Dust in Flowing Magnetized Plasma

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Plasma flows occur in almost every laboratory device and interactions of flowing plasmas with near-wall impurities and/or dust significantly affects the efficiency and lifetime of such devices. The charged dust inside the magnetized flowing plasma moves primarily under the influence of the plasma drag and electric forces. Here, the charge on the dust, plasma potential, and plasma density are calculated self-consistently. The electrons are assumed non-Boltzmannian and the effect of electron magnetization and electron-atom collisions on the dust charge is calculated in a self-consistent fashion. For various plasma magnetization parameters viz. the ratio of the electron and ion cyclotron frequencies to their respective collision frequencies, plasma-atom and ionization frequencies, the evolution of the plasma potential and density in the flow region is investigated. The variation of the dust charge profile is shown to be a sensitive function of plasma parameters.

Keywords: Dusty plasma, magnetic field, flowing plasma, dust charge, plasma potential.

1. Introduction

The experimental work on dust structures, on flowing plasmas in the presence of dust, etc., has attracted considerable interest in the last few years [1]. Dust particles can carry both negative as well as positive charge depending upon the ambient plasma conditions. The charged dusts not only levitate over a negatively charged wall due to balance between the gravitational and electrostatic forces but also move under the action of fields and flows in the plasma [2]. The controlled experiment with massive dust grains in the plasma flows allows us to investigate the spatial and temporal scales hitherto inaccessible by probe techniques. For example, the kinetics of individual dust can be investigated in considerable detail in the presence of plasma sheath [3-5].

The micrometre-sized dust has been utilized as a diagnostic tool to investigate the plasma edge characteristics as well as the characteristics of flowing plasmas (see [6] and references therein). Often presence of the magnetic field is inevitable in all such investigations and, therefore, it is important to study the effect of such a field on the formation of plasma flows. The dust near the plasma edge can acquire positive or negative charge depending upon the field near the plasma-wall boundary. The charging of the dust and its dynamics in the plasma-wall regions have been investigated in the recent past [1, 2, 4-6].

The role of the magnetic field near the plasma wall was examined in Refs. [7, 8]. It is known that the physical characteristics of the magnetized collisional plasma are sensitive to the discharge parameters. For example, it is known that the plasma sheath width decreases with increasing ion–neutral collision frequency or with increasing ionization frequency [8]. On the other hand, the sheath width is not a very sensitive function of electron magnetization. However, ion magnetization causes a significant change in the sheath characteristics as well as the parameters of the sheath plasma flow. These observations were inferred in [8] where a transverse (to the wall) magnetic field was assumed.

Here, we generalize the previous studies and investigate the flowing edge plasma properties in the presence of an oblique magnetic field. The obliqueness of the field determines the charge on the grain inside the plasma flow. We anticipate that the equilibrium and dynamics of dust in the plasma flow will critically depend on the orientation of the magnetic field relative to the direction of the flow. Thus we investigate the effect of an oblique magnetic field on a collisional flowing plasma and explore various limiting cases.

In this work, we have assumed that the dust particles are not numerous and thus, the dynamics of an isolated grain is investigated. The laboratory dusty plasma experiments encompass both low (~1–40mTorr) as well as high (~50mTorr) neutral pressure regimes [1, 2]. In the high pressure limit, the plasma–neutral collision affects the structure of the plasma flow and consequently, the dynamics of the dust. Further, the ionization in the plasma could also become important in the high pressure regime. Therefore, the charge on the dust, plasma potential, and plasma drag forces are calculated self-consistently in the present work. The electrons are assumed non-Boltzmannian and the effect of electron magnetization

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and electron-atom collisions on the dust dynamics is calculated in a self-consistent fashion.

2. The plasma model

A two-component plasma consisting of electrons and singly charged ions is considered in the presence of a magnetic field that is at an oblique angle to the direction of the plasma flow. The plane plasma boundary is located at $z = 0$ with the plasma filling the half space $z < 0$ and $\boldsymbol{B}/B = (\sin\theta, 0, \cos\theta)$. The description of such a plasma is given in terms of continuity and momentum equations for respective species with a suitable closure model, namely, an equation of state. The equations are

$$\frac{d}{dz}(n_i v_i z) = \nu_I n_e,$$

$$\frac{d}{dz}(n_e v_{ez}) = \nu_I n_e,$$

$$v_{iz}\frac{dv_{iz}}{dz} = \frac{e}{m_i}E_z - \omega_{ci}v_{iy}\sin\theta - \frac{v_{ti}^2}{n_i}\frac{dn_i}{dz} - \nu_{in}v_{iz},$$

