Formation of Sheath in the Presence of Dust: An Analysis of the Forces

R. Moulick

Department of Physics
School of Chemical Engineering and Physical Sciences
Lovely Professional University
Phagwara, Punjab – 144411 (India)

Abstract

Dust in plasma is an important consideration for many processing experiments. Even in fusion relevant experiments, dust is an unavoidable particle. Hence, it is important to understand the overall dynamics of the particle inside the plasma chamber. In this paper, various forces on the dust particle and their nature is analyzed during the formation of sheath. Dust particles are assumed to be dropped via a dust dropper and the dynamics is pursued from the bulk of the plasma to the wall. Results are obtained for varying ion temperature and it is observed to yield important consequences both on the dust charging and overall dust dynamics.

Keywords: *Plasma Sheath, Dust-In-Plasma, Dust Particles, Drag Force.*

1. Introduction

The fourth state of matter, a soup of electrons and ions, and dynamically vibrant state of matter is known as the plasma [1], [2]. It has a dynamically rich variety of phenomena occurring in it-and has a high tendency of being unstable. Plasma, which is in contact with a wall forms a thin layer of positively charged particles, known as the sheath. This thin layer is responsible for the electrostatic shielding of the plasma [3]–[5].

Dust particles are the tiny particles present in the plasma [6]. They may be originated as a product of electron hitting the wall or corrosion of the wall. Often, dust particles are dropped into the plasma chamber in order to perform rich variety of complex plasma experiments. For doing this, a dust dropper is associated with the plasma chamber [7]. Performance of experiments related to the dust crystallization requires a negatively biased metal plate to be inserted into the plasma. The dust particles dropped off the dust dropper falls under gravity and are deposited near the metal plate. A schematic of the problem is shown in the following figure-1.

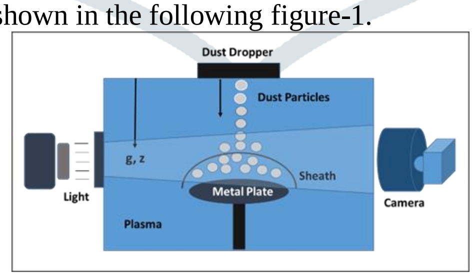

Figure 1. Schematic of the problem

In this article, the prime objective is to study the non-neutral region or the plasma sheath in the presence of dust particles. In addition, the effect of collision is also highlighted. There are however two regimes of collision. The first being the regime of constant collision cross section and the second is that of the constant collision frequency [8]. This is an important consideration in the field of plasma surface interaction. From the recent past, fusion experiments are gaining momentum. Dust in sheath must be understood in order to eliminate the possibility of unwanted contamination of the plasma [9], [10].

Once the dust particle in present in the plasma, it may have various forces acting on it namely the electrostatic force, ion drag force, neutral drag force, gravitational force. This piece of work is concerned with the presence of the three most vital of them i.e. electrostatic force, ion drag force and gravitational force. For extremely small particles, the gravitational force may be neglected. In this paper, we comment on effect of ion-electron temperature ratio on the dust charge and forces on the dust particles at moderate collision. This in turn will have its effect on the dust crystallization.

In the following, section 2 discusses the basic equations used in the modelling. Evolution of plasma profiles have been discussed in the section 3 and finally the paper is concluded in section 4.

2. Basic Equations and Modelling

The problem is modelled via fluid equations considering the ion continuity and momentum equations. Fluid equations are also considered for the dust particles and electrons are considered to be Boltzmann distributed. The vertical direction is considered as the z-direction and it is aligned with the direction of gravity (as clear from the schematic).

The ion continuity and momentum equations are written as follows.

$$\frac{d}{dz}(n_i v_i) = \nu_{ni} n_e - \nu_{id} n_d \quad (1)$$

$$n_i m_i v_i \frac{dv_i}{dz} = -n_i e \frac{d\phi}{dz} - \nu_i n_i m_i v_i \quad (2)$$

In the ion continuity equation, the first term account for the ion-electron pair produced through ionization and the second term accounts for the loss of the ions to the dust particles. The loss happens as a process of shielding the dust or by attachment with the surface. In the ion momentum equation, only the electrostatic term and the ion neutral collision term has been used.

