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Modelling of PKE-Nefedov dusty plasma micro-gravity experiments

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I. INTRODUCTION

In order to eliminate the dominant force due to gravity, micro-gravity experiments have been set up to study the behaviour of micron-sized particles in gas discharges. These experiments have been carried out in the International Space Station (ISS). Interesting phenomena, such as the formation of a 3D crystal have been observed in the PKE experimental set-up [1]. The 3D Coulomb crystal that is formed surrounds a dust-free region, the so-called 'void'. The mechanism behind the formation of this void is not yet clearly identified. In a previous article [2] we described a fluid model for a dusty discharge. With this model we have shown that the ion drag force is the best candidate to describe the mechanism behind the formation of the void, provided the standard ion drag force expression proposed by Barnes et al [3] is enhanced at least by a factor five.

We have extended this model by taking also the dust particle material heating into account, to model its effect on the gas temperature profile. In this paper we mainly discuss a study of the importance of self-consistent modelling in the case of an argon discharge containing a large amount of dust particles. Also a new ion drag force expression proposed by Khrapak et al. [4] will be discussed. Classical scattering theory [5] used to calculate the momentum-transfer cross section between the positive ions and the particles in glow discharges seems to underestimate the ion-dust elastic scattering. The analysis carried out by Khrapak shows that for a range of values of the plasma coupling parameter β ($\beta = Ze^2/\lambda_D m_i v_i^2$, where Z is the dust charge number, λ_D is the linearized Debye length, m_i is the ion mass and v_i the ion velocity), the ion drag force usually exceeds the electrostatic force in the limit of a weak field. Implementation of this new ion drag force expression in our model may eliminate the necessity to enhance the ion drag force.

II. DUST MODEL

We have developed a two-dimensional fluid model for an argon-dust discharge in which the dust particles are also treated as a fluid. Further details about this model are described in a previous article [2]. In this paragraph we mainly focus on the newly added mechanism in the model that deals with the dust particle material heating. Also the implementation of the new ion drag expression will be shortly discussed.

To model the plasma-dust particle interactions it is important to know the energy fluxes towards and from the dust particles, the balance of which results in a certain dust particle material temperature. The dust particle material temperature can effect the gas temperature which in turn could effect the other elementary processes in the plasma.

The thermal balance of the particles can be written for dust particles as an equality between the thermal influx Q_{in} and the thermal outflux Q_{out}. For a stationary situation the thermal influx Q_{in} is given by $Q_{in} = J_{rec}$, where J_{rec} is the recombination energy flux of the ion-and electron flux towards the dust particles surface. For a maxwellian electron energy distribution function, J_{rec} is given by:

$$J_{rec} = n_d n_e \sqrt{\frac{k_B T_e}{2\pi m_e}} \exp\left(\frac{eV_{fl}}{k_B T_e}\right) E_i , \qquad (1)$$

where n_d is the dust density, n_e is the electron density, T_e is the electron temperature, m_e is the electron mass ,V_{fl} is the floating potential and E_i the ionisation energy, which is 15.7 eV for argon.

The thermal output flux Q_{out} is given by: $Q_{out}=J_{th}+J_{rad}$. In the pressure range considered here, the thermal conduction by the gas J_{th} is governed by the Knudsen theory [6]. J_{rad} is the radiative cooling. J_{th} is given by:

$$J_{th} = \frac{\gamma+1}{16(\gamma-1)} \frac{p}{\sqrt{T_g}} \sqrt{\frac{8k_B}{\pi m}} \alpha (T_p - T_g) , \qquad (2)$$

where $\gamma=c_p/c_v$ is the heat capacity ratio, m is the gas molecule mass, p is the gas pressure, T_p is the dust particle material temperature, T_g is the gas temperature and α is the accommodation coefficient.

The radiation cooling term J_{rad} follows directly from the Stefan-Boltzmann law:

$$J_{rad} = \varepsilon\sigma (T_p^4 - T_w^4) , \qquad (3)$$

where ε is the emissivity, σ is the Stefan-Boltzmann constant and T_w is the wall temperature.

For an argon discharge γ=5/3 and α=0.86 have been suggested in the literature [7]. The emissivity of the melamine-formaldehyde (MF) particles that are used in the PKE-Nefedov experiments is supposed to be 0.9 [8]. Equation 2 and 3 are coupled to the temperature balance for the gas and solved with an iterative method.

The next item that has been added in our model is Khrapak's ion drag force expression:

$$F_i = \frac{8\sqrt{2\pi}}{3} \beta \lambda_D^2 \Gamma_i m_i v_{th} , \qquad (4)$$

where Γ_i is the ion flux and v_{th} is the thermal velocity of the ions. Equation 4 is an approximation and is only applicable for sub-thermal ion-drift velocities. Also the plasma coupling parameter β has to be in a certain range, 1<β<10. Further details are described in Khrapak's article.