$$v_{iz}\frac{dv_{iy}}{dz} = \omega_{ci}(v_{iz}\sin\theta - v_{ix}\cos\theta) - \nu_{in}v_{iy},$$

$$v_{iz}\frac{dv_{ix}}{dz} = \omega_{ci}v_{iy}\cos\theta - \nu_{in}\,v_{ix},$$

$$0 = -\frac{e}{m_e}E_z + \omega_{ce}v_{ey}\sin\theta - \frac{v_{te}^2}{n_e}\frac{dn_e}{dz} - \nu_{en}v_{ez},$$

$$0 = \omega_{ce}(v_{ez}\sin\theta - v_{ex}\cos\theta) + \nu_{en}v_{ey},$$

$$0 = \omega_{ce}v_{ey}\cos\theta - \nu_{en}v_{ex}.$$

Here, m_j is the mass, $v_{tj} = (T_j\ / m_j)^{1/2}$ is the plasma thermal velocity, v_{jz} and v_{jy} are the z and y components of the plasma fluid velocities, $E_z = -\, d\varphi / dz$ is the sheath electric field and $\omega_{cj} = |e|\ B\ /\ m_j c$ is the cyclotron frequency. The electron inertia has been neglected while writing these equations. The $\nu_I = \gamma_I\ \ n_n$ is the ionization frequency and $\nu_{j\,n} = \langle\sigma v\rangle_j\, \rho_n / (m_n + m_j)$. Here, m_n and n_n are the mass and the number density of the neutral particle, respectively. Note that in these equations, the electron–ion and ion–electron collisions have been neglected in comparison with their collisions with the neutrals. While calculating $\langle\sigma v\rangle_{i\,n}$, $T_i = 0.05$ eV was assumed.

We shall write down the above set of equations in the normalized coordinates

$$\hat{\nu}_I = \frac{\nu_I}{\omega_{pi}},\quad \hat{\nu}_{in} = \frac{\nu_{in}}{\omega_{pi}},\quad \hat{\nu}_{en} = \frac{m_e\nu_{en}}{m_i\omega_{pi}}$$

$$\xi = \frac{z}{\lambda_{De}},\quad \Phi = \frac{e\phi}{T_e},\quad N_j = \frac{n_j}{n_0},\quad u_j = \frac{v_j}{c_s},$$

Here, $c_s = (T_e\ /\ m_i)^{1/2}$ is the ion-acoustic speed, $\lambda_{De} = (T_e/4\pi n_0 e^2)^{1/2}$ is the electron Debye length and $\omega_{pi} = (4\pi n_0 e^2/m_i)^{1/2}$ is the ion plasma frequency. The plasma number density n_0 corresponds to the quasineutral density at the plasma-sheath boundary $z = 0$. We note that the electron-Debye length and plasma frequencies are defined by using n_0 which is the reference plasma number density and will not change with the changing number density inside the sheath.

The following normalized set of equations can be written as

$$\frac{dN_i}{d\xi} = \frac{N_i}{(u_{iz}^2 - (T_i/T_e))}\left[\frac{d\Phi}{d\xi} + \nu_{in}(u_{iz} + \beta_i u_{iy}\sin\theta) + \nu_I\frac{n_e}{n_i}u_{iz}\right],$$

$$\frac{du_{iz}}{d\xi} = -\frac{u_{iz}}{(u_{iz}^2 - (T_i/T_e)}\left[\frac{d\Phi}{d\xi} + \nu_{in}(u_{iz} + \beta_i u_{iy}\sin\theta) + \nu_I\frac{T_i}{T_e}\frac{n_e}{n_i}\frac{1}{u_{iz}}\right],$$

$$\frac{du_{iy}}{d\xi} = \nu_{in}\beta_i\left(\sin\theta - \frac{u_{ix}}{u_{iz}}\cos\theta\right) - \nu_{in}\frac{u_{iy}}{u_{iz}},$$

$$\frac{du_{ix}}{d\xi} = \nu_{in}\beta_i\frac{u_{iy}}{u_{iz}}\cos\theta - \nu_{in}\frac{u_{ix}}{u_{iz}},$$

$$\frac{dN_e}{d\xi} = N_e\left[\frac{d\Phi}{d\xi} - \nu_{en}\left(\frac{1+\beta_e^2\sin^2\theta}{1+\beta_e^2\cos^2\theta}\right)u_{ez}\right],$$

$$\frac{du_{ez}}{d\xi} = -\left[\frac{d\Phi}{d\xi} - \nu_{en}\left(\frac{1+\beta_e^2\sin^2\theta}{1+\beta_e^2\cos^2\theta}\right)u_{ez}\right]u_{iz} + \nu_I,$$

