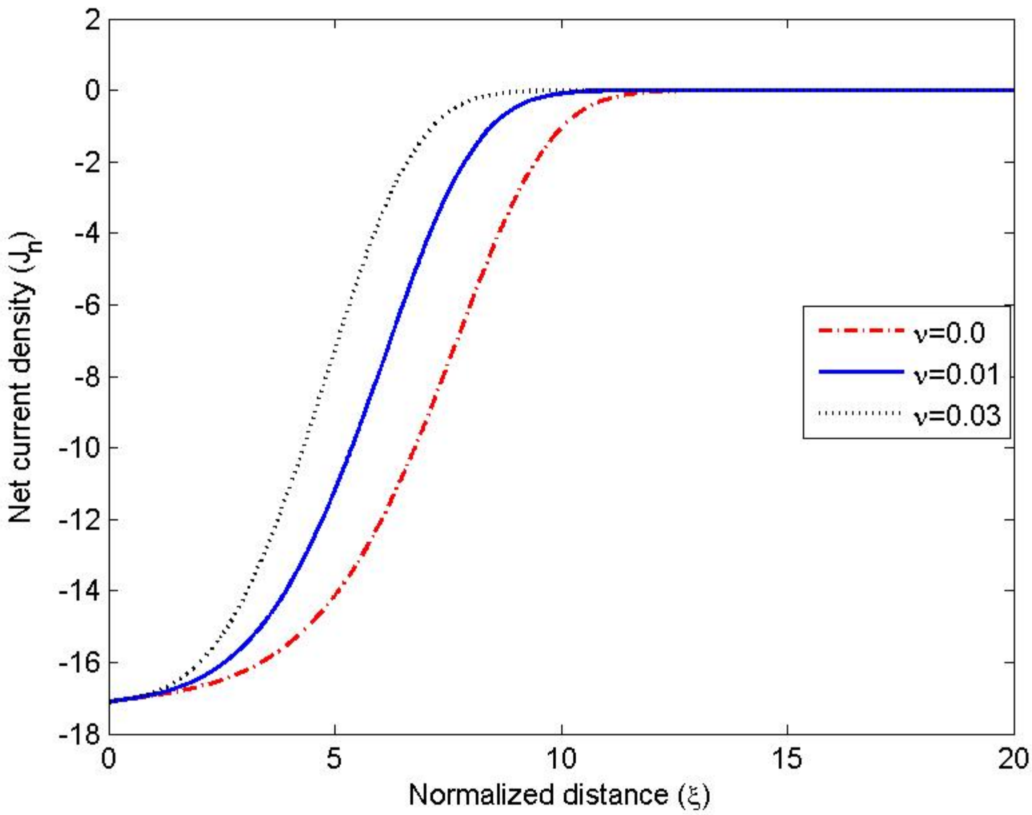

Figure 4.11: Net current density (J_n) as the function of normalized distance (ξ) for the different values of collision frequency.

4.2.6 Kinetic Energy Profile

The kinetic energy (E_k) versus normalized distance (ξ) at constant magnetic field B = 0.137 T and obliqueness $\theta = 30^0$ for three different values of collision frequency is shown in Figure 4.12. The kinetic energy at the sheath edge is the lowest, and its magnitude increases uniformly towards the wall in all instances. Because ions' velocity increases as they approach the wall, their kinetic energy increases as well. The kinetic energy of ions increases at the wall from about 60 to 79 for the increase in collision frequency from 0.00 to 0.03.