Here the symbols have their usual meaning (Refer [11]) except for ν_{ni}, ν_{id} and ν_i, which represents the frequency of ionization, frequency of ion-dust attachment and frequency of ion-neutral collision.

The continuity and momentum equations for the dust particles are given by

$$\frac{d}{dz}(n_d v_d) = 0 \quad (3)$$

$$n_d m_d v_d \frac{dv_d}{dz} = -n_d q_d \frac{d\phi}{dz} + n_d m_d g + n_d F_i \quad (4)$$

Since there is no generation or loss of the dust particles, the right hand side of equation (3) is zero. In equation (4) the three terms on the right correspond for the electrostatic force, gravitational force and the ion drag force respectively. Again, the ion drag force is expressed as the sum of collection drag and coulomb drag (Refer [11] for detailed expressions).

The governing equation for the electrons can be written as

$$T_e \frac{dn_e}{dz} = n_e e \frac{d\phi}{dz} \quad (5)$$

Finally, the above set of equations are closed via the Poisson's equation

$$\frac{d^2\phi}{dz^2} = -\frac{e}{\epsilon_0}(n_i - n_e) - q_d n_d \quad (6)$$

For collisional dust charging, the charging equations provided by Khrapak et al.[12] has been used.

$$I_i = 4\pi r_d n_0 D_i \frac{\left(\frac{\eta_d}{\gamma}\right)}{1-\exp\left(-\frac{\eta_d}{\gamma}\right)} \quad (7)$$

$$I_e = \sqrt{8\pi}\, r_d^2 n_0 v_{Te} \exp(-\eta_d) \quad (8)$$

Here, v_{Te} is the thermal velocity of the electrons and γ, r_d, n_0, D_i are the temperature ratio of the ions and the electrons, dust radius, equilibrium plasma density and the diffusion coefficient respectively. η_d is the normalized dust surface potential.

For the purpose of modelling collision, two models have been used namely the constant collision cross section and constant collision frequency. Collision parameter in each case can be written as

$$K = \frac{\lambda_{ni}}{\lambda_i}$$

However, the collision frequency is expressed as follows.

a. For constant collision cross section

$$\nu_i = \frac{|v_i|}{\lambda_i}$$

b. For constant collision frequency

$$\nu_i = \frac{c_s}{\lambda_i}$$

We however restrict ourselves to the use of the first collision model. The above equations are normalized using appropriate normalization constants (as proposed in reference [11]) and solved using an ode-45 routine available in MATLAB.

3. Results and Discussions

In this section we concentrate on the evolutionary profiles of various forces acting on the dust particle, based on the constant collision cross section model. In the figures below, the left hand side is the bulk side of the plasma, while the right hand side represents the wall.

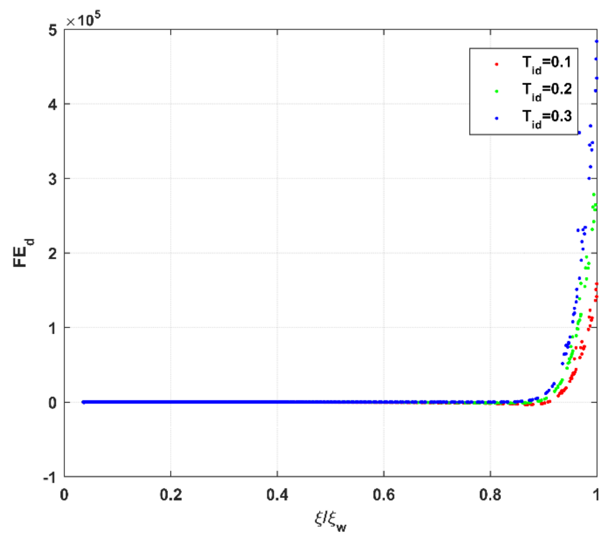

Figure 2. Evolution of the electrostatic force on the dust particles at different temperature ratios