III. RESULTS AND DISCUSSION

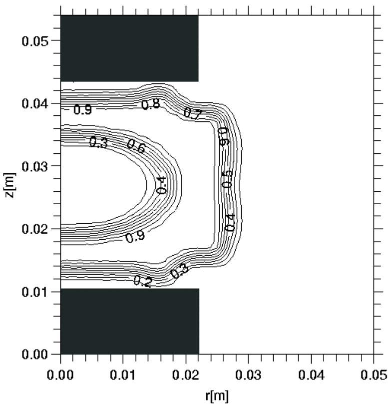

Figure 1. Dust density profile normalized with a factor $1.5\text{x}10^{10}$ m^{-3}.

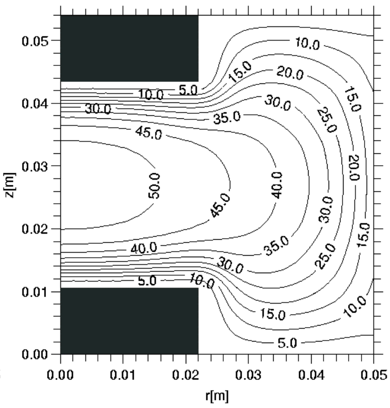

Figure 2. Time-averaged potential distribution V(r,z) in a dust-free plasma.

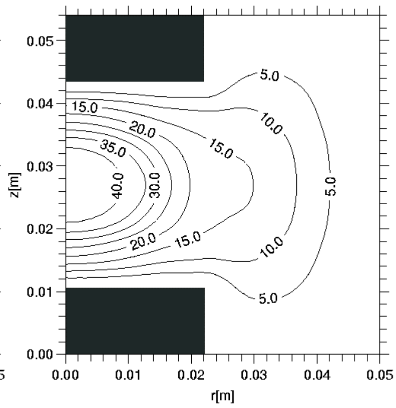

Figure 3. Time-averaged potential distribution V(r,z) in a dusty plasma.

The PKE chamber has been modelled. The reactor is cylindrically symmetric. The electrodes are both driven by a radio-frequency power source at a frequency of 13.56 MHz,. The peak-to-peak voltage is 70 V, this results in a power dissipation of about 0.04 W. The pressure is 40 Pa. The reactor wall temperature is assumed to be 273 K. The dust particle radius is 7.5 μm. The simulation starts with a zero dust density profile. During the simulation dust particles are injected from the electrodes by making use of a source term, the injection rate is about 250000 particles per second. The result is a dust crystal consisting of 700000 dust particles, with a void in the middle [Fig1.]. This result has been obtained using the standard ion drag force expression of Barnes enhanced with a factor 5. The ion drag force equation of Khrapak gives an enhancement of the ion drag force in the void region of at least a factor 5 compared to Barnes expression. Khrapak makes use of the unscreened-Coulomb potential to get an analytical expression for the orbital cross section, which makes equation 4 not valid for large dust particle sizes. To stay within the β limit, the dust particle radius must be smaller than 2 μm in our model. Comparing figure 2 and 3, a significant change in the plasma potential can be observed. The plasma potential decreases in the centre of the discharge in the case of a dusty plasma. This shows the importance of taking into account both the contribution of the charge on the dust in the Poisson equation and the recombination on the dust.

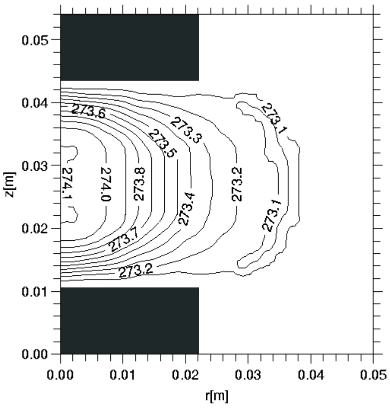

Figure 4. Gas temperature in a dusty plasma in K.

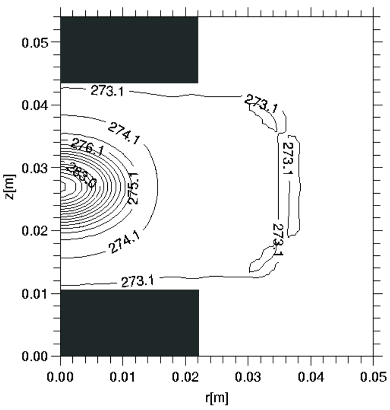

Figure 5. Dust particle material temperature in a dusty plasma in K.

Both mechanisms must be coupled in a self-consistent manner to the rf behaviour of the discharge. Figure 4 shows the gas temperature in a dusty plasma. The maximum temperature gradient in axial direction is about 1 K/cm. In figure 5, it can be seen that if a dust particle would settle in the centre of the discharge it would get a maximum temperature of 283.5 K.

IV.CONCLUSIONS

We have shown that modelling of a dusty plasma should include the influence of the dust on the potential distribution and the plasma density. Study of Khrapak's theory shows that for the plasma settings we have used it gives an enhancement of the ion drag force of at least a factor 5 compared to Barnes. For the modelled plasma settings the dust particle radius should be smaller than 2 μm to stay within the β limit. Calculations of the dust particle material temperature show that it can differ considerably from the gas temperature at certain positions in the plasma.

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