$$\frac{d^2\Phi}{d\xi^2} = N_e - N_i.$$

Here, β_j, which is the ratio of plasma-cyclotron to plasma-collision frequencies, a measure of the relative importance of Lorentz force against the collisional momentum exchange in the plasma momentum equation. For example, if $\beta_j << 1$ then one may assume that the plasma is weakly magnetized, whereas in the opposite limit, the plasma is frozen in the magnetic flux. The above set of equations is supplemented by the boundary conditions $N_e = N_i = 1$, $u_{iz} = 1$, $u_{iy} = 0$, $u_{ex} = u_{ez} = 0$, $\Phi = 0$, $d\Phi/d\xi = -\nu_{in}$.

We use the above set of equations with the corresponding boundary conditions to investigate the flowing plasma edge structure in various parameter regimes. The consistency of our equations with the boundary conditions requires $\nu_I = 0$ at the plasma boundary. Therefore, we have assumed that the electric field has a finite value at the plasma boundary. We thus solve the equations with the boundary conditions $\Phi = 0$, $d\Phi/d\xi = 0$.

We show that they are very similar to the case when $d\Phi/d\xi \neq 0$. The edge potential can be determined by knowing the detailed particle orbit and its interaction with the wall. However, this work is not concerned with the self-consistent calculation of the edge potential and thus determines the edge potential from the location of zero electron density. While writing the condition at the plasma boundary, we have assumed the Bohm criterion $u_{iz} = 1$.

It should be pointed out that in a magnetized plasma, the Bohm criterion will only be approximate as strongly magnetized ions will be inhibited from reaching the acoustic speed at the boundary. Our numerical solution of the problem assumes u_{iz} = 1for both strongly and weakly magnetized cases. Therefore, in the strongly magnetized case these results will somewhat overestimate the absolute value of the edge potential although the basic plasma characteristics will not change.

3. Results

In figures 1(a)–(d), the parameters $\beta_i = 0.1$, $\beta_e = 10$, $\nu_I = 0.001\omega_{pi}$, $\nu_{i,en} = 0.1\omega_{pi}$ are fixed and the angle between the magnetic field and the direction of plasma flow, θ, is varied. Recall that collision frequencies are given in the units of the ion plasma frequency. We give the plot for $\theta = \pi/2$, i.e. when the field is perpendicular to the flow (dotted curve) and when the field is parallel to the flow, $\theta = 0$. When the magnetic field is perpendicular to the flow ($\theta = \pi/2$), the effect of the magnetic field is diminished on the plasma flow. Whereas the *z* component of the plasma flow does not feel the Lorentz force, the *x* and *y* components of the flow are affected by the magnetic field. For $\beta_e = 10$, the *x* and *y* components of the electron flow are strongly inhibited by the field. And since the *z* component of the flow is unaffected by the presence of the field, the plasma edge will have a larger negative potential. For $\theta = \pi / 2$ the plasma edge potential reaches −10 corresponding to −10 V for T_e = 1 eV at $z = 8\,\lambda_{De}$. The increase in the angle leads to the change of the flow structure (for $\theta = 0$ the plasma edge potential is ~2.5 V).

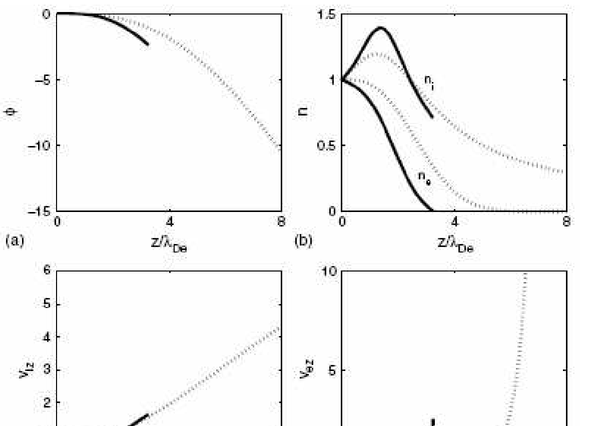

Fig.1 The plasma potential (a) and ion and electron number densities (b), ion (c) and electron (d) velocity profiles for $\theta = \pi/2$ (dotted line) and $\theta = 0$ (solid line). The collision and magnetization parameters are $\nu_I = 0.001\omega_{pi}$, $\nu_{i,en} = 0.1\omega_{pi}$, $\beta_i = 0.1$, $\beta_e = 10$.