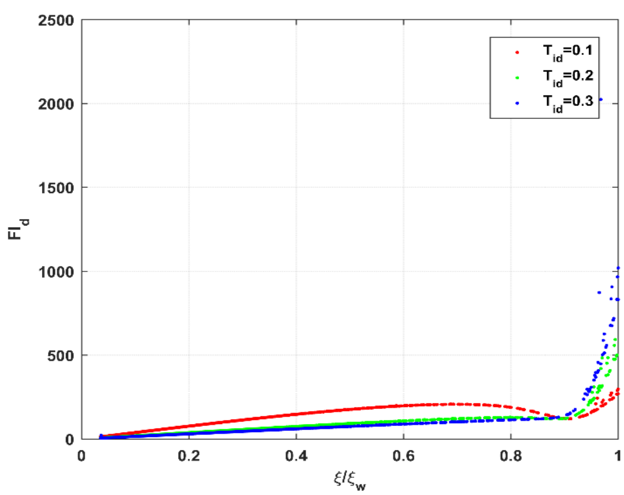

Figure 3. Evolution of Ion drag force on the dust particles at different temperature ratios

Figures 2 and 3 depict the evolution of the electrostatic and ion drag force on the dust particles with space coordinates at varying ion-electron temperature ratios. It is evident that, electrostatic force comes in action only when the dust is in the field of the wall potential. Prior to this region the electrostatic force remains dormant and does not affect the dust dynamics. On the other hand, ion drag force is present from the very beginning of the dust dynamics. Near the wall it increases its magnitude, although the magnitude is less than the electrostatic force.

It is observed that with the increase in the ion to electron temperature ratio, the ion drag force on the dust decreases in the bulk region of the plasma. However, the same is enhanced beyond the sheath edge towards the wall. Electrostatic force however, responds proportionally with the increasing temperature ratio. It is also evident from the figure-2, electrostatic force has a tendency to become negative in front of the wall at even at moderate level of collision. With the increase in the temperature ratio, this tendency decreases and electrostatic force remains positive all throughout the domain. In front of the wall, the dust particles are repelled. As a result of this, electrostatic force has a tendency to go negative. However, with the increase in temperature ratio, the repulsion is reduced in magnitude, which results in the overall positive evolution of the electrostatic force. In order to understand this let us refer to figure-4.

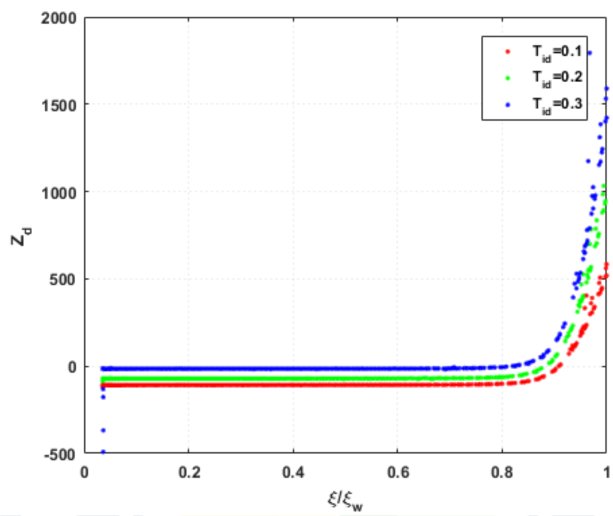

Figure 4. Evolution of the dust charges with different temperature ratio.

Figure 4 shows the evolution of the dust charges at different temperature ratios. An interesting fact that is observed is that the dust charges are seen to increase with increasing temperature ratio of the ions. The observation depicts that with increasing ion temperature, the overall dust charge is seen to be positive with respect to the other temperature ratios. This happens by the enhanced ion mobility. The ions are responsible for making the dust surface more and more positive. This in turn reduces the repulsive nature of the dust near the wall. In short, this gives us a hint that the dust will rather be attracted towards the wall instead of being repulsive, with increased ion temperature.

4. Conclusions

This article is concerned with variation of various forces on the dust particles at different values of ion-electron temperature ratio. The observations yield important results. The results are summarized below.

a. With the increasing temperature of the ions the overall dust charge remains positive.
b. Due to the positive nature of the dust charge, the dust particles are attracted by the wall rather than being repulsive.
c. Ion drag force flips its magnitude in the bulk region and within the plasma sheath.

The consequences are important from the perspective of the dust dynamics for dust crystallization, fusion chambers and other processing chambers.

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