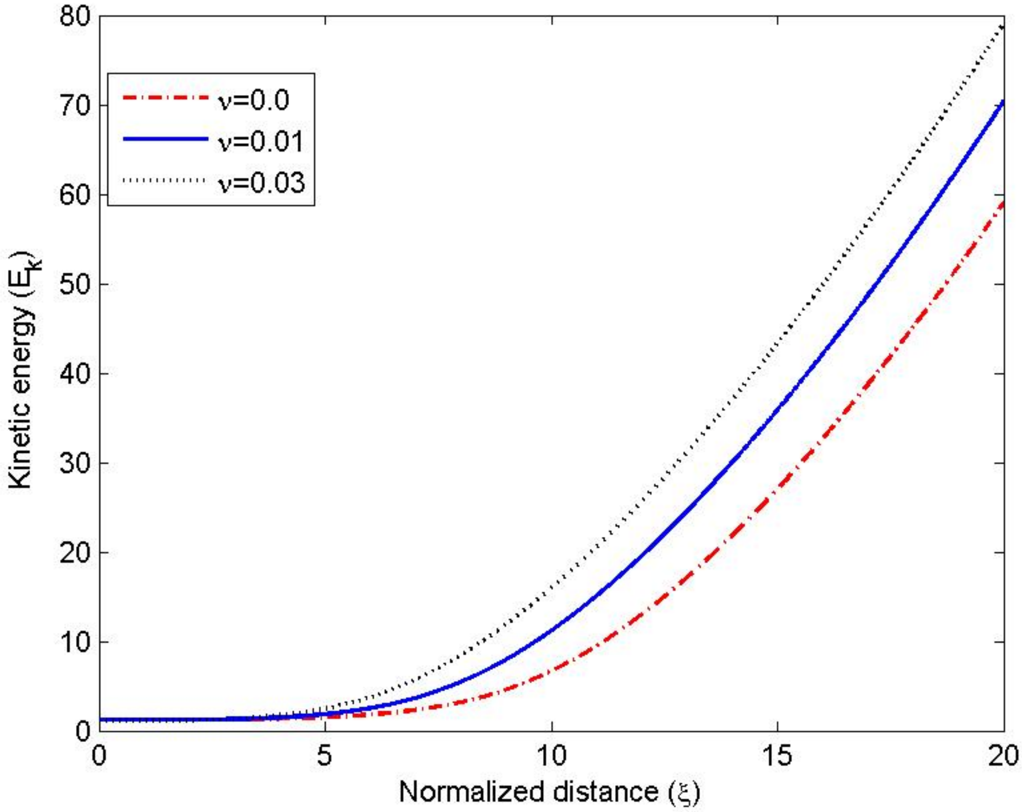

Figure 4.12: Kinetic energy (E_k) as the function of normalized distance (ξ) for the different values of collision frequency.

Chapter 5

Conclusions and Future Prospects

5.1 Conclusions

Using a fluid approach, the effect of collision and ion Mach number on electro-negative magnetized plasma sheath was investigated. The electro-negative magnetized plasma sheath consists of singly charged positive hydrogen ions (H^+), negative chlorine (Cl^-) ions and some neutral particles. In the present work, we assume non-isothermal plasma with $T_e \neq T_i$. The electrons and negative ions are in thermal equilibrium and obey Boltzmann distribution whereas ions follow the fluid equation. In order to study the effect of collision and ion Mach number on electronegative magnetized plasma sheath, the potential profile, ion density profile, ion velocity profile, space charge density profile, net current density profile and kinetic energy profile has been investigated.

It is found that the magnitude of potential increases towards the wall for the increase in collision frequency and ion Mach number to satisfy the Bohm condition. The effect of Lorentz force and collisional force increases near the sheath edge, which causes the accumulation of ions and hence density is maximum at the sheath edge. The bump nature occurs on the density profile at the sheath edge due to the prominent Lorentz and collision force effects, which lead charged particles to spend longer time at the sheath edge. However, the decreasing rate of negative charged particles much faster than ions. The velocity of ions decreases at the sheath edge and increases towards the wall. According to continuity equation, the velocity of ions at the wall increases to conserve the ion flux. It is found that the normalized velocity of ions increases towards the wall. The velocity of ion is increased at the wall as the consequence the kinetic energy of ions gets increased in both case.

On increasing the collision frequency and ion Mach number, the net positive space charge density also increases and shift towards the sheath edge. The net current density increases towards the wall and gets saturated. The saturation point of the net current density shifts towards the sheath edge with the increasing ion Mach number. Finally, it is concluded that the effect of collisional force and Lorentz force at the sheath entrance decreases by increasing the ion Mach number and, which helps to control the particles flux towards the wall. The obtained results are in agreement with previously reported results [13].

5.2 Future Prospects

This work can be extended in future by considering;

(1) Higher dimensional analysis.

(2) The time dependent sheath model.

(3) By varying magnetic field.

(4) Different co-ordinate system.