The ion and electron number densities (figure 1(b)) decrease faster with the decrease in the angle with the direction of the flow. In figures 1(c) and (d), the *z* component of the ion and electron velocities are shown. As seen from figure 1(c), the decrease in the angle causes a significant decrease in the ion velocity. With the decrease in θ, all three components of the ion flow velocity feel the Lorentz forces and, thus, the decrease in θ causes a significant decrease in the ion velocity. The ion number density plot (figure 1(b)) shows an increase in the density, keeping the ion flux constant. The electron velocity shows a sharp rise in the velocity towards the plasma edge.

In order to calculate the charge on a micrometer-sized grain placed in the plasma flow, we employ the orbit motion limited (OML) theory of grain charging [1, 2]. This implies that for a spherical grain of radius *a*: (1) $a \ll \lambda_{De}$ and (2) $a \ll \rho_e \equiv v_{te}/\omega_{ce}$.

In figures 2(a) and (c) the charge on the grain is calculated using OML theory for $\beta_i = 0.1$, $\beta_e = 10$ and $\beta_i = 5$, $\beta_e = 10\ \beta i$. The other parameters are similar as for figure 1. The charge is given in units of $10^3\ e$. We see from figure 2(a) that when $\theta = \pi / 2$ (dotted curve), i.e. the magnetic field is not affecting the *z* component of the plasma flow, the grain will have less negative charge in comparison with $\theta = 0$ (solid curve). In addition, for $\theta = \pi / 2$, the grain near the plasma edge acquires a large positive charge.

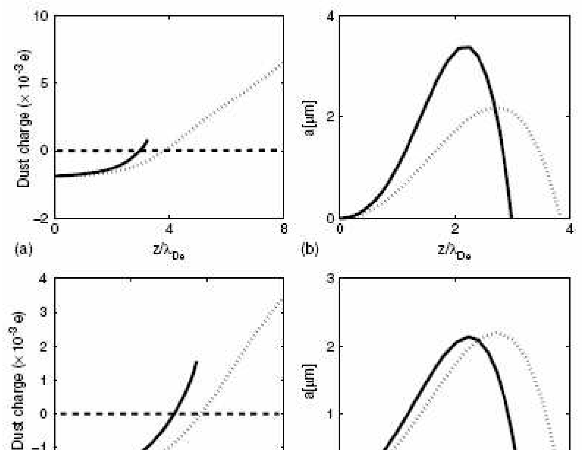

Fig.2 The dust charge (a) and (c), and the distribution of dust particles of different sizes (b) and electron (d) in the flowing plasma for $\beta_i = 0.1$, $\beta_e = 10$ (a) and (b), and for $\beta_i = 5$, $\beta_e = 10$ (c) and (d). The collision parameters are $\nu_I = 0.001\omega_{pi}$, $\nu_{i,en} = 0.1\omega_{pi}$. The dotted line corresponds to $\theta = \pi/2$ and the solid line corresponds to $\theta = 0$.

When $\theta = 0$, the z-component of the plasma flow is inhibited by the Lorentz force resulting in smaller grain charge (figure 2(b)). Since the structure of the plasma flow changes (figure 1(a)) for this case, the profile terminates at ~ 3.6 with a very small positive charge on the grain near the plasma edge.

With the increase in the ion magnetization, i.e. $\beta_i = 5$, the dust acquires smaller positive charge (figure 2(c)) in comparison with the previous case. This should be anticipated since the increase in the ion magnetization implies that the Lorentz force inhibits the ion flow strongly in comparison with the $\beta_i = 0.1$ case. This results in fewer ions reaching the grain surface in the plasma flow. Thus we see (figure 2(c)) that the grain acquires less positive charge in comparison with the weakly magnetized case.

3. Conclusions

To summarize: The flowing plasma characteristics are sensitive functions of the ambient magnetic field direction with respect to direction of the flow. The most pronounced effect of the field is felt by the flows across the field. The effect of the field on the other components of the flow is somewhat weaker, but not insignificant.

The profile of the flowing plasma is changed with changing angle between the field and the flow. The grains are negatively charged inside the plasma except near the edge area where the grain charge could become positive. When the magnetic field is parallel to the flow, grains of smaller size stay deeper inside the flow in comparison with the case when the field is directed perpendicular to the flow.

The profiles of the flow parameters change significantly not only when the ion cyclotron frequency is increased by an order of magnitude but also by the angle of the field orientation. Therefore, ion magnetization and field direction causes significant change in the flowing plasma characteristics. With the increase in the ion-magnetization level, or the decrease in the angle θ between the field and the flow, the flow velocity increases. The grains acquire less negative charge. The grains of larger size can stay inside the plasma flow with increased magnetization.

Acknowledgments

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