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Appendix

1. **Input File**

```
close all
clear all
% All parameters are in S.I unit.
e=1.6e-19; %Charge of electron
k=1.38e-23; % Boltzmann constant
ni0=5*10^14; % positive ion density at x=0
ne0=2*10^14; % Electron density at x=0
nn0=0.15*10^14; % negative ion density at x=0
Te=3*11600; % Electron temperature
Ti=0.6*11600; % Ion temperature
T=Ti/Te; % Normalized temperature
sigma=25; % Ratio of electron temperature to the negative ion
temperature
delta=nn0/ne0; % Ratio of negative ion density to electron density at
x=0
mi=1.672e-27; % Mass of ion
me=9.1e-31; % Mass of electron
mn=35.453*mi; % Mass of negative ion
epsilon=8.85419e-12; % Electric free space constant
wpi=sqrt(ni0*e^2/epsilon/mi); % plasma frequency
Cs=sqrt(k*Te/mi); % Acoustic velocity of ion
```

2. **Solution of Fluid Equations**

```
function dx=ishwor(t,x,theta,sigma,gamma,delta,nu,M);
dx=zeros(5,1);
dx(1)=x(2);
dx(2)=M*(1+delta)/x(3)-exp(-x(1))-delta*exp(-sigma*x(1));
dx(3)=(x(2)/x(3)-gamma*sin(theta)*x(5)/x(3)-nu);
dx(4)=gamma*cos(theta)*x(5)/x(3)-nu*x(4)/x(3);
dx(5)=gamma*sin(theta)-gamma*cos(theta)*x(4)/x(3)-nu*x(5)/x(3);
```

3. **Command File**

i. **For Normalized Ion Density, ion Velocity and potential at different Mach number**

```
close all;
clear all;
input;
theta=(pi/180)*30;
B=0.137;
nu=0.01;
wci=e*B/mi;
wpi=sqrt(ni0*e^2/epsilon/mi);
gamma=wci/wpi;
M=1.0;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0
0],[],sigma,gamma,theta,delta,nu,M);
u1=spline(t,x(:,3),0:0.01:20);
N1=M*(1+delta)./u1;
eta1=spline(t,x(:,1),0:0.01:20);
M=1.3;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0
0],[],sigma,gamma,theta,delta,nu,M);
u2=spline(t,x(:,3),0:0.01:20);
N2=M*(1+delta)./u2;
eta2=spline(t,x(:,1),0:0.01:20);
M=1.5;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0
0],[],sigma,gamma,theta,delta,nu,M);
u3=spline(t,x(:,3),0:0.01:20);
N3=M*(1+delta)./u3;
eta3=spline(t,x(:,1),0:0.01:20);
plot(t,N1,'r',t,N2,'b',t,N3,'k');
plot(t,u1,'r',t,u2,'b',t,u3,'k');
plot(t,eta1,'r',t,eta2,'b',t,eta3,'k');
```

ii. **For space charge density (ρ) at different Mach number**

```
close all;
clear all;
input;
theta=(pi/180)*30;
B=0.137;
nu=0.01;
wci=e*B/mi;
wpi=sqrt(ni0*e^2/epsilon/mi);
gamma=wci/wpi;
M=1.0;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0 0],[],sigma,gamma,theta,delta,nu,M);
u1=spline(t,x(:,3),0:0.01:20);
eta1=spline(t,x(:,1),0:0.01:20);
Ni1=(M*(1+delta))./u1;
Ne1=exp(-eta1);
Nn1=delta*exp(-sigma*eta1);
rho1=Ni1-Ne1-Nn1;
M=1.3;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0 0],[],sigma,gamma,theta,delta,nu,M);
u2=spline(t,x(:,3),0:0.01:20);
eta2=spline(t,x(:,1),0:0.01:20);
Ni2=(M*(1+delta))./u2;
Ne2=exp(-eta2);
Nn2=delta*exp(-sigma*eta2);
rho2 = Ni2 - Ne2 - Nn2;
M=1.5;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0 0],[],sigma,gamma,theta,delta,nu,M);
u3=spline(t,x(:,3),0:0.01:20);
eta3=spline(t,x(:,1),0:0.01:20);
Ni3=(M*(1+delta))./u3;
Ne3=exp(-eta3);
Nn3=delta*exp(-sigma*eta3);
rho3 = Ni3 - Ne3 - Nn3;
plot(t, rho1,'r',t,rho2,'b',t,rho3,'k');
```

iii. **For current density (J) at different Mach number**

```
close all;
clear all;
input;
theta=(pi/180)*30;
B=0.137;
nu=0.01;
wci=e*B/mi;
wpi=sqrt(ni0*e^2/epsilon/mi);
gamma=wci/wpi;
M=1;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0 0],[],sigma,gamma,theta,delta,nu,M);
u1=spline(t,x(:,3),0:0.01:20);
eta1=spline(t,x(:,1),0:0.01:20);
Ni1=(M*(1+delta))./u1;
Ne1=exp(-eta1);
Nn1=delta*exp(-sigma*eta1);
J1=Ni1*x(3)-(Ne1*sqrt(0.5*mi/pi/me))-(Nn1*sqrt(0.5*mi/pi/mn));
M=1.3;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0 0],[],sigma,gamma,theta,delta,nu,M);
u2=spline(t,x(:,3),0:0.01:20);
eta2=spline(t,x(:,1),0:0.01:20);
Ni2=(M*(1+delta))./u2;
Ne2=exp(-eta2);
Nn2=delta*exp(-sigma*eta2);
J2=Ni2*x(3)-(Ne2*sqrt(0.5*mi/pi/me))-(Nn2*sqrt(0.5*mi/pi/mn));
M=1.5;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0 0],[],sigma,gamma,theta,delta,nu,M);
u3=spline(t,x(:,3),0:0.01:20);
eta3=spline(t,x(:,1),0:0.01:20);
Ni3=(M*(1+delta))./u3;
Ne3=exp(-eta3);
Nn3=delta*exp(-sigma*eta3);
J3=Ni3*x(3)-(Ne3*sqrt(0.5*mi/pi/me))-(Nn3*sqrt(0.5*mi/pi/mn));
plot(t,J1,'r',t,J2,'b',t,J3,'k')
```

iv. **For Kinetic Energy(E_k) at different Mach number**

```
input;
theta=(pi/180)*30;
B=0.137;
nu=0.01;
wci=e*B/mi;
wpi=sqrt(ni0*e^2/epsilon/mi);
gamma=wci/wpi;
M=1;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0 0],[],sigma,gamma,theta,delta,nu,M);
u1=spline(t,x(:,3),0:0.01:20);
eta1=spline(t,x(:,1),0:0.01:20);
Ni1=(M*(1+delta))./u1;
Ne1=exp(-eta1);
Nn1=delta*exp(-sigma*eta1);
Ek1 = (u1).^2;
J1=Ni1*x(3)-(Ne1*sqrt(0.5*mi/pi/me))-(Nn1*sqrt(0.5*mi/pi/mn));
M=1.3;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0 0],[],sigma,gamma,theta,delta,nu,M);
u2=spline(t,x(:,3),0:0.01:20);
eta2=spline(t,x(:,1),0:0.01:20);
Ni2=(M*(1+delta))./u2;
Ne2=exp(-eta2);
Nn2=delta*exp(-sigma*eta2);
Ek2 = (u2).^2;
J2=Ni2*x(3)-(Ne2*sqrt(0.5*mi/pi/me))-(Nn2*sqrt(0.5*mi/pi/mn));
M=1.5;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0 0],[],sigma,gamma,theta,delta,nu,M);
u3=spline(t,x(:,3),0:0.01:20);
eta3=spline(t,x(:,1),0:0.01:20);
Ni3=(M*(1+delta))./u3;
Ne3=exp(-eta3);
Nn3=delta*exp(-sigma*eta3);
Ek3 = (u3).^2;
J3=Ni3*x(3)-(Ne3*sqrt(0.5*mi/pi/me))-(Nn3*sqrt(0.5*mi/pi/mn));
plot(t,Ek1,'r',t,Ek2,'b',t,Ek3,'k')
```

4. **For a normalized potential, density and velocity of ion at different collision frequency.**

```
close all;
clear all;
input;
M=sqrt(T+1);
theta=(pi/180)*30;
B=0.137;
wci=e*B/mi;
wpi=sqrt(ni0*e^2/epsilon/mi);
gamma=wci/wpi;
nu=0.0;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0
0],[],sigma,gamma,theta,delta,nu,M);
u1=spline(t,x(:,3),0:0.01:20);
N1=M*(1+delta)./u1;
eta1=spline(t,x(:,1),0:0.01:20);
nu=0.01;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0
0],[],sigma,gamma,theta,delta,nu,M);
u2=spline(t,x(:,3),0:0.01:20);
N2=M*(1+delta)./u2;
eta2=spline(t,x(:,1),0:0.01:20);
nu=0.03;
[t, x]=ode45(@ishwor,[0:0.01:20],[0 0.01 M 0
0],[],sigma,gamma,theta,delta,nu,M);
u3=spline(t,x(:,3),0:0.01:20);
N3=M*(1+delta)./u3;
eta3=spline(t,x(:,1),0:0.01:20);
plot(t,eta1,'r',t,eta2,'b',t,eta3,'k');
plot(t,u1,'r',t,u2,'b',t,u3,'k');
plot(t,N1,'r',t,N2,'b',t,N3,'k